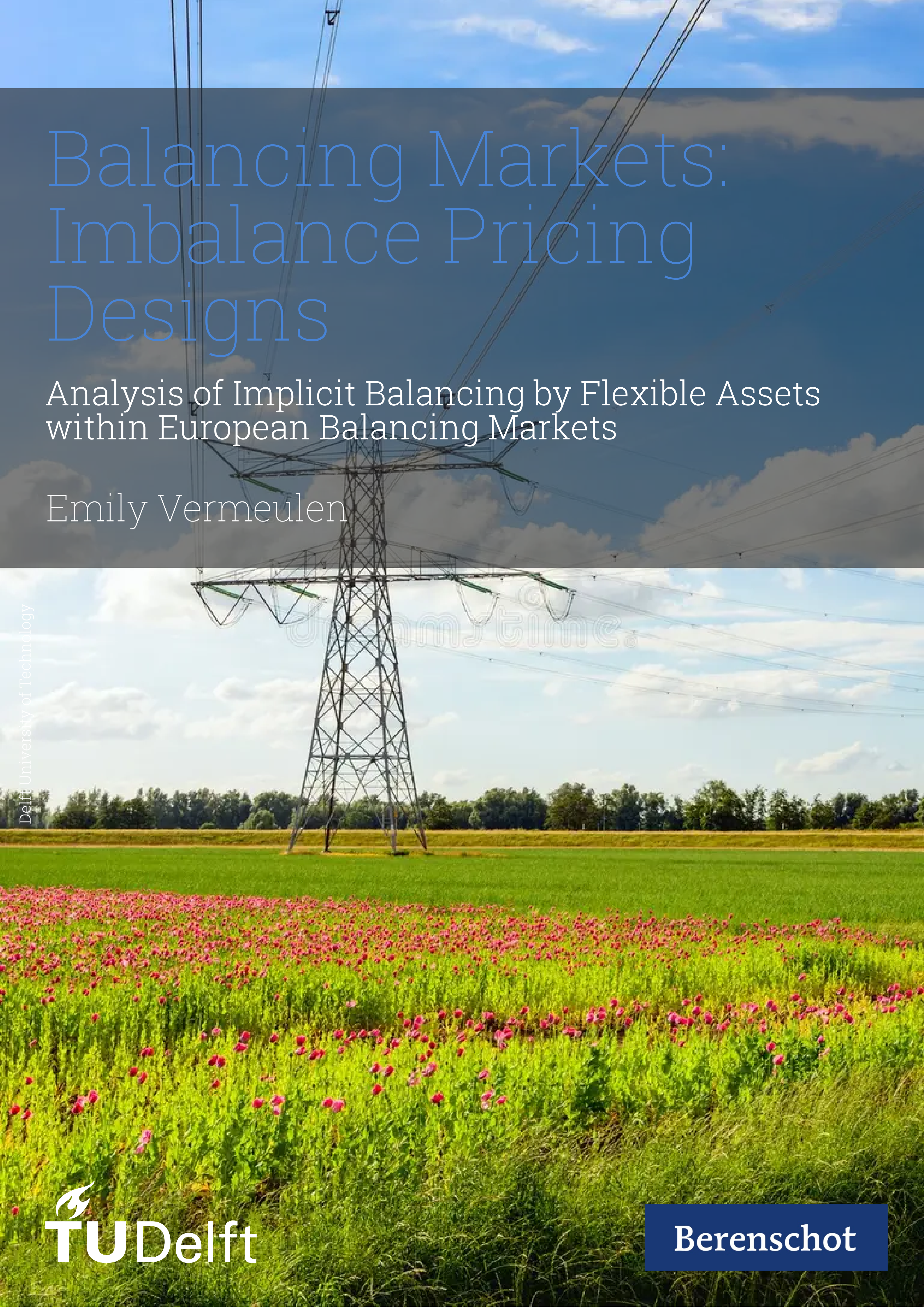

Balancing Markets: Imbalance Pricing Designs

Analysis of Implicit Balancing by Flexible Assets within European Balancing Markets

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Analysis of Implicit Balancing by Flexible Assets within European Balancing Markets

by

Emily Vermeulen

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The process of writing this master's thesis has been intellectually demanding but also fulfilling. Taking a deep dive into the balancing market has been a fascinating challenge, given its technical complexities and the distinctive characteristics of electricity markets from a technical, institutional, and economic perspective. I especially value the challenge of integrating the technical aspects of balancing market structures and pricing mechanisms into a coherent model, while maintaining a broader perspective on the implications and significance of the results.

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Emily Vermeulen
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Executive summary

The increasingly integrated renewable energy sources have a strong intermittency in electricity supply, resulting in increasing mismatches between electricity supply and demand. This has led to an increase in imbalances in the electricity grid, heightening the need for regulating power, such as flexible assets. Currently, the balancing markets are experiencing a high volatility in system imbalance and imbalance prices, resulting in market and system instability.

Previous studies have largely focused on how renewable energy sources lead to an increase in system imbalance and have stressed the need for flexible assets. Furthermore, several studies show that flexible assets can make significant profits in today's balancing markets by optimising their implicit balancing strategy. However, little attention has been devoted to the price incentives provided by the different pricing designs in the EU and how their remuneration structure affects the implicit balancing behaviour of flexible assets. As flexible assets are increasingly deployed on the balancing market, any strategic or gaming behaviour might have a significant negative impact on grid stability and system costs. Therefore, this research aims to answer the following research question:

What implicit balancing behaviour do flexible assets show in different imbalance settlement designs and what balancing market design recommendations can be provided based on this?

This research question is explored using mainly a quantitative approach. First, a literature review on European balancing markets is provided, explaining how the EU Balancing Guideline forms a framework for the balancing markets in EU. Furthermore, the balancing markets in the Netherlands and Belgium, which serve as case studies in the modelling, are explored in detail. Then, two linear optimisation models are developed to simulate the balancing markets of both countries and to show how the price incentives provided by the markets influence the behaviour of a flexible asset that aims to optimise its profit. Additionally, the impact of the asset's implicit balancing, following three different strategies, on imbalance prices and the asset's own profit is examined. A comparison is made between the results under the two different pricing designs, showing how different design choices affect the opportunities for strategic behaviour and potential market exploitation. The main insights obtained can be summarised as follows:

- A flexible asset can, under certain circumstances, exploit the market with gaming behaviour, in which it intentionally amplifies the imbalance price and thereby enlarges its own profit.
- Marginal pricing, provides a larger opportunity window for strategic and gaming behaviour compared to the averaging of marginal prices. Establishing the imbalance price based on the average of all marginal prices during an ISP can mitigate the asset's effect on the imbalance price, but can eventually not prevent extreme imbalance prices either.
- There are advantages and disadvantages to both single and dual pricing. Single pricing provides a more stable pricing system, but is limited in discouraging overreactive implicit balancing. The dual pricing design discourages overreactive balancing stronger, but this can lead to great losses for BRPs, increasing their financial risks, and can decrease market stability.
- The volume of the system imbalance plays an important role; in ISP with lower system imbalances, flexible assets can only increase the imbalance price to a very limited extend, before a market saturation point is reached where all system imbalance is balanced implicitly. With higher system imbalances, flexible assets can push the imbalance price to much higher, or even extreme values.

As balancing markets evolve with increasing volatility in system imbalances and higher volumes of flexible assets, transaction costs are expected to rise due to higher levels of market participation, growing complexity in forecasting, and potential market saturation effects in quarter-hours with lower system imbalances. These expectations for future conditions emphasise the need for pricing designs that ensure grid stability and market efficiency. Therefore, this research provides several recommendations:

- TSOs should consider re-evaluating the overall pricing design for FRR and imbalance. These two pricing designs are highly interconnected, as imbalance prices should reflect the costs made for FRR. Marginal pricing has both advantages and disadvantages, as it can reduce strategic bidding for FRR, but can reward gaming behaviour in implicit balancing, leading to market instability. A different pricing design might provide a more stable market, where strategic implicit balancing is discouraged.
- The choice between single and dual pricing needs to be carefully considered. Based on this research's findings, single pricing leads to less risks for BRPs and contributes to market stability. However, additional research into the decision-making process of flexible assets under the risks present in both pricing designs is needed to be able to make a stronger recommendation.
- Adjusting other market design variables could help reduce volatility, such as loosening FRR qualification requirements to encourage flexible assets to provide FRR instead of implicit balancing and reducing the ISP to five minutes. Yet, further research is needed to assess the full implications of adjusting these design choices.

The findings presented by this research contribute to current efforts to improve balancing market designs, by showing that both pricing designs have vulnerabilities that allow flexible assets to exploit the market under certain circumstances, which is inconsistent with the objectives of the balancing market. The discussed design choices and future research recommendations contribute to improving balancing markets, to regain grid stability and market efficiency.

However, there are some limitations to consider. The model contains significant simplifications, such as the aggregation of multiple flexible assets into a single asset, which does not fully capture the decision-making process of multiple individual actors with a flexible asset in the real world. Additionally, the assumption that the flexible asset has perfect information and foresight does not correspond to reality. Furthermore, the heuristic optimisation method used may not always produce the optimal strategy for the flexible asset. Based on these limitations, several suggestions for future research are made. For example, using a bi-level optimisation method might provide more refined results of the asset's strategic behaviour. Future research could also consider the wider context of the market, such as how imbalance pricing influences the decision-making processes of numerous BRPs acting simultaneously, without perfect or with limited market information. An analysis from a game-theoretic point of view, showing the interactions among various actors, might lead to more refined or different outcomes when the different pricing designs are compared.

Nomenclature

Abbreviations

Abbreviation	Definition
aFRR	Automatic Frequency Restoration Reserve
BESS	Battery Energy Storage System
BRP	Balance Responsible Party
BSP	Balance Service Provider
FCR	Frequency Containment Reserve
IGCC	International Grid Control Cooperation
ISP	Imbalance Settlement Period
MDP	Marginal Decremental Price
mFRR	Manual Frequency Restoration Reserve
MIP	Marginal Incremental Price
PICASSO	Platform for the International Coordination of Automatic frequency restoration reserves and Stable System Operation
RES	Renewable Energy System
TSO	Transmission System Operator
VoAA	Value of avoided activation

Table 1: Abbreviations [1]–[4]

Technical terms

Term	Definition
Balance Responsible Party (BRP)	Market participant or representative for a market participant, who is (financially) responsible for maintaining balance on the grid
Balance Service Provider (BSP)	Market participant that offers balancing reserves to the TSO
Frequency Containment Reserves (FCR)	To meet international balancing responsibilities, the TSO buys certain amounts of FCR. BSPs that are contracted for FCR, activate FCR automatically in case of imbalance
Automatic Frequency Restoration Reserve (aFRR)	aFRR is a service obtained by the TSO from the market to maintain balance. It can also be referred to as ‘regulating power’
Manual Frequency Restoration Reserve (mFRR)	mFRR is a service obtained by the TSO from the market to maintain balance. This service is activated manually, only if the aFRR services cannot restore the balance, which is why mFRR is also referred to as ‘incident reserve’
Upward regulation	Increase of electricity input or decrease of electricity withdrawn at the TSO’s request to maintain balance on the electricity grid
Downward regulation	Decrease of electricity input or increase of electricity withdrawn at the TSO’s request to maintain balance on the electricity grid
Positive balancing energy	Balancing power provided by the BSP, relative injection of energy
Negative balancing energy	Balancing power provided by the BSP, relative withdrawal of energy
Downward bid	Bid by the BSP to provide downward regulation. The bid contains the price [€/MWh] and volume [MWh] per ISP
Upward bid	Bid by the BSP to provide upward regulation. The bid contains the price [€/MWh] and volume [MWh] per ISP
Balancing energy price	The price that is paid for the energy delivered or purchased by the BSP, as requested by the TSO
Imbalance settlement period (ISP)	Time unit used to calculate the total imbalance volume caused by BRPs
BRP surplus	BRP has relatively injected more energy than its commercial trading schedule. Downward regulation needed
BRP shortage	BRP has relatively withdrawn more energy than its commercial trading schedule. Upward regulation needed
Imbalance (settlement) price	The price in each ISP for the imbalance in each direction (positive, zero or negative), paid by the BRPs causing imbalance
Regulation state	Describes different situations of activating balancing energy and determines the imbalance price per ISP
Mid price	The average of the lowest upward bid and the highest downward bid in the merit order. This price determines the imbalance price in specific situations
Floor	The maximum of VoAA in positive direction and VoAA in negative direction for a specific ISP
Cap	The minimum of VoAA in positive direction and VoAA in negative direction for a specific ISP

Table 2: Technical terms and definitions [1], [3], [5]

Symbols and Variables

Symbol	Definition	Unit
C	Maximum capacity of asset	[MWh]
e_t	Net energy produced or consumed by the flexible asset	[MWh]
MP	Marginal Price	[€/MWh]
OC	Optimisation cycle	
$R^{+/-}$	Set of upward (+) and downward (-) regulation bids, indexed $r^{+/-}$	
RS	Regulation State (NL)	
SD	Satisfied Demand	
SI	System Imbalance	[MWh]
T	Set of time steps in optimisation horizon (1 ISP)	
$V_t^{r^{+/-}}$	Activated balancing energy volume of upward (+) or downward (+) regulation bid	[MWh]
z	Binary variable to determine the net position of the flexible asset based on the imbalance price(s)	
α	Additional component (BE)	[€/MWh]
λ	Imbalance price (BE)	[€/MWh]
$\lambda^{+/-}$	Imbalance price for a BRP surplus (+) and a BRP shortage (-) (NL)	[€/MWh]
$\Lambda_t^{r^{+/-}}$	Activation price of upward (+) and downward (-) regulation bid $r^{+/-}$ at time step t	[€/MWh]
$\Lambda_t^{M^{+/-}}$	Marginal price of activated upward (+) and downward (-) regulation at time step t	[€/MWh]
$\phi^{+/-}$	Balancing energy price is positive (+) and negative (-) direction	[€/MWh]
ϕ^{mid}	Mid price (NL)	[€/MWh]

Table 3: Symbols and variables

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1 Introduction

In this chapter, the research topic will be introduced by providing the context of balancing markets. After this, the current problem and knowledge gap will be introduced to emphasise the relevance of this research topic. Furthermore, the research questions will be introduced and an overview on the research structure will be provided.

1.1. Context

As renewable energy sources (RES) become more integrated into our energy system, balancing energy demand with energy supply becomes increasingly complex [6]. For example, high solar irradiance and strong winds during summer days can cause substantial peaks in energy supply, while energy demand typically peaks in the morning and evening. These demand peaks are increasing, due to the electrification of the energy system [7]. The combination of increased RES and major shifts in electricity demand has increased the imbalance in the energy grid, heightening the need for regulating power [7], [8]. Currently, 47% of the total electricity production in the Netherlands comes from renewable sources [9]. As the country aims for a fully renewable-based energy system, the demand for regulating power will increase. However, the impact of flexible assets on the electricity system is still uncertain [10]. These developments and uncertainties in the electricity sector are not only present in the Netherlands, but are an important topic in many EU countries [11].

With increasing demand for regulating power, the deployment of flexible assets in the balancing market as power reserves has become a lucrative business model [11]. This is a positive development, as the extra regulating power provided by flexible assets is highly needed [7]. Flexible assets are able to activate high volumes within a very short time frame and can respond rapidly to market dynamics [7]. On the one hand, flexible assets can be deployed on the balancing market by offering contracted balancing volumes, providing regulating power that can be activated by a TSO. This process is called *active* or *explicit balancing*. On the other hand, flexible assets can also perform *passive* or *implicit balancing*, where they take out-of-balance positions in reaction to the imbalance prices, without the intervention of a TSO. However, implicit balancing can lead to an overreacting market, especially when there are many actors implicitly balancing with flexible assets [12]. Consequently, the question is raised whether the design of the balancing markets provides the right price incentives for these flexible assets, such that they actually contribute to the balancing markets [10].

In the European Union, the EU Balancing Guideline provides a guideline for all EU member states on how they should organise their balancing markets [1], with some design variables left up to the member states to determine. For example, most EU countries apply the single pricing system to determine imbalance prices, which is considered the standard design in the EU guideline [13]. However, in the Netherlands, the balancing market operates under a dual pricing system. The specific differences of various the pricing systems are elaborated in Chapter 2.

1.2. Problem Statement

A common misconception is that all flexible assets, including residential battery systems, actively participate in the balancing market by submitting bids on the various balancing markets. In reality, many flexible assets, including clusters of residential batteries from, for example, Zonneplan and Frank Energie [14], only passively engage in the balancing market. They respond to imbalance prices with implicit balancing by taking out-of-balance positions [14]. However, imbalance prices are determined retrospectively, meaning that passive balancing actions are of speculative nature and can be highly risky [14], [15].

Balancing markets generally involve small volumes: for example, the Dutch balancing market has a volume of approximately 5 TWh per year, which is relatively small compared to their day-ahead market of 50 TWh per year [16]. Because of these small volumes, deploying flexible assets can have a significant impact on the market with relatively small capacities. Furthermore, imbalance prices can be very volatile, leading to high risks for market participants. Interestingly, data from the ENTSO-E European platform on financial income and expenses on the balancing markets show that the income and expenses of the Dutch balancing market in 2023 are, respectively, $\sim$260% and $\sim$380% times higher than in the Belgian balancing market [17], while the Belgian electricity market is only two times smaller [9] [18]. This implies that the Dutch balancing market is much more volatile and far more money is involved. However, it is unclear what aspects of the two markets cause these differences in income and expenses on the balancing market.

In the Dutch dual pricing system, 'regulation state 2' is one of the possible scenarios, which leads to two different imbalance prices for a single imbalance settlement period (ISP). When regulation state 2 applies for an ISP, projected profits from implicit balancing actions can rapidly turn into substantial losses [12]. Over the past year, the frequency of regulation state 2, caused by overreactions in the balancing system [12], has increased and the Dutch balancing market has evolved into one of the most volatile in the European Union [19]. In the request from the Dutch TSO TenneT to the ACM, the regulatory authority in the Netherlands, to maintain the dual pricing system, TenneT promised it would attempt to keep the occurrence of regulation state 2 below 10% of the time to minimize risks [20]. However, in 2024 regulation state 2 occurred 15% of the time, largely exceeding the target of a maximum of 10% of the time. In 2023, regulation state 2 applied to 7% of the ISPs and in 2022 9% [21].

In addition, another problem might arise with the increasing volume of flexible assets. The algorithms and strategies used by actors with flexible assets are becoming increasingly advanced, enabling them to more accurately forecast system imbalances and imbalance prices [14]. The hypothesis in this thesis is that these advanced forecasting abilities might lead to strategic behaviour or gaming opportunities. A potential form of strategic behaviour involves manipulating the system imbalance to increase imbalance prices. The specifics of possible strategic behaviour will be explained extensively in Chapters 2 and 3. The suggestion that gaming opportunities are present in today's balancing market, highlights the need to research the robustness of the imbalance pricing systems and the future challenges posed by increasingly sophisticated flexible assets operations.

1.3. Literature Scan and Knowledge Gap

Ten to fifteen years ago, several research papers already highlight a significant increase in the need for regulating power to maintain grid balance, due to the variability and limited predictability of renewable energy production [22]–[24]. They also emphasise that full balancing exposure is only feasible if balancing markets are well-functioning. The more RES in the electricity system, the less manageable the system becomes, when balancing costs are not allocated to those responsible for it [23]. A more recent study by Poplavskaya et al. [25] shows that the relevance of balancing markets has been widely acknowledged in literature by now, as it fulfils an important role within the European electricity markets. Many researchers therefore stress the importance of harmonizing European balancing markets to enhance the economic efficiency of the markets [22], [26].

The relatively early studies also identify a high-profit potential for aggregators and regulating (flexible) assets in the balancing markets [27], [28]. They forecast limited but notable economic benefits for household aggregators offering services in the Dutch balancing markets [27]. Tohidi et al. [29] argue that residential aggregators could lower system costs and enhance demand response mechanisms, increasing residential profits. However, these early studies assume that flexible assets will mostly be contracted by the TSO for active balancing [22], [26].

More recent studies affirm the positive business case for aggregators and flexible assets such as BESS in the balancing markets. Using quantitative models, these studies demonstrate the lucrative nature of these assets [13], [30]–[34]. However, many of these papers base their business case on implicit balancing, as market parties nowadays deploy their flexible assets mostly by performing implicit balancing. Additionally, recent research indicates that the increase in RES has indeed raised imbalance volumes and costs in the Netherlands [35], which contributes to the business case of flexible assets on the balancing markets [13], [31], [33], [36]. Staffel et al. [35] even show that there is a significant correlation between weather circumstances and prices on the balancing markets.

Lamert et al. [32] and Demir et al. [34] suggest that large-scale assets providing flexibility in power can yield substantial profits, even with risk-contained trading strategies. Smets et al. [13] show high expected profits if BESS are used for implicit balancing, by taking out-of-balance positions on the balancing market. Besides yielding profits, Toubeau et al. [37] show that optimisation strategies of BESS contribute to the balancing the electricity grid. Smets et al. [13] even argue that BESS can reduce system imbalance in up to 75% of all cases and thus improve the cost-efficiency of power systems.

However, none of the papers have established how different imbalance pricing designs affect imbalance prices and thus profits of flexible assets. Farrokhseresht et al. [31] do point out that differences in balancing market designs may have an even greater effect on biddings and imbalance prices than the increasing feed-in of RES. Müsgens et al. [38] and Van der Veen [26] identify that settlement rules are key elements of the balancing market design, but do not go into the effect of pricing designs on assets balancing implicitly. Case studies that show a profitable business case for BESS, such as those by Toubeau et al. [37] and Smets et al. [13], use a certain pricing system as input, but their research does not show how the given pricing design variables might affect their results. Abdelmotteleb et al. [33] do argue that the lack of information on foreseen imbalance prices and regulation states in the Dutch pricing design disadvantages opportunities to optimise flexibility portfolios, but did not research what quantitative effects the pricing design has on flexible assets. So far, a comparison between different imbalance pricing systems has not yet been made. This represents a significant academic knowledge gap.

Furthermore, while there is some research on how flexible assets and BESS can respond to (predicted) imbalance prices to optimise their profit, very little research has been done on the interdependency aspect of the relation between balancing markets and flexible assets that implicitly balance. With implicit balancing, assets take out-of-balance positions on the balancing market. Their out-of-balance position is valued against the imbalance price. In Chapter 2 this mechanism is explained in detail. One of the most important aspects is how out-of-balance positions not only respond to predicted imbalance prices, but also influence the system imbalance, and thus imbalance prices simultaneously. Therefore, asset's implicit balancing actions can have a considerable impact on balancing markets, which raises the question whether flexible assets might be able to take strategic out-of-balance positions and increase the imbalance price to their own benefit, without contributing to, or even while damaging, the balancing system. In [25] is shown that balancing market designs contain design features that makes them susceptible to gaming and strategic behaviour in the bidding process. However, no research has been conducted on possible strategic out-of-balance positions.

This literature scan reveals a substantial knowledge gap in understanding how imbalance pricing design variables affect the implicit balancing behaviour of flexible assets such as BESS. Many papers identify the increasing need for regulating power, due to the increasing integration of RES, and address the increasing imbalance prices. Moreover, multiple papers analyse how market participants can respond and propose various optimisation strategies for flexible assets on the balancing market, but do not show how the strategies of flexible assets might be enhanced in such a way that they exploit the market.

1.4. Relevance within CoSEM

The electricity grid and the balancing markets exemplify a complex system, having technical, market, governance and societal aspects. The physical constraints of electricity require strict operational measures to ensure grid stability. In the market domain, market liberalisation has opened the electricity system to market players, creating competitive dynamics. Meanwhile, the governance and societal aspects are underscored by the recognition of electricity as a basic right in Europe, necessitating strict regulation to maintain electricity affordable, reliable, and accessible for everyone. Balancing markets, although relatively small compared to other electricity markets, play a critical role, as they maintain grid stability. Analysing this multidisciplinary problem requires a systems engineering approach, while keeping in mind the institutional and technical context. Therefore, this research topic aligns well with the master program Complex Systems Engineering and Management.

1.5. Research Questions and Approach

Taking into account the knowledge gap identified in Section 1.3, this research focusses on the EU design variables for the imbalance pricing mechanisms and the price incentives they provide for implicit balancing behaviour of flexible assets. Vice versa, the research will also look into the possible effect of flexible assets on the balancing markets under the different pricing designs. Therefore, the main research question is formulated as follows:

What implicit balancing behaviour do flexible assets show in different imbalance settlement designs and what balancing market design recommendations can be provided based on this?

The main research question is divided into three sub-questions. First, the theoretical and empirical concepts need to be established and the price differences following different pricing designs will be shown. To this end, the Dutch and Belgian pricing designs will be analysed in detail and applied in the remaining research. Then, the implicit balancing actions of a flexible asset will be researched. These two research perspectives will be translated into design recommendations. The three sub-questions that capture these three parts of the research are formulated as follows:

1. What design variables exist in the EU target model for the imbalance settlement design, and what design choices have been made in the Dutch and Belgian market design?

As the balancing markets are rather complex and the details of the different market designs not widely known, this research will start with a detailed theoretical and empirical background, providing a systematic review on balancing markets, the design variables in the EU Balancing Guideline, and the Dutch and Belgian imbalance price mechanisms. To be able to answer the first sub-question, it is important to understand the balancing market designs in detail. Subsequently, the effect of the different designs will be explored by computing imbalance prices in an optimisation model. Using historical data of Dutch imbalance volumes and regulation bids, both the Dutch and Belgian market will be simulated. In this way, the resulting imbalance prices based on the two pricing mechanisms can be compared.

2. What financial incentives do the different imbalance settlement designs give to flexible assets, and how does the asset's behaviour impact the system and the imbalance prices?

This question aims to assess the incentives that the two pricing mechanisms give flexible assets. A flexible asset will be added to the optimisation model explained sub-question 1. The asset will aim to maximise its profit by optimising its behaviour. Analysing the asset's behaviour will show whether there is a difference in the price incentives following the two designs. It will also provide insight into the robustness of the two pricing designs against the strategic behaviour of the asset.

3. Given the modelling results and the insights obtained in the theoretical and empirical analysis, what key elements should be considered in the imbalance pricing designs?

This sub-question aims to provide a design recommendation for the general imbalance pricing design. The modelling results will be analysed and the two pricing designs will be compared. Then, the results will be put into broader context, enabling to theoretically and empirically reflect on the design variables provided by the EU Balancing Guideline and provide a recommendation which design variables member states should implement in their market design.

To address the research questions, a mostly quantitative approach is used. Specifically, a linear optimisation method will be used, which is a widely recognised method in energy market research [13], [32], [33]. This method is appropriate to answer the research question, due to its suitability for calculating imbalance prices using both the Dutch and Belgian imbalance pricing mechanisms and simulating the implicit balancing behaviour of a flexible asset [13]. The modelling results will be analysed to compare the different price mechanisms.

As this research focusses on a comparison between the two pricing systems, the input needs to be identical in both models. Thus, only data from the Netherlands will be used, both for the Dutch model and the Belgian model. The programming language Julia will be used to build the models. Julia has been developed at MIT, a programming language that provides both high-level and high-performance programming and is especially suitable for energy optimisation problems [39].

1.6. Research Structure

Following this introduction, Chapter 2 provides an extensive literature review of the balancing market, both from a theoretical and empirical perspective. The theoretical review discusses the objective of balancing markets, the EU Balancing Guideline and the institutional arrangements. Moreover, it provides an analysis on the design variables chosen in both the Dutch and Belgian balancing market and some empirical examples. Next, Chapter 3 explains the general modelling strategy, and provides a detailed description of the model set-up and key-assumptions made in the modelling process, as well as the model validation and verification. Chapter 4 presents and discusses the modelling results, and provides an analysis on the results. In Chapter 5 the modelling results will be put into a broader context and the findings in this research are discussed. Finally, in Chapter 6, the conclusion, reflections and future research suggestions are presented.

2 Literature Review: European Balancing Markets

This chapter provides a comprehensive review of balancing markets and specifically focusses on the balancing market design in the Netherlands and Belgium. The first part of the chapter contains a theoretical review, addressing the establishment and objective of balancing markets, an overview of the various balancing mechanisms and actors. Then, the EU Balancing Guideline providing a framework for balancing markets will be analysed, after which a short institutional analysis of the balancing market is conducted. Furthermore, this chapter provides an empirical examination of the balancing markets in the Netherlands and Belgium, including a detailed explanation of how the pricing designs are formulated and applied in practice. The concepts discussed in this chapter form the foundation for the modelling component of this research and provide the context for effectively interpreting and discussing the modelling results.

2.1. General Background

Balancing markets were created along with the liberalisation of the European energy markets in the 1990s, which introduced competition and decentralised decision-making into the previously monopolistic and vertically integrated electricity system [26]. This transition required mechanisms to address the physical and economic complexities of maintaining grid stability while ensuring market freedoms, as intended with the market liberalisation [26], [22].

Currently, the transmission and distribution of electricity remain highly regulated due to their nature as natural monopolies [40]. The construction and operation of transmission networks require substantial upfront investments and entail high sunk costs, making competition inefficient [26]. In contrast, electricity generation and retail are less regulated, as there is significant competition possible in these parts of the electricity system. Figure 2.1 shows an overview of the different roles in the European liberalised energy system [40].

In other parts of the world, the energy systems can be set-up differently. However, as this research focusses on balancing markets with European context, other possible designs are disregarded.

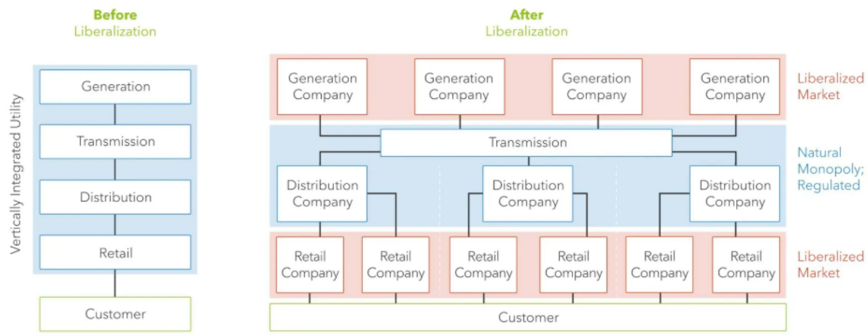


Figure 2.1: Liberalisation of the European electricity market [40]

In today's liberalised electricity system, multiple electricity markets operate across different time frames, as shown in Figure 2.2. On the forward and futures market, long-term contracts are traded. On the day-ahead market, the energy is traded one day before delivery. On the intraday market, market participants can adjust their portfolio closer to real-time. Market participants can trade energy on these markets, meaning they can take positions and optimise their portfolio [41]. However, these markets all close before real-time and do not fully cover the unpredictable and dynamic nature of real-time grid operations. Furthermore, TSOs do not have perfect market information, making it impossible to accurately forecast necessary real-time grid operations [41].

A TSO is responsible for maintaining grid stability within its control area, amongst other obligations. Therefore, the TSO acquires balancing reserves from market parties and activates balancing energy, provided by market parties, in real-time as needed [41]. TSOs are prohibited from producing or consuming energy, apart from their basic operational needs, and therefore rely entirely on market participants to supply balancing reserves [4]. Figure 2.2 shows the temporal relationships of the various energy markets, highlighting the position of balancing markets within the electricity system.

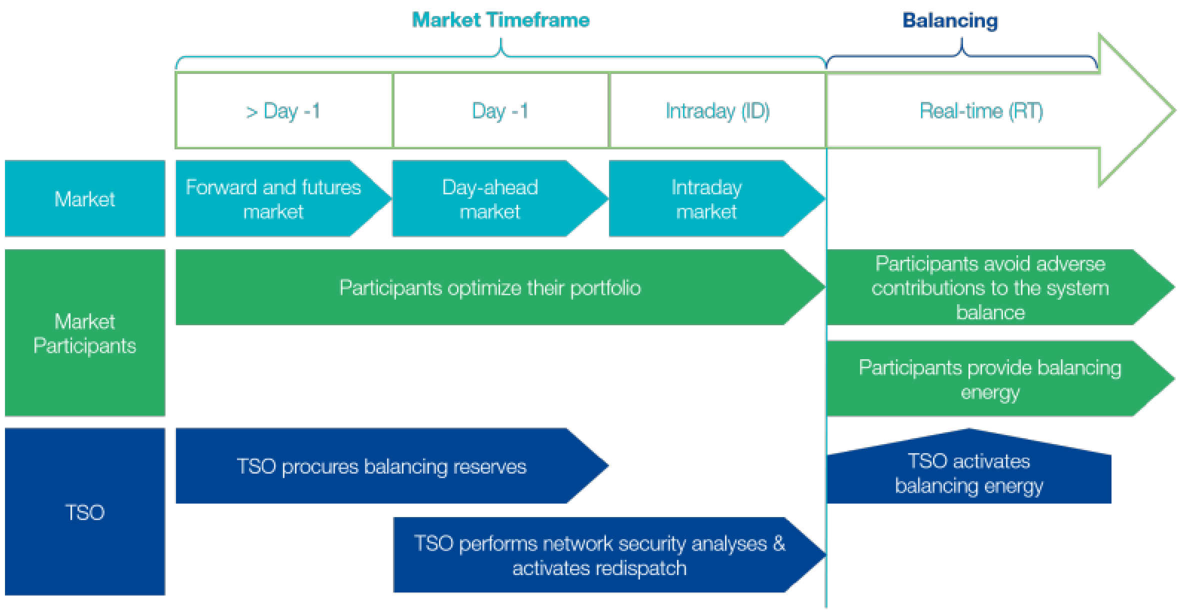


Figure 2.2: Temporal overview of energy markets [41]

Balancing markets provide a dual purpose within the electricity system [26]. On the one hand, balancing mechanisms allow TSOs to handle imbalances arising from forecasting errors or unforeseen circumstances. This physically ensures ensures grid stability and reliability [26]. On the other hand, balancing markets give market participants (BRPs) the opportunity to deviate from their predefined energy schedules and thereby change their market position in real-time [42], [22]. These deviations can be strategic choices. In other words, the physical domain and market domain of the electricity system meet through the real-time balancing markets, making its design intricate [43], [25].

2.1.1. Objective of Balancing Markets

As there are limited storage options in the electricity market, unlike most commodity markets, one of its main challenges is ensuring that electricity supply meets demand in real-time [26]. The primal physical objective of balancing markets is to stabilise grid operations. The electricity system is in balance when the system's frequency is uphold a certain level, which is set at 50 Hz in the European grid [41]. Deviations from this target indicate an imbalance between production and consumption. The degree of frequency deviation determines the system's operational state:

- A frequency range of 49.8–50.2 Hz is classified as normal.
- Frequencies between 49.2–49.8 Hz or 50.2–50.8 Hz constitute an "alert" state.
- Frequencies below 49.2 Hz or above 50.8 Hz signal an emergency, risking system collapse [41].

Figure 2.3: Frequency range and operational states of high voltage grid [41]

2.1.2. Types of Balancing Markets

To maintain grid stability, there are three different products within the balancing markets in Europe [4]. These products address different types of imbalances and use distinct mechanisms:

- Frequency Containment Reserves (FCR): This market stabilises grid-wide frequency deviations within interconnected systems, such as the synchronous grid of continental Europe. These balancing reserves are activated automatically, without the interference of a TSO. The only responsibility of TSOs is to contract sufficient FCR balancing volume each year [44].
- Automatic Frequency Restoration Reserves (aFRR): Operate at the level of control areas, each managed by a single TSO. Balancing reserves in this market are contracted and activated by the TSO [44].
- Manual Frequency Restoration Reserves (mFRR): Operate at the level of control areas, each managed by a single TSO. Balancing reserves in this market are contracted and activated by the TSO [44].

Furthermore, there exist different types of imbalance. The distinction between imbalance types reflects the layered nature of balancing challenges:

- Grid imbalances: imbalances in synchronous zones (see Figure 2.4) are addressed by activating FCR mechanisms [41].
- Control area imbalances: imbalances occur within specific TSO control areas and are addressed by activating aFRR balancing energy. If aFRR reserves are not sufficient in case of emergency states, mFRR activations are needed [41].
- BRP imbalances: These imbalances arise from discrepancies between a BRP's scheduled energy programme and its actual generation or consumption in real-time [41].

Grid imbalances are determined by measuring the frequency. All market parties contracted for FCR measure the frequency of the grid at all times themselves, as this balancing reserve is activated automatically [41]. The figure below shows an overview of all synchronous grids in Europe.

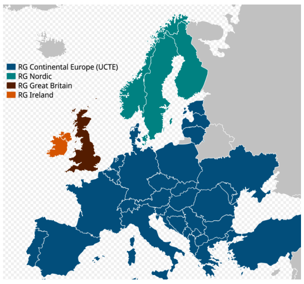


Figure 2.4: The synchronous zones in Europe [45]

The TSOs address deviations in balance in their control areas through real-time interventions, minimising the system imbalance (SI) of the control area, which can in principle be defined as [41]:

$$SI = (Production + Import) - (Consumption + Export) \tag{2.1}$$

When $SI = 0$, the system is in balance. If SI is set to 0, the following equation can be derived:

$$Production - Consumption = Import - Export \tag{2.2}$$

Therefore, the system imbalance within a control area can be measured at the interconnectors of this control area[41]. Any deviations from import or export volumes suggest that there is an imbalance in the control area. Figure 2.5 gives an example of a control area, in this case the control area in the Netherlands.

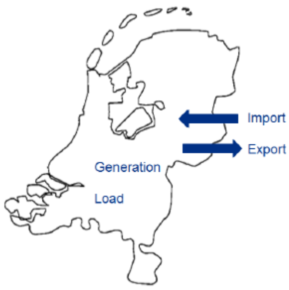


Figure 2.5: Control Area in the Netherlands with TenneT as TSO [41]

A positive system imbalance, with a frequency exceeding 50 Hz, requires downward regulation. If this were to happen on the grid, FCR downward regulation is activated automatically. Simultaneously, negative imbalances can occur within a control area, such as the control area in the Netherlands controlled by TenneT. This imbalance requires upward regulation using aFRR reserves. At the same time, there can be several BRPs with a shortage and several with a surplus [41].

The economic objective of the balancing market is to ensure cost-efficiency in real-time alignment of electricity supply and demand [26]. Furthermore, balancing markets give, as far as possible, market participants the three fundamental freedoms in the energy market: freedom of dispatch, transaction, and location [41]. These freedoms incentivise innovation and efficiency by allowing participants to optimise their operations within competitive markets [41]. The inherent volatility of electricity, combined with the physical need for grid stability, requires mechanisms to correct imbalances [26]. Balancing markets achieve this by creating price signals that reflect the cost of deviations, thereby encouraging market participants to internalise the costs of their out-of-balance positions, with the goal of fostering economically optimal behaviour in the system [22].

2.2. Actors in Balancing Markets

There are three important market roles within the balancing markets: the TSO, BRPs and BSPs.

As mentioned previously, TSO play a central role in ensuring the stability and reliability of the electricity grid [25]. The TSO has three primary responsibilities:

- System Oversight: TSOs validate energy programs submitted by BRPs and ensure compliance with technical and regulatory requirements
- Balancing Market Management: TSOs procure balancing reserves (FCR, aFRR, mFRR) from BSPs
- Grid Balancing: TSOs maintain the real-time balance on the electricity grid by activating balancing energy within their control area [25], [41]

The TSO acts as a neutral market facilitator, as the TSO is solely responsible for contracting balancing mechanisms, activating balancing energy provided by BSPs, and overseeing BRPs [25].

Figure 2.6 shows an overview of the three different market participants that deliver flexibility.

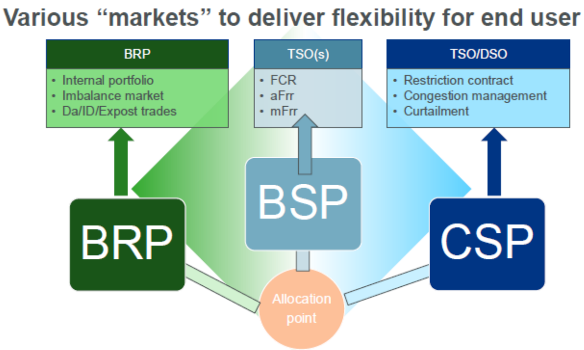


Figure 2.6: Overview market roles [41]

Note: Congestion Service Providers (CSPs) are not directly connected to the imbalance pricing designs and are thus excluded from this research

2.2.1. BRPs

BRPs are key market participants with the fundamental role and financial responsibility to maintain grid stability by keeping their portfolios in balance [1], [13], [26]. BRPs operate on all electricity markets and take market positions by participating in the day-ahead, intraday, and balancing markets to optimise their portfolio. Based on their position at the closing of the day-ahead markets, BRPs anticipate their energy generation and/or consumption to determine their energy programs or E-programs and submit these to the TSO for validation. After BRPs have submitted their E-programs, they strategically adjust their position before real-time on the intraday market to further enhance their portfolio [41]. Any deviations from submitted E-programs are considered as the BRP's imbalance, and corrected through the imbalance settlement process, where BRPs need to compensate the TSO for their imbalance by paying the imbalance price [1], [25], [26]. Thus, BRPs are in principle financially incentivised to maintain their internal balance. However, BRPs can choose to deliberately take out-of-balance positions to try to make a profit based on the imbalance prices. In this case, the BRP intentionally deviates from its energy schedule. This process is called implicit or passive balancing [26].

Figure 2.7 highlights the activities and responsibilities of BRPs. It shows how the BRP bridges the financial and physical domains of the electricity market.

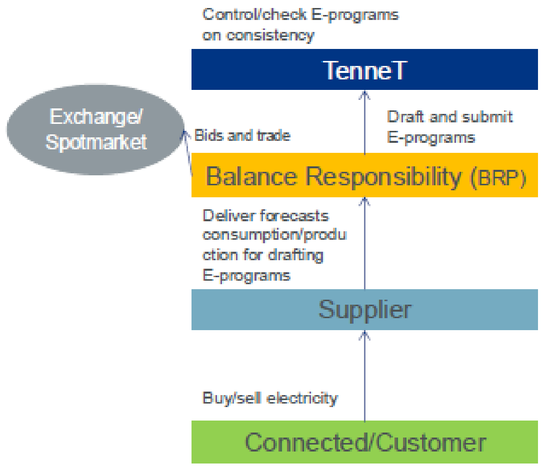


Figure 2.7: Role BRP in balancing market [41]

As BRPs are the only market parties that perform implicit balancing and are also the ones whom the TSO settles the imbalances, this research will primarily focus on BRPs.

2.2.2. BSPs

BSPs are actors that provide balancing capacity and energy to TSOs to address real-time grid imbalances. They participate in balancing capacity markets (FCR, aFRR, and mFRR) and provide bids on the balancing energy bid ladder for activation by TSOs [13], [41]. One BSP can provide multiple types of balancing energy at the same time. BSPs have to pre-qualify their assets, such as flexible gas-fired power plants or aggregated battery energy storage systems, with the TSO. These assets must be capable of fast responses to balancing requests by the TSO. In real-time, BSPs respond to activation signals from the TSO by providing positive or negative balancing energy, depending on the system needs [4].

As explained in Section 2.3, only qualified BSPs are contracted by the TSO. BSPs that are contracted are obliged to submit bids [4]. If the TSO allows it within their approved methodology, BSPs that are not contracted are allowed to place bids too, as long as the actor is qualified as BSP [1]. These bids are called 'free bids' and their purpose is to enhance competition in the balancing markets and attract more balancing energy suppliers [3].

Figure 2.8 illustrates the BSP's central role in the balancing market.

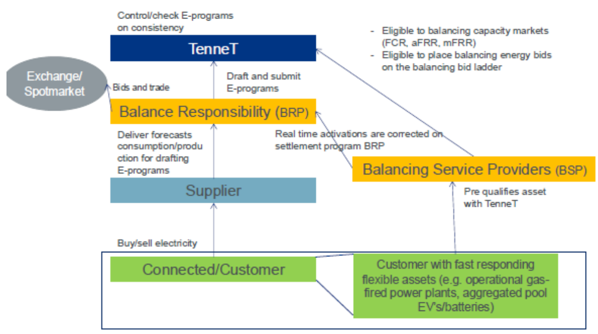


Figure 2.8: Role BSP in balancing market [41]

The roles of BRPs and BSPs are interconnected, but distinct. BRPs aim to maintain their own portfolio balance through proactive market participation or they deliberately take out-of-balance positions through implicit balancing. BSPs provide the balancing energy necessary for system-wide stability [4].

This division ensures that market participants have the freedom to optimise their positions, while the physical constraints of electricity grids are met through balancing actions [44].

2.2.3. Dual role as BSP and BRP

A market participant can have a dual role as a BSP and BRP, and gain a strategic advantage over actors that solely operate as BRP [41]. For each ISP, BSPs have an advantage relative to BRPs, as they receive more information on activated balancing energy in real-time. After all, BSPs know whether their bids are activated. TSOs are required to publish information on the system balance, balancing energy bids and activation of balancing energy as soon as possible, but no later than 30 minutes after real-time [1]. A 30-minute delay in publishing information gives BRPs, that operate as BSP as well, a significant advantage in the market. In several EU countries, information on the balancing market is published after a few minutes [2], [3], but even a few minutes can give market participants with a dual role a large advantage, as these BRPs have more time within an ISP to adjust their portfolio, in reaction to the development of the imbalance and the expected imbalance price. Suppose the information on the balancing actions has a 5 minute delay, BRPs have only 10 minutes left in the ISP to adjust their position, based on the information of only the first minute in the ISP. Market parties with a dual role already have information on whether their bids as BSP have been activated in the first 5 minutes of certain ISP, meaning they have a considerably better view on the course of imbalance and prices in this ISP. So, market participants with a dual role can adjust their market position more adequately.

2.2.4. Flexible assets in balancing markets

Flexible assets represent a transformative innovation within balancing markets, offering a new form of flexibility on balancing markets [37]. They can operate as BRP, BSP, or as both BRP and BSP, which enlarges their strategic advantage. Their ability to rapidly charge and discharge makes them ideal for providing balancing services such as FCR, aFRR, and mFRR [46].

As BSPs, flexible assets can provide rapid-response balancing services, fulfilling today's increasing need for flexible balancing reserves. As BRPs, flexible assets can implicitly imbalance by taking out-of-balance positions to maximise their profits [13]. In theory, flexible assets can largely contribute to ensuring grid stability, due to their ability to rapidly response and provide balancing energy or implicit balancing in both directions [37]. This would support market competitiveness and innovation, which aligns with theoretical principles of the balancing market design. However, as explained in Chapter 1, it is unclear if the pricing designs provide the correct price incentives for these flexible assets. It is yet to be determined what the potential of strategic behaviour flexible assets is in different pricing designs.

2.3. EU Balancing Guideline

This section will review the EU Balancing Guideline and provide an overview of the EU design for FRR balancing markets, as well as the design variables regarding pricing systems.

2.3.1. Structure of the FRR markets

As explained previously, the TSO has both aFRR and mFRR at its disposal to restore balance in its control area [25]. FCR is used for grid-wide imbalances and does not directly influence the imbalance settlement prices, and thus is disregarded from now on.

The balancing markets within a control area consist of three main phases: balance planning, real-time system balancing, and balance settlement [43]. Each phase involves specific actions and responsibilities distributed among BRPs, BSPs, and the TSO. Figure 2.9 provides a schematic of the balancing market structure. The TSO is shown as System Operator (SO) in this figure.

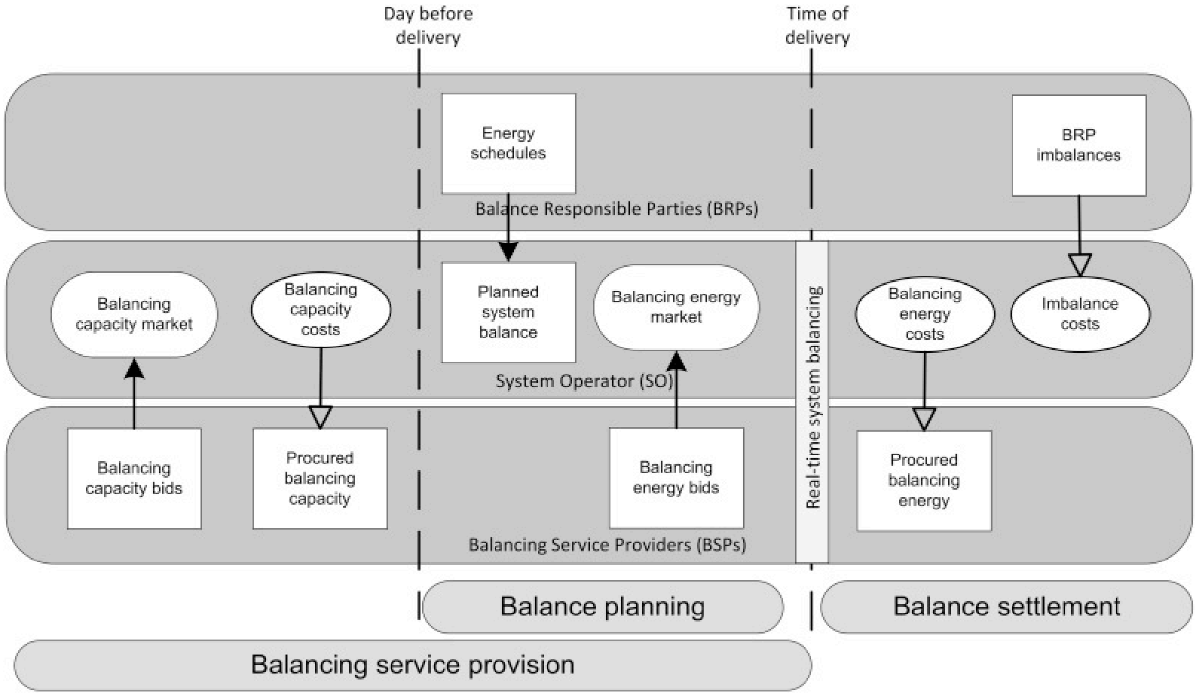


Figure 2.9: Schematic of the balancing market structure [43]

In the initial balancing service provision phase, market participants place their balancing capacity bids, upon which the TSO procures the necessary balancing capacity [4]. In the balance planning phase, which occurs on the day before delivery, BRPs prepare and submit their energy schedules to the TSO, outlining their expected production or consumption for each ISP. At the same time, BSPs submit bids for FRR. [43].

On the day of delivery, the focus shifts to real-time system balancing. Any deviations from BRPs' planned energy schedules result in imbalances [3]. The TSO activates aFRR based on common merit order lists of the bids submitted by the BSPs, based on the real-time imbalance. In case the provided aFRR volumes are not sufficient to restore the imbalance, the TSO can activate mFRR [3].

Finally, the imbalance settlement phase ensures that all financial transactions associated with balancing actions are completed. All activated balancing energy is settled on an ISP basis [3]. BSPs that provided regulation receive the balancing energy price. BRP imbalances or, in other words, schedule deviations are settled against the imbalance price [43]. The systematics to determine the balancing energy price and the imbalance settlement prices are described in the following subsection.

Both aFRR and mFRR are contracted by the TSO and BSPs providing these reserves have to place bids. TSOs should, in principle, use cost-effective balancing energy bids, based on the common merit order [1]. However, TSOs are allowed to propose another model for activating bids. If this model shows an equal of better cost-benefit result to the merit order model, the TSO is allowed to implement this [1].

The EU Balancing Guideline establishes specific requirements for the pricing design in the markets for aFRR and mFRR, as well as for the calculation of imbalance prices [1]. Within these guidelines, certain design variables are mandated by the EU, while others are left to the TSO to decide. The two sections following will describe these pricing designs.

2.3.2. Pricing in FRR markets

The activated bids of aFRR and mFRR provide a certain amount of balancing energy. This balancing energy needs to be settled against the balancing energy price. TSOs are required to establish a procedure for the calculation of the activated volume of balancing energy for each ISP [1]. A positive sign for balancing energy indicates a relative injection of electricity by the BSP, i.e. upward regulation, and a negative sign indicated a relative withdrawal, i.e. downward regulation [1], [3].

Regarding this pricing formation, the EU mandates that TSOs develop a methodology to determine the prices for balancing energy. This methodology should, in principle, be based on marginal pricing (pay-as-cleared) and determine at least one price for balancing energy. The methodology must also clearly define how the activation of balancing energy bids for purposes other than system balancing, affects the balancing energy price [1]. In particular, bids activated for internal congestion management are not permitted to determine the marginal balancing energy price. The pricing design is required to provide market participants with correct price signals and incentives to contribute efficiently to the balancing process [1].

However, the TSO is allowed to propose another methodology, as long as this provides correct price signals and incentives to market participants [1]. Thus, a TSO could, for example, choose a pay-as-bid system, where all BSPs are paid their own bid if their bid is activated.

The sign of the balancing energy price determines the direction of the payment between the TSO and BSP [3]. Table 2.1 provides an overview of the payment directions in the different circumstances. In case that both positive and negative balancing energy has been activated within the same ISP and only one balancing energy price is determined, then this price is applied for balancing energy in both directions [1]. However, it is possible to determine two balancing energy prices, one for positive and one for negative balancing energy.

Table 2.1: Overview payment direction balancing energy prices [1]

	Positive balancing energy price	Negative balancing energy price
Positive balancing energy (upward regulation)	Payment from TSO to BSP	Payment from BSP to TSO
Negative balancing energy (downward regulation)	Payment from BSP to TSO	Payment from TSO to BSP

2.3.3. Imbalance price settlement

The EU requires TSOs to establish a methodology for calculating the imbalance price, which may be positive or negative. This method has to incorporate a definition of the value of avoided activation of balancing energy, based on either activated aFRR or activated mFRR. The imbalance price must be determined for every ISP and for each imbalance direction [1]. The ISP In situations involving negative imbalances, the imbalance price is not allowed to be below the weighted average price of activated positive balancing energy, or below the value of avoided activation if no balancing energy is activated. Similarly, for positive imbalances, the price is not allowed to exceed the weighted average price of negatively activated balancing energy, or exceed the value of avoided activation if no balancing energy is activated [1]. When both positive and negative balancing energies are activated, the imbalance price is determined in accordance with at least one of these principles [1]. In other words, the imbalance price is not allowed to be higher, or lower, than the balancing energy price established by the TSO for a certain ISP.

The imbalance volume and direction are determined for every BRP and are equal to the BRPs deviation from its energy schedule. A positive imbalance, i.e. a BRP surplus, means that the BRP has relatively injected more energy. This could be either more production than anticipated or less consumption. A negative imbalance, i.e. a BRP shortage, means that a BRP has relatively withdrawn energy. This could be either less production than anticipated or more consumption [3], [41].

TSOs are allowed to choose between a single pricing method and the dual pricing method. In the single pricing model, there is always one imbalance price determined, which is applied for both a positive and negative imbalance. This method is the default method to determine the imbalance price [1]. In case the TSO chooses the dual pricing model, specific conditions and a detailed methodology have to be defined and the proposal needs to be approved by the regulatory authority. In a dual pricing system, two imbalance prices can be determined, one for a positive imbalance and one for a negative imbalance [1]. The imbalance price for negative imbalance can never be less than the price for positive activated balancing energy. Vice versa, the imbalance price for positive imbalance is never more than the price for negative activated balancing energy [1]. In principle, this results in a zero-sum game for the TSO, meaning the TSO does not make a profit or a loss on the imbalance settlement [3], [41].

Similar to the balancing energy price, the sign of the imbalance price determines the payment direction between the TSO and the BRP [3]. Table 2.2 provides an overview of the payment direction for each possible scenario.

Table 2.2: Overview payment direction imbalance prices [1]

	Positive imbalance price	Negative imbalance price
Positive imbalance (BRP surplus)	Payment from TSO to BRP	Payment from BRP to TSO
Negative imbalance (BRP shortage)	Payment from BRP to TSO	Payment from TSO to BRP

After the balancing energy prices have been settled, the imbalance prices are determined. TSOs have to publish the real-time data within 30 minutes, for the sake of transparency [1].

2.4. Institutional analysis

The balancing markets are an institutional arrangement, where physical exchanges (the power system) and financial transactions (the power market) meet in the unbundled electricity market[43] [47]. This section examines the balancing market from an institutional economic perspective, based on the theory of Transaction Costs Economics.

Electricity's dual nature as a public and private good creates unique institutional challenges [48]. Access to the electricity grid and unconditional electricity consumption is, fundamentally, considered a public right. To comply with this right, physical regulation of the electricity grid is needed, enabling unconditional supply of energy to the public at any moment in time, while preventing technical complications or even blackouts [25], [41], [49]. Meanwhile, electricity is excludable and rival in consumption, which are characteristics of a private good. Electricity is considered a commodity, which is to be traded on markets and is subject to competition, including balancing energy [49]. This duality necessitates hybrid governance structures, combining competitive market mechanisms with centralized coordination by TSOs [48].

These governance structures have to accommodate the unique characteristics of electricity: it is intangible, non-storable, and requires continuous balancing of supply and demand [41], [43]. This complexity asks for a robust governance structure to ensure effective coordination among market participants, by minimising mismatches in supply and demand. As Van der Veen et al. [43] highlight, balancing markets operate under stringent technical and regulatory constraints, which shape the incentives for market participants. TSOs operate as single buyers in balancing markets, ensuring that market-based procurement aligns with the technical requirements of grid stability [43], [49]. This setup supports decentralised decision-making by market participants, while ensuring centralized oversight of grid operations. Within the EU Balancing framework, different types of balancing energy are activated through distinct mechanisms: FCR is decentralized and automatically activated, whereas aFRR and mFRR are centrally controlled and activated by the TSO [26].

2.4.1. Transaction costs in balancing markets

Transaction costs play a significant role in the functioning of balancing markets [26] and need to be taken carefully into consideration in the design of balancing markets. Transaction costs are associated with market participation, bid submissions, compliance, and monitoring, and influence the market performance. The institutional design of balancing markets, provided by the EU Balancing Guideline, aims to minimise transaction costs, by designing standardised bid processes, pricing mechanisms, and market rules [1]. The standardised balancing mechanisms streamline interactions between market participants and enable TSOs to procure balancing services in a more cost-effective and predictable manner, while ensuring timely and reliable grid stabilisation [23], [43].

Müsgens [38] and Van der Veen [43] argue that a pay-as-cleared system, also called uniform pricing, for balancing energy reduces information asymmetry and increases transparency. With uniform pricing, a BSP's bid is independent of others' behaviour, so it enhances market efficiency, as BSPs are more likely to keep their bid in line with their marginal costs [38]. Besides, marginal pricing uses the common merit order to activate bids, ensuring that the most cost-effective bid is activated first [38]. Furthermore, marginal pricing provides more transparency with regards to market information, reducing transaction costs [43].

However, residual transaction costs persist. For instance, monitoring compliance and managing cross-border imbalances require continuous coordination and enforcement. Additionally, the settlement period significantly influences transaction costs [43]. For example, shortening the Imbalance Settlement Period (ISP) from 15 minutes to 5 minutes, may reduce forecasting errors by allowing more refined imbalance settlements, which better reflect the deviations in real-time [43]. However, it could simultaneously increase administrative costs, as it requires three times more bids, settlement calculations and market participants have to adjust their portfolio more frequently [25].

As explained in Section 2.3, the EU Balancing Guideline provides a framework for member states, but TSOs are given relatively much freedom to propose their own methodologies, leading to quite some different pricing designs in the EU, when examined at a detailed level [48]. Certain pricing designs and design choices might contribute to market transparency and cost-effectiveness within a certain member states, but the variation between the member states can lead to higher transaction costs for cross-boarder balancing [26]. Vandezande et al. already argued in 2008 that to efficiently integrate European balancing markets, harmonization of market rules and pricing mechanisms are required to reduce barriers to participation and improve liquidity [50].

An example of regulatory differences is the variation in bidding requirements across EU member states. Some countries require symmetric bids for aFRR, meaning that participants must submit both upward and downward balancing bids, while other TSOs allow asymmetric bids, where participants can submit bids for only one direction [25]. This difference affects market participation and cost-efficiency, as symmetric bid requirements can reduce market flexibility and increase costs for participants who cannot provide both upward and downward reserves [25]. In the imbalance pricing designs, numerous regulatory differences between control areas can be seen as well [2], [3]. Section 2.5 will provide a detailed example of such differences between imbalance pricing designs, by explaining the pricing designs of the Dutch and Belgian balancing market detail.

2.5. Empirical Analysis

This research is focused on analysing imbalance pricing designs, by comparing the Dutch and Belgian pricing designs. Therefore, it is important to understand both markets in detail from an empirical point of view. This section provides an extensive review of both balancing markets and the imbalance pricing design, based on the regulations and balancing rules established and provided by the Dutch TSO TenneT and the Belgian TSO Elia.

2.5.1. Pricing on the FRR markets

Netherlands

In the Netherlands, a hybrid pricing mechanism is followed for aFRR that differentiates between capacity procurement and activated balancing energy [41]. Capacity bids are settled using a pay-as-bid system, where BSPs submit their prices, and the TSO accepts bids based on the most cost-effective offers. BSPs that are not contracted by the TSO are allowed to place bids as well, attracting more suppliers of balancing energy. This approach contributes to market and price competition, minimising procurement costs for the TSO [3]. The process of awarding capacity bids and activating aFRR is shown schematically in Figure 2.10. Activated aFRR is compensated with the balancing energy price, which is computed using a pay-as-cleared system, also called uniform or marginal pricing. This means that all BSPs receive the marginal price for their activated balancing volume across the entire ISP, which is determined by the highest activated bid for positive balancing energy (upward regulation) or the lowest activated bid for negative balancing energy (downward regulation) [3]. The remuneration process for aFRR is very similar to the imbalance pricing design.

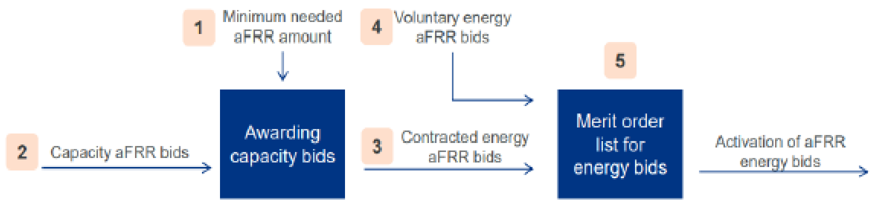


Figure 2.10: Schematics of contracting and activating aFRR [41]

As aFRR is activated following the merit order principle, the most cost-effective balancing bids are activated first. Within each ISP, one balancing energy price is determined per regulation direction [3]. A schematic of marginal pricing for balancing energy is provided in Figure 2.11. If mFRR is activated during the same ISP, and its clearing price is higher (for upward regulation) or lower (for downward regulation, then the mFRR price will set the final balancing energy price [3].

Capacity bids for mFRR are settled using a pay-as-bid system, similar to the aFRR market. Unlike aFRR, no bids are placed for the activation of mFRR, the TSO activates the contracted quantity as needed without using a merit order [3]. Instead, mFRR is activated based on physical trade-offs [51]. This approach gives the TSO more flexibility in activation, but may lead to higher costs and less price transparency compared to a merit order system [38], [43]. After the quarter hour, the mFRR volume is settled against the balancing energy price that is applied to the corresponding direction of activated volume [3]. The balancing energy price is determined by the maximum, or minimum, of the marginal price for both aFRR and mFRR [3].

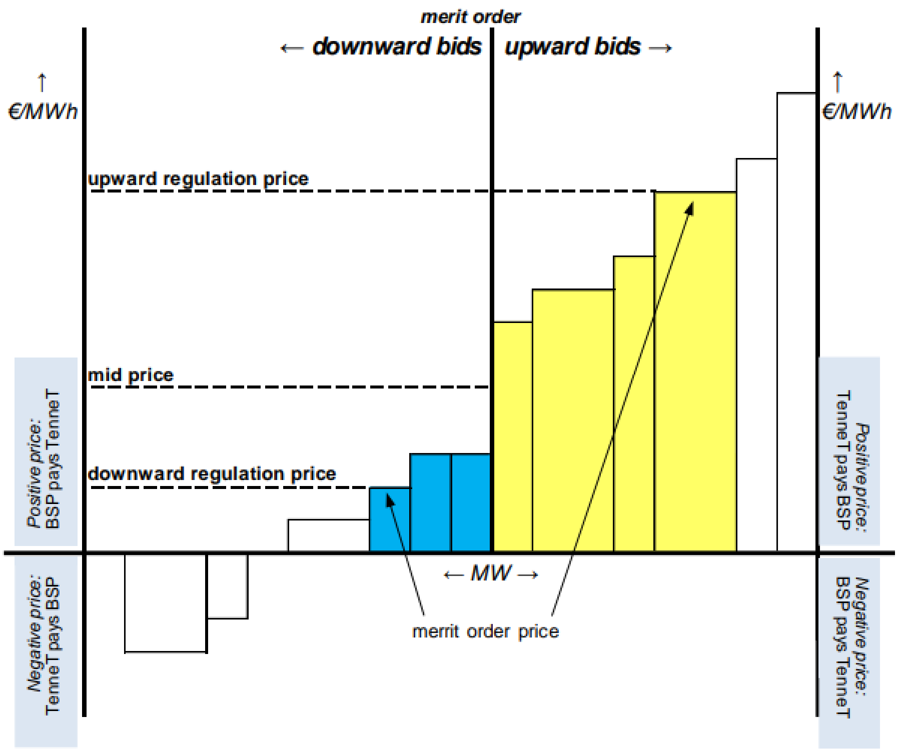


Figure 2.11: Marginal pricing for balancing energy, based on the merit order [3]

Belgium

Elia also contracts aFRR capacity through a bidding process. Similarly to the Dutch market, both contracted BSPs and non-contracted BSPs are allowed to submit bids. Figure 2.10 therefore also serves as a schematic of the Belgian process of procuring capacity and activating aFRR bids. This open approach is intended to attract multiple providers, thereby promoting competition in price formation [52].

In Belgium, the regulations for aFRR and mFRR have undergone significant changes during recent years, to align the market designs more with the design used in other European countries, such as the Netherlands, aiming to enhance transparency and competitiveness on the European markets [53]. Historically, activated balancing energy in the Belgian aFRR market was remunerated on a pay-as-bid basis, where each BSP was paid its individual bid price [53]. However, Elia has recently transitioned to a marginal pricing system. Thus, all activated bids receive a uniform clearing price, determined by the marginal bid for the corresponding optimisation cycle, which is the highest accepted bid in the case of upward regulation or the lowest accepted bid in the case of downward regulation [2], [52]. This recent change to marginal pricing is designed to improve market transparency, reduce strategic bidding behaviour, and align the Belgian aFRR market with broader European practices [54].

In contrast to the Dutch market, the balancing energy price in Belgium is determined for each optimisation cycle separately, instead of one balancing energy price that applies to the entire ISP [52]. This means that for every time step of 4 seconds, the clearing price for FRR is determined. This leads to 225 balancing energy prices per ISP, instead of one balancing energy price. This is in great contrast to the imbalance pricing design, in which only one price is formulated for every ISP.

The mFRR market in Belgium complements aFRR by addressing larger and more prolonged imbalances [55]. Similarly to the Dutch market and the aFRR capacity contracts in Belgium, mFRR capacity is procured based on a pay-as-bid system [55]. However, in contrast to the Netherlands, the activation of mFRR is based on the merit order of the submitted bids, based on a separate merit order list from aFRR. The activated mFRR volumes are settled using marginal pricing as well. In Belgium, the aFRR volumes are settled separately from mFRR volumes [55].

2.5.2. Imbalance settlement price

This subsection explains both the Belgian and Dutch imbalance pricing design. These pricing designs serve as input in the modelling part of this research.

Belgium

In Belgium, the imbalance pricing design uses the single pricing design, following the standard set by the EU Balancing Guideline [1]. Moreover, the price is in principle derived from the settlement prices on the aFRR and mFRR market, with an additional component added in specific situations [2]. The imbalance price is calculated as follows:

$$\lambda = \begin{cases} MIP + \alpha & \text{if} \quad SI \leq 0, \\ MDP - \alpha & \text{if} \quad SI = 0. \end{cases} \tag{2.3}$$

Where:

- SI is the system imbalance
- λ is the imbalance price
- α is the additional component [2]

The main component is defined as the Marginal Incremental Price (MIP) if the system imbalance is negative or zero (i.e., when net upward regulation is required) and equals the Marginal Decremental Price (MDP) if the system imbalance is strictly positive (i.e., when net downward regulation is required) [54]. MIP is based on the maximum value of several elements, MDP on the minimum value of these elements. One of the components that serves as input for both MIP and MDP is the element account for aFRR, in other words, the element that reflects the costs made on the aFRR market for both upward and downward regulation [2]. Equation 2.4 displays how the element accounting for aFRR is calculated [2].

$$aFRR\ element = \frac{\Sigma_{OC}\ (abs(aFRR\ SD_{OC}) \times MP\ aFRR_{OC})}{\Sigma\ (abs(aFRR\ SD_{OC}))} \tag{2.4}$$

Where:

- $aFRR\ SD_{OC}$ is the aFRR satisfied demand, i.e. the absolute value of the activated volume for the optimisation cycle

- $MP\ aFRR_{OC}$ is the aFRR marginal price for the optimisation cycle [2]

The calculation of the aFRR element has recently been updated by Elia, along with the update in the pricing design for the aFRR market. Previously, the aFRR element was based on the volume-weighted average of all activated bids for aFRR [2]. This was in line with the pay-as-bid system that was applied on the aFRR market. However, since the TSO has changed to the marginal pricing method for aFRR, the element accounting for aFRR in the imbalance price is now based on the weighted average of the marginal prices for aFRR [2].

The MIP equals the maximum of the following elements [2]:

- Element accounting for aFRR regulation
- Element accounting for mFRR regulation
  - This is the marginal price of mFRR activation in positive direction
- The imbalance price limitation measured, called the 'floor'
  - The floor is equal to the maximum of VoAA in positive direction and VoAA in negative direction for the concerning ISP [2]

The VoAA corresponds to the first bid for a given ISP, considering both the bids for aFRR and mFRR [2]. This is the lowest bid for upward regulation and the highest bid for downward regulation in the merit order list.

MDP equals the minimum of the following elements [2]:

- Element accounting for aFRR regulation
- Element accounting for mFRR regulation
  - This is the marginal price of mFRR activation in negative direction
- The imbalance price limitation measure, called the 'cap'
  - The cap is equal to the minimum of the VoAA in positive direction and VoAA in negative direction for the concerning ISP [2]

The additional component (α) is added to the MIP if the system imbalance is negative or zero to form the imbalance price. In case the system imbalance is strictly positive, the additional component is subtracted from the MDP [54]. The additional component only applies in specific situations, such as during periods of extreme reserve activation. This component is used to ensure that BRPs act in the interest of system balancing [56]. Although this additional component is not directly in line with the EU Balancing Guideline, Elia argues that its effect is in line with the goal of enhancing balancing efficiency [2]. Therefore, Elia is allowed to apply this additional component.

The sign of the net system imbalance determines whether MIP or MDP is used to determine the imbalance price [2]. As a single pricing design is used, there is always one imbalance price set, even for ISPs in which both upward regulation and downward regulation have been activated [1]. Thus, the direction of the system imbalance is a crucial component in the computation of the imbalance price.

Elia published imbalance prices for each minute, to provide as much transparency to the market as possible. The 1-minute imbalance prices provide an indication of the imbalance price that will be established for the ISP (of 15 minutes) [54]. Since late 2024, Elia has even begun publishing their forecast on the imbalance price, including a confidence indicator, 1 minute before the ISP to stimulate BRPs to adjust their portfolio based on the latest information [54]. This is in great contrast to the approach of TenneT, which will be discussed in the following part.

Netherlands

In the Netherlands, the imbalance price equals, in most scenarios, the balancing energy price and is based on a dual pricing system [3]. In short, this means that there is the possibility that two different imbalance prices are determined within one ISP; one for BRP surpluses and one for BRP shortages.

In the Netherlands, the direction and the gradient of the activated balancing energy determine how the imbalance price is calculated, which is in contrast to the Belgian method that uses the direction of the system imbalance. TenneT indicates the different balancing scenarios as ‘regulation states’ [3]. There are four different regulation states, an overview is presented in Table 2.3.

Table 2.3: Overview regulation states [3]

Regulation state 0	Applies when TenneT has neither activated any upward nor any downward regulation power.
Regulation state +1	Applies when TenneT has activated upward regulation power or when the series of balance deltas within the ISP exclusively increases or is constant (if both upward and downward regulation took place within the ISP)
Regulation state -1	Applies when TenneT has activated downward regulation power or when the series of balance deltas within the ISP exclusively decreases or is constant (if both upward and downward regulation took place within the ISP)
Regulation state 2	Applies when the series of balance deltas within the ISP both increases and decreases (if both upward and downward regulation took place within the ISP)

The ’series of balance deltas’ are the gradient of the activated balancing energy [3]. For example, if the activated balancing energy is only increasing in volume, all gradients in the ISP are positive. In other words, the series of balance deltas are continuously increasing, thus regulation state 1 is applied.

In case of regulation state 0, the mid price is used to determine the imbalance price. The mid price is the average of the lowest bid for upward balancing and the highest bid for downward balancing [3]. This price is relatively similar to the floor and cap in the Belgian pricing design. When regulation state 1 applies for a certain ISP, the imbalance price equals the balancing energy price that is determined for aFRR and mFRR in positive direction. In case of regulation state -1, the imbalance price equals the balancing energy price that is determined for aFRR and mFRR in negative direction. In these three scenarios, only one imbalance price is formed [3]. Below, the imbalance pricing in regulation state 0, 1 and -1 is shown in a mathematical formulating:

$$\lambda = \phi^{mid} \quad \text{if} \quad rs = 0 \tag{2.5}$$

$$\lambda = \phi^{+} \quad \text{if} \quad rs = 1 \tag{2.6}$$

$$\lambda = \phi^{-} \quad \text{if} \quad rs = -1 \tag{2.7}$$

Where:

- λ is the imbalance price that is applied for both a BRP surplus and a BRP shortage
- ϕ^{mid} is the mid price
- ϕ^{+} is the balancing energy price for upward regulation (+) or downward regulation (-)

The ’dual’ nature of this imbalance pricing design is relevant in case of regulation state 2. In this scenario, the TSO has activated both positive and negative balancing energy, and the volumes both increased and decreased within the same ISP. In this case, two imbalance prices are determined [3]. The balancing energy price for aFRR and mFRR in positive direction determines the imbalance price for negative imbalance, i.e., a BRP shortage. Vice versa, the balancing energy price for aFRR and mFRR in negative direction determines the imbalance price for positive imbalance, i.e., a BRP surplus [3].

In regulation state 2, there is a chance that a reverse pricing situation occurs. In the case of reverse pricing, the mid price is higher than the balancing energy price for upward regulation or lower than the balancing energy price for downward balancing [3]. This can happen when the biddings for aFRR in downward regulation start at a higher price than the biddings for upward regulation. Because two imbalance prices are formed in regulation state 2, the price for downward regulation is used for the imbalance price for a BRP surplus. If the balancing energy price for downward regulation exceeds the mid price, the BRP would profit from the fact that regulation state 2 is applied. This results in a counter-intuitive incentive on the balancing market [57], which is why the mid price is used to determine the imbalance settlement price in the case of reverse pricing [3]. Below, the different scenarios and formulas for the imbalance price are presented:

If $rs = 2,$

$$\lambda^{+} = \begin{cases} \phi^{-}, & \text{if} \quad \phi^{-} \leq \phi^{mid}, \\ \phi^{m}, & \text{if} \quad \phi^{-} \leq \phi^{mid}. \end{cases} \tag{2.8}$$

$$\lambda^{-} = \begin{cases} \phi^{+}, & \text{if} \quad \phi^{+} \leq \phi^{mid}, \\ \phi^{m}, & \text{if} \quad \phi^{+} \leq \phi^{mid}. \end{cases} \tag{2.9}$$

Where:

- $\lambda^{+/-}$ is the imbalance price that is applied a BRP surplus (+) and a BRP shortage (-)
- ϕ^{mid} is the mid price
- ϕ^{+} is the balancing energy price for upward regulation (+) or downward regulation (-)

It is important to notice that in case of regulation state 2, the zero-sum game of the imbalance pricing design for TSOs, as intended by the EU Balancing Guideline [1], no longer applies. In case TenneT makes a profit in regulation state 2, these profits are used to lower net tariffs for BRPs. In this way, the TSO gains nothing from the imbalance settlement, the possible extra payments made by the market parties, flow back to the market [3], [41].

2.6. Comparing the Designs

2.6.1. Analysis of example ISPs

To fully understand how the imbalance price is calculated in specific situations on the balancing markets, several examples have been constructed, based on real data from the Dutch balancing market. These examples are presented in Appendix A. The three most interesting examples are presented in the main text, explaining the characteristics of both the Belgian imbalance pricing design and the Dutch design in detail.

Figure 2.12 shows an example ISP where both downward and upward regulation was activated. In Belgium, the BSPs providing upward regulation in a certain optimisation cycle are paid the marginal price of that optimisation cycle. In reality, the optimisation cycle is set to four seconds, but the data used in the graph is based on optimisation cycles of 1 minute. So, in this particular ISP, a Belgian BSP providing upward regulation in, for example, minute 8 would receive €99.79 from the TSO. A Belgian BSP providing downward regulation in minute 2, has to pay €33.94 to the TSO. Also see Table 2.1 for an overview of the direction of transactions between the TSO and BSP. As the net system imbalance for this ISP is negative, the MIP forms the main component in the imbalance price in the Belgian market. In this example, MIP is equal to €96.25, meaning that all BRPs with a net surplus receive €96.25 and all BRPs with a net shortage have to pay €96.25 to the TSO.

In the Netherlands, the lowest price within this ISP applies for downward regulation, which is equal to €33.94 in this case. For upward activated balancing energy, the highest price applies, in this case €115.00. BSPs that provided upward balancing volume receive €115.00 from the TSO and BSPs that provided downward regulation have to pay €33.94 to the TSO. As the series of balance deltas is exclusively increasing, regulation state 1 applies. There is no point during this ISP where the regulation is in a downward development; the blue line never decreases. Thus, the imbalance price is settled at the highest activated bid, equal to €115.00. Thus, BRPs with a surplus receive €115.00 from the TSO and BRPs with a shortage have to pay €115.00 to the TSO (also see Table 2.2).

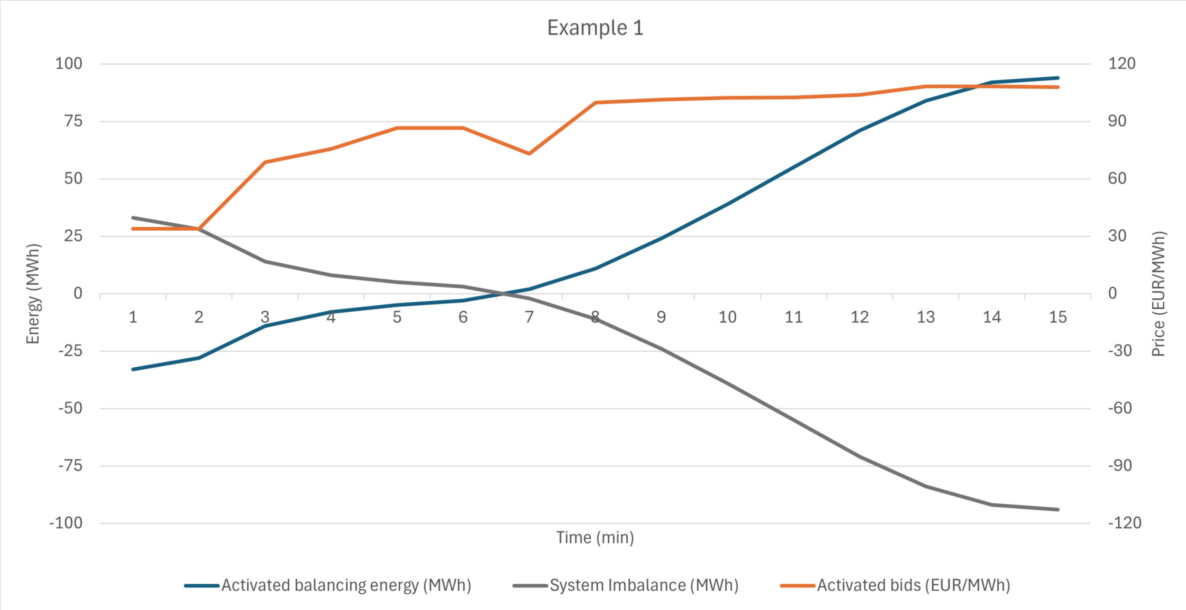


Figure 2.12: Example 1: Course of example ISP (Regulation state 1 |Net SI < 0)

Table 2.4 provides a schematic of the payment directions that apply to this particular example.

Table 2.4: Overview of payments and transaction directions in Example 1

Balancing energy				
	NL		BE	
	Price	Direction	Price and direction	
Upward balancing energy	€ 115.00	TSO to BSP	Depending on marginal price per OC	
Downward balancing energy	€ 33.94	BSP to TSO	Depending on marginal price per OC	
Imbalance settlement				
	NL		BE	
	Price	Direction	Price	Direction
Surplus	€ 115.00	TSO to BRP	€ 96.25	TSO to BRP
Shortage	€ 115.00	BRP to TSo	€ 96.25	BRP to TSO

Figure 2.13 shows an example ISP where downward and upward regulation has taken place. In Belgium, the marginal price per optimisation cycle determines the price for the BSP delivering regulation volume for that cycle. Thus, the price and the direction of the payment depend on the marginal price for a certain optimisation cycle and the sign of this price, as shown in Table 2.5. In the Netherlands, the lowest price within this ISP applies for downward activated balancing energy, which is equal to €-21.69 in this case. This is a negative price for downward regulation, reversing the transaction, so the TSO pays the BSP the absolute price of €21.69 (also see Table 2.1). For upward activated balancing energy, the highest price applies, in this case €86.52. BSPs that provided upward activated balancing receive €86.52 from the TSO.

The net system imbalance is positive for this ISP, which means that the MDP applies for the imbalance price in the Belgian market. In this case, the aFRR element determines the MDP, equalling €26.64. Thus, a Belgian BRP with a surplus is paid €26.64 by the TSO and a Belgian BRP with a shortage has to pay €26.64. In the Dutch market, regulation state 1 applies, as the series of balance deltas exclusively decreases. In other words, the activated balancing energy is always in a decreasing motion.

There is no point during this ISP where the regulation is in an upward development; the blue line never increases. Thus, the imbalance price is settled at the lowest bids, equal to €-21.69. Thus, BRPs with a surplus have to pay the absolute price of €21.69 to the TSO and BRPs with a shortage receive €21.69 from the TSO.

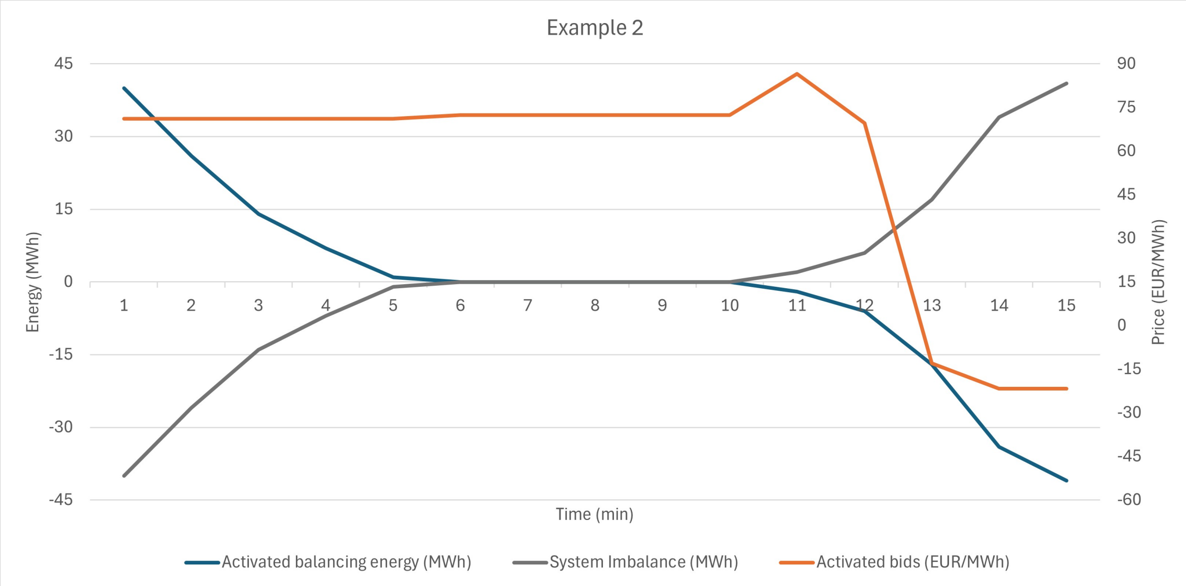


Figure 2.13: Example 2: Course of example ISP (Regulation state -1 |Net SI > 0)

Table 2.5 provides an overview of the price and payment directions that apply to the example 2.

Table 2.5: Overview of payments and transaction directions in Example 2

Balancing energy				
	NL		BE	
	Price	Direction	Price and direction	
Upward balancing energy	€ 86.52	TSO to BSP	Depending on marginal price per OC	
Downward balancing energy	€ 21.69	TSO to BSP	Depending on marginal price per OC	
Imbalance settlement				
	NL		BE	
	Price	Direction	Price	Direction
Surplus	€ -21.69	BRP to TSO	€ 26.64	TSO to BRP
Shortage	€ -21.69	TSO to BRP	€ 26.64	BRP to TSO

In Example 3, presented in Figure 2.14, again both upward and downward regulation have taken place. The net system imbalance is positive, so the MDP is used to determine the imbalance price in the Belgian market. In the Netherlands, regulation state 2 applies for this ISP, as both upward and downward regulation take place *and* the series of balance deltas within the ISP has increased and decreased. Both positive, though very little, and negative balancing energy are activated. The activated balancing energy is in a decreasing motion the first six minutes, but increases again after minute 7, which leads to the regulation state 2 classification.

Similarly to the examples above, the BSPs are paid based on the marginal price. In the Belgian market, this marginal price is determined per optimisation cycle. In the Dutch market, the highest activated bid in the entire ISP sets the balancing energy price for upward balancing energy, and the lowest activated bid determines the balancing energy price for downward balancing energy. The balancing energy prices and payment directions are shown in Table 2.6.

As regulation state 2 applies, two imbalance prices are determined in the Dutch market. BRPs with a shortage have to pay €110.86 to the TSO and BRPs with a surplus have to pay €40.23 to the TSO (also see Table 2.2). In the Belgian market, the MDP determines the imbalance price, since the net system imbalance is positive. For this ISP, the aFRR element equals €-23.93, leading to a negative imbalance price.

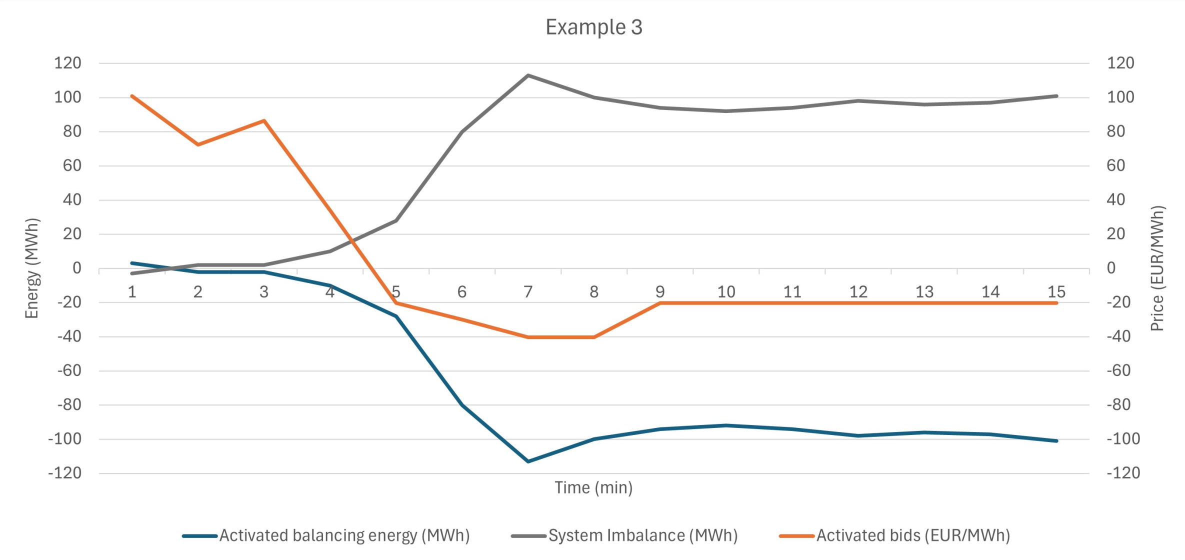


Figure 2.14: Example 3: Course of example ISP (Regulation state 2 |Net SI > 0)

Table 2.6: Overview of payments and transaction directions in Example 3

Balancing energy				
	NL		BE	
	Price	Direction	Price and direction	
Upward balancing energy	€ 100.86	TSO to BSP	Depending on marginal price per OC	
Downward balancing energy	€ -40.23	TSO to BSP	Depending on marginal price per OC	
Imbalance settlement				
	NL		BE	
	Price	Direction	Price	Direction
Surplus	€ -40.23	BRP to TSO	€ -23.93	BRP to TSO
Shortage	€ 100.86	BRP to TSO	€ -23.93	TSO to BRP

2.6.2. Publishing of Information

To enable BRPs to take positions on the energy market in the Netherlands, TenneT real-time publishes information about the system imbalance and activated balancing energy and corresponding bids with a few minutes delay. Besides this, TenneT also sends an update to the market when mFRR is activated [3]. The information on the system imbalance used to be published with a 2 minute delay, but due to the recent imbalance price fluctuations and fast response of flexible assets, TenneT has, at least temporarily, extended the period of delay to 5 minutes [58].

The recent extra delay in publishing information is in great contrast to the Belgian market. This difference shows that the two TSOs have different strategies when it comes to market transparency and ensuring grid stability. Elia's approach aims to provide BRPs with the most current data as fast as possible, enabling BRPs to better match their portfolios to the situation. In contrast, TenneT's delay in providing information indicates a more cautious communication strategy, trying to encourage BRPs to maintain their internal imbalance as small as possible. This contradictory strategy of the two TSOs will be discussed further in Chapter 5.

2.7. Strategic implicit balancing

In the empirical analysis on the two pricing designs, something interesting stands out. In the balancing markets in both the Netherlands and Belgium, the imbalance price is influenced by activations of balancing energy and corresponding bids on a small time step basis. In this research, the optimisation cycle of FRR activation is set to one minute, but in reality these optimisation cycles are only a few seconds [2]. However, the imbalance price settlement is performed on a quarter-hour basis, which cannot fully encapsulate the fluctuations between the optimisation cycles that have taken place with a certain ISP. These different time intervals lead to the concern that strategic out-of-balance positions are possible.

As stated in Chapter 1, the forecasting abilities of actors on the balancing market are becoming increasingly advanced. The hypothesis in this thesis is that pricing designs might foster strategic behaviour or gaming opportunities. A potential form of strategic behaviour involves manipulating the system imbalance to increase imbalance prices. For instance, a flexible asset could strategically allocate its balancing energy, trying to find the optimum between the maximum amount of balancing energy deployed during an ISP and the maximum (or minimum) imbalance price. After all, the BRP's net out-of-balance position at the end of the ISP is rewarded (or penalised) with the imbalance price, but its out-of-balance positions during the ISP influence the imbalance price. The BRP's implicit balancing could also be strategically deactivated during the minute with the highest imbalance (and thus the highest price). This strategy would allow the battery to secure the maximum (or minimum) imbalance price for the largest possible volume, by performing implicit balancing in the remaining 14 minutes of the imbalance settlement period. During this most expensive minute, the asset could even try to amplify the system imbalance, by producing balancing energy in the undesirable direction. Increasing the system imbalance leads to a higher (or lower) imbalance price, as more FRR needs to be activated to balance the electricity grid. As long as the BRP's net out-of-balance position is in the 'correct' direction, depending on the sign of imbalance price, at the end of the quarter-hour, it is paid the increased (or decreased) imbalance price.

In this research, a distinction is made between strategic behaviour and gaming behaviour. When this research refers to a flexible asset showing *strategic behaviour*, the optimal allocation of balancing energy in the 'correct' direction is meant, with the goal of deliberately keeping the imbalance price as high as possible. When this research refers to *gaming behaviour*, the deliberate amplification of the system imbalance, and thereby increase in imbalance price, is meant. Based on these identified possibilities for strategic and gaming behaviour, several asset strategies will be formulated in Chapter 3.

3 Methodology

This chapter outlines the methodology used for this research. As stated in Chapter 1, a mostly quantitative approach is used by building an optimisation model in the programming language Julia. The data and input for the model are obtained from the following sources:

- Data on historical imbalance volumes, and upward and downward bids on the aFRR market will be sourced from TenneT [59].
- Specifics on both pricing mechanisms are provided in the document "Imbalance Pricing System" provided by the Dutch TSO TenneT [3] and the document "Terms and Conditions for balance responsible parties (BRPs)" provided by the Belgian TSO Elia [2].

In this chapter, the modelling strategy for the optimisation model in Julia is presented. The modelling strategy provides a conceptual overview of the two sub-models that will be created, based on the general formulas that simulate the balancing markets and the general market organisation. The conceptual model visualises how the models are organised. Only after this is the model set-up explained in detail, including a list of the most important assumptions made. Finally, the validation and verification steps will be presented.

3.1. Modelling strategy

In multiple papers it is argued that flexible assets in balancing markets can be classified as optimisation problems [13], [30], [37]. Therefore, both the balancing market and the flexible asset are simulated using an optimisation model. The flexible asset performs implicit balancing with full look-ahead.

3.1.1. Conceptual model

The model consists of two key components:

1. **Market Model**: Simulates the aFRR and mFRR clearing process based on the imbalance settlement mechanisms operational in the Netherlands and Belgium.
2. **Asset Model**: Represents the decision-making process of a flexible asset participating in the market, optimising its implicit balancing actions.

First, the market model is optimised, after which the preliminary imbalance price is determined. The specific linear optimisation problem used for the market and the computation of the imbalance price is explained in Section 3.2. Based on the preliminary price and activated regulation volumes, the asset optimisation model is solved, with the allocated energy produced or consumed by the asset per time step as output. The linear optimisation problem simulating the asset's behaviour is explained in Section 3.3. As the asset does not take into account its influence on the market, several additional constraints for activating power are added to the optimisation problem, to simulate the decision-making for activation as well as possible. These additional constraints will be explained in Section 3.3 as well. The first part of the cycle is visualised in the conceptual model shown in Figure 3.1.

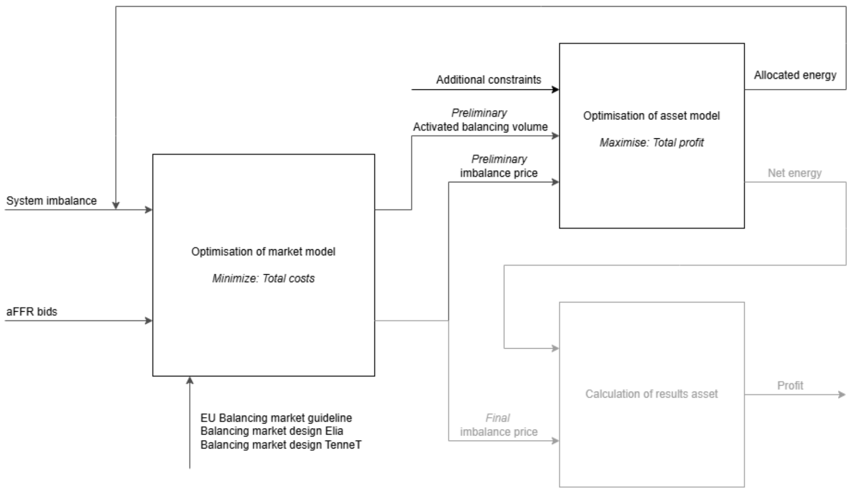


Figure 3.1: Conceptual representation of the two models, highlighting the first part of the cycle

The energy produced or consumed per time step by the flexible asset, serving as implicit balancing energy, is then used to re-adjust the system imbalance accordingly, re-optimise the market model and redetermine the imbalance price. Based on the final imbalance price and the net power activated by the asset, the asset's profit is calculated. This second part of the cycle is visualised in Figure 3.2

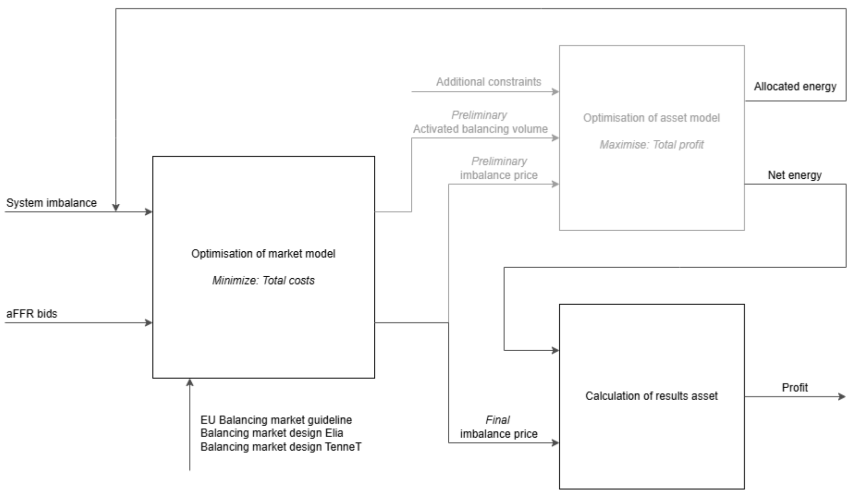


Figure 3.2: Conceptual representation of the two models, highlighting the second part of the cycle

As the implicit balancing actions of the flexible asset influence the system imbalance in real time, the flexible asset's actions therefore influence the imbalance price. This interaction could be represented as a bi-level optimisation problem, as it involves two interdependent decision-making levels [13]. The profit maximisation of the flexible asset can be seen as the upper-level problem, as it optimises its implicit balancing actions based on the imbalance price, but its balancing actions in turn influence the imbalance price. The balancing market serves as the lower-level problem. At this level, the imbalance price is determined based on the market clearing, depending on the imbalance in the system, which is influenced by the asset's power, leading to a complex interdependent relation between the two optimisation problems.

However, in this research, the optimisation problem is solved using a heuristic approach with two separate optimisation models, instead of one bi-level optimisation model. The heuristic approach uses the modelling cycle above to determine the energy allocation of the flexible asset and the resulting imbalance price. In the first modelling cycle, the flexible asset optimises a small capacity of 10 MWh, which only has a small influence on the market model and imbalance price. This modelling cycle is then repeated iteratively, letting the asset optimise an additional 10 MWh based on the updated market outputs in each cycle. Through this iterative process, the asset can take into account its effect on the balancing markets and the imbalance price in steps of 10 MWh.

A bi-level optimisation strategy would reflect the interaction of the flexible asset with the system imbalance and imbalance prices even better, however, due to time constraints for this master thesis and the author's inexperience with bi-level optimisation, the conceptual model shown above is solved using a heuristic approach. Building a bi-level optimisation model would not only require quite some time, it is also very difficult to include all the details on the two imbalance pricing designs. Thus, comparing the bi-level approach to the heuristic approach, the marginal effect on this research's results and conclusion would be minimal. So, it was chosen that the time and effort was better spent researching the two balancing markets extensively and computing different experiments than building a bi-level optimisation model.

3.2. Model set-up: Market model

The market model simulates the clearing process the balancing market, where the TSO activates aFRR and mFRR to maintain the system balance. The volume is activated using the merit order. The equations of this optimisation model are based on the equations presented in [13]. This activation process can be described as the following linear optimisation problem:

Objective function

$$Min. \sum_{t\in T}\left(\sum_{r^+\in R^+} V_t^{r^+} \times \Lambda_t^{r^+} - \sum_{r^-\in R^-} V_t^{r^-} \times \Lambda_t^{r^-}\right) \tag{3.1}$$

s.t.

$$\sum_{r^+\in R^+} V_t^{r^+} - \sum_{r^-\in R^-} V_t^{r^-} = SI_t \tag{3.2}$$

where:

- $V^{r^{+}/-}$ is the activation volume of upward(+) or downward(-) regulation bid at time step t
- $\Lambda^{r^{+}/-}$ is the activation price of upward(+) or downward(-) regulation bid at time step t
- SI_t is the system imbalance at time step t

The market clearing process seeks to minimise the total cost of activated balancing energy, which is represented in the objective function. The constraint represents the market clearing conditions: the activated volume needs to resolve the system imbalance, with the volumes matching exactly in opposite direction.

3.2.1. Imbalance settlement pricing design

The imbalance settlement pricing is based on the two pricing designs described in Chapter 2.

Belgian pricing design

In the Belgian model, the imbalance settlement price is equal to the MIP in case of a net negative system imbalance and to the MDP in case of a net positive system:

$$\lambda = \begin{cases} MIP & \text{if} \quad SI \leq 0, \\ MDP & \text{if} \quad SI > 0. \end{cases} \tag{3.3}$$

Where:

- SI is the system imbalance
- λ is the imbalance price

The MIP and MDP are based on the maximum (or minimum) value of three components: the element accounting for aFRR, the marginal price for mFRR if mFRR is activated, and the floor (or cap) value. Equation 3.4 displays how the aFRR element is calculated.

$$aFRR\ element = \frac{\sum_{t\in T}\left(\mid V_{t,aFRR}^{r+/-}\mid \times \Lambda_{t,aFRR}^{M+/-}\right)}{\sum_{t\in T}\left(\mid V_{t,aFRR}^{r+/-}\mid\right)} \tag{3.4}$$

Where:

- $V_{t,aFRR}^{r+/-}$ is the activated aFRR volume for time step t
- $\Lambda_{t,aFRR}^{M+/-}$ is the marginal price for activated aFRR at time step t

In reality, the optimisation cycle is set to four seconds in the Belgian market. However, in the model, the optimisation cycle is set to one time step, which is equal to one minute, as shown in the formula provided above.

Since there are no mFRR bids in the data from the Dutch market, the mFRR activations in the model are approximated using the highest aFRR bid as the marginal price. Thus, in case mFRR is activated in the model, the highest (or lowest) activated bid forms the marginal price for mFRR:

$$mFRR^{+}\ element = max\left(\Lambda_t^{M+}\right) \qquad \forall t\in T \tag{3.5}$$

$$mFRR^{-}\ element = min\left(\Lambda_t^{M-}\right) \qquad \forall t\in T \tag{3.6}$$

Where:

- Λ_t^{M+} is the marginal price for activated upward regulation at time step t
- Λ_t^{M-} is the marginal price for activated upward regulation at time step t

The floor value is based on the maximum of lowest bid for upward regulation and the highest bid for downward regulation, while the cap value is equal to the minimum to these first bids, also defined as the VoAA. As the regulation bids apply for every time step during the ISP, this value is constant during the ISP.

$$floor = max\ \left(min\ R^{+},\ max\ R^{-}\right) \tag{3.7}$$

$$cap = min\ \left(min\ R^{+},\ max\ R^{-}\right) \tag{3.8}$$

Where:

- R^{+} contains all bids for upward regulation for the concerning ISP
- R^{-} contains all bids for downward regulation for the concerning ISP

So, the determination of MIP and MDP can be summarized in the following formula:

$$MIP = max\ \left(aFRR\,element,\ mFRR^{+}\ element,\ floor\right) \tag{3.9}$$

$$MDP = min\ \left(aFRR\,element,\ mFRR^{-}\ element,\ cap\right) \tag{3.10}$$

Dutch pricing design

In the Dutch model, the imbalance settlement price is equal to the marginal price of either upward regulation or downward regulation, depending on the regulation state:

$$\lambda^{+/-} = \phi^{mid} \qquad \text{if} \quad rs = 0 \tag{3.11}$$

$$\lambda^{+/-} = \phi^{+} \qquad \text{if} \quad rs = 1 \tag{3.12}$$

$$\lambda^{+/-} = \phi^{-} \qquad \text{if} \quad rs = -1 \tag{3.13}$$

If $rs = 2,$

$$\lambda^{+} = \begin{cases} \phi^{-}, & \text{if} \quad \phi^{-} \leq \phi^{mid}, \\ \phi^{mid}, & \text{if} \quad \phi^{-} \leq \phi^{mid}. \end{cases} \tag{3.14}$$

$$\lambda^{-} = \begin{cases} \phi^{+}, & \text{if} \quad \phi^{+} \leq \phi^{mid}, \\ \phi^{mid}, & \text{if} \quad \phi^{+} \leq \phi^{mid}. \end{cases} \tag{3.15}$$

Where:

- λ^{+} is the imbalance price for a BRP surplus
- λ^{-} is the imbalance price for a BRP shortage
- ϕ^{mid} is the mid price
- ϕ^{+} is the balancing energy price for upward regulation
- ϕ^{-} is the balancing energy price for downward regulation

In the formulas presented above, it is clearly visible that the balancing energy price for upward regulation is used for the shortage imbalance price and the balancing energy price for downward regulation determines the surplus imbalance price in regulation state 2. So, when regulation state 2 applies, the imbalance price for a shortage is high in positive direction, and the imbalance price for a surplus is low, often in negative direction. This ensures that BRP always have to pay in case of regulation state 2.

The price for upward regulation is based on the highest activated bid for upward regulation during the ISP and the price for downward regulation is based on the lowest activated bid for downward regulation during the ISP, as shown in the formulas provided below. Similarly to the Belgian market model, when mFRR is activated, the highest (or lowest) activated aFRR bid determines the marginal price for mFRR. Thus, in the Dutch market model, the highest (or lowest) activated bid forms the balancing energy price for activated FRR altogether.

$$\phi^{+} = max\ (\Lambda_t^{M^{+}}) \qquad \forall t \in T \tag{3.16}$$

$$\phi^{-} = min\ (\Lambda_t^{M^{-}}) \qquad \forall t \in T \tag{3.17}$$

The mid price is the average of the lowest bid for upward regulation and the highest bid for downward regulation and determined as follows:

$$\phi^{mid} = \frac{min\ R^{+}\ + max\ R^{-}}{2} \tag{3.18}$$

As the imbalance settlement price is determined after an ISP, this price does not influence the market clearing. So, the formulas to calculate the imbalance price are not taken into account in the optimisation problem, but are applied after the market model is optimised following the optimisation problem presented in Equations 3.1 and 3.2.

The formulas presented above display how the two market models are built. The optimisation problem formulate is identical for both market models, but the calculation of the imbalance price differs. The most important differences between the two models are the following:

- In the Dutch market model, the mid-price is calculated and can be applied in regulation state 2 in case of reverse pricing. In the Belgian market model, the 'floor price' and 'cap price', are determined, serving as imbalance price limitation measure
- In the Dutch model, the marginal price is used to determine the balancing energy price. This means that the minute with the highest activated bid determines the imbalance price. In the

Belgian model, the average of all marginal prices per optimisation cycle (set to 1 minute in the model) can determine the MIP and the MDP. In case of mFRR activation, the marginal price is used as input for MIP and MDP.

- In the Dutch market model, the regulation state determines which marginal price is used for the imbalance settlement price and whether one or two imbalance prices are formed. In the Belgian market model, the net system imbalance, i.e. the sum of the system imbalance, determines whether the MIP or the MDP is applied for the imbalance price.

Furthermore, assumptions are made in the two market models. The most important assumptions are listed below:

- Cross-border imbalance netting such as IGCC and PICASSO are disregarded to focus on national balancing mechanisms and the impact of the flexible asset on the control area of the TSO and aFRR market.
- The TSO has perfect information on the system imbalance and is perfectly able to counteract this. Thus, the system imbalance equals the aggregated activation of balancing volumes.
- Like in [13], it is assumed that the flexible asset is the only actor with strategic out-of-balance positions. The TSO has perfect information on the strategic out-of-balance position of the flexible asset and can perfectly counteract this by adjusting the activated balancing energy. This perfect foresight is assumed throughout the modelling cycle to leave out the impact of uncertainty in the system. In this way, the results focus on showing the differences in the two imbalance pricing designs and the incentives given by the imbalance prices.
- The additional pricing element (α component) in the Belgian imbalance pricing system is excluded, as this is more in line with the EU balancing guideline [13] and thus allows for a better comparison of the two pricing systems.

3.3. Model set-up: Asset model

The asset model simulates a flexible asset that performs implicit balancing actions with the sole purpose of maximising its profit. The asset can choose to produce energy (positive sign) or consume energy (negative sign) for every minute. Its net position is determined by the sum of the energy produced and consumed during the ISP. The net amount of energy is multiplied by the imbalance price to calculate its profit. If the flexible asset has a net positive volume, it is considered a BRP surplus. Inversely, if the asset has a net negative volume, it is considered a BRP shortage.

The asset's strategy to maximise its profit can in principle be characterised as the following linear optimisation problem:

Asset in Belgian market:
Objective function

$$Max. \sum_{t \in T} e_t \times \lambda \tag{3.19}$$

s.t.

$$-C \times (1 - z) \;\leq\; \sum_{t \in T} e_t \;\leq\; C \times z \tag{3.20}$$

Asset in the Dutch market:
Objective function

$$Max. \sum_{t \in T} e_t \times \left(\lambda^{+} \times z + \lambda^{-} \times (1 - z)\right) \tag{3.21}$$

s.t.

$$-C \times (1 - z) \;\leq\; \sum_{t \in T} e_t \;\leq\; C \times z \tag{3.22}$$

where:

- e_t is the energy produced or consumed by the asset at time step t
- λ is the imbalance price in the Belgian model

- $\lambda^{+/-}$ is the imbalance price for a BRP surplus(+) or BRP shortage(-) in the Dutch model
- z is a binary variable to determine which imbalance price will be applied
- C is the maximum capacity of the flexible asset for the ISP

The objective function is different for the Belgian model and the Dutch model, as there can be two imbalance prices determined for the same ISP in the Dutch model, which is why the asset needs to determine which imbalance price is most profitable and based on the sign of that imbalance price, what the sign of its net power at the end of the ISP needs to be.

In the linear optimisation problem formulated above, the asset does not anticipate the potential changes in the imbalance price caused by the asset's own power allocation. As explained in Section 3.1, letting the asset anticipate its effect on the market would require a bi-level optimisation, as it involves two interdependent decision-making levels. However, in this research, a heuristic method is used that approaches this.

To examine the impact of different possible behaviours that the asset can show, three different strategies are formulated for the asset model:

1. The *basic* strategy,
2. The *smart* strategy,
3. The *gaming* strategy.

In the basic strategy, the asset distributes its power equally over all fifteen minutes in the ISP, without trying to influence the imbalance prices. In the smart strategy, the asset tries to optimise its behaviour, by optimising its energy allocation to maintain the imbalance price as high as possible. In the gaming strategy, the asset tries to increase the imbalance price by amplifying the system imbalance at the most expensive minute. The additional constraints formulated for each strategy are explained below.

3.3.1. Basic strategy

In the basic strategy, the energy is equally allocated across all minutes in the ISP. The equations used in this strategy are the objective function (Equations 3.19 and 3.21) and the constraints (Equation 3.20 and 3.22) presented above. Furthermore, additional the constraints are formulated to prevent the asset from over-regulation:

$$SI_t < 0 \;\;\Rightarrow\;\; e_t \leq -SI_t \tag{3.23}$$
$$SI_t > 0 \;\;\Rightarrow\;\; e_t \geq -SI_t \tag{3.24}$$
$$SI_t = 0 \;\;\Rightarrow\;\; e_t = 0 \tag{3.25}$$

These constraints prevent the asset from over regulating, which could change the regulation state or the net system imbalance. Over-regulation can lead to a completely different imbalance price, potentially turning the asset's profit into a loss. In reality, a flexible asset would also at all times try to avoid over-regulation, as a change in sign of the imbalance price can turn a profit into a great loss.

Furthermore, the asset is forces to spread its capacity equally across each time step, using the following equation:

$$e_t = \frac{1}{15} \times C \qquad \forall\, t \in T \tag{3.26}$$

3.3.2. Smart strategy

In the settings for the smart strategy, the objective function presented above are updated with an additional aspect:

Belgian model:

$$Max. \sum_{t \in T} e_t \times \left(\lambda - 0.001 \times \left(\Lambda_t^{M^+} + \Lambda_t^{M^-}\right)\right) \tag{3.27}$$

Dutch model:

$$Max. \sum_{t \in T} e_t \times \left(\left(\lambda^+ \times z + \lambda^- \times (1 - z)\right) - 0.001 \times \left(\Lambda_t^{M^+} + \Lambda_t^{M^-}\right)\right) \tag{3.28}$$

where:

- $\lambda^{+/-}$ is the imbalance price for a BRP surplus(+) or BRP shortage(-) in the Dutch model
- $\Lambda^{M^{+}/-}$ is the marginal activation price for upward(+) or downward(-) regulation at time step t
- z is a binary variable to determine which imbalance price applies

By incorporating the marginal activation price of the upward or downward regulation at time step t in the objective function, the asset automatically favours to produce or consume in the least expensive minute, followed by the second least expensive minute and so on. This sequence of preferred minutes for implicit balancing ensures that the imbalance price is maintained at a higher level for as long as possible.

In this strategy, the additional constraints preventing the asset from over-regulation (Equation 3.23 are applied as well.

3.3.3. Gaming strategy

In the third strategy, the asset, as in the smart strategy, not only optimises its allocation to keep the imbalance price as high as possible, it also tries to increase (or further decrease) the imbalance price by making the system imbalance worse at the most expensive minute. So, the two additional constraints used in the smart strategy apply to this strategy as well. However, another constraint is added to the asset model in both the Dutch market and Belgian market, which forces the asset to show strategic behaviour in the most expensive minute:

$$If \;\; t = t_{skip}$$

$$\begin{aligned} &If \;\; SI_t < 0 \\ &\qquad e_t = -\frac{1}{5} \times C \end{aligned} \tag{3.29}$$

$$If \;\; SI_t \geq 0$$

$$e_t = \begin{cases} 0 & \text{if } \lambda \geq 0 \;\; \vee \;\; \Lambda_t^{M^-} \geq 0 \\ \frac{1}{5} \times C & \text{if } \lambda < 0 \;\; \vee \;\; \Lambda_t^{M^-} < 0 \end{cases} \tag{3.30}$$

where:

- t_{skip} is the time step with the highest, or lowest, activated bid for upward, or downward, regulation
- e_t is the energy produced or consumed by the asset at time step t
- SI_t is the system imbalance at time step t
- C is the maximum capacity of the flexible asset for the ISP
- λ is the imbalance price (used for the Belgian model)
- Λ^{M^-} is the marginal activation price for downward(-) regulation at time step t

These additional constraints, presented in Equations 3.29 and 3.30, 'force' the asset to amplify the system imbalance at the most expensive minute. During all other minutes, the asset can implicitly balance in the opposite direction of the system imbalance, with a maximum of -SI, as shown in Equations 3.23.

Purposely amplifying the system imbalance results in a lower net surplus or net shortage for the asset at the end of the ISP, and thus a lower profit if the imbalance price would not be influenced by the assets behaviour. Therefore, the asset would not apply this strategy following solely the objective function, as its impact on the imbalance price is not taken into account. However, worsening the system imbalance at the most expensive minute can drive up the imbalance price, eventually leading to a higher profit for the asset. Thus, with this constraint, the flexible asset strategically improves its own position in most scenarios. This gaming behaviour is applied in both markets.

When the system has a positive net system imbalance (in the Belgian market model) or is in regulation state -1 (in the Dutch market model), the sign of the marginal price needs to be incorporated into the strategy. If there is a positive marginal price for downward regulation (Dutch model) or positive imbalance price (Belgian model) , the asset will produce energy, automatically increasing the system imbalance. An increasing positive system imbalance will eventually lead to a negative imbalance price, at which point the asset can no longer make a profit with producing energy. Thus, in this situation, the asset is forced to do nothing at the most expensive minute, keeping the imbalance price positive for as long as possible. If there is a negative marginal price for downward regulation (Dutch model) or a negative imbalance price (Belgian model), the asset benefits from increasing the system imbalance, which is why in this scenario the asset's power is set at $\frac{1}{5} \times C$.

The amount of energy that the asset is forced to use in the most expensive minute is set at 20% of the capacity. This input value is chosen based on iterative testing with arbitrary values varying from 10%, resulting in a relatively low impact on the imbalance price, to 45%. 45% is the maximum the asset can use to worsen the system imbalance, as >50% would lead to a net position of 0 or a sign change in the asset's position. After all, the energy allocated to amplify the system imbalance is in the incorrect direction and needs to be compensated by at least the same volume of energy in the correct direction, to ensure a net position in the correct direction at the end of the ISP. The value was set at 20%, as using this part of the asset's capacity to worsen the system imbalance provides balanced results, where the potential impact of the asset's strategy on the imbalance price is demonstrated, while the asset maintains a relatively high profit in the experimental iterations with lower capacities.

Like in the market model, several assumptions were made for the asset model. The following list contains the most important assumptions made:

- The asset operates under full look-ahead of the system imbalance and activated regulation, while in the real-world, the asset has an information delay of five minutes (as of November 2024) in the Netherlands [42]. In Belgium, the TSO publishes near real-time forecasts of the system imbalance and the imbalance price, but the asset is always subject to uncertainties [54].
- The model assumes no depreciation or marginal costs associated with producing or consuming.
- The asset follows a binary decision-making process to determine optimal participation in each imbalance settlement period. The binary value z forces the asset to either have a shortage or have a surplus.

As explained in Section 3.1, the market model and the asset model are combined to analyse the interdependent relationship between the market and the asset. The first part of the analysis will focus on the power allocation during a single ISP and its impact on the system imbalance and imbalance price will be analysed. In the second part, experimental iterations will be performed, where the market-asset dynamic for one ISP will be iterated in steps of 10 MWh of asset capacity. This means that the market-asset optimisation, as presented in Figures 3.1 and 3.2 will run in a loop until the asset can no longer make a profit. By using this iterating sequence of market optimisation and asset optimisation, a bi-level optimisation will be approached. With each allocation of 10 MWh capacity, the asset takes into account its effect of all previous allocations on the market and bases its new power allocation on the latest market optimisation. The experimental iterations represent the growing volume of flexible assets deployed on the balancing markets in both the Netherlands and Belgium. In real life, the volumes reached after 10-20 iterations would entail multiple flexible assets. However, in the model, this is aggregated to one flexible asset, assuming that in the real world assets would operate under the exact same strategy. This is a key assumption, as the interaction between multiple market parties and the unknown decision-making processes of other market parties leads to uncertainties in the real world. However, these uncertainties are not taken into account in the model.

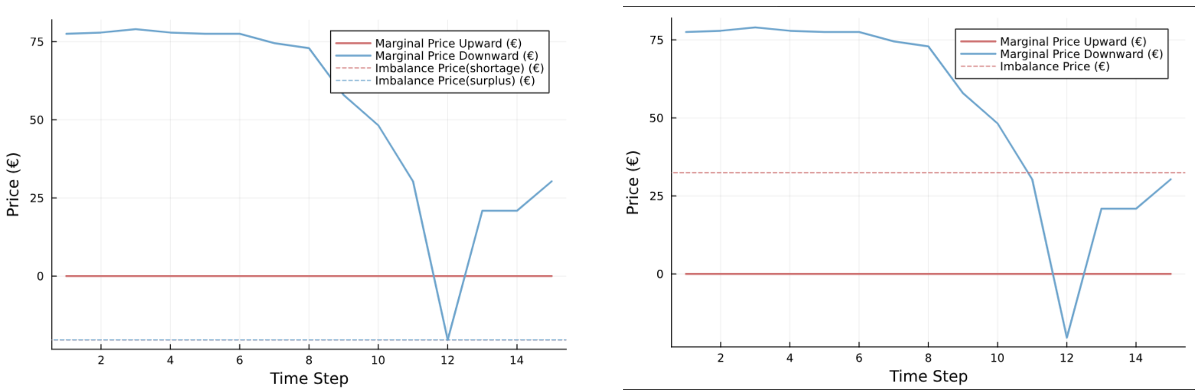
3.4. Model validation and verification

Validation steps were taken to assess whether the models provide meaningful insights for this research and accurately reflect the market dynamics. As data from the Netherlands was used, the marginal activated bids and imbalance prices generated by the market model following the Dutch pricing structure should, in theory, match the prices published by TenneT. However, the prices do not correspond for the following reason: The system imbalance in the model is based on the 'balance deltas', i.e. the activated aFRR and mFRR volumes, published by TenneT. The data shows, ”the power quantities operationally requested by TenneT through aFRR and emergency power, halfway through each minute, along with the prices of the pricing bids. The values in this table refer to a snapshot. Between two-minute snapshots, additional bids may be activated that impact the final balancing energy and imbalance price” [60, p. 1]. Thus, the imbalance settlement prices published by TenneT in the datasets for the Imbalance Settlement Prices [61] can deviate from the prices calculated in the optimisation model. Thus, a comparison between the generated prices in the model and the published prices can never provide a satisfactory validation.

Furthermore, the asset model was validated carefully as well, and compared to the expected behaviour of a flexible asset based on the theoretical and empirical insights obtained in the analysis presented in Chapter 2 . Especially the asset’s optimisation behaviour and its effect on the market were taken into consideration, making sure the heuristic method approaches the real situation well enough to answer the research questions. This is done by iteratively testing the models, comparing the modelling results with the expected outcomes. The specific steps taken are explained below.

The model validation is done manually by comparing the computed values with the expected results based on the model input. The most important validation steps include the following:

- The imbalance prices are correctly computed by the market models based on bid activations. An example of this can be seen in Figure 3.3. In the Dutch market (Figure 3.3a), the imbalance price (the dotted line) is set equal to the lowest activated bid, which determines the marginal price for this ISP. No upward regulation was activated in this ISP, hence the marginal price for upward regulation is 0 for every minute of this ISP. In Figure 3.3b, it is shown that the imbalance price (the dotted line) is much higher, since the imbalance price is based on the average of all marginal prices during this ISP.



(a) Dutch market model

(b) Belgian market model

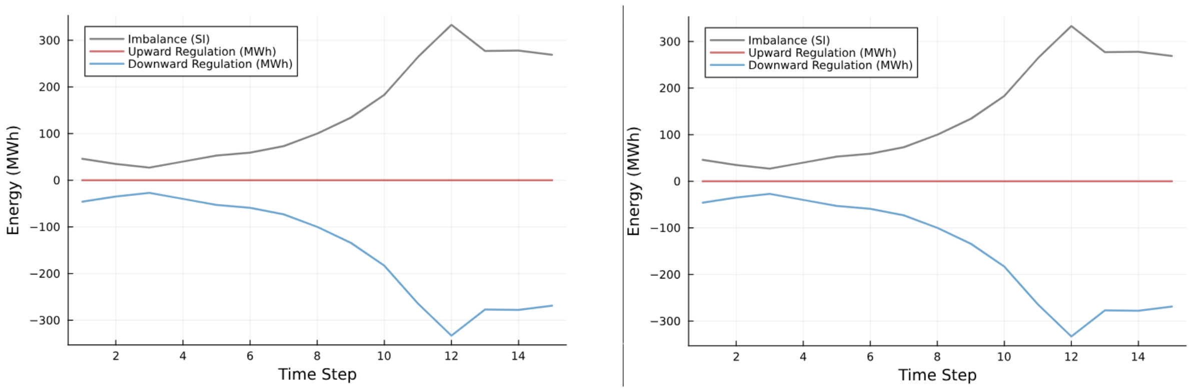
Figure 3.3: Activated marginal bids per minute and imbalance prices

- Only strictly necessary balancing volumes are activated.
- The asset accurately favours the least expensive minute, simulating the real-life possible strategy to keep imbalance prices as high as possible and therefore optimising it’s own profit.
- Re-optimising the market in response to asset behaviour leads to different market output, showing how the asset can influence the balancing markets.
- Iterating the market-asset interaction until convergence is achieved correctly demonstrates how increasing flexible asset participation affects market outcomes and the imbalance prices.

In addition to the validation steps, verification steps are taken as well, to ensure that both models are built correctly. The most crucial points of verification include:

- The market models are able to optimise upward and downward regulation, activating the least expensive bids first.

- The sum of the activated regulation volume matches the imbalance in the opposite direction. Figure 3.4 shows an example of activated balancing volumes, based on the system imbalance. The activated balancing volume is exactly opposite to the system imbalance for every time step. The graphs show that this is done equally in both the Dutch and Belgian market models, as should.

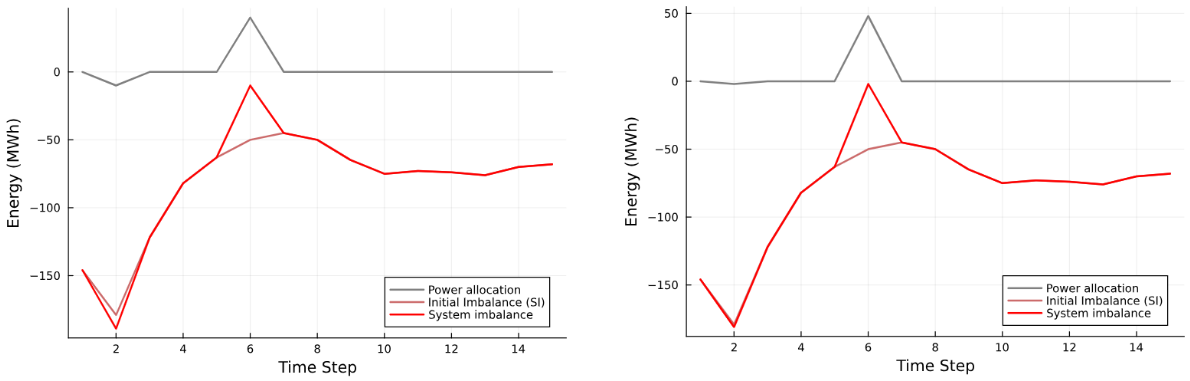


(a) Dutch market model

(b) Belgian market model

Figure 3.4: System imbalance and activated regulation

- The values for mid-price, floor, cap, marginal prices, MIP and MDP, and mFRR elements computed by the model match manually calculated values.
- The asset model responds optimally to imbalance prices by adjusting its strategy, taking into account the marginal prices for each time step.
- The interaction between the asset model and the market model is correct and accurately shows how the asset's balancing behaviour influences the system imbalance. An example of the asset's behaviour is provided in Figure 3.5. During this ISP, the imbalance price in both the Dutch model and the Belgian market is positive, meaning that the asset should have a net surplus. The graphs clearly show that the asset deploys most of its capacity in positive direction, at the least expensive minute. Meanwhile, it uses some of its capacity to implicitly balance in negative direction, amplifying the system imbalance at the most expensive minute. This behaviour follows the heuristic rules implemented to enlarge the asset's profit.



(a) Asset in Dutch market model

(b) Asset in Belgian market model

Figure 3.5: Activated marginal bids per minute and imbalance prices

- The new system imbalance is reflected correctly in the updated imbalance prices.
- The final asset profit is correctly calculated based on the updated imbalance prices.

After the implementation of the model is completed and all validating and verifying steps are taken, results are generated in both models, using different sets of input data. These modelling results are presented in Chapter 4.

4 Analysis

In this chapter, the modelling results will be presented and analysed. The analysis starts with an explanation of the different scenarios that are selected, serving as data input for the experiments. Then an overview of the differences between the imbalance prices in the two markets is presented, after which the experiments are explained, and the results are presented. The results are presented using two different scopes. For some scenarios, several deep dives will be made into specific ISPs and specific volumes of the flexible asset, to grasp the price incentives provided by the designs, the behaviour of the flexible asset, and its impact on the system on a quarter-hour basis. Next, the resulting imbalance prices and the profit made by the asset in the iterative model runs, as explained in Chapter 3, are presented. Finally, a general analysis of the results will be provided, highlighting the most important and interesting results from the different scenarios.

4.1. Selection of ISPs

As this research focusses on analysing specific ISPs to assess the interaction between the asset's behaviour and the market, several ISPs were selected to serve as examples for different scenarios possible on the balancing market. The data set derived from 2024 Dutch market data was processed using a pivot table in Excel. Data from after 01-10-2024 was excluded, as the Netherlands joined PICASSO on October 18, 2024. Data from the period immediately before and after the launch of PICASSO may have been affected by market adjustments and stabilisation, potentially leading to unrepresentative fluctuations in the system imbalance and aFRR biddings.

Based on the results extracted with the pivot table, June was chosen as the reference month for data extraction. This month exhibited significant variation in extreme prices while maintaining an average price level, indicating a high degree of volatility. Such conditions provide a valuable and varied dataset for analysing pricing trends and market dynamics.

Within the selected month, all ISPs without mFRR activation were clustered into six distinct groups, which are presented in Table 4.1. This clustering allows for a more structured selection of ISPs with different circumstances.

Table 4.1: Clustered groups of data without mFRR activation

Cluster	**1**	**2**	**3**	**4**	**5**	**6**
Regulation state	1	1	-1	-1	2	2
Imbalance prices (in Dutch input data)	Low	High	Low	High	Large difference	Small difference

In every cluster, an ISP was selected using the random sampling method to avoid biased selection of data. Furthermore, all ISPs in June with mFRR activation were clustered into two groups: one with upward mFRR activation and one with downward mFRR activation. From these two clusters, two scenarios were selected, again using the random sampling method. These two selections resulted in eight scenarios that will provide the input data for the modelling. The characteristics of each scenario are presented in Table 4.2.

Table 4.2: Characteristics of the eight different scenarios

Scenario	Regulation state	Net SI	Volume SI	Activation of mFRR
1	1	Negative	Low	No
2	1	Negative	High	No
3	-1	Positive	Low	No
4	-1	Positive	High	No
5	2	Positive	High	No
6	2	Positive	Low	No
7	1	Negative	High	Yes
8	-1	Positive	High	Yes

Its important to note that not all, in real-life possible, scenario's and potential differences between the imbalance prices are covered in these six scenario's. These selected scenario's serve as a sampling of possible scenarios and aim to illustrate how the two pricing systems can lead to fairly different imbalance prices and price incentives.

4.2. Structure of Results

For each scenario, the results of the market model are presented, based on the Dutch imbalance pricing design and the Belgian imbalance pricing design. These results are presented in Section 4.3. In addition, the initial market conditions in each scenario are presented in Appendix B. For each scenario, a table is presented, showing all pricing values in both pricing designs, such as the mid price and balancing energy prices and the floor, cap, MIP and MDP, based on the original data of the ISP, before any balancing energy is deployed by the asset. Moreover, a graph showing the development of the system imbalance during the quarter hour and the activated marginal prices in each time step is presented for each scenario. The combination of the table and the graph fulfils two functions: 1) it provides insight in the initial conditions of the ISP in which the asset was deployed and 2) it provides insight in how the two different pricing designs lead to different imbalance prices, even though the input data is identical.

Furthermore, the three asset strategies presented in Chapter 3 are applied to the eight scenarios. Each scenario is run with each strategy using the iterative method, as explained in Chapter 3. In each iteration, the asset allocates an additional 10 MWh of capacity, taking into account its effect on the market from the previous iterations. The results of these iterative runs are used to examine the following:

1. The price incentives yielded by the two different pricing
2. The assets can react to the price incentives and how its resulting behaviour influence the imbalance price
3. If and how the asset can increase its own profit by influencing the imbalance price

To examine these aspects, two different graphs are presented for each scenario. The iterative loop is stopped when one of the following three situations applies:

- The asset can no longer make a profit
- The maximum amount of runs with mFRR activation is reached (set at 5 runs for scenario 1 to 6 and set at 10 runs for scenario 7 and 8)
- The maximum amount of runs is reached (set at 500 runs, but this is not reached in any of the scenarios)

In each scenario, one of these situations is reached at a different asset capacity level, which is why all graphs with the results have varying domains.

In Section 4.4 of this chapter, the most interesting graphs and results of the iterative analysis are presented, which are derived from Scenario 2, 4 and 5. These scenarios show the most interesting results and cover different behaviours of the asset's allocation. For these three scenarios, an additional analysis is done, which zooms in on the asset's behaviour and the development of the imbalance price on a quarter-hour level. First, the behaviour of the asset using the three strategies (as explained in Chapter 3) and its interdependent relationship with the balancing market are analysed for each scenario. In a separate graph, the development of activated marginal prices during the ISP, after the gaming strategy is deployed by the asset, is shown. The gaming strategy is highlighted, as this strategy best shows the potential impact of the asset on activated marginal prices. This quarter-hour approach provides the opportunity to show the allocation of the asset's capacity and the change in the system imbalance and activated regulation per time step, contributing to a better understanding of the interdependent relation between the market and the asset. It also contributes to a better analysis and interpretation of the results of the iterative model runs.

The results of all other scenarios are presented in Appendix B. For these scenarios, only the results of the iterative model runs are presented. Figure 4.3 shows an overview of the different scenarios and the structure used to present the results.

Table 4.3: Overview of presented results in main text (M) and appendix (A)

Scenario	Results initial state	Results imbalance prices	Results on iterative level	Results on QH-level
1	A	M	A	-
2	A	M	M	M
3	A	M	A	-
4	A	M	M	M
5	A	M	M	M
6	A	M	A	-
7	A	M	A	-
8	A	M	A	-

4.3. Results market model

The first sub question in this research is focused on the design variables that are applied in the Dutch and Belgian market design. Although most of the research answering this question has already been presented in Chapter 2, the actual difference in prices that can arise from the two systems has not yet been explicitly shown. The two market models were run with input data from the first six selected ISPs. In Figure 4.1 the resulting imbalance prices are shown.

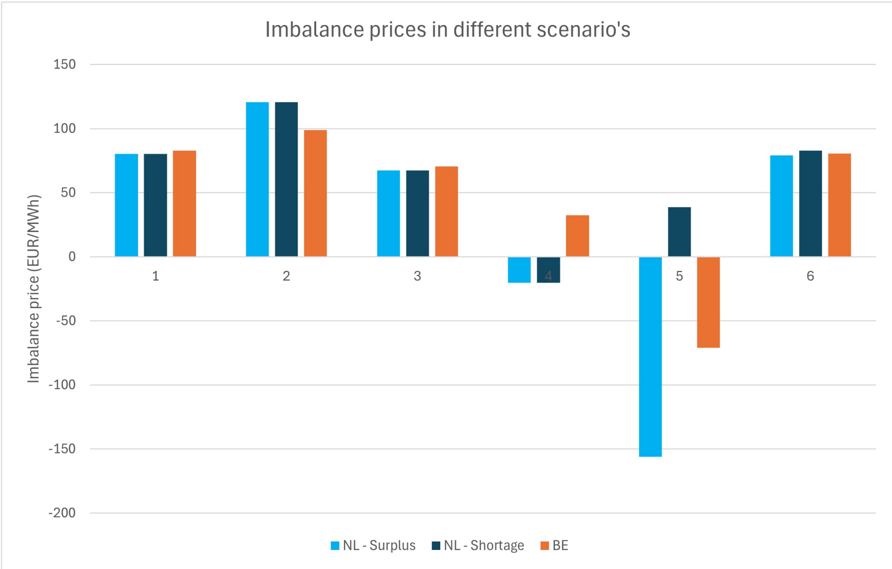


Figure 4.1: Imbalance prices in Dutch and Belgian market, based on the same input data

In some scenarios, the imbalance prices are almost identical in the two markets. Especially when the system imbalance is relatively low (in both positive and negative directions), the differences are small or even insignificant. This can be explained by the fact that with lower system imbalances, the highest (or lowest) marginal price is often similar to the average of the marginal prices, as only a few lower bids are activated. However, in some cases, the similarity derives from the threshold values defined in both pricing designs (e.g. the mid price, floor, and cap). For example, in Scenario 1, the imbalance prices are almost similar. However, they are based on two different input values: the Dutch imbalance prices are based on the highest marginal price during this ISP, while the Belgian imbalance price is based on the 'floor' value. With higher imbalances, it is clearly visible that the prices in the Dutch market clearly take on higher values compared to the Belgian imbalance prices, due to the marginal pricing method.

In Scenario 4, the imbalance price has even a different sign in the two markets. As the Belgian imbalance price is based on the average marginal prices, it stays positive much longer, even when negative bids are activated. In contrast to this, as soon as a negative bid is activated in the Dutch market, the sign of the imbalance price changes. This aspect of the two pricing systems can have a great influence on the behaviour of assets: in the Belgian market the asset will in principle pursue a net positive balance, amplifying the systems imbalance, while in the Dutch market the asset will in principle pursue a net negative balance, correcting the system imbalance.

When an ISP is classified as regulation state 2 in the Dutch market, such as in Scenario 5 and 6, the differences in prices are clearly visible. For example, in Scenario 5, the Belgian imbalance price has a negative value. This would incentivise the flexible asset to consume energy, thus balancing downward. In the Dutch market, two imbalance prices are formed: a negative price for a BRP surplus and a positive price for a BRP shortage. In this situation, no BRP can generate a profit from implicit balancing and will always have to pay if it has an out-of-balance position. Consequently, a flexible asset will not produce any implicit balancing energy. However, there are scenario's within regulation state 2 where an asset can generate a profit. In Scenario 6, the marginal price for downward regulation remains positive. In this case, the Dutch imbalance price for a surplus is positive, meaning that the asset can generate a profit by producing energy.

4.4. Results of market-asset optimisation flow

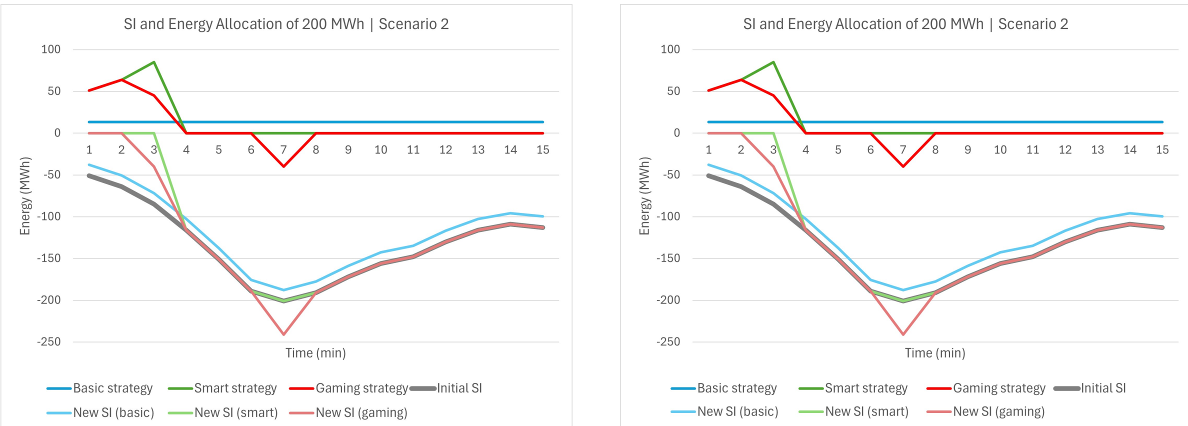
As explained in Section 4.2, the results of Scenarios 2, 4, and 5 will be presented in this section. Both the results on a quarter-hour level and the results from the iterative model runs with the three scenarios will be presented for these three scenarios.

4.4.1. Scenario 2

In this scenario, regulation state 1 is applied in the Dutch market, which means that the imbalance price is based on the marginal price for upward regulation. In the Belgian market, the net negative system imbalance results in MIP being used for the imbalance price.

In Figure 4.2, there is a clear difference visible between the three different strategies. When the asset allocates a capacity of 200 MWh following the basic strategy, it results in a linear line (blue line). This equal distribution of its energy capacity results in an equal reduction of the system imbalance for every time step, which is visible when the light blue line and the grey line are compared. With the smart strategy, the asset clearly deploys all its capacity in the least expensive minutes (green line), resulting in the system imbalance being balanced to 0 in minutes 1-2 (light green line). In the gaming strategy, the asset also uses most of its capacity during the least expensive minutes. However, in this strategy, the asset uses 20% of its capacity to amplify the system imbalance at the most expensive minute, in which the initial system imbalance was already at its lowest point. This is visualised in the drop in the red line at minute 7 and the decrease in system imbalance at the same minute. Dedicating 20% of the asset's capacity to amplifying the system imbalance results in less energy production in the least expensive minutes (1-4), compared to the smart strategy. This is why there is less negative system imbalance during the first minutes in the smart strategy (light green line) compared to the gaming strategy (light red line). Furthermore, it is clearly visible that the system imbalance has become more negative at the most expensive minute (light red line) after the asset has allocated its energy using the gaming strategy.

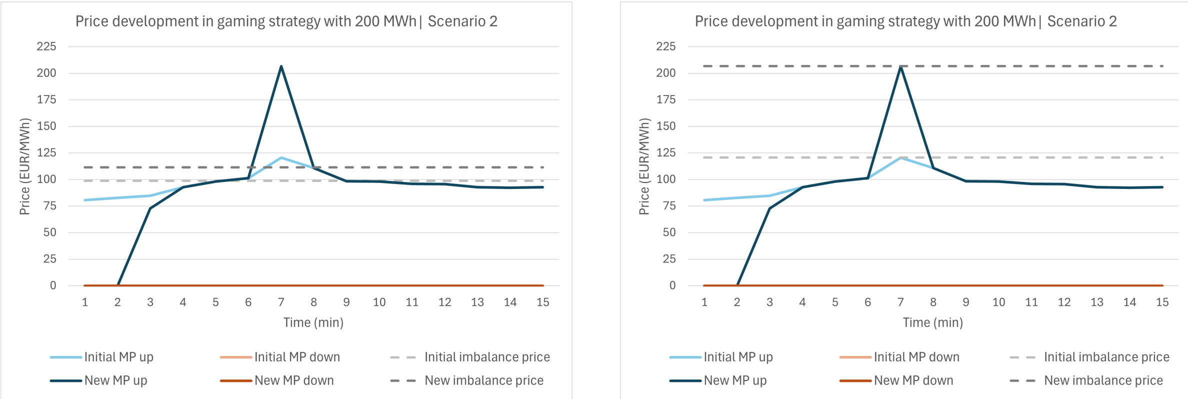
When Figure 4.2a and Figure 4.2b are compared, it can be seen that the graphs are identical. As the imbalance price is positive in both markets, the three strategies result in identical behaviour. However, the resulting imbalance price differs in the two markets. Figure 4.3 shows that the new imbalance price in the Dutch market is €206.69 per MWh after the asset has allocated 200 MWh of capacity using the gaming strategy. In the Belgian market, the same strategy results in a new imbalance price of only €111.52 per MWh. This shows that there is a significant difference between the two pricing designs; the asset has a much larger effect on the Dutch imbalance price compared to the Belgian market. The marginal pricing method applied in the Dutch imbalance pricing design is more vulnerable for gaming strategies.



(a) Energy allocation asset in Belgian market

(b) Energy allocation asset in Dutch market

Figure 4.2: Comparison of energy allocation assets in Belgian and Dutch markets



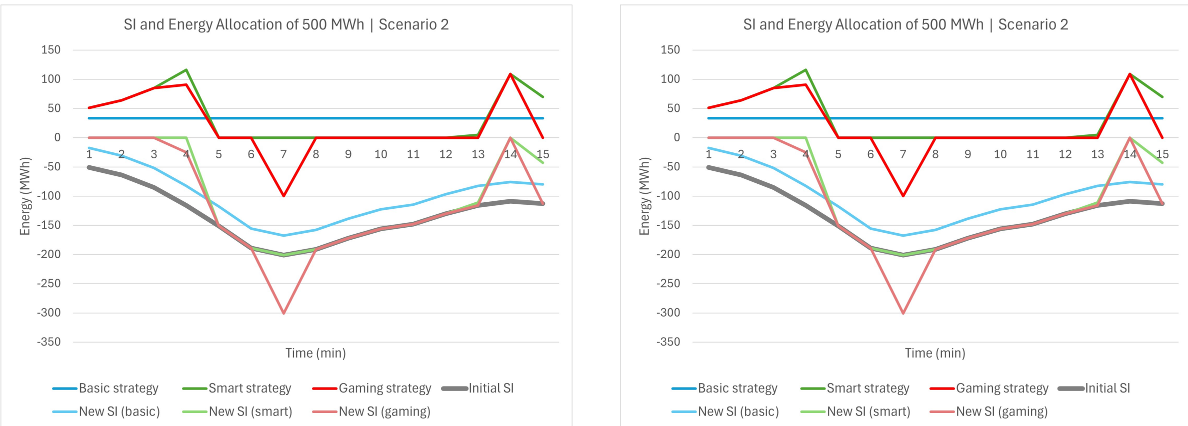
(a) Development of imbalance price in Belgian market

(b) Development of imbalance price in Dutch market

Figure 4.3: Comparison of imbalance prices in Belgian and Dutch markets

In Figure 4.4, the energy allocation is shown with a capacity of 500 MWh. In all three strategies, the asset shows a similar behaviour, except that the values are now higher. Furthermore, once the system imbalance in the first few minutes has been 'balanced', the asset starts producing energy in the following cheapest minutes, which are minutes 13-15 for this ISP. Additionally, it is clearly visible that the system imbalance has become even more negative at the most expensive minute, following the gaming strategy. The behaviour of the asset is still identical in both markets.

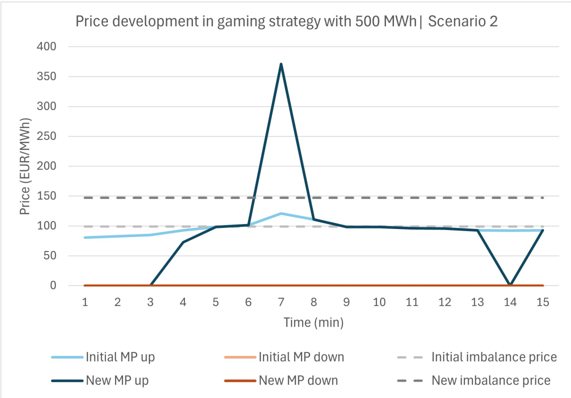
However, like with the 200 MWh capacity, the new imbalance price differs in the two markets, which can be seen in Figure 4.5. In the Dutch market, the imbalance price has risen to €371.13 per MWh, while the price in the Belgian market has 'only' risen to €147.03 per MWh. In this scenario, it is evident that there can be a great difference in the imbalance price, purely caused by the difference in pricing design. The Dutch pricing design leads to an imbalance price that is 2.5 times higher than the imbalance price in the Belgian market, even though all other circumstances are identical. Under these circumstances, gaming behaviour is rewarded much more in the Dutch pricing design.



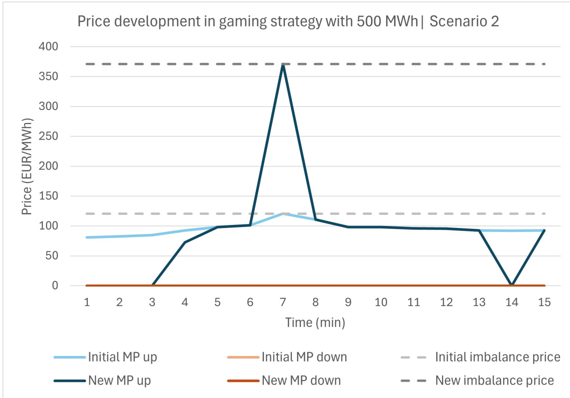
(a) Energy allocation asset in Belgian market

(b) Energy allocation asset in Dutch market

Figure 4.4: Comparison of energy allocation assets in Belgian and Dutch markets



(a) Development of imbalance price in Belgian market



(b) Development of imbalance price in Dutch market

Figure 4.5: Comparison of imbalance prices in Belgian and Dutch markets

When looking at results from the iterative model runs, the effect of the gaming strategy compared to the other two strategies becomes clearly visible. Although the smart strategy leaves the imbalance price intact a little longer than the basic strategy, this effect is negligible compared to the gaming strategy. In Figure 4.6, it is evident that the gaming strategy pushes the imbalance price in both markets to very high levels, by pushing the system imbalance into the deep negative domains at the most expensive minute. Eventually, mFRR activation is reached. This raises the imbalance price to extreme levels. Figure 4.6 confirms the observation made earlier that the Belgian imbalance price remains relatively low when the asset allocates lower energy capacities. For example, the difference in the imbalance prices shown in Figure 4.3 at a capacity of 200 MWh and in Figure 4.5 at a capacity of 500 MWh is also evident in the graph presented below. However, the Belgian imbalance price eventually also increases to extreme levels. This can be explained by the fact that more and more system imbalance, starting from the cheapest minutes, is 'balanced' by the asset, resulting in only the expensive minutes remaining. If there are only minutes with high bid activations, the average of marginal prices increases more and more in the Belgian market. Eventually, the imbalance price reaches extreme levels in both markets when mFRR is activated; as marginal pricing now also applies in the Belgian market.

In Figure 4.7, the evident difference between the strategies in terms of the profit made by the asset is visualised. The basic strategy yields a linear profit, and the asset can eventually no longer make a profit any more when all the system imbalance is 'balanced' by its energy production. Using the smart strategy, the asset can make a little more profit with the same capacity, since it allocates its energy more strategically by determining the cheapest minute for every 10 MWh. However, the profit made in these two strategies is in large contrast to the profit made with the gaming strategy. By driving up the imbalance price, the asset can generate a much larger profit in both markets. The profit made under the Belgian design increases less rapidly in the beginning, which is in line with the slower increase in the imbalance price seen in Figure 4.6, but eventually catches up when mFRR is activated. As the model is limited to a maximum of 5 iterations with mFRR, the assets profit is eventually capped.

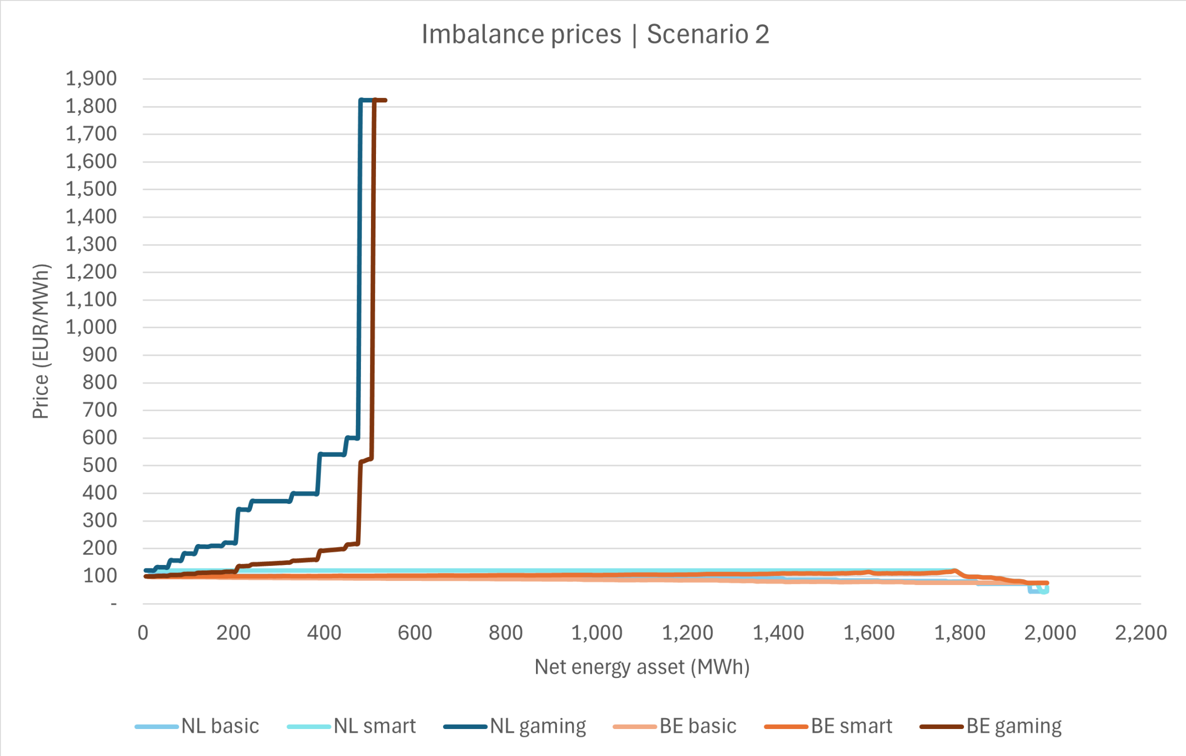


Figure 4.6: Imbalance prices in Scenario 2

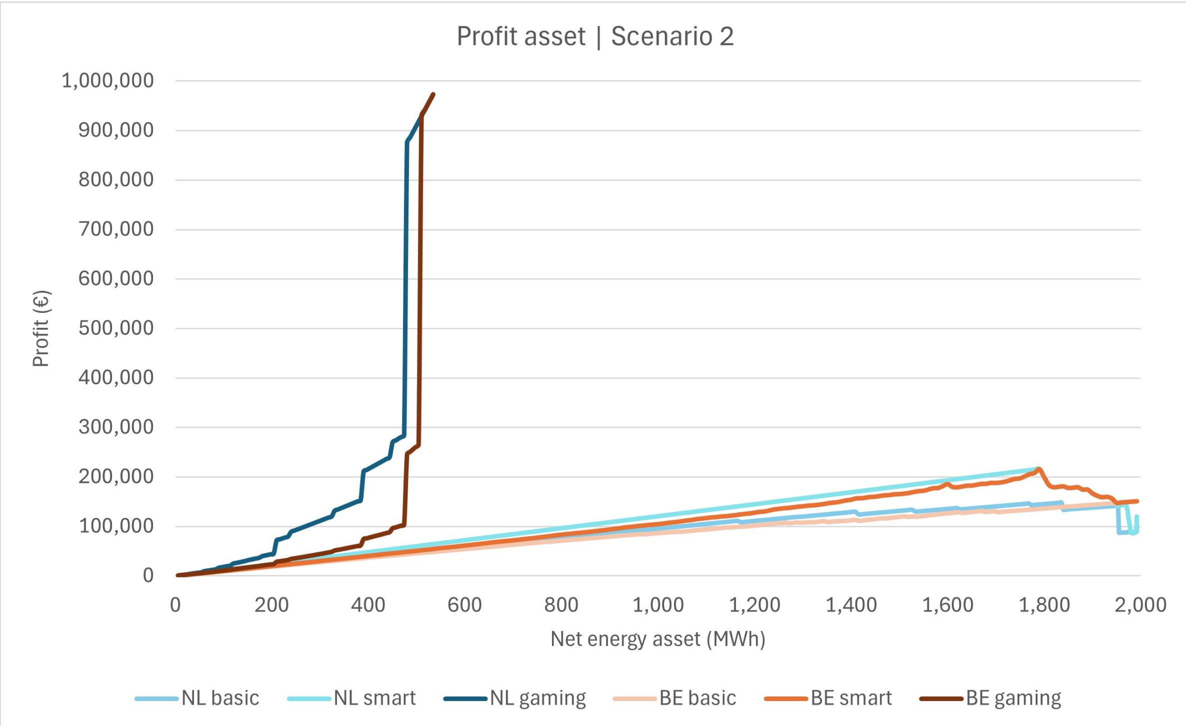


Figure 4.7: Asset's profit in Scenario 2

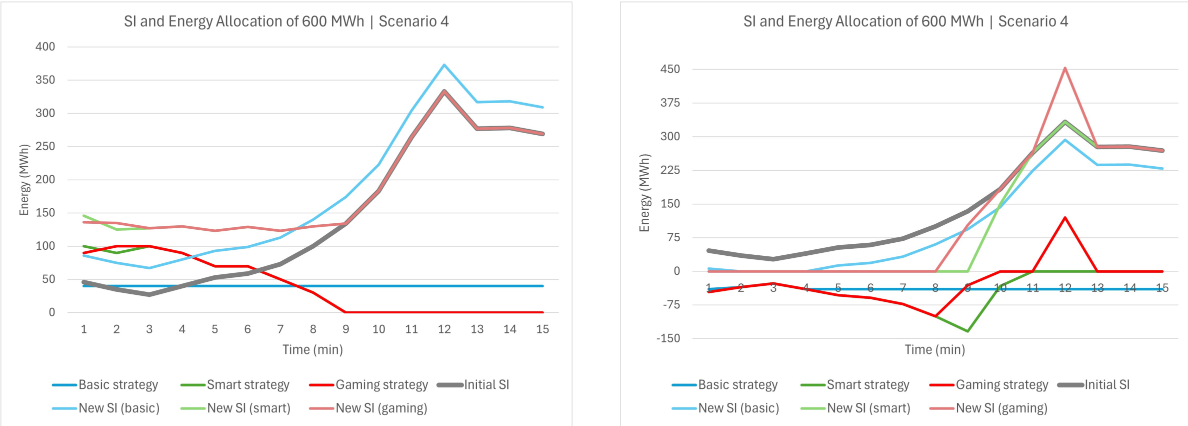
Another important observation made when the results between Scenario 1 and Scenario 2 are compared is that the opportunity window to increase the system imbalance and thereby the imbalance price is much larger in Scenario 2. In Scenario 1, similar conditions apply, with a net negative system imbalance and regulation state 1, but the total volume of system imbalance is low compared to Scenario 2. When the system imbalance volumes are lower during an ISP, the asset has a smaller opportunity to increase the imbalance price. After all, it only uses 20% of its capacity to amplify the system imbalance at the most expensive minute with the gaming strategy. The other 80% of the capacity is used to balance the system imbalance in the other 14 minutes. With lower system imbalances, the point where all system imbalance in those 14 minutes is balanced to 0 is reached at a much lower asset capacity. Therefore, the asset can only deploy a limited amount of energy to amplify the system imbalance in Scenario 1 (also see Appendix B), and the increase in the imbalance price is therefore limited. In Scenario 2, as presented in this chapter, the asset does have the opportunity to do this, allowing the asset to more effectively exploit market conditions to increase its own profit.

4.4.2. Scenario 4

With a strictly positive system imbalance, the behaviour of the asset is different in the two markets. For this scenario, the Belgian imbalance price is still positive, while the Dutch imbalance price has already turned negative under these circumstances. This results in the asset allocating its energy differently. In the Belgian market, the asset has a net surplus, as shown in Figure 4.8a. The basic strategy shows a constant energy production again, while with the smart and gaming strategy, the energy is allocated in the least expensive minutes. In this case, the extra constraint of enlarging the system imbalance at the most expensive minute in the gaming strategy is not applicable (as explained in Chapter 3, as amplifying the system imbalance would only drive the imbalance price faster into the negative range. As soon as the imbalance price becomes negative, the asset does not make a profit with its out-of-balance position in positive direction. Under all three strategies, the asset produces energy due to the positive imbalance price, causing the system imbalance to increase instead of decrease. From these results, it can be derived that a net positive system in combination with a positive imbalance price provides the incentive to increase the system imbalance, rather than decrease the system imbalance. This incentive applies regardless of the strategy used by the asset. As the Belgian pricing design uses the averaging method, this combination happens more often than with the Dutch pricing design. However, gaming behaviour is not incentivised, as increasing the system imbalance eventually leads to a negative imbalance price, at which point the asset's profit turns into a loss.

In the Dutch market, the asset has a net shortage, which can be seen in Figure 4.8b, since the Dutch imbalance price is already negative based on the original data. In the basic strategy, the asset consumes energy consistently across the ISP, lowering the system imbalance at each time step. In the smart strategy, the asset allocates its consumption to the least expensive minutes, causing the system imbalance to decrease in these minutes. In contrast to the Belgian market, the extra constraint of enlarging the system imbalance in the most expensive minute is applied in the gaming strategy. At minute 13, the asset produces energy, which increases the system imbalance.

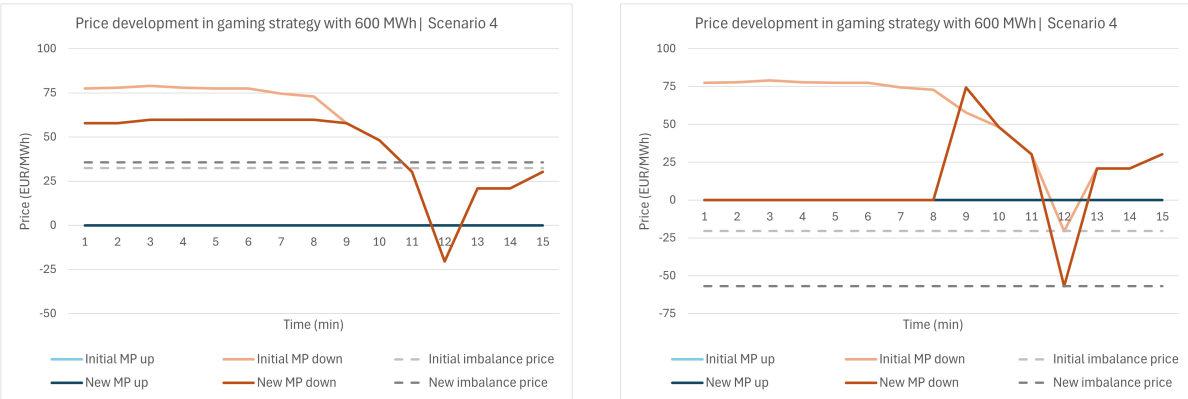
In the Dutch market, the gaming strategy leads to a beneficial effect for the asset: The imbalance price decreases further into the negative range, which can be seen in Figure 4.9b). In the Belgian market, the imbalance price even increases slightly, caused by a higher imbalance price at the least expensive minute, causing the higher activated marginal prices to weigh in more when calculating the average (see Figure 4.9a). Eventually, the imbalance price decreases when a higher capacity is allocated, as shown in the iterative analysis.



(a) Energy allocation asset in Belgian market

(b) Energy allocation asset in Dutch market

Figure 4.8: Comparison of energy allocation assets in Belgian and Dutch markets



(a) Development of imbalance price in Belgian market

(b) Development of imbalance price in Dutch market

Figure 4.9: Comparison of imbalance prices in Belgian and Dutch markets

In the iterative analysis, the significant difference of the asset's behaviour in the two markets, due to differences in their pricing mechanisms, becomes clearly visible. The difference in sign of the net position of the asset is caused by the difference in sign of the imbalance price, as shown in Figure 4.10.

Using the gaming strategy, the asset can exploit the price sensitivity in the Dutch market much more, by amplifying the system imbalance at the most expensive minute. This is in great contrast to the basic and smart strategy. As shown in Figure 4.11, in the basic strategy, the asset can not only deploy a relatively small capacity before it can no longer make a profit, it also does not have the ability to increase the imbalance price for its own gain. In the smart strategy, it can keep the imbalance price very stable for many iterations, but it does not enlarge the asset's profit.

In contrast, the still positive imbalance price in the Belgian market prohibits the imbalance price from the option to increase the imbalance price with the gaming strategy. As shown in Figure 4.10, the imbalance price slowly transition into a negative imbalance price in all three strategies, although the smart strategy and gaming strategy can delay this effect much longer. The more capacity the asset deploys, the lower the imbalance price, which results in a decreasing profit for the asset, as shown in Figure 4.11. Eventually, the asset can no longer make any profit.

Furthermore, when comparing the results of this scenario to Scenario 3 (see Appendix B), the difference in price vulnerability between an ISP with a low system imbalance compared to an ISP with a high system imbalance is observed again. In Scenario 4, the asset can realise large profits in the Dutch market, due to the combination of regulation state -1 with a negative price and the large system imbalances. With lower system imbalance volumes, the opportunity window to increase the imbalance price is smaller, like observed earlier when scenario 1 and 2 were compared. Overall, the results show that in this scenario, the high system imbalance volumes offer a great advantage to the gaming strategy in the Dutch market due to the fact that the imbalance price is negative in the original state. Therefore, the asset can exploit the market by increasing the imbalance price to extreme negative values, whereas the Belgian pricing design prevents such outcomes, as the imbalance price is still positive in the original state.

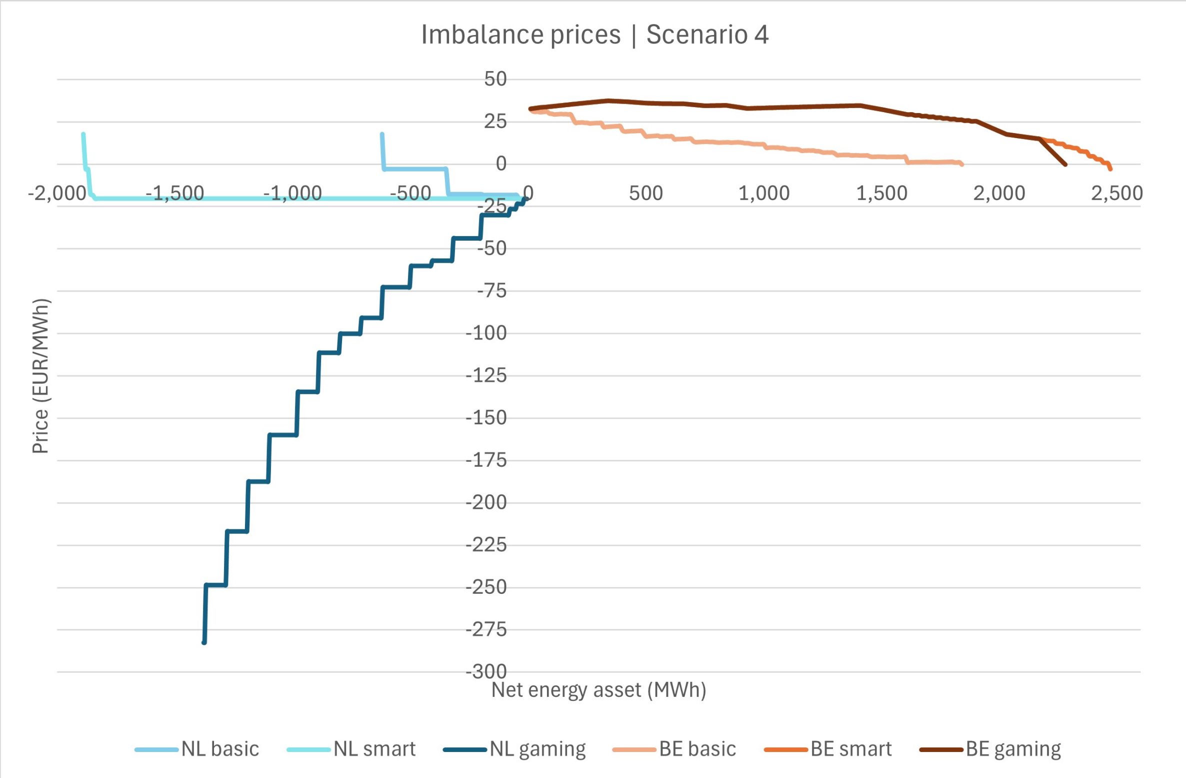


Figure 4.10: Imbalance prices in Scenario 4

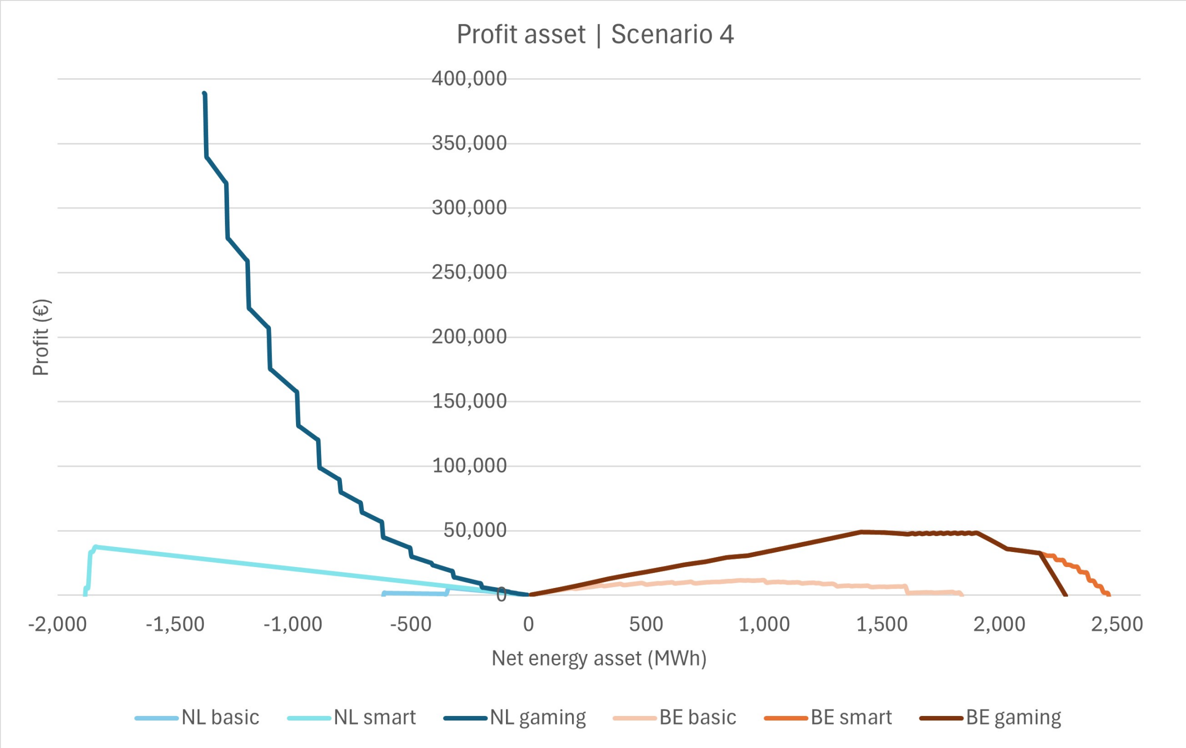


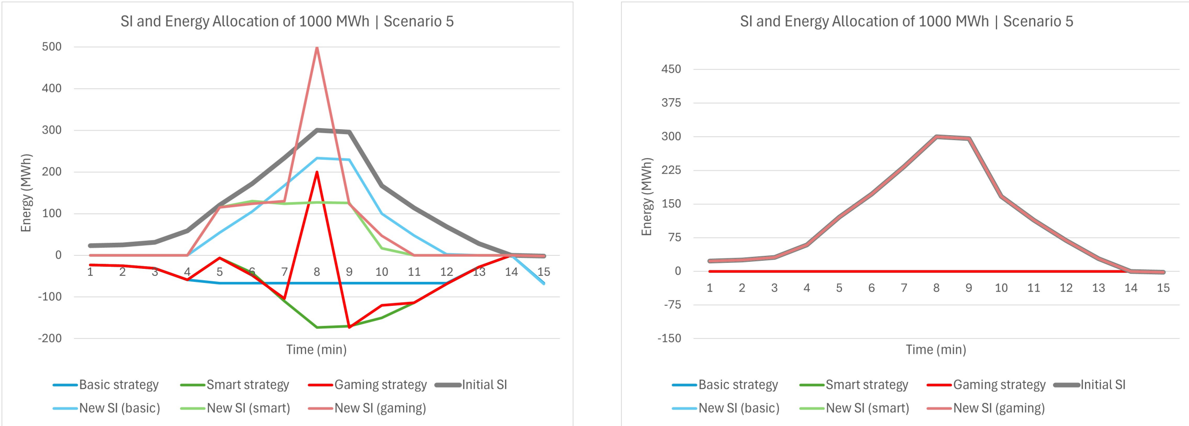
Figure 4.11: Asset's profit in Scenario 4

4.4.3. Scenario 5

In Scenario 5, an ISP with both upward and downward regulation in the initial situation is used as input. In the Dutch market, regulation state 2 applies for this ISP, as the system imbalance becomes slightly negative in the last minute of this ISP. Although the negative volume of the system imbalance is so small in the last minute that it is nearly invisible in Figure 4.12, regulation state 2 still applies. However, the net system imbalance is overwhelmingly positive, resulting in MDP serving as input for the imbalance price in the Belgian market.

The MDP is negative for this ISP, meaning that the asset deploys most of its volume in negative direction in all three strategies, as can be seen in Figure 4.12a. Additionally, in the gaming strategy, it uses 20% of its capacity to amplify the system imbalance at the most expensive minute, resulting in an even lower marginal price for this time step. This leads to a large decrease in the imbalance price, which can be seen in Figure 4.13a. The behaviour and price development observed in this scenario are very similar to the results observed in Scenario 2, only this time the signs have changed, as this ISP has a combination of a positive system imbalance with a negative imbalance price.

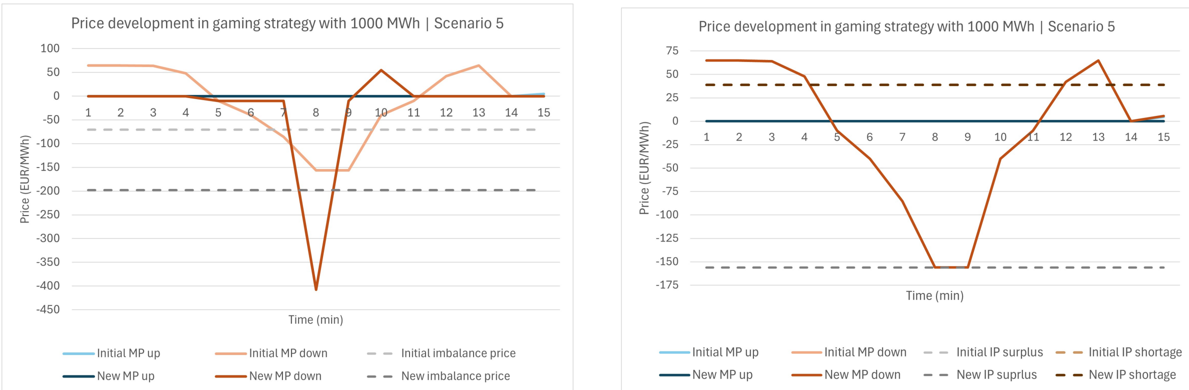
In the Dutch market, the asset does not produce or consume any energy as it cannot make a profit in either direction. Due to regulation state 2, the imbalance price for a BRP surplus is negative and the imbalance price for a BRP shortage is positive (see Figure 4.13b. This means that the asset has to pay the imbalance price to the TSO, no matter the direction of its out-of-balance position. Therefore, the asset does not produce any power in this scenario and the system imbalance remains identical (see Figure 4.12b.



(a) Energy allocation asset in Belgian market

(b) Energy allocation asset in Dutch market

Figure 4.12: Comparison of energy allocation assets in Belgian and Dutch markets



(a) Development of imbalance price in Belgian market

(b) Development of imbalance price in Dutch market

Figure 4.13: Comparison of imbalance prices in Belgian and Dutch markets - 2

When looking at the iterative model runs of this ISP, it stands out immediately that the asset does not deploy any power in the Dutch market, as explained above. In the Belgian market, the asset shows similar behaviour under the basic strategy compared to Scenario 2, only the sign of its net position has changed. In the basic strategy and the smart strategy, the imbalance price decreases slowly, causing the asset's profit to slowly decrease as well. In the gaming strategy, the asset can decrease the imbalance price far into the negative domain (see Figure 4.14) and thereby largely increase its own profit. Eventually, all system imbalance becomes balanced by the assets energy consumption, at which point the imbalance price increases again and approaches 0, and the asset can no longer make a profit.

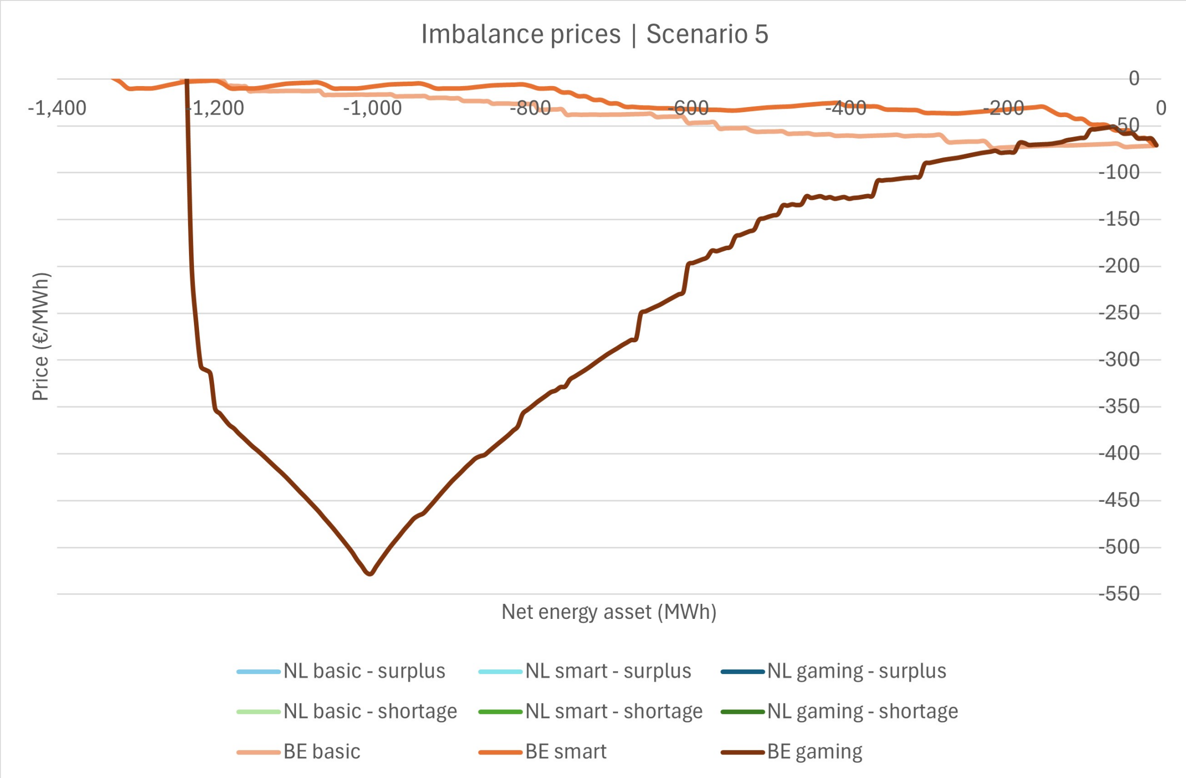


Figure 4.14: Imbalance prices in Scenario 5

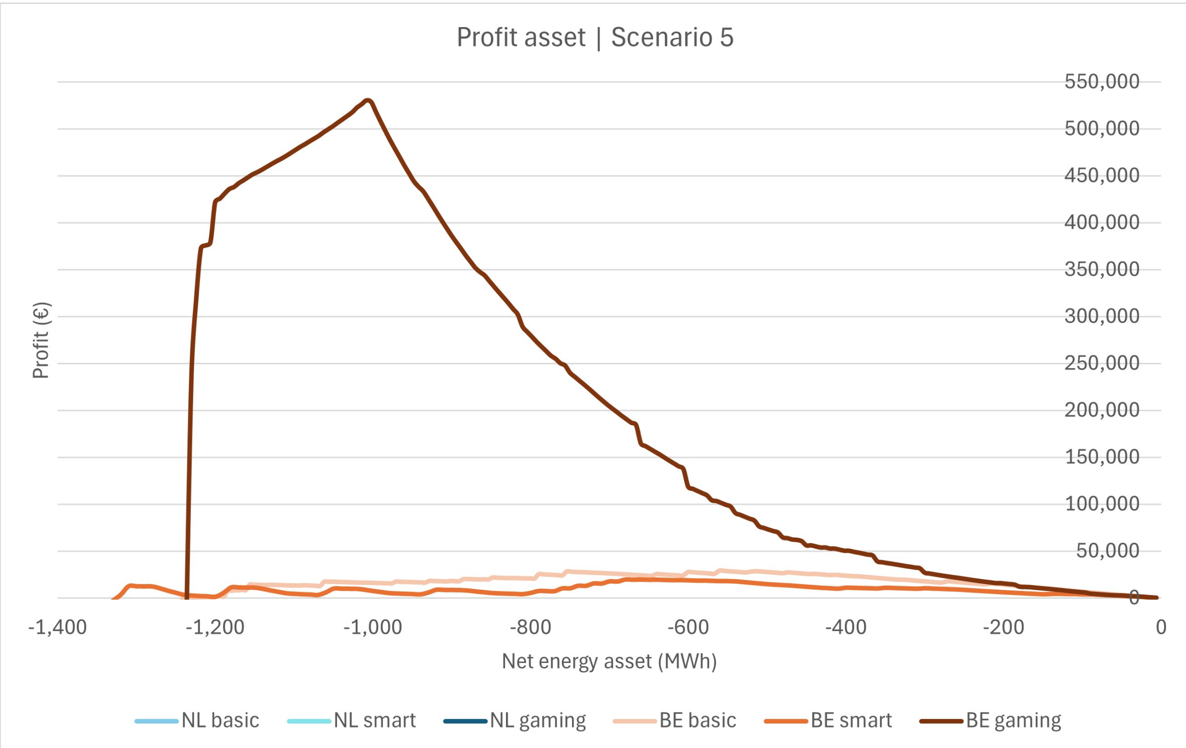


Figure 4.15: Asset's profit in Scenario 5

4.5. Analysis of Results

The modelling results show that flexible assets can indeed pursue gaming behaviour, as shown through the results of the gaming strategy, by deliberate adjusting its out-of-balance position for certain time steps during an ISP. In particular, the model shows that the asset's deliberate increase of the system imbalance at the most expensive minute can lead to a large increase (or decrease) in the imbalance price in both the Dutch and Belgian market, expanding the asset's profit. In some scenarios, this gaming behaviour can even push the system to trigger mFRR activation, which highlights how significant the asset's impact on the balancing market can be.

One of the most important results is that the smart strategy often outperforms the basic strategy slightly, but the gaming strategy outperforms the other two strategies largely. Using the basic strategy, the asset's profit decreases faster in most scenarios when deploying higher capacities. In these cases, producing additional implicit balancing volume does not translate into further profit for the asset; it can even decrease its marginal profit. When the asset uses the smart strategy, the imbalance prices remain as high (or low) as the original price for a longer period. However, the imbalance eventually decreases (or increases) with this strategy as well. As the asset increases its balancing volume, without strategically amplifying the system imbalance in the most expensive minute, it lowers (or raises) the imbalance price, and therefore 'cannibalises' its own profit. In both the Dutch market and the Belgian market, the point of market saturation is reached in most of the scenarios.

Another important finding is that the volume of the system imbalance plays a critical role in the assets ability to influence the imbalance price. With low system imbalances, both in positive and negative direction, the point of market saturation is reached relatively fast, even with the gaming strategy. The asset can simply not increase the imbalance price enough by strategically amplifying the system imbalance, before either there is no system imbalance 'left' to implicitly balance any more, or before the imbalance price changes in sign.

In contrast, with higher system imbalances, the asset can deploy a much larger capacity and can therefore amplify the system imbalance more at the most expensive minute in the gaming strategy. In other words, as the asset can deploy a larger capacity, its 20% of capacity used to amplify the system imbalance at the most expensive minute is larger in terms of absolute values. This opportunity presented in ISPs with large system imbalances leads to exponential increases in the imbalance prices and thus the asset's profit. This not only leads to highly volatile imbalance prices, it can also lead to an unstable electricity grid.

The averaging of marginal prices for the aFRR element in the Belgian market can soften the increase in imbalance price under the gaming strategy, especially with small and semi-large asset capacities. However, when the asset's net balancing volume enlarges even further, the softening effect of averaging the marginal prices becomes smaller. This is caused by the most extreme minute with a large system imbalance and a high marginal price, whereas all other minutes the system imbalance has become very small or even negligible, which increases the weighted average of the marginal prices. The softening effect even completely ceases when mFRR is activated, as in this case, the highest marginal price during the ISP applies for the imbalance price.

The comparative analysis between the Dutch and Belgian markets provides further insights into strategic and gaming opportunities. In both the Dutch and Belgian market the use of a gaming strategy, in many cases, leads to equal or higher profits compared to the basic strategy and smart strategy. However, the Belgian averaging method softens the impact of the asset to a great extent. Furthermore, the situation with a combination of a positive system imbalance and a positive imbalance price, a combination in which the gaming strategy does not yield additional profits, happens more often when the Belgian pricing design applies. On the other hand, in case of regulation state 2, the asset is likely not produce or consume any energy, so in these ISPs there is no gaming behaviour possible in the Dutch market. Nevertheless, the results have shown that strategic out-of-balance positions and gaming behaviour can amplify the imbalance prices for numerous scenario's, leading to high profits for the flexible asset. Thus, both pricing systems reward strategic and gaming behaviour and provide incorrect remuneration for flexible assets, at least in most scenarios. The analysis also demonstrates that the extent of the opportunity to increase the imbalance prices to high levels is highly dependent on the initial system imbalance volumes and the sign of the initial imbalance price.

5 Discussion

This chapter provides a synthesis of the modelling results and the theoretical framework outlined in the earlier chapters. The modelling results will be put into context and integrated with the findings in the theoretical analysis.

5.1. Analysis of Modelling Results within Broader Context

As explained in Chapter 2, the energy market liberalisation introduced multiple electricity markets and market time frames. However, real-time grid unpredictability necessitates balancing markets to secure physical stability, while enabling market participation and market competition. Flexible assets can play an important role within balancing markets, due to their rapid response capabilities and ability to provide relatively high volumes in both balancing directions. With the increasing imbalance on the electricity grid, partially due to the increasing integration of RES, the increasing deployment of flexible assets for implicit balancing can be seen as a positive development. However, because of their ability to implicitly balance quickly and with relatively high volumes in both directions, a discussion has arisen whether the balancing market designs can accommodate flexible assets and whether they provide the right price incentives for flexible assets.

The EU balancing guideline shapes European balancing markets by providing a target model. Within this target model, several design variables can be decided by the member states. Both the Dutch and Belgian market models must comply with the EU balancing guideline and appear to have a very similarly structured balancing market and imbalance pricing structure. However, as extensively shown in this research, the two balancing markets are not similar when it comes to the pricing design and the price incentives for implicit balancing. With the goal of providing design recommendations for the imbalance settlement pricing design, this research is focused on comparing the balancing market design variables in the two markets and the interdependent relationship between the balancing market and flexible assets. The model built for this research deploys a flexible asset and shows possible strategic out-of-balance positions in both markets.

The modelling results illustrate that flexible assets can adopt strategic out-of-balance positions to keep imbalance prices high, and gaming behaviour to increase imbalance prices, and consequently increase their own profits. This opportunity is observed in both balancing markets, at least in numerous scenarios. The results show that both designs facilitate strategic behaviour, yet the opportunity window for strategic behaviour and effect of this behaviour can vary in the two markets, indicating that the design variables applied in the two pricing designs can provide different price incentives.

In the Dutch market, the asset can greatly influence imbalance prices with relatively lower volumes using a gaming strategy, as the imbalance price is solely based on the highest activated bid during the entire ISP. Conversely, in the Belgian market, the impact of gaming behaviour is lower, as the imbalance price is based on the average of all marginal prices, determined per optimisation cycle, within the ISP. This ensures a less aggressive impact on imbalance prices, resulting in more moderate asset profits compared to the Dutch system. However, in some scenarios, the Belgian design cannot prevent the asset from eventually pushing the imbalance price to extreme values either.

Moreover, with negative imbalance prices, the asset has the opportunity to strategically decrease the imbalance price even further, while this is not the case with a positive system imbalance and positive imbalance prices. As the Dutch imbalance prices turn negative at much lower positive system imbalance volumes, the opportunity window for gaming behaviour is wider in the Dutch market than in the Belgium market, in case of positive system imbalances.

However, in most ISPs where regulation state 2 applies, the asset cannot make a profit at all in the Dutch market, because of the two imbalance prices formed. As the Belgian market has no regulation state 2, the Belgian market provides more opportunities for strategic out-of-balance positions in these circumstances. In Table 5.1 an overview of the advantages and disadvantages of both pricing designs is presented.

Table 5.1: Overview with advantages and disadvantages of both pricing designs

	Dutch design	**Belgian design**
Incentive for strategic behaviour	Provides an incentive for strategic behaviour in most scenarios, except scenarios with low postive SI and RS 2	Provides an incentive for strategic behaviour in most scenarios, except scenarios with low to medium positive SI
Extent to which gaming behaviour leads to increased profits for asset	Marginal pricing provides a large opportunity window for gaming behaviour, as the imbalance price increases easily	Averaging of marginal prices mitigates the impact of gaming behaviour on imbalance prices, as steep increases are delayed
Extreme prices	Gaming behaviour can lead to extreme prices in some scenarios	Gaming behaviour can lead to extreme prices in some scenarios
Activation of mFRR	Flexible assets can cause the need to activate mFRR in some scenarios	Flexible assets can cause the need to activate mFRR in some scenarios
Preventing over-regulation	Dual pricing strongly discourages overreactive implicit balancing	Single pricing discourages overreactive implicit balancing to a certain extent
Stability	Dual pricing provides a less stable pricing system and market environment	Single pricing provides a more stable pricing system and market environment
Risk of market saturation	High risk with lower system imbalances, moderate risk with higher system imbalances	High risk with lower system imbalances, moderate risk with higher system imbalances

Besides the asset's impact of the different pricing designs, another important factor was identified in the modelling results. The volume of the system imbalance plays an important role in the extend to which the asset can deploy strategic and gaming behaviour. In quarter hours with low system imbalances, the imbalance prices quickly approach a value of 0, as the asset can implicitly balance all system imbalance with relatively small capacities. These market saturation effects shown in the experiments suggest that in the real world, low volumes of system imbalance bring a higher risk to the asset of losing profit, when deploying higher volumes. The risks are even greater in the Dutch market, as the risk of overreactive implicit balancing, and thereby potentially switching the ISP to regulation state 2 is prominent. This particular risk was not incorporated into the model, as the additional constraints prevented the asset from turning the sign of the system imbalance. However, this risk can have a significant impact on the behaviour of flexible assets in the real world. Flexible assets might limit their implicit balancing, or try to avoid regulation state 2 at all, when system imbalances are low, limiting the risk of turning an ISP into regulation state 2 and thereby limiting the risk of turning their profit into a loss. The risk of market saturation in both markets and of driving an ISP turning into a regulation state 2 is much less prominent at higher system imbalance, as the sign of the system imbalance changes less rapidly.

Overall, the results show clearly that the impact of gaming behaviour can be high in both markets, in some scenarios. This confirms this research' hypothesis that the imbalance pricing designs provide inappropriate remuneration to flexible assets. Although less aggressive at lower capacities in the Belgian market, flexible assets have quite a large opportunity for gaming behaviour in both markets, where they can exploit the market for their own gain. In some scenarios, even the activation of mFRR is triggered. This leads to high volatilities in the imbalance prices and thus high uncertainties for BRPs. Additionally, these high system imbalances lead to instability in the electricity grid. These two main effects are in direct opposition to the objectives of the balancing markets.

5.2. Current Developments and Future Context

Recent developments in European balancing markets, such as the implementation of PICASSO and the shift from pay-as-bid to marginal pricing for aFRR in various countries, demonstrate a trend toward improving market transparency, market and system stability, and market efficiency in general in and across different European countries. This emphasises the need for pricing models that can better manage volatility in system imbalances and imbalance prices. This observation is strengthened by recent operational changes, such as TenneT's decision to delay the publication of real-time activation data and Elia's move to forecast conditions before real-time. With ambitions to further increase the integration of RES in the electricity system, the need for balancing capacity is expected to grow even further, making market efficiency and system and market stability even more crucial in the future.

The model results show that strategic and, especially, gaming behaviour is possible and can be highly profitable for flexible assets, at least under the assumption of perfect information. Considering the constantly improving forecasting models and algorithms in today's energy system, it is therefore likely that flexible assets are, or will soon be, able to exploit the balancing market with strategic out-of-balance positions and gaming behaviour. Gaming behaviour that deliberately amplifies the system imbalance decreases market efficiency, since purposely driving up imbalance prices results in additional system costs. Moreover, these strategies can lead to both physical instabilities on the electricity grid, since the implicit balancing actions fluctuate per minute, and to market instabilities, as the activated FRR bids and imbalance prices can become highly volatile.

As more RES are integrated into the electricity grid, system imbalances are likely to become even more frequent and volatile. This not only necessitates more regulation power, it also requires more stable market conditions that can ensure grid stability if higher levels of flexible balancing capacity are required. The combination of the expected growth in volatility in the system imbalance due to RES and the expected growth in need for balancing capacity, makes the effectiveness of imbalance pricing mechanisms even more critical. Consequently, the findings in this research underscore the need for adjustments in pricing mechanisms.

Yet, the modelling results also suggest that an increasing volume of flexible assets can lead to market saturation, particularly if they engage in implicit balancing. Looking ahead, the expected growth in flexible assets such as large BESS, residential batteries and storage systems such as vehicle-to-grid and flexible power from RES, it is certainly possible that market saturation will be reached in the real world [7]. It is often argued that the increasing integration of RES will intensify the system imbalances, and that market saturation will thus not easily be reached. This is partially true, as, for example, TenneT expects to need 2 GW of FRR power by 2030, compared to the 1300 MW currently contracted in the Netherlands [58]. However, this increase will likely be less than the increase in flexible assets [7], given, for example, the expectation that the amount of flexible power can increase to 25 GW in 2030 in the Netherlands [62]. This means that the asset capacity volumes shown in the modelling correspond to the expected order of magnitude of available flexible power in the electricity grid and that the market saturation effects are likely to occur in the near future.

The alternating scenarios between ISPs experiencing market saturation effects and ISPs with extreme prices lead to significant fluctuations in system and market conditions, creating uncertainty for market participants and potentially leading to grid instabilities. Moreover, if the number of ISPs in which (low volumes of) FRR is activated decreases, bidding behaviour for aFRR and mFRR may change, as market participants must recover their costs over a smaller number of ISPs, potentially leading to higher bids. This can increase the system costs of the balancing market. As more and more flexible assets participate in implicit balancing, current pricing mechanisms may struggle to ensure market efficiency and stable market conditions.

5.3. Consequences for Stakeholders and Market Actors

The implications of these results extend to all stakeholders, including TSOs, BRPs, and BSPs. For TSOs, the ability of flexible assets to amplify imbalance prices raises concerns about grid stability and the potential for market exploitation. The results of this research emphasise the need to reconsider and reevaluate imbalance pricing designs. The design recommendations, which will be presented in Section 5.5 and in Chapter 6, can serve as input for the redesign of imbalance pricing systems.

BRPs operate in a complex decision-making environment, which is beyond the scope of the modelling in this research. In practice, their profits do not depend solely on imbalance prices, but also on positions they have taken on the futures, day-ahead, and intraday markets prior to the balancing market. Thus, the overall profitability of a BRP's portfolio is influenced by cross-market positions. Flexible assets used solely for implicit balancing could follow the strategic patterns outlined in this research. However, even when solely operation on the balancing market, the overall profit is dependent on a BRPs position across ISPs. Consuming, or implicitly balancing in negative direction against a small loss, might still become a profit when the same electricity is later used for upward implicit balancing. Additionally, BRPs must balance the risk of triggering a switch in the sign in the imbalance price due to over-reactive implicit balancing, resulting in a change of regulation state in the Dutch market and a change in the direction of the system imbalance in the Belgian market. A turn in the sign of the imbalance price can have a significant impact on the total realised profits from strategic positioning.

5.4. Transactional Costs and Market Efficiency

As discussed in Chapter 2, the institutional analysis of balancing markets emphasises that standardised bid processes, pricing mechanisms, and regulatory rules are designed to reduce information asymmetry and lower transaction costs. Marginal pricing has been shown to reduce strategic bidding for aFRR and mFRR and reduce information asymmetry. However, the model built in this research shows that marginal pricing for imbalance settlement facilitates quicker and more aggressive price adjustments, offering flexible assets more opportunities to strategically manipulate imbalance prices. Therefore, the averaging method might result in better market efficiency, as it mitigates strategic behaviour of flexible assets, while maintaining the benefits of reduced strategic bidding for aFRR and mFRR and market transparency.

Additionally, the theoretical framework highlighted that shortening the ISP from 15 minutes to, for example, 5 minutes allows for more refined imbalance settlements. The modelling results suggest that a shorter ISP would limit the opportunity window for assets to show strategic and gaming behaviour. After all, if an ISP lasts only five minutes and an asset amplifies the system imbalance in the most expensive minute, it has only four minutes to counteract this effect and maximise its net imbalance position in the correct direction. However, while shortening the ISP reduces opportunities for market exploitation, it also increases transaction costs for both market parties and the TSO, as the number of transactions would triple. Therefore, further research is needed to assess both the increase in transaction costs and the effectiveness of a 5-minute ISP in mitigating gaming behaviour.

As volumes of BESS and other flexible assets continue to grow, as discussed in Section 5.2, the effects of market saturation may become increasingly relevant. First, transaction costs could rise due to higher market participation which increases competition, and due to greater complexity in forecasting and trading strategies. As interactions between market participants become more intricate, forecasting the system behaviour will become more difficult, adding to the challenges of efficient market operations. Second, if too many flexible assets engage in implicit balancing, they may neutralise each other's effects, as implicit balancing inherently reduces the amount of required FRR activation during an ISP, and thus reduces the price level of activated bids. This lowers returns for market participants and increases uncertainty in expected revenues, which could significantly impact investment decisions. Market saturation may reduce the profitability of both explicit and implicit balancing, influencing the economic viability of new entrants. Additionally, it could challenge the TSO's ability to procure sufficient FRR capacity. If the number of ISPs with activated aFRR and mFRR decreases, TSOs may struggle to contract enough capacity, as providing FRR might become less financial attractive. This would further increase transaction costs in the system.

At the same time, system imbalance volatility is expected to increase. The more frequent periods with extreme imbalance, caused by, for example, unexpected drops in RES production, still require sufficient balancing capacity to maintain grid stability. This dual effect, where saturation decreases market opportunities but imbalance volatility increases the need for regulating power at specific times, highlights the need to reconsider market design to ensure reliable balancing services while maintaining efficiency.

Furthermore, the modelling results indicate that in scenarios with low volumes of system imbalance volumes, the risk of overreactive implicit balancing is significant. Especially in a dual pricing system, where overreactive implicit balancing triggers regulation state 2, this can have a great negative impact on the BRP's profit. Consequently, overreactive implicit balancing, whether caused by the BRP itself or other BRPs, forms a great financial risk. The idea behind imposing this risk of regulation state 2 is to persuade BRPs and flexible assets to maintain their individual balance. Yet, recent developments, including TenneT's decision to delay the publishing of information to five minutes, to reduce the occurrence of regulation state 2 [58], prove that this objective is not obtained with the risk of regulation state 2. This suggests that regulation state 2 no longer accommodates the present market circumstances. However, with the expected increase in imbalance volatility, BRPs are increasingly exposed to high risks, increasing their transaction costs. Additionally, the total system costs increase, as all BRPs have to pay for their imbalances in case of regulation state 2, which decreases market efficiency. This suggests that the single pricing system offers a better alternative, as it provides a more stable market where BRPs are exposed to less financial risks in case of overreactive implicit balancing. However, the modelling in this research does not take uncertainties into account, so to accurately formulate a definitive conclusion on this topic, more research focused on behaviour of market parties under uncertainties such as overreactive implicit balancing and regulation state 2 is required.

While imbalance price volatility currently provides strong investment incentives, market saturation effects could change these opportunities over time. Early entrants may benefit from the price volatility, but as more assets enter the market, competition increases, and prices might decrease, reducing profits and impacting long-term investment prospects. This raises questions about whether regulatory interventions are necessary to manage saturation effects and ensure continued deployment of flexible assets for implicit balancing, without distorting market dynamics. Future research should explore how transaction costs will evolve under the expected developments on the balancing markets, taking into account the market saturation and gaming behaviour of flexible assets shown in the modelling results of this research.

5.5. Design Recommendations for Balancing Markets

Based on the insights obtained, several recommendations for the imbalance pricing design can be proposed.

First, balancing markets that apply a marginal pricing system may allow for more aggressive market exploitation compared to systems that use an average of marginal prices. Although the averaging method does not completely prevent strategic behaviour and gaming behaviour can still result in extreme imbalance prices under certain conditions, it can help mitigate the extent of market exploitation. Therefore, balancing markets may consider implementing a pricing system where the imbalance price is determined based on an average of marginal prices, rather than solely on the most extreme activated bid, thereby reducing excessive price fluctuations.

Another recommendation is to change the imbalance pricing design in terms of how the BRP's imbalance is determined. At present, the BRP is charged based on its net imbalance at the end of an ISP, but this could also be changed to charging the BRP in either imbalance direction, both in the positive and the negative direction. This can limit the opportunities to show gaming behaviour by flexible assets, as a BRP's imbalance in the unwanted direction cannot be compensated by strategic out-of-balance positions in the 'correct' direction during the rest of the ISP.

Additionally, the decision between dual and single pricing mechanisms must be carefully evaluated. Dual pricing discourages overreactive implicit balancing more effectively, potentially reducing extreme price fluctuations. However, it also imposes higher risks for market participants with out-of-balance positions, whether strategic or not, and thus causes higher transaction costs. Conversely, single pricing may also discourage overreactive implicit balancing, although less abruptly, while offering a pricing model that better reflects actual system balancing costs. This can contribute to a more stable market environment and provide incentives that align with efficient market operation. The choice between single and dual pricing ultimately depends on the regulatory framework, the priorities of the TSO, such as their view on transaction costs, and whether the focus is to incentivise market participants to maintain their internal balance or on encouraging them to participate in implicit balancing.

Furthermore, another approach that is recommended is to increase the accessibility of the aFRR market for flexible assets. By loosening terms and technical conditions for aFRR, flexible assets can be incentivised to participate in the balancing market by offering aFRR and mFRR, rather than participate via implicit balancing. One of the benefits of this approach is that the chance for gaming behaviour is reduced, because the TSO controls the balancing volume and the activation direction. Second, it reduces the risk of overreactive implicit balancing, again because the TSO controls the activated balancing energy. Moreover, it mitigates market saturation effects such as observed in the modelling results, as the system imbalances are not being implicitly balanced. Additionally, it might help the TSO with the procure of sufficient balancing capacity, were this to become harder under the future conditions of balancing markets.

The last recommendation includes considering revising the ISP to five minutes. Due to time constraints, this research has not focused on the effect of reducing the ISP to five minutes, so its positive effects are not yet clear. However, this could be researched relatively easily, using the optimisation model built for this research. However, it is known that reducing the ISP to 5 minutes may increase transaction costs for market participants and TSOs, due to the increase in the number of transactions. However, these additional costs could be offset by improvements in market efficiency and reduced opportunities for strategic behaviour. More research is needed to quantify these trade-offs and determine whether a shorter ISP would benefit the balancing markets.

5.6. Academic Reflections

This research contributes to the academic debates on balancing market design by examining how imbalance pricing design variables influence the implicit balancing behaviour of flexible assets. The modelling results demonstrate that the two pricing mechanisms significantly affect not only the potential profits for flexible assets, but also their ability to engage in strategic out□of□balance positions and gaming behaviour, to change imbalance prices to their own benefit.

When comparing these results with previous studies, this research both confirms and extends earlier insights. For instance, numerous studies by, for example, Lamert et al. [32], Demir et al. [34], and Smets et al. [13] show substantial profit potentials for flexible assets when deploying implicit balancing strategies. Toubeau et al. [37] and Smets et al. [13] also argue that implicit balancing by flexible assets reduces a significant amount of system imbalance, which aligns mostly with the results found in this research. In some scenarios, the asset counterbalances almost all system imbalance. However, this research also shows that, under certain conditions, strategic and gaming behaviour is very well possible and this can increase the asset's profit significantly. By this, the model reveals that, while a marginal pricing system may reduce information asymmetry and streamline transaction processes, it simultaneously enables assets to manipulate imbalance prices.

By comparing the interdependency of the implicit balancing by a flexible asset and the two imbalance pricing designs, a notable knowledge gap earlier identified in the literature is addressed. The insights obtained suggest that the intended price incentives do not always correspond to the provided remuneration for the behaviour of flexible assets, as both pricing designs provide opportunities for strategic and gaming behaviour, which can greatly impact system stability and the overall market efficiency. Given the increasing volatility due to the integration of RES and the current price volatility in the balancing markets, these insights are critical. The provided design recommendations provide guidance for the EU, TSOs and market parties, in order to restore grid and market stability.

5.7. Limitations of the Methodology and Model

Despite the valuable insights obtained, the research methodology and the developed model contain several limitations.

An important limitation is the simplifying aggregation of multiple flexible assets into a single representative actor. In reality, the asset would be numerous flexible assets that operate independently with their own strategy and timing, and this aggregation may exaggerate the consistency of strategic actions that drive up imbalance prices. Additionally, the model assumes that the asset and the TSO have perfect market information and foresight into future market conditions, such as knowledge of the most expensive minute, the exact system imbalance and the exact marginal prices at every minute. In practice, flexible assets face significant uncertainties regarding these aspects and strategic positions of other market participants, which even increase with delays in receiving market data. Not to mention, the imbalance price is always determined after the ISP. These important uncertainties ensure that market parties, such as flexible assets, can never optimise their strategy 100%. Additionally, this can very well lead to even less consistent strategic actions of flexible assets, possibly increasing market instability.

Another important limitation arises from the choice for the optimisation framework. The research uses a linear optimisation framework supported by a heuristic approach, rather than a bi-level optimisation framework, which would allow for a more dynamic optimisation of the assets position. Although the heuristic method provides valuable insights, it may not always result in the global optimum, potentially leading to only suboptimal representations of the asset's strategic decision-making. Moreover, the model is implemented in Julia using JuMP and solved with Gurobi. Due to current limitations, these tools cannot handle non-linearities, necessitating the formulation of a linear optimisation problem that requires simplifications of balancing market dynamics. The outcomes are also sensitive to the parameter choices and input data, such as aFRR biddings and system imbalance conditions. The ISPs serving the input data were randomly selected to avoid bias, but these ISPs do not cover all possible scenarios.

Lastly, the research primarily focuses on the incentives provided by different imbalance pricing systems and the effect on the implicit balancing actions of flexible assets. In doing so, it does not account for the broader impact of these pricing designs on other market aspects. For instance, the pricing structures also influence bidding strategies for aFRR and mFRR, as well as the decisions made by BRPs that are not operating as flexible assets, on how position their individual balance. Additionally, the model simplifies the market dynamics over time by focusing on isolated ISPs, rather than simulating sequential ISPs, to capture the temporal market dynamics in real-life. This approach restricts the model's ability to fully reflect the complexities of market operations over time. By not incorporating these broader market aspects, interactions between actors and complexities of market operations over time, the model may overlook important effects and market dynamics that could further affect the total market and system efficiency.

6 Conclusion

The increasing integration of RES has fundamentally changed the dynamics of electricity systems. The variability and limited predictability of RES have made balancing electricity supply and demand more complex, which raises the need for regulating power to maintain grid stability. This research is motivated by the observation that today's imbalance markets are highly volatile and can lead to high system costs. Moreover, the hypothesis underlying this research is that flexible assets can use strategic behaviour by taking out-of-balance positions and, thereby, are able to influence imbalance prices. The central research question guiding this thesis is:

What implicit balancing behaviour do flexible assets show in different imbalance settlement designs and what balancing market design recommendations can be provided based on this?

To address this research question, three sub-questions were formulated. First, the design variables within the EU target model for imbalance settlement pricing are examined, and the specific design choices implemented in the Dutch and Belgian markets are compared. Second, the research investigates the financial incentives for flexible assets provided through these different imbalance settlement designs and how the actions of flexible assets affect both the system imbalance and the resulting imbalance prices. Third, based on the theoretical and empirical analyses and modelling results, the research identifies design variables that should be considered carefully in imbalance pricing designs.

The balancing market has a dual objective. The primary physical goal is to stabilise the electricity grid by ensuring that supply and demand are continuously matched, to prevent inconsistencies in the access to electricity supply or blackouts. Economically, the balancing market provides market participants with the flexibility to deviate from their predefined energy programmes in order to optimise their overall market portfolios.

The EU Balancing Guideline provides a framework for balancing markets in the EU, but allows TSOs significant freedom in design choices, as long as the TSO shows how its design choices meet the objectives of the balancing market. This research focuses specifically on the design choices made in the Netherlands and Belgium. In the Dutch market, a dual pricing system is employed, where imbalance prices are determined by the marginal price observed within an ISP. In contrast, the Belgian market has a single pricing system, in which the imbalance price is based on the average of all marginal prices within the ISP. Furthermore, the Dutch imbalance settlement is based on the direction of regulation, while the Belgian imbalance settlement is based on the net system imbalance. These divergent approaches have significant implications for the way flexible assets operate. Specifically, the price incentives for flexible assets and the market impacts of their strategies can vary between the two systems, depending on the market circumstances.

The modelling results presented in this thesis indicate that flexible assets can indeed adopt strategic out-of-balance positions and gaming behaviour to influence imbalance prices and thereby maximise their own profits. The pricing system and settlement mechanisms employed play a crucial role in determining the potential for such strategic behaviour. Different methods of imbalance price calculation, such as marginal pricing or averaging of marginal prices, impact the extent to which a single strategic action affects market prices. Furthermore, the volume of system imbalance plays an important role in the extent to which flexible assets can influence imbalance prices. The lower the system imbalance volume, the less opportunity there is for flexible assets to increase the imbalance price before reaching market saturation, where no system imbalance remains to be balanced. Overall, these findings confirm the earlier stated hypothesis that flexibility assets can exploit the market with strategic behaviour.

6.1. Design recommendations

Based on the findings in this research, several design recommendations can be made. First, TSOs should critically consider the choice of the pricing mechanism used for aFRR and mFRR. The pricing design for these two balancing products directly influences the imbalance pricing design, as the imbalance prices should reflect the costs incurred to activate aFRR and mFRR volume. While a marginal pricing system is argued to reduce strategic bidding for FRR, it also creates more opportunities for strategic implicit balancing behaviour by flexible assets. An averaging method for marginal prices can reduce the impact of strategic behaviour to a certain extent, although it cannot prevent strategic behaviour altogether. Therefore, a careful consideration has to be made between decreasing strategic bidding and strategic implicit balancing.

In addition, the decision between dual and single pricing mechanisms must be carefully weighed. Dual pricing penalises overreactive implicit balancing more rigorously, with the goal of reducing volatility. However, it also creates higher risks for out-of-balance positions of BRPs. Single pricing provides a more stable market environment for BRPs and eventually penalises overreactive implicit balancing as well. Additionally, single pricing may offer a closer reflection of actual TSO costs, supporting a more efficient market design. Based on the findings in this research, a single pricing design appears to align more closely with the objectives of balancing markets.

To reduce market volatility, design variables outside the specific variables of the imbalance pricing design can also be considered. For example, loosening the qualification process for providing FRR can incentivise flexible assets to participate actively in the balancing market by providing aFRR and mFRR. In this way, the TSO regains control over the balancing volumes, preventing overreactive implicit balancing behaviour and reducing strategic or gaming behaviour. Furthermore, shortening the ISP to five minutes and modifying the settlement process for individual BRP imbalances, such as separately settling positive and negative imbalances, could influence market stability. However, further research is required to determine the consequences of adjusting these design variables in the broader context of the balancing market design. In the last part of this conclusion, suggestions for further research are presented.

6.2. General reflections

Reflecting on the research process, the decision to build an optimisation model in Julia was appropriate for addressing the research questions, despite limited prior experience with the software. The use of Julia, together with JuMP and Gurobi, allowed for a detailed analysis of the strategic behaviour of flexible assets under different market conditions. However, the study relied heavily on modelling, and while the empirical and theoretical components provided a solid foundation, further research that incorporates a deeper theoretical and empirical analysis, focussing on, for example, the role of transactions and the decision-making process of multiple market parties in relation to each other, would complement this work and could be pursued as an independent research project.

The modelling approach was effective for the purposes of this research, yet it is important to note that an heuristic optimisation method was chosen, instead of a more complex bi-level optimisation framework. A bi-level approach might have captured a broader range of strategic behaviour under different market conditions, which could have provided a more comprehensive review of a flexible asset's behaviour. Despite this limitation, the heuristic approach provided a clear view of how different pricing designs can influence the implicit balancing actions of flexible assets.

Lastly, this research focuses specifically on the impact of different pricing systems on the behaviour of flexible assets, but these pricing designs also affect bidding strategies in the aFRR and mFRR markets, decisions made by other BRPs and other market aspects. Thus, when implementing or changing an imbalance pricing design, it should be taken into account that the pricing design impacts more than just the implicit balancing actions of flexible assets, to ensure that the overall balancing market remains both efficient and stable.

6.3. Future research recommendations

There are several directions for future research that could be built on the findings of this master thesis. Further research into the specific question discussed in this research is recommended to apply a bi-level optimisation framework to conduct an even more accurate analysis of flexible assets balancing implicitly. This would address some of the limitations of the current model and provide a deeper understanding of strategic interactions in balancing markets.

Moreover, future research is recommended to expand the analysis and include the broader market effects of imbalance pricing designs. For instance, examining how the imbalance pricing design affects the decision-making of flexible assets and BRPs over time, across different ISPs and perhaps across different markets. This could provide important insights into how strategic behaviour can affect the market over time.

Another highly interesting research approach would be to analyse strategic behaviour when the interaction between different actors is included. Research that considers scenarios in which multiple actors with flexible assets participate could show important insights into the effects of strategic behaviour on the behaviour and decision-making process of other actors, on the market stability, and on individual profits and risks for actors.

Finally, researching the effects of shorter ISPs, for example, ISPs of five minutes. This would allow to research the effect on the interdependent relation between the balancing market and flexible assets and would provide a good understanding if this design choice has the intended effect of limiting options for strategic behaviour. Reducing the length of ISPs should be evaluated within the broader context of the balancing markets, to be able to determine whether shortening ISPs eventually leads to more market efficiency and stability.

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A

Empirical Examples Dutch Pricing Design

A.1. Example A1

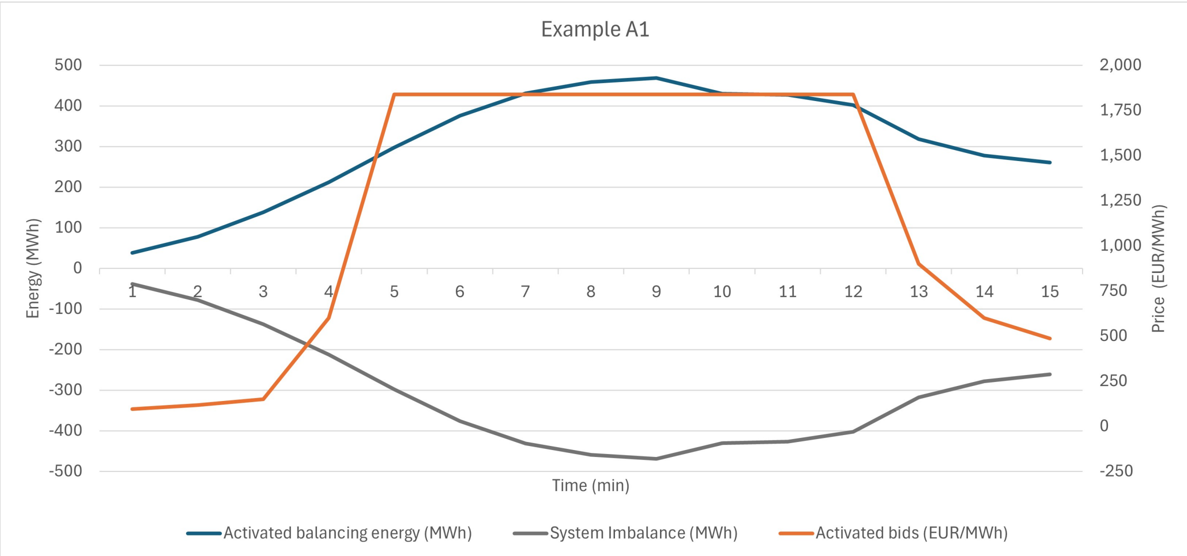

Figure A.1: Example A1: Course of example ISP (Regulation state 1 |Net SI < 0)

Table A.1: Overview of payments and transaction directions in Example A1

Balancing energy				
	NL		BE	
	Price	Direction	Price and direction	
Upward balancing energy	€ 1838.19	TSO to BSP	Depending on marginal price per OC	
Downward balancing energy	n/a	n/a	n/a	
Imbalance settlement				
	NL		BE	
	Price	Direction	Price	Direction
Surplus	€ 1838.19	TSO to BRP	€ 1471.73	TSO to BRP
Shortage	€ 1838.19	BRP to TSO	€ 1471.73	BRP to TSO

A.2. Example A2

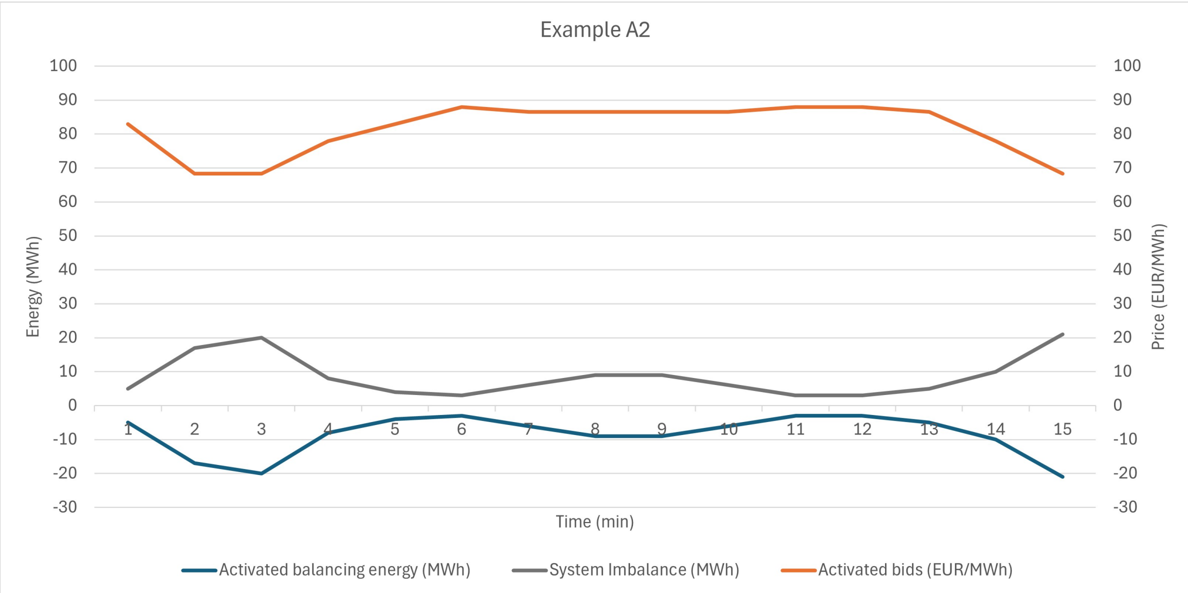

Figure A.2: Example A2: Course of example ISP (Regulation state -1 |Net SI > 0)

Table A.2: Overview of payments and transaction directions in Example A2

Balancing energy				
	NL		BE	
	Price	Direction	Price and direction	
Upward balancing energy	n/a	n/a	n/a	
Downward balancing energy	€ 68.28	TSO to BSP	Depending on marginal price per OC	
Imbalance settlement				
	NL		BE	
	Price	Direction	Price	Direction
Surplus	€ 68.28	TSO to BRP	€ 76.64	TSO to BRP
Shortage	€ 68.28	BRP to TSO	€ 76.64	BRP to TSO

B

Results scenarios

B.1. Scenario 1

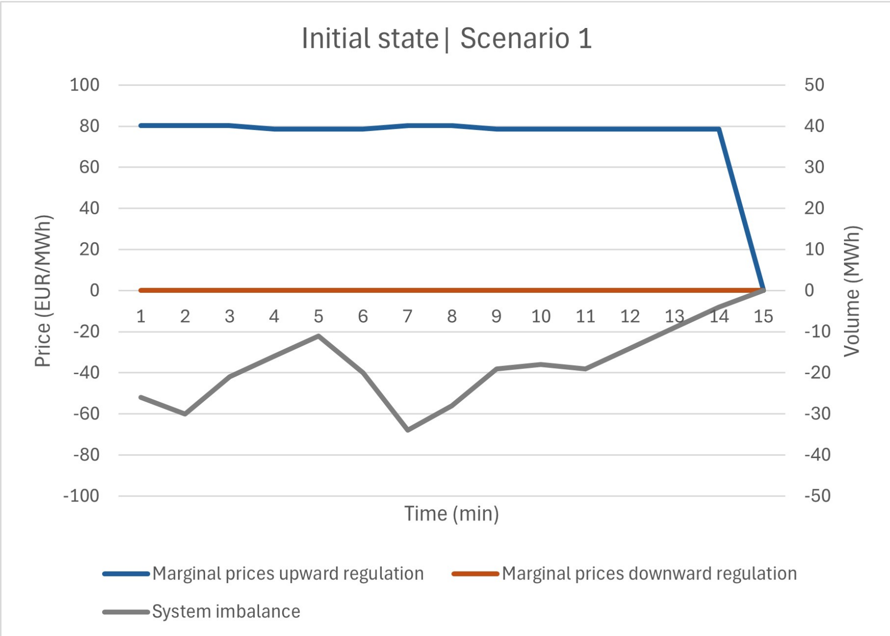

Figure B.1: Marginal prices and system imbalance per minute in original ISP | Scenario 1

NL		BE	
Regulation state	1	Net SI	Negative
Midprice	80.79	Floor	82.88
Balancing energy price		Cap	78.69
Upward regulation	80.19	aFRR element	79.47
Downward regulation	0.00	MIP	82.88
		MDP	78.69
Imbalance price			
BRP surplus	**80.19**		
BRP shortage	**80.19**	**82.88**	

Table B.1: Price differences between NL and BE in €/MWh | Scenario 1

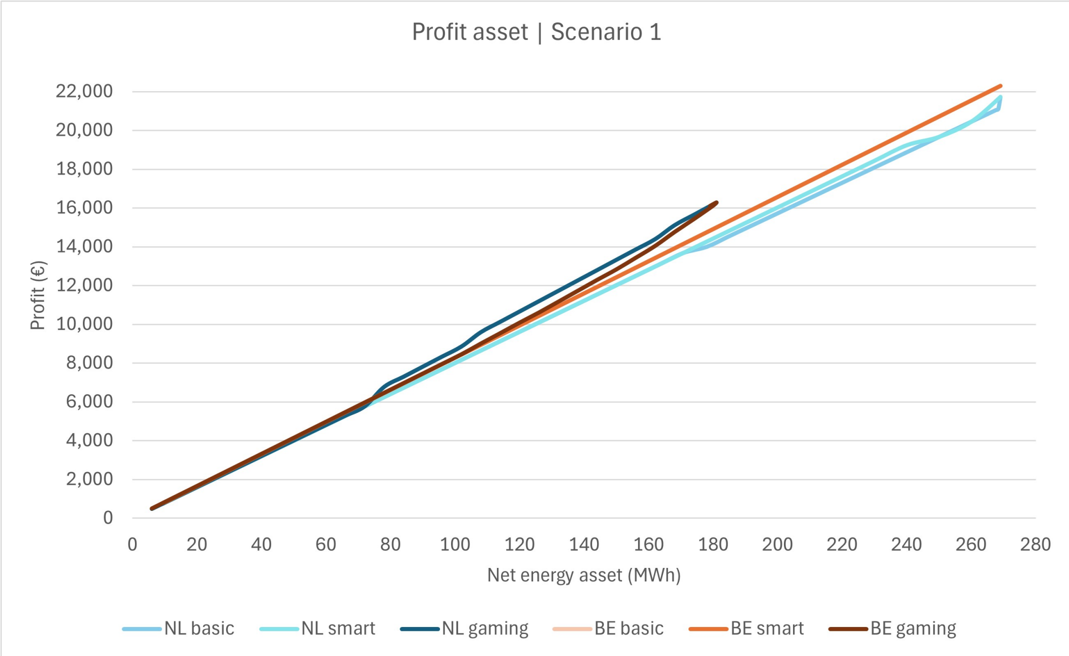

Figure B.2: Asset's profit | Scenario 1

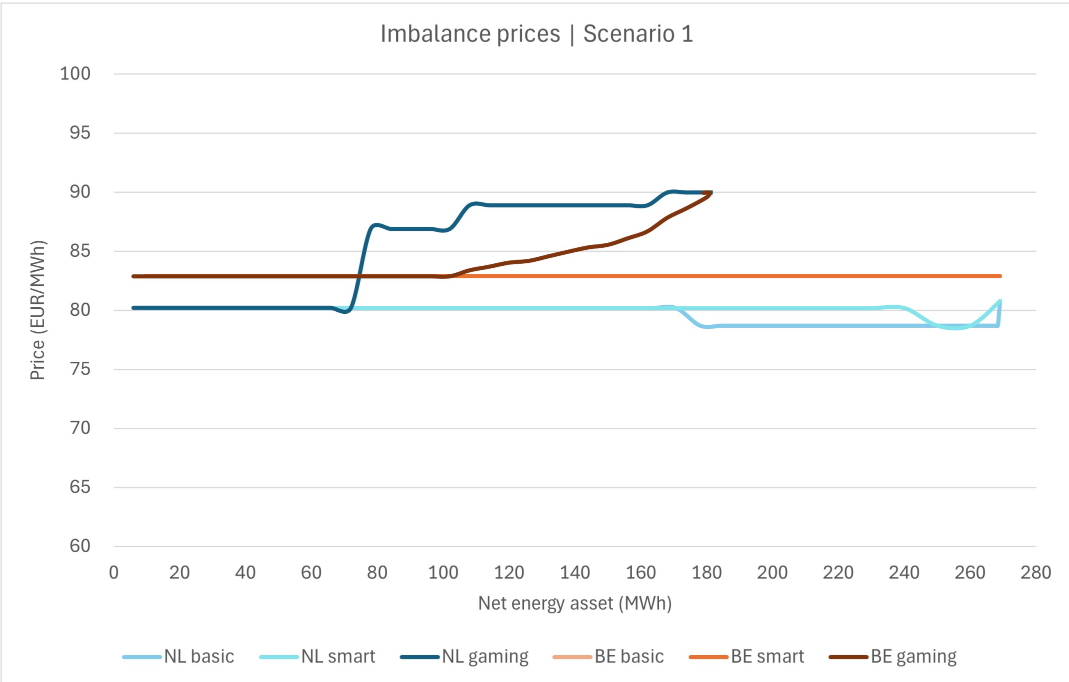

Figure B.3: Imbalance prices | Scenario 1

B.2. Scenario 2

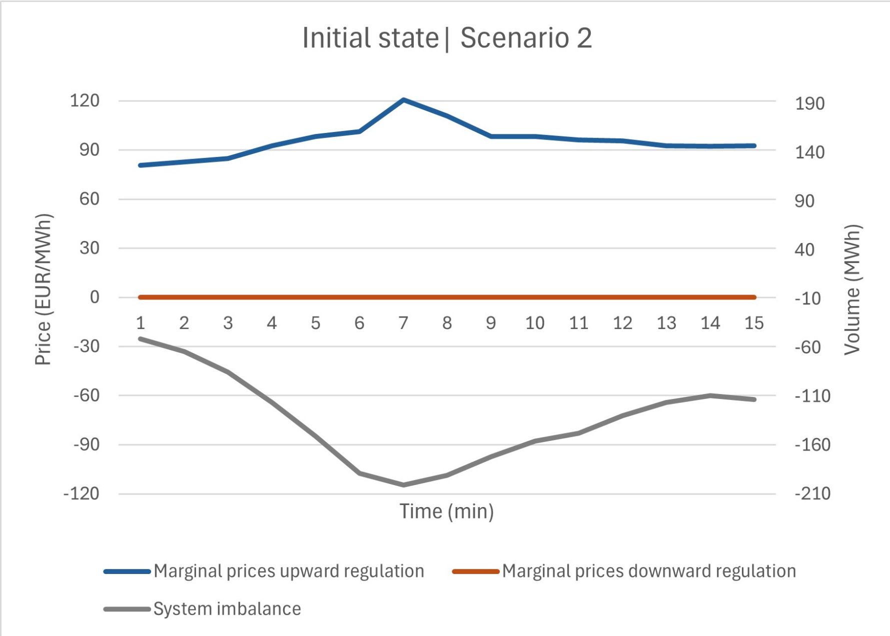

Figure B.4: Marginal prices and system imbalance per minute in original ISP | Scenario 2

NL		BE	
Regulation state	1	Net SI	Negative
Midprice	60.22	Floor	75.69
Balancing energy price		Cap	44.76
Upward regulation	120.69	aFRR element	98.85
Downward regulation	0.00	MIP	98.85
		MDP	44.76
Imbalance price			
BRP surplus	**120.69**		
BRP shortage	**120.69**	**98.85**	

Table B.2: Price differences between NL and BE in €/MWh| Scenario 2

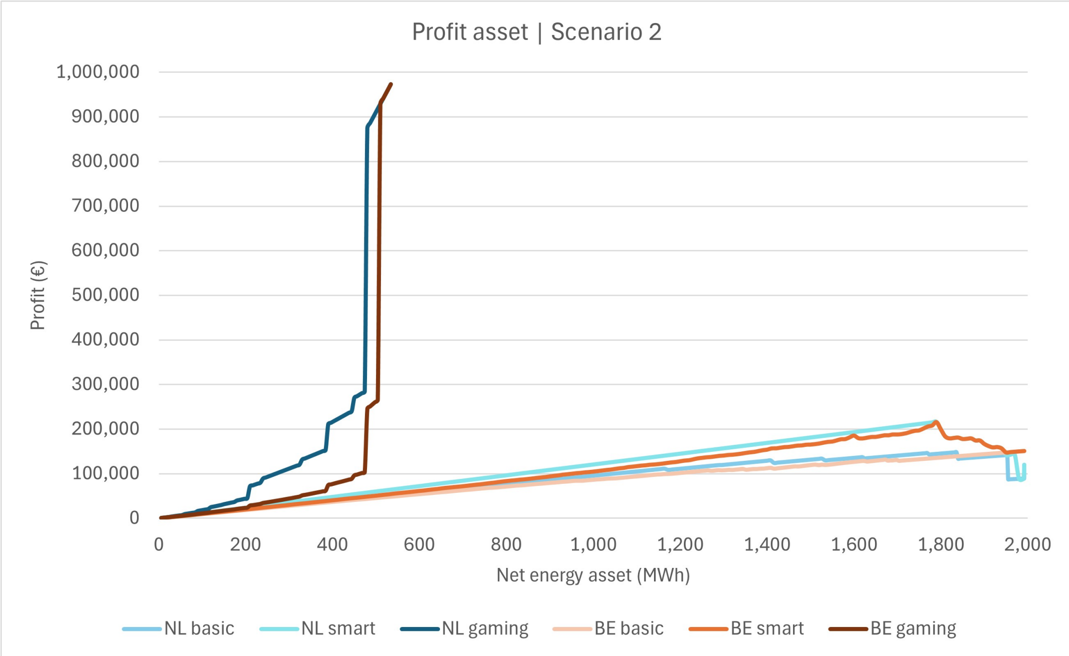

Figure B.5: Asset's profit | Scenario 2

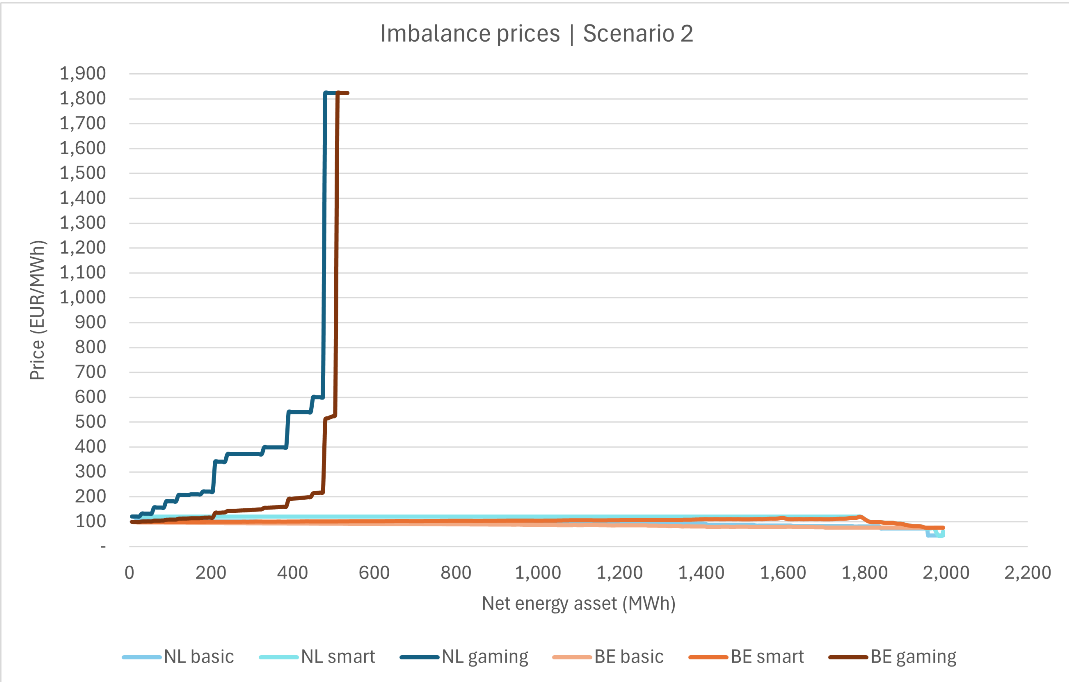

Figure B.6: Imbalance prices | Scenario 2

B.3. Scenario 3

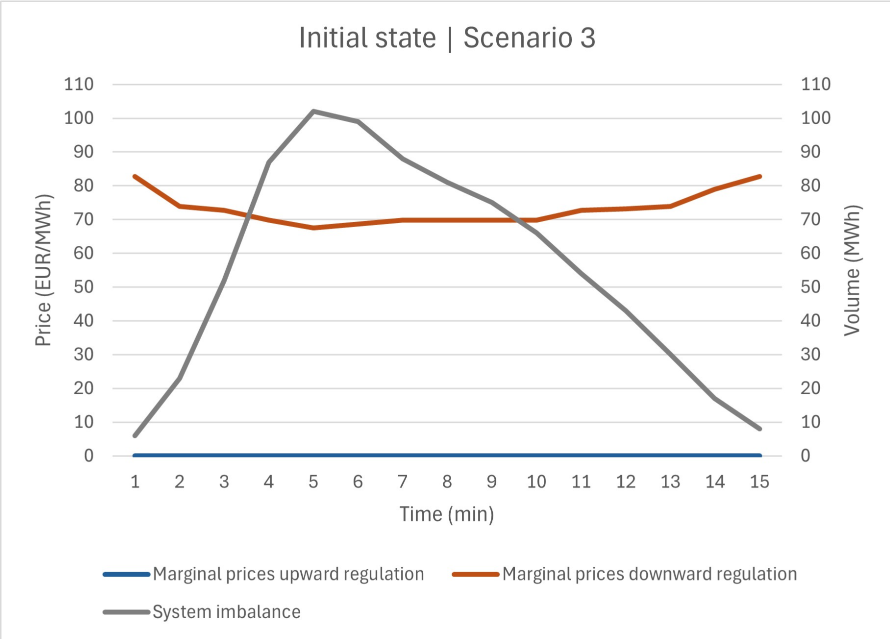

Figure B.7: Marginal prices and system imbalance per minute in original ISP | Scenario 3

NL		**BE**	
Regulation state	-1	Net SI	Positive
Midprice	81.37	Floor	82.69
Balancing energy price		Cap	80.04
Upward regulation	0.00	aFRR element	70.60
Downward regulation	67.44	MIP	82.69
		MDP	70.60
Imbalance price			
BRP surplus	**67.44**		
BRP shortage	**67.44**	**70.60**	

Table B.3: Price differences between NL and BE in €/MWh| Scenario 3

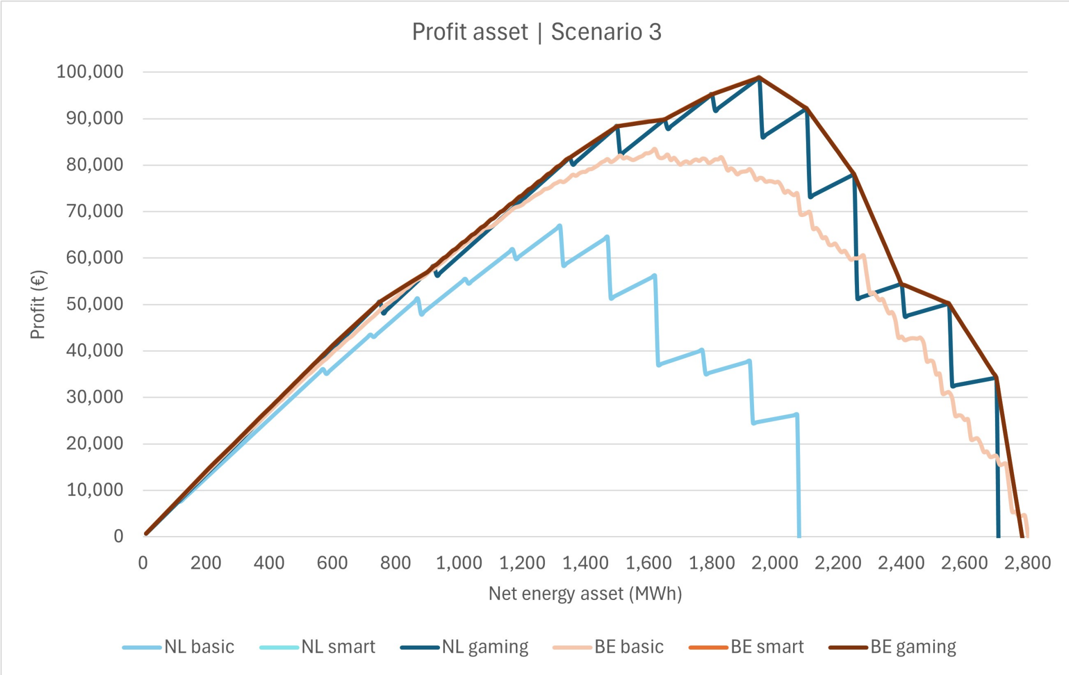

Figure B.8: Asset's profit | Scenario 3

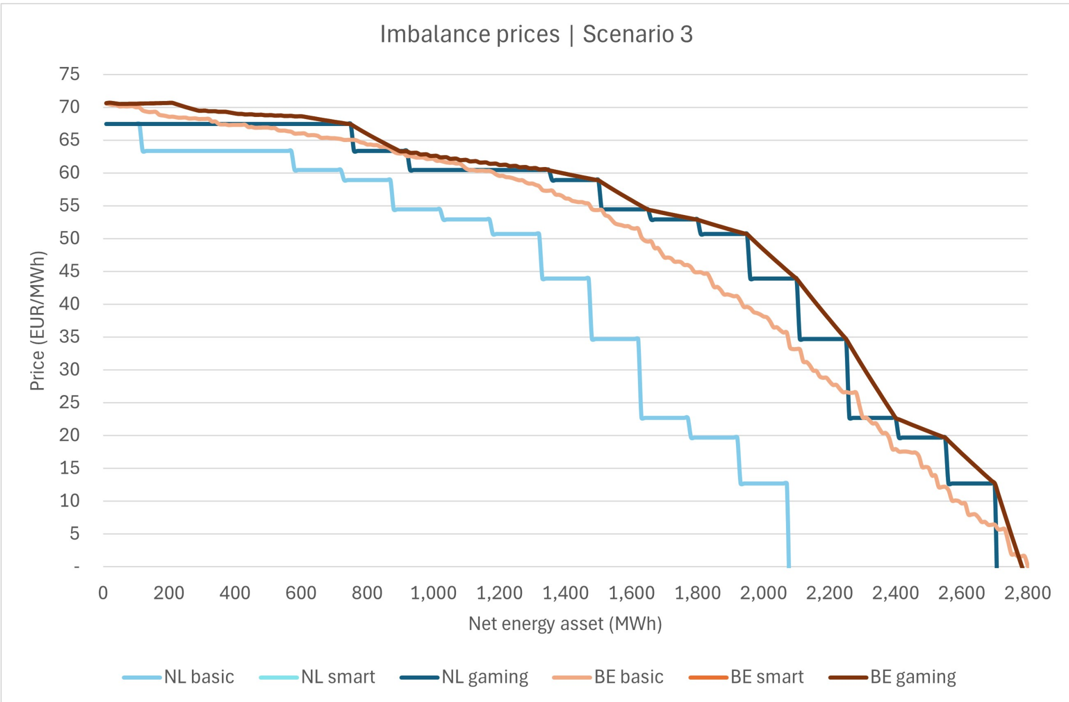

Figure B.9: Imbalance prices | Scenario 3

B.4. Scenario 4

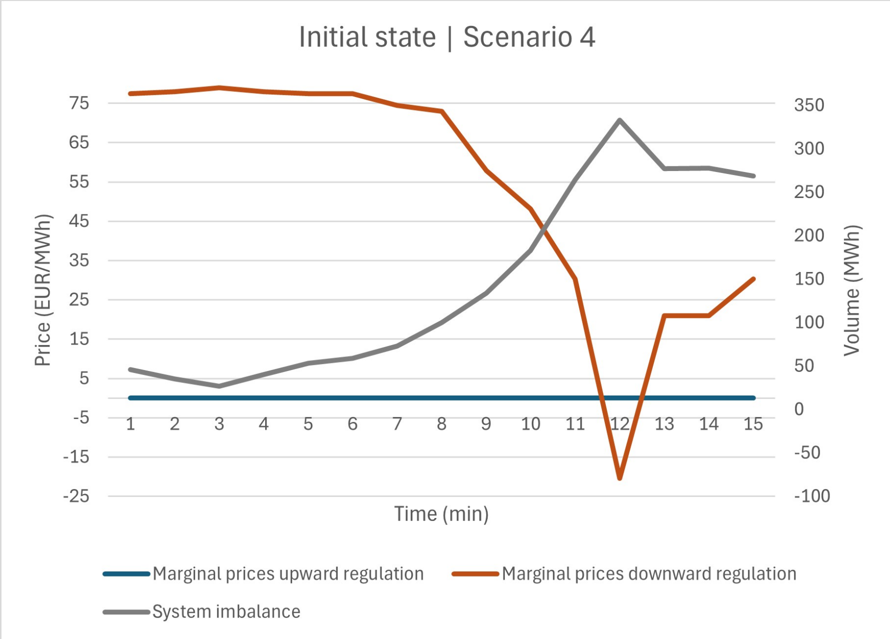

Figure B.10: Marginal prices and system imbalance per minute in original ISP | Scenario 4

NL		**BE**	
Regulation state	-1	Net SI	Positive
Midprice	86.15	Floor	87.92
Balancing energy price		Cap	84.38
Upward regulation	0.00	aFRR element	32.47
Downward regulation	-20.42	MIP	87.92
		MDP	32.47

Imbalance price		
BRP surplus	**-20.42**	
BRP shortage	**-20.42**	**32.47**

Table B.4: Price differences between NL and BE in €/MWh | Scenario 4

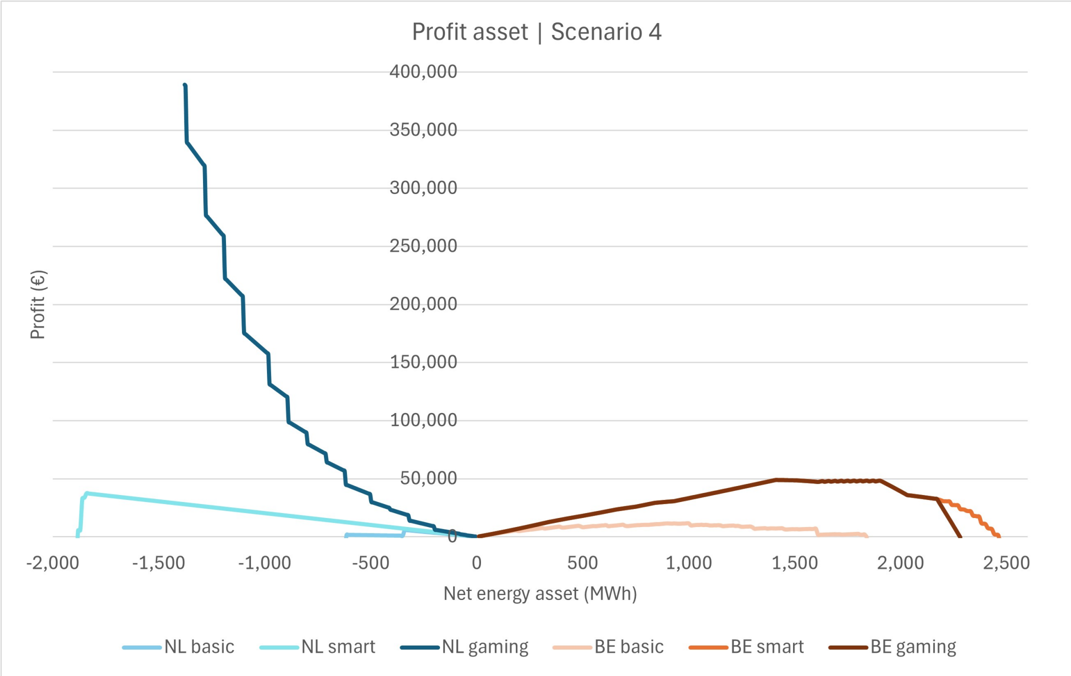

Figure B.11: Asset's profit | Scenario 4

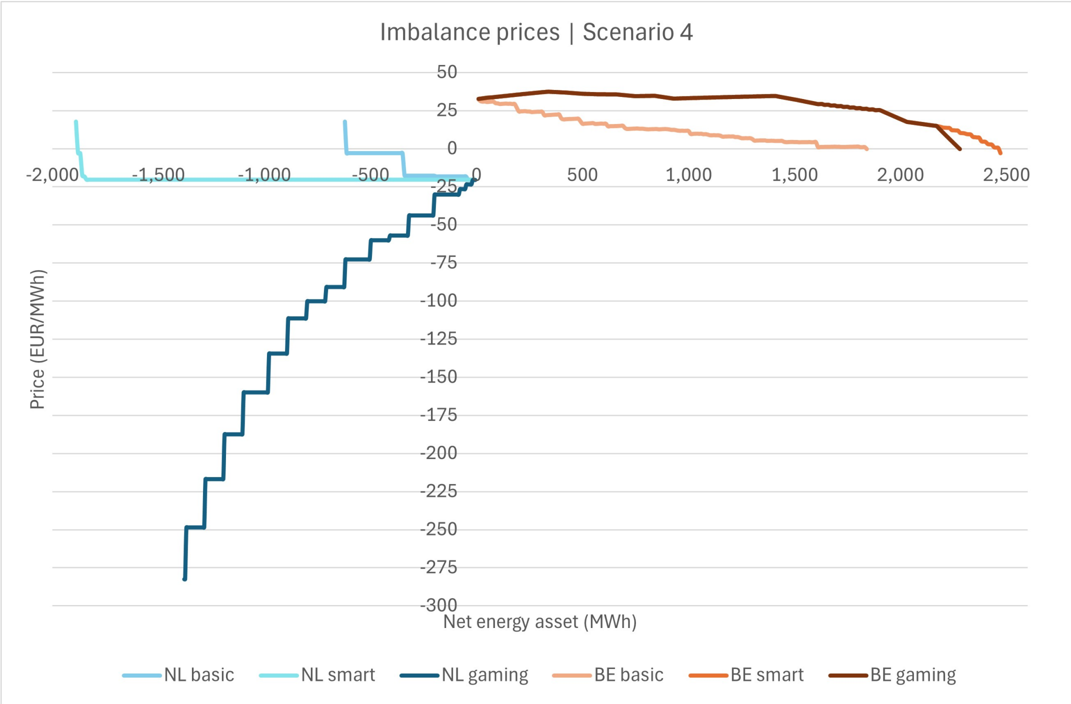

Figure B.12: Imbalance prices | Scenario 4

B.5. Scenario 5

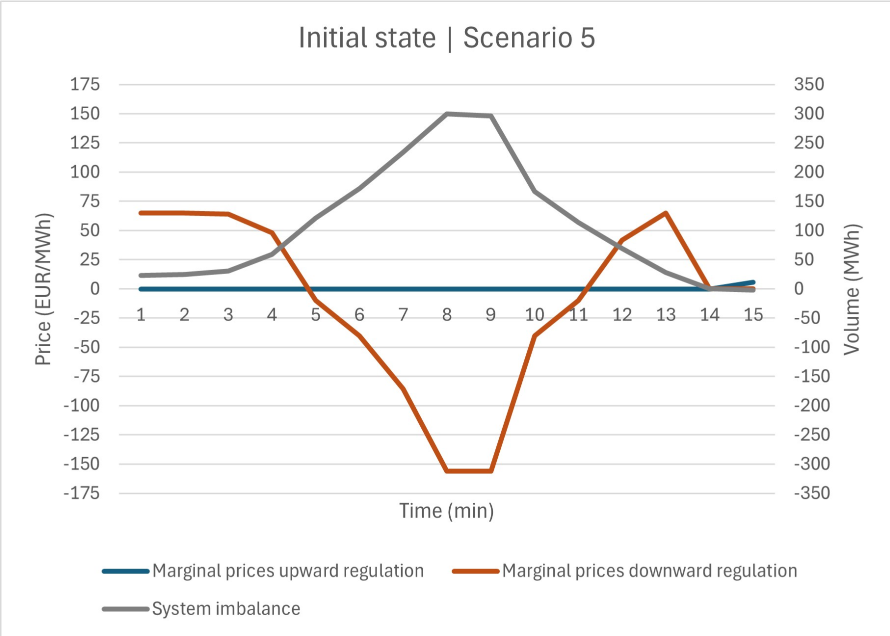

Figure B.13: Marginal prices and system imbalance per minute in original ISP | Scenario 5

NL		BE	
Regulation state	2	Net SI	Positive
Midprice	38.83	Floor	71.98
Balancing energy price		Cap	5.68
Upward regulation	5.68	aFRR element	-70.87
Downward regulation	-156.09	MIP	71.98
		MDP	-70.87
Imbalance price			
BRP surplus	**-156.83**		
BRP shortage	**38.83**	**-70.87**	

Table B.5: Price difference between NL and BE in €/MWh | Scenario 5

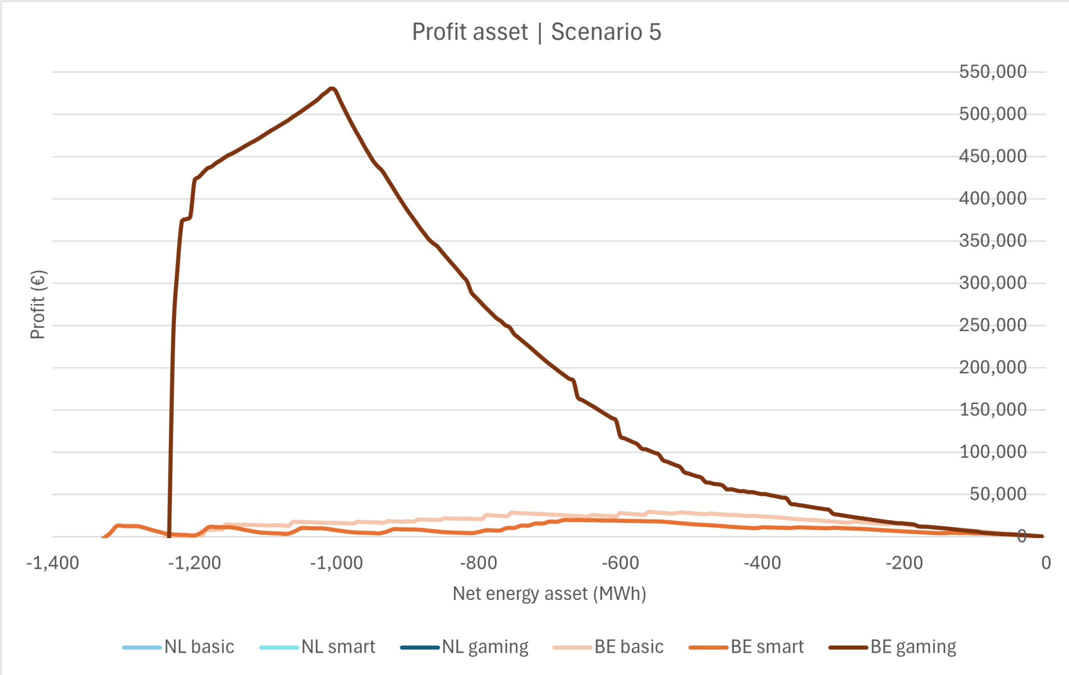

Figure B.14: Asset's profit | Scenario 5

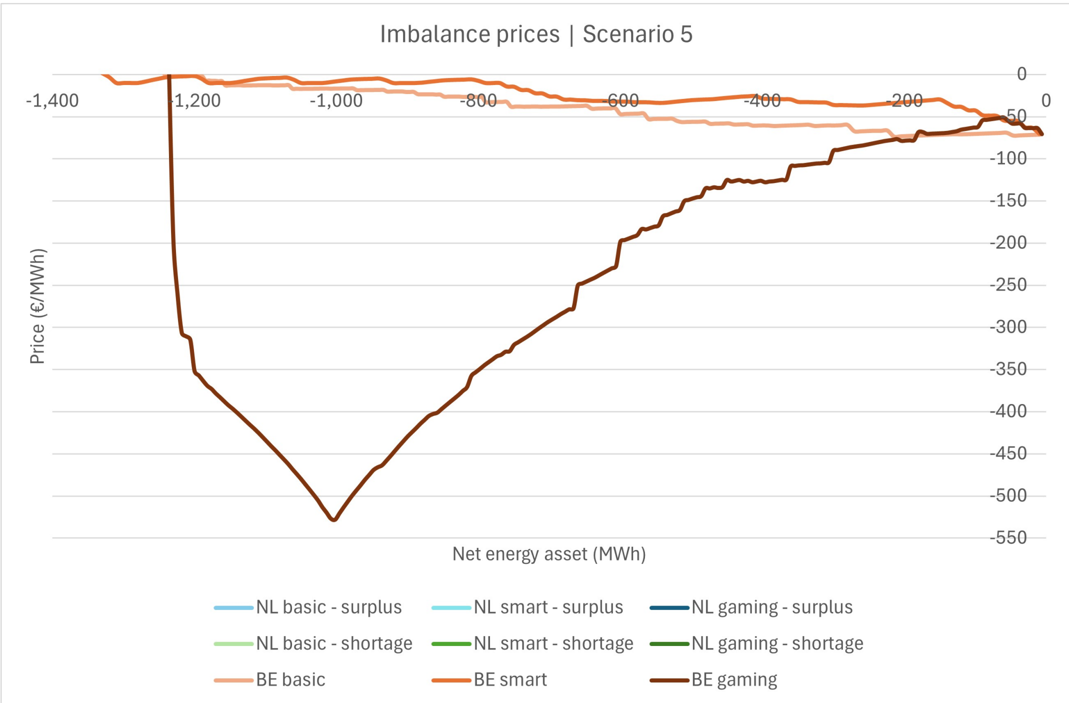

Figure B.15: Imbalance prices | Scenario 5

B.6. Scenario 6

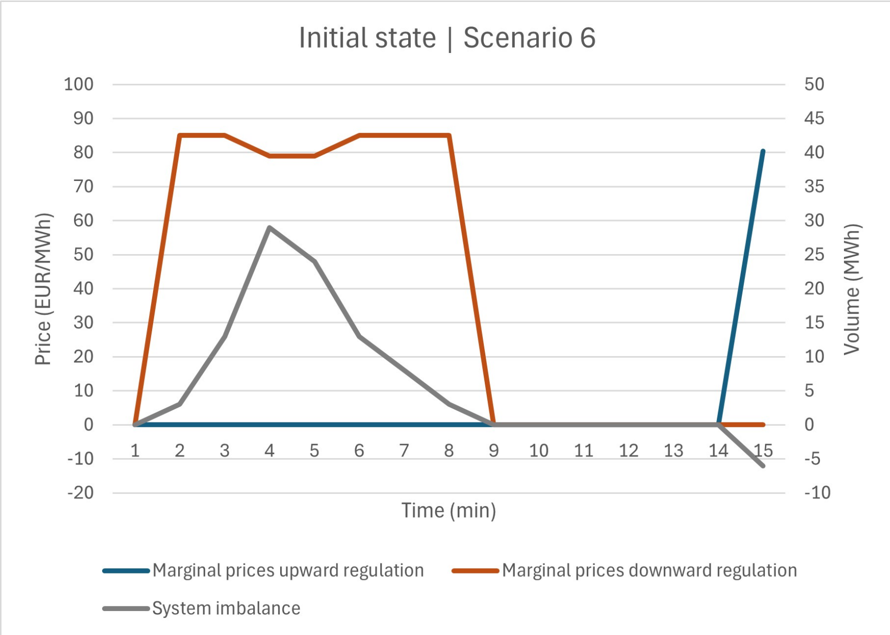

Figure B.16: Marginal prices and system imbalance per minute in original ISP | Scenario 6

NL		BE	
Regulation state	2	Net SI	Positive
Midprice	82.74	Floor	85.00
Balancing energy price		Cap	80.48
Upward regulation	80.84	aFRR element	81.54
Downward regulation	79.04	MIP	85.00
		MDP	80.48
Imbalance price			
BRP surplus	**79.04**		
BRP shortage	**82.74**	**80.48**	

Table B.6: Price difference between NL and BE in €/MWh | Scenario 6

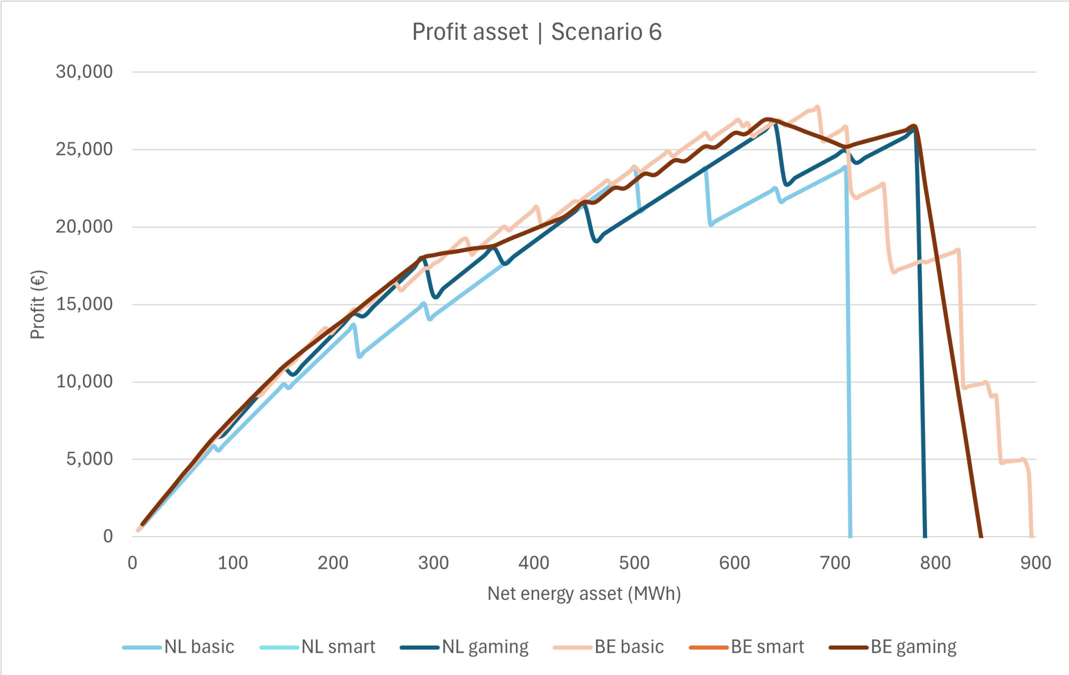

Figure B.17: Asset's profit | Scenario 6

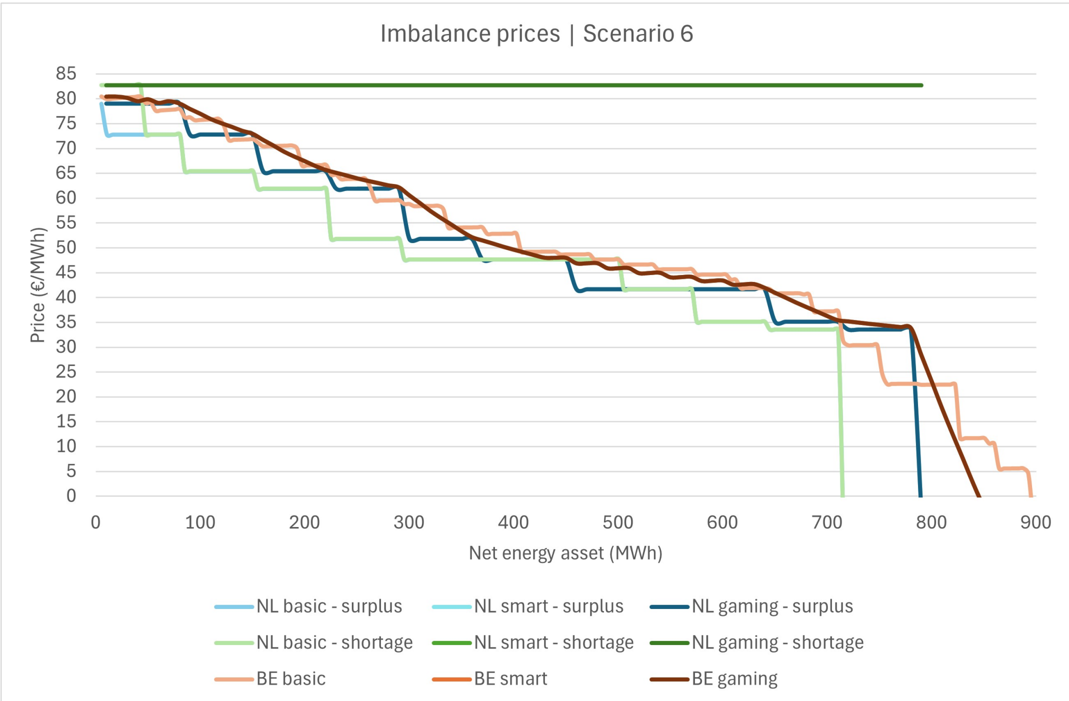

Figure B.18: Imbalance prices | Scenario 6

B.7. Scenario 7

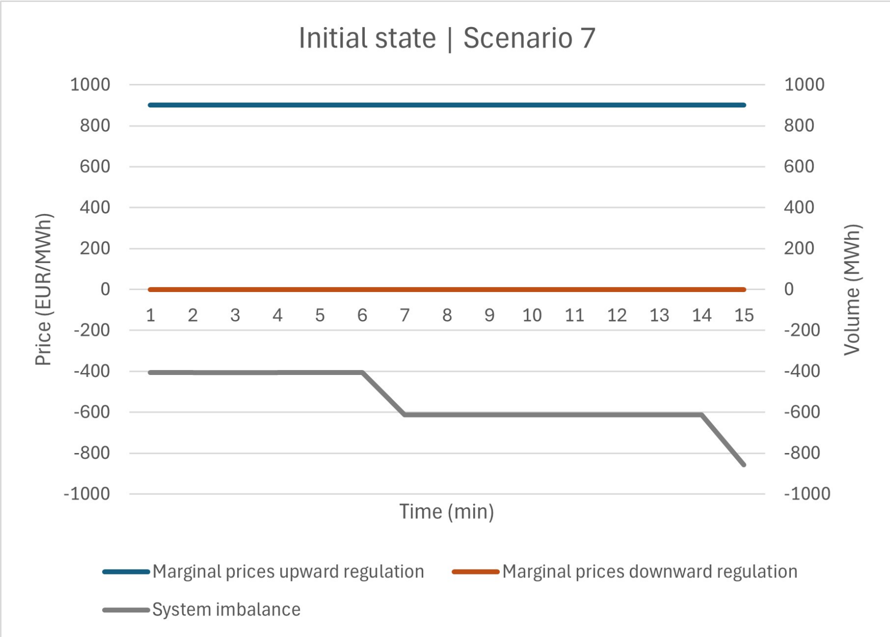

Figure B.19: Marginal prices and system imbalance per minute in original ISP | Scenario 7

NL		**BE**	
Regulation state	1	Net SI	Negative
Midprice	69.61	Floor	77.26
Balancing energy price		Cap	61.95
Upward regulation	900	aFRR element	542.27
Downward regulation	0.00	MIP	900.00
		MDP	900.00
Imbalance price			
BRP surplus	**900.00**		
BRP shortage	**900.00**	**900.00**	

Table B.7: Price differences between NL and BE in €/MWh | Scenario 7

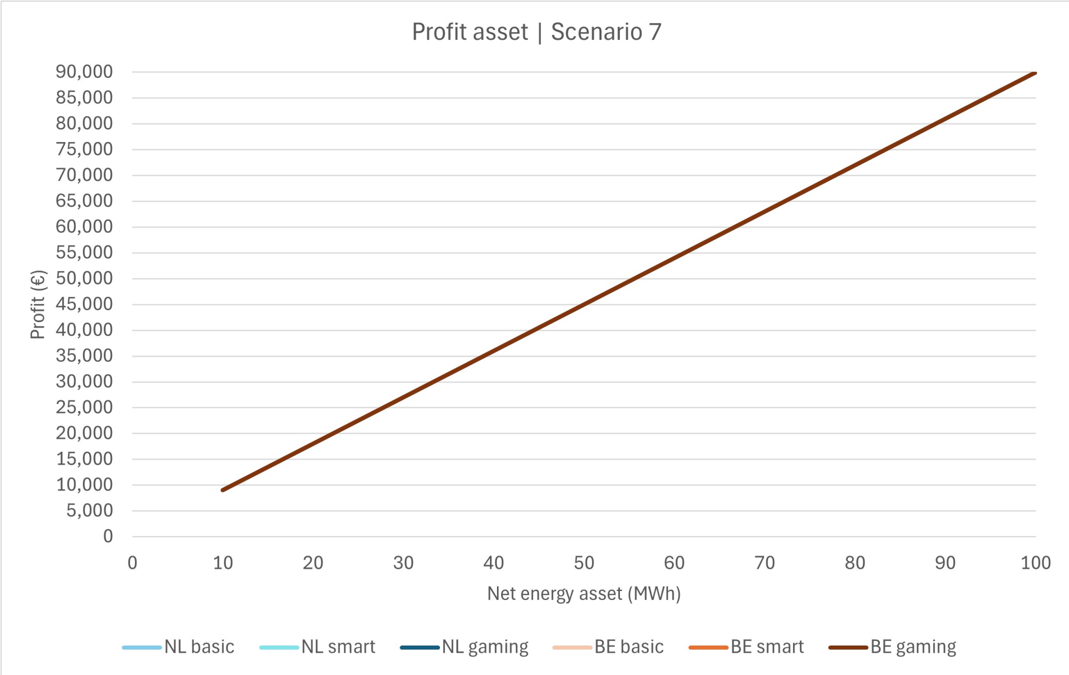

Figure B.20: Asset's profit | Scenario 7

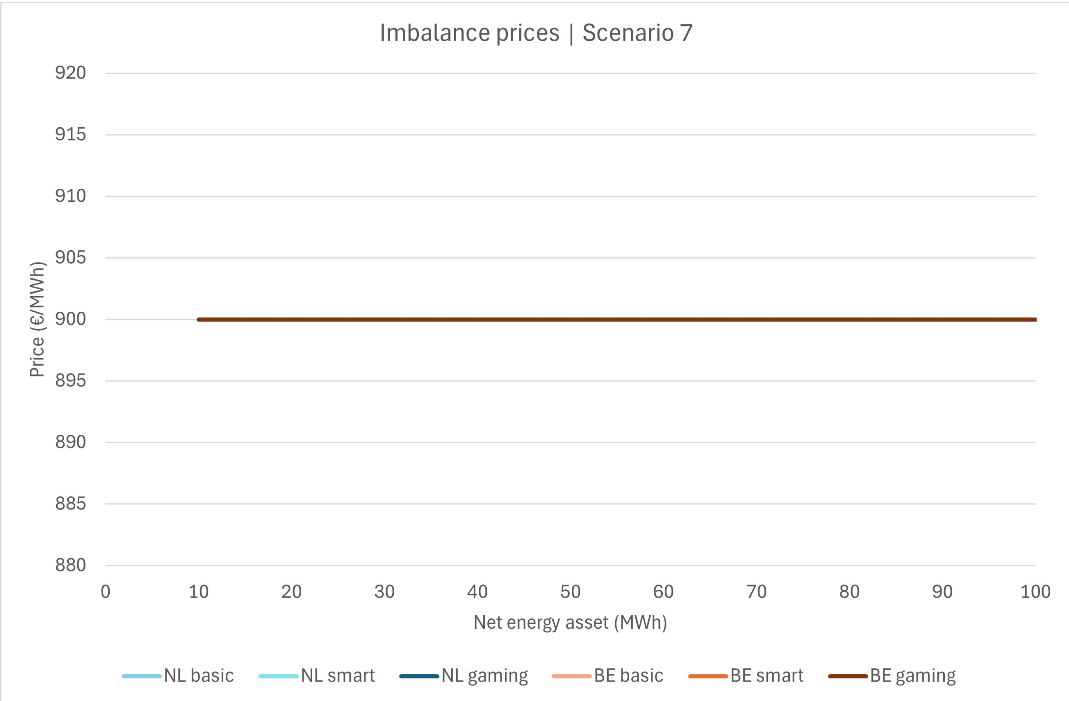

Figure B.21: Imbalance prices | Scenario 7

Note that all strategies in both markets show the same results, hence only the BE gaming strategy is visible in the graph (as all other strategies are underneath this line)

B.8. Scenario 8

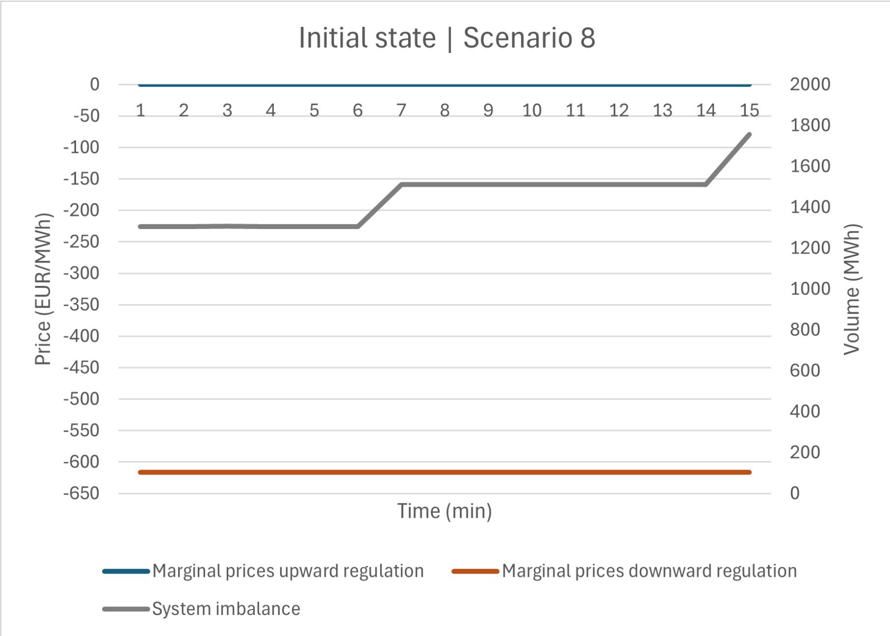

Figure B.22: Marginal prices and system imbalance per minute in original ISP | Scenario 8

NL		BE	
Regulation state	-1	Net SI	Positive
Midprice	67.05	Floor	69.43
Balancing energy price		Cap	64.67
Upward regulation	0	aFRR element	516.90
Downward regulation	616.60	MIP	69.43
		MDP	616.60
Imbalance price			
BRP surplus	**616.60**		
BRP shortage	**616.60**	**616.60**	

Table B.8: Price differences between NL and BE in €/MWh| Scenario 8

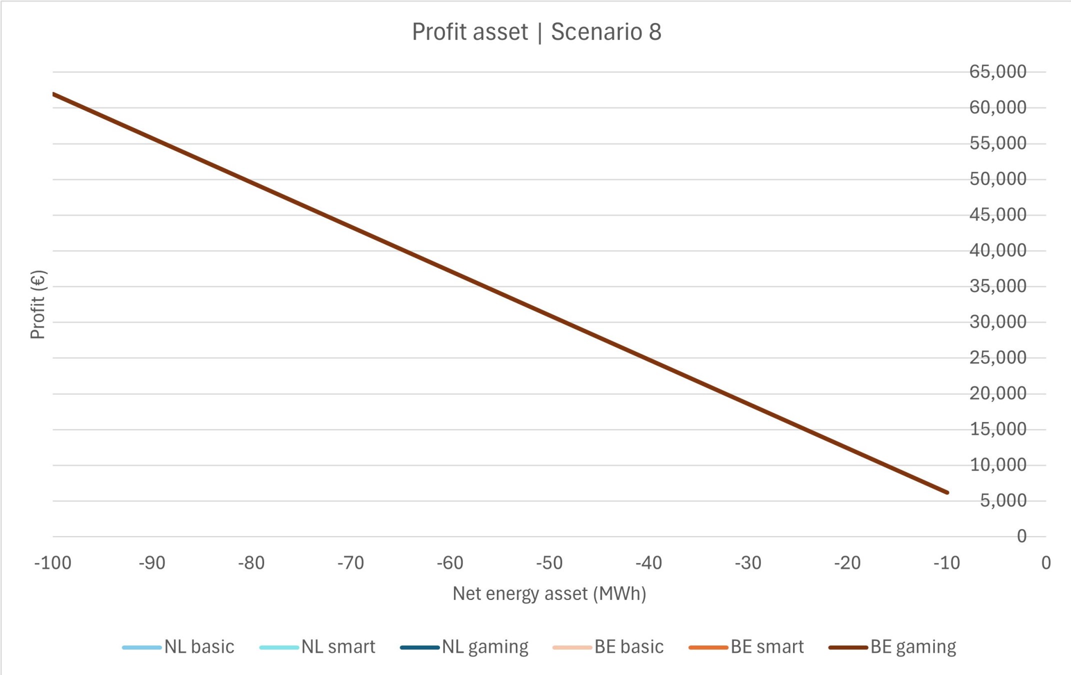

Figure B.23: Asset's profit | Scenario 8

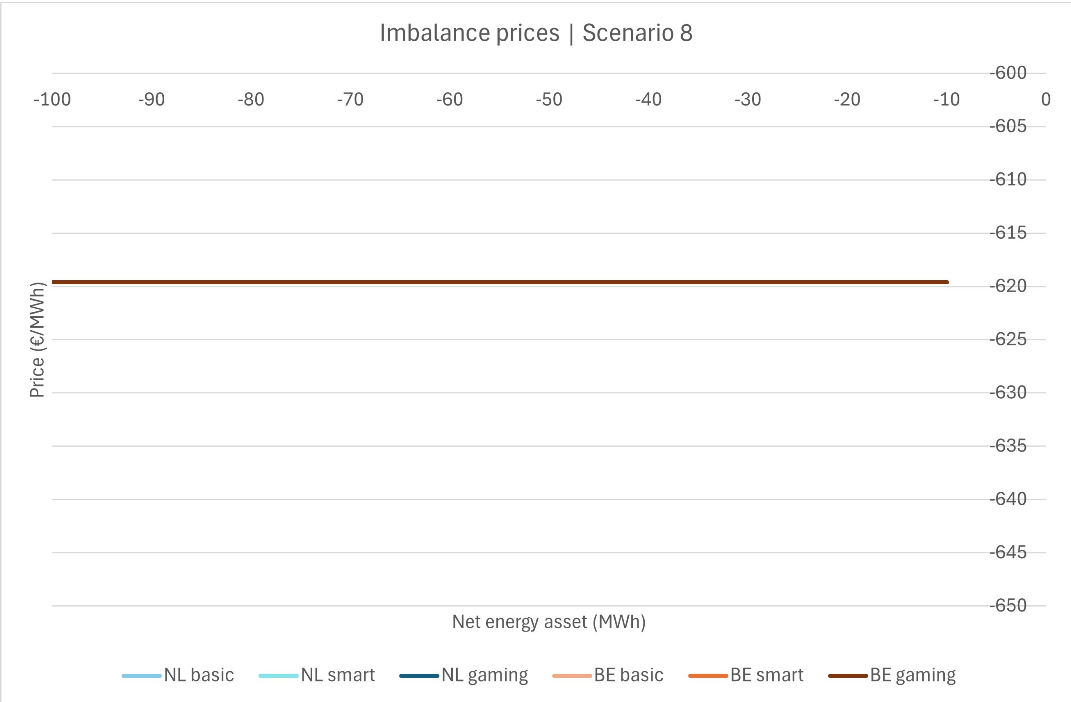

Figure B.24: Imbalance prices | Scenario 8

Note that all strategies in both markets show the same results, hence only the BE gaming strategy is visible in the graph (as all other strategies are underneath this line)