

Deliverable 2

Detailed analysis of industrial reference cases

GALILEO

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Detailed analysis of industrial reference cases

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Author Name	**Affiliation**
Abhimanyu Kaushal, Lina Silva Rodriguez, Jacob Mason, Brecht Ruttens, Tom Cuypers, Anibal Sanjab	VITO/EnergyVille
Malliga Suewattana, Filip Tysebaert	ENTRAS
Emma Menegatti, Binli Xiao	KU Leuven
Reviewed by	
Helena Gerard	VITO/EnergyVille
Joppe Schildermans	Aperam
Thomas Verbruggen	Nyrstar
Cristian-Renato Boruntea	Tessenderlo
Adeline Wantiez	LCL Data Centers
Benny Holemans, Bart Van Camp	Tiense Suiker

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Executive Summary

The GALILEO project aims to accelerate industrial decarbonization, electrification, and flexibility provision in Belgium by improving the understanding, valorisation, and integration of industrial flexibility into future electricity markets. The project combines detailed industrial process modelling, electricity market modelling, and industrial reference cases to identify technical, economic, and regulatory barriers to flexibility provision and to develop future-proof market and product designs. Within this framework, the project develops integrated market and bidding models to assess the value of industrial flexibility under different market designs, and applies these methodologies to representative industrial business use cases (BUCs) from key Belgian industrial sectors. This deliverable presents a consolidated public overview of the BUCs developed within the GALILEO project. This public report brings together the principal findings of these BUCs, highlighting the main technical and economic conclusions where company specific sensitive information is normalyzed.

The investigated BUCs cover a broad range of industrial processes and flexibility technologies, including waste heat recovery systems, electric boilers, electrolysis processes, steam turbines, integrated steam networks, and battery energy storage systems. For each case, process-market-specific optimization models were developed to quantify the available flexibility, evaluate different electricity market participation strategies, and assess the technical suitability of the industrial assets for Belgian electricity markets. Together, these studies demonstrate how process constraints, asset characteristics, and market conditions determine both the flexibility that can be delivered and its associated economic value.

Although the investigated industrial sites differ substantially, several common findings emerge. First, all BUCs demonstrate that industrial assets can provide valuable flexibility services while maintaining their primary industrial function when process constraints are explicitly represented in the optimization models. Rather than relying on generic flexibility assumptions, the assessments capture the operational characteristics of each industrial process, enabling realistic evaluations of both technical flexibility potential and economic performance.

Second, the results show that the most profitable market participation strategy is highly dependent on the characteristics of the industrial process. At Nyrstar, the highest economic value is achieved by stacking revenues across multiple electricity markets, exploiting the operational flexibility of the electrolysis process. Tessenderlo derives most of its flexibility revenues from participation in the downward aFRR market, while combining multiple market products further improves profitability. Tiense Suiker already realizes significant savings through optimized participation in the day-ahead (DA) market, with upward manual Frequency Restoration Reserves (mFRR) providing

the largest additional revenues. Unlike the other industrial cases, its flexibility potential is strongly influenced by the seasonal production cycle, with most reserve capacity and balancing energy delivered during the beet campaign.

The case study for the Aperam ORC demonstrates that the ORC system and thermal buffer provide technically feasible industrial flexibility while improving waste-heat utilisation and creating additional value through electricity market participation. Participation in automatic Frequency Restoration Reserves (aFRR) substantially increases revenues, while coordinated participation across multiple markets delivers the highest overall economic value. The results also underline the importance of jointly sizing the ORC capacity and thermal buffer to balance flexibility provision, waste-heat recovery, and economic performance.

The Aperam e-boiler case study demonstrates that the e-boiler and thermal buffer provide technically feasible and economically attractive demand-side flexibility while increasing renewable electricity self-consumption, reducing low-value exports and natural gas use, and maintaining secure heat supply. DA optimisation lowers procurement costs, while upward reserve services, particularly aFRR-up, and coordinated multi-market participation provide the highest economic value. Increasing e-boiler capacity has the strongest effect on performance, while larger thermal buffers provide additional flexibility.

The LCL Data Centers case study assessed the techno-economic potential of Battery Energy Storage System (BESS) in renewable-integrated data centres. The results show that optimal sizing and profitability depend on investment cost, degradation, renewable generation, and electricity prices. BESS can reduce high-price grid offtake, improve renewable utilisation, support arbitrage, and increase Photovoltaic (PV) revenues, while flexible connection agreements may enable expansion in congested grid areas when sufficient on-site flexibility and clear contractual conditions are available.

The BUCs further demonstrate that no single flexibility technology or market participation strategy is universally optimal. Industrial flexibility originates from diverse physical mechanisms, including process buffering, thermal storage, controllable electricity demand, steam generation, electricity generation, and battery storage. Consequently, the most suitable flexibility solution depends on the operational characteristics and constraints of each industrial process rather than on the market design alone.

Finally, the industrial BUCs highlight the close relationship between industrial flexibility and decarbonisation. Several flexibility technologies, including electrification, thermal storage, waste heat recovery, and battery storage, simultaneously contribute to reducing greenhouse gas emissions and increasing operational flexibility. The strategic assessment at Tiense Suiker further illustrates that process electrification through Mechanical Vapour Recompression (MVR) represents the preferred long-term decarbonisation pathway, while emphasizing the increasing importance of appropriate renewable electricity procurement strategies as industrial processes become more dependent on electricity markets.

Overall, the GALILEO industrial BUCs demonstrate that industrial flexibility can make a significant contribution to future low-carbon electricity systems while supporting industrial competitiveness. However, the results also confirm that flexibility solutions are inherently site-specific. Unlocking their full potential therefore requires technology-neutral market frameworks that enable participation across multiple electricity markets, recog-

nise process-specific operational constraints, and support investments that simultaneously strengthen industrial decarbonisation and electricity system flexibility.

Chapter 1

Aperam BUC 1A: Summary of Key Findings

1.1 Introduction

Aperam Stainless Steel Belgium is an energy-intensive steel producer with major operations at its Genk site, where recycled scrap metal is processed into stainless steel products. Its operations depend on significant electricity and heat consumption across steel refining, rolling, and finishing processes.

Within GALILEO, Aperam's focus is on identifying how decarbonization investments and industrial energy assets can also support flexibility provision. The company is exploring ways to reduce exposure to energy price volatility, improve the integration of renewable electricity, and assess whether flexible operation can strengthen the business case for lower-carbon production.

1.1.1 BUC 1A description

This Business Use Case (BUC) investigates how waste heat recovery in stainless steel production can enable energy flexibility through the integration of an Organic Rankine Cycle (ORC) combined with intermediate thermal storage. The study focuses on recovering waste heat from the Electric Arc Furnace (EAF) and the Argon Oxygen Decarburization (AOD) process at Aperam Stainless Steel Belgium NV. The thermal output from these installations is highly variable over time due to the batch-based nature of steel production and process operation. In particular, the AOD cooling system produces hot pressurized water at approximately 200°C with a fluctuating thermal output ranging from 0–110 MW and an average thermal power of around 20.3 MW. Similarly, the EAF generates recoverable heat with a thermal output ranging from 0–28.4 MW and an average thermal power of approximately 11.0 MW.

Because ORC systems typically operate most efficiently under relatively stable conditions, an intermediate thermal buffer can decouple fluctuating waste heat availability from electricity generation and enable more controllable ORC operation. The study investigates whether increasing thermal buffer capacity or ORC electrical capacity can increase the duration and magnitude of flexibility available for electricity market participation.

The study focuses on how changes in ORC power capacity and thermal storage size affect both the quantity and duration of flexibility that can be provided. By storing excess thermal energy and scheduling ORC electricity generation, the study evaluates the potential to shift electricity production over time and participate in electricity markets. Unlike flexibility approaches that modify core industrial processes, the stainless steel production process itself remains unchanged, while flexibility is created through the interaction between waste heat recovery, thermal storage, and dispatch optimization.

A key aspect of the research is determining which flexibility services can realistically be provided by the ORC and thermal storage configuration and identifying the technical and market limitations that may restrict participation. The use case provides insights into how industrial waste heat recovery systems can evolve from purely energy efficiency measures into active flexibility assets capable of supporting future electricity systems.

Research questions

The following research questions are investigated within the scope of this BUC analysis across the different project tasks:

1. What is the relation between changes in technical specifications (thermal buffer and ORC size) and the flexibility that can be provided?
   (a) What amount of flexibility can be provided?
   (b) What is the potential value of flexibility in the DA, aFRR, mFRR, and imbalance settlement with the ORC and thermal storage?
2. What are the possible flexible services that this technology can provide? What are limitations keeping it from being a viable option? What market requirements must change (and to what extent) for it to be a viable option?
3. What relationship between “remuneration/reduction in energy costs” and “flexibility service quantities provided” is needed to make the ORC system a viable investment?

Research Questions 1 and 3 are addressed in the following sections, while research question 2 is addressed in two parts: the technical suitability of the ORC and thermal buffer system to provide different flexibility mechanisms (technical fit) is addressed in this chapter, while the market design changes required to enable additional flexibility are discussed in Deliverable D3: Market Design to Support Industrial Competitiveness and Flexibility [1].

1.2 Flexibility potential assessment

The flexibility potential of the proposed energy systems is assessed using a common modelling framework consisting of two interconnected models: a process model and a market model. This framework is applied to the ORC with thermal storage system.

The process model provides a digital representation of the physical energy system and determines its optimal operation under representative industrial operating conditions. For this use case, the model captures the interaction between the main energy conversion technologies, thermal energy storage, and the associated heat and electricity flows. The resulting operational dispatch profiles describe the technical behaviour of the system while respecting process constraints.

The operational profiles generated by the process model are subsequently transferred to the market model, which evaluates the economic performance of the system under electricity market conditions. The market model optimizes the scheduling of electricity production according to market prices and quantifies the economic value of the operational flexibility provided by the system. The following sections describe the process model developed for this use case before presenting the corresponding market assessment.

1.2.1 Process Model

The process model represents the operation of an integrated waste heat recovery system consisting of industrial waste heat sources, thermal energy storage, and an ORC for electricity generation. The model provides a simplified representation of the main energy flows, capturing how waste heat released during steel production can be temporarily stored and subsequently converted into electricity. Rather than modelling every physical process in detail, the approach focuses on the operational interaction between the principal system components while preserving the key technical constraints that govern system performance, as illustrated in Figure 1.1.

This model determines the optimal dispatch of the ORC and thermal storage system using waste heat availability profiles and electricity price data as inputs. Operational decisions are obtained through a rolling-horizon optimization framework that schedules thermal storage charging and discharging together with ORC electricity generation while respecting the technical constraints of the system. Multiple system configurations are evaluated by varying both the ORC capacity and the thermal storage capacity in order to assess their influence on system performance and operational flexibility.

1.2.2 Market model

The market model determines the optimal market participation strategy (i.e., bidding strategy) for the ORC system by maximizing the economic value of its participation in electricity markets while respecting all technical and operational constraints of the integrated waste heat recovery system. The model simultaneously schedules electricity generation in the DA market and participation in the balancing markets, namely the aFRR and mFRR, while accounting for imbalance settlement opportunities. By co-optimizing these market opportunities, the model quantifies the flexibility that can be offered to each market, compares their technical and economic performance, and evaluates revenue stacking by dynamically allocating the available flexibility across the considered electricity markets to maximize the overall economic value. This process of coordinated market participation enables the estimation of the revenues that can be

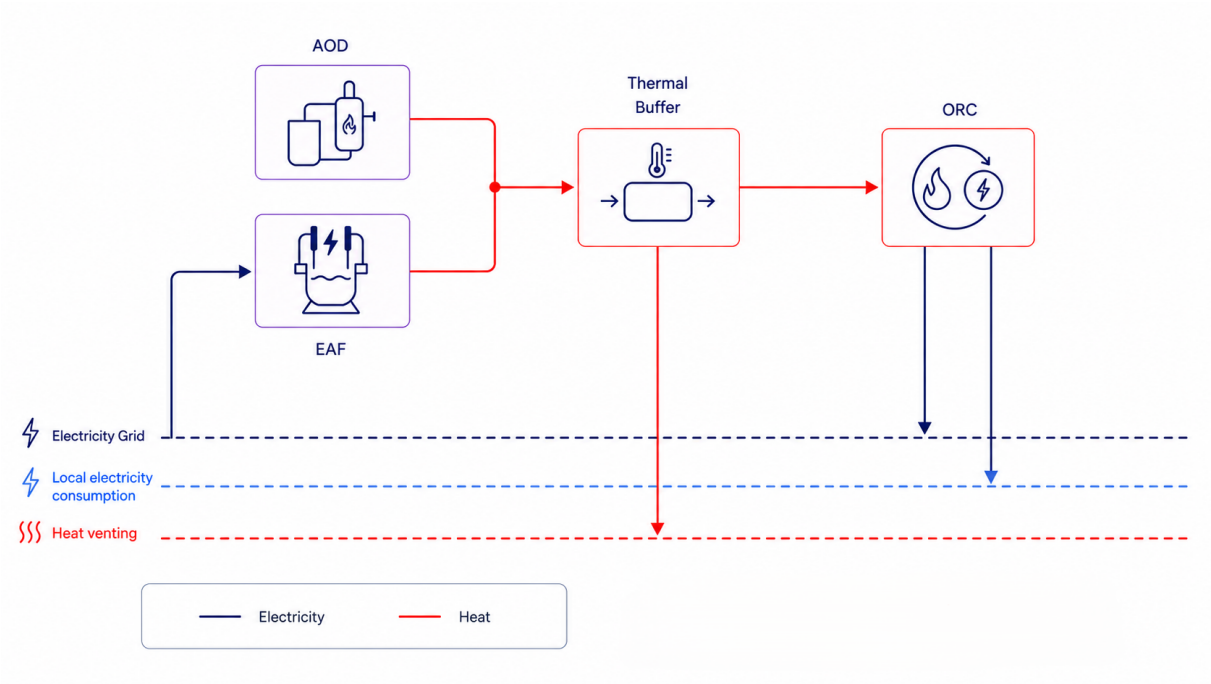


Figure 1.1: Schematic overview of heat recovery from the AOD and EAF processes through a thermal buffer and ORC system.

generated by the ORC system through participation in the DA, aFRR, mFRR, and imbalance markets, providing the basis for the techno-economic assessment and business case evaluation. Figure 1.2 provides an overview of the market model framework and the interactions between the market inputs, the process model, and the market model.

The simulations were performed using historical Belgian electricity market data for the 2024 calendar year with a temporal resolution of 15 minutes, matching the settlement period of the considered electricity markets [2, 3, 4, 5, 6]. The market model assumes a perfect foresight setting for the use case analysis and uses historical balancing activation volumes to determine when and how much reserved flexibility is activated. Under the perfect foresight assumption, all market prices and balancing activation requests are considered to be known in advance. Sensitivity scenarios were additionally evaluated by varying the activation factor to represent future balancing market conditions with increased competition among flexibility providers.

1.3 Results

1.3.1 Process Model Results

The process model analysis considers two ORC capacities (5 MW and 6 MW) combined with thermal storage capacities ranging from 8 to 40 MWh using historical Belgian Day-Ahead electricity prices for 2025. The assessment focuses on the coordinated operation of the ORC and thermal storage system, including the temporal dispatch of electricity generation, charging and discharging of the thermal buffer, and the occurrence of heat rejection. Particular attention is given to the influence of ORC capacity and thermal

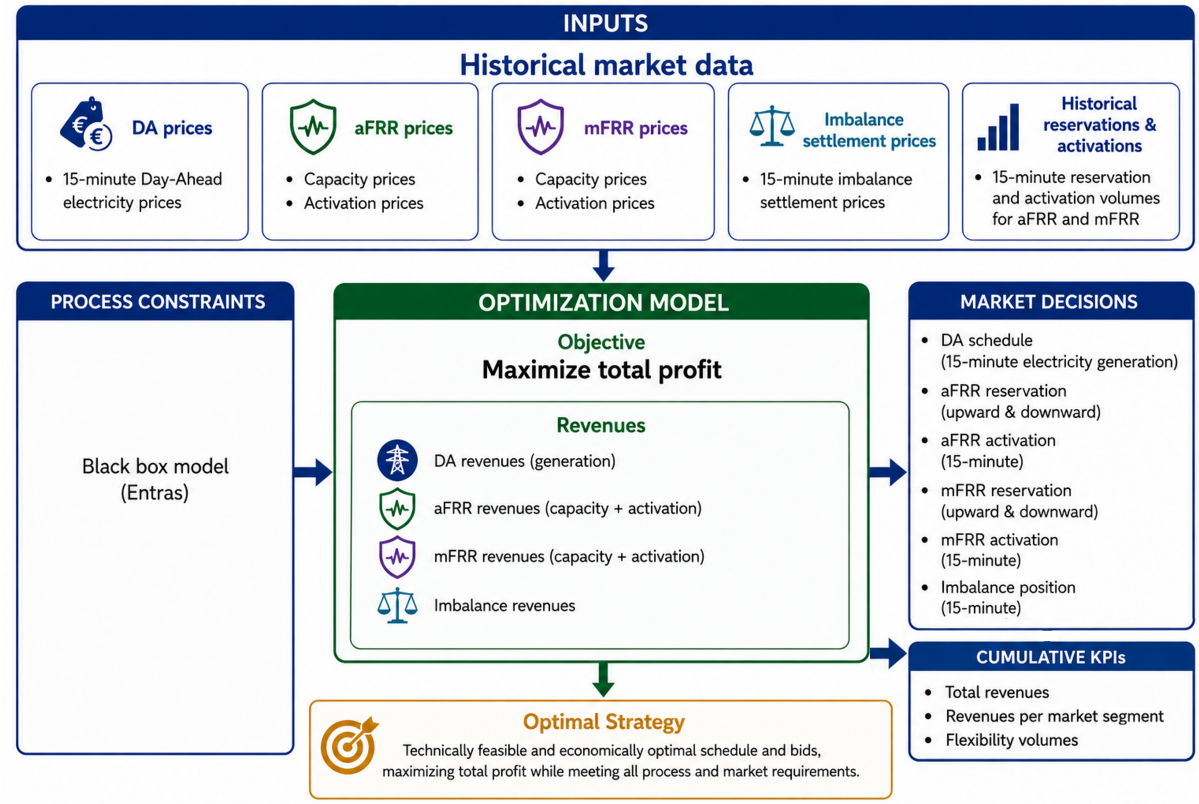


Figure 1.2: VITO's market model and flexibility valuation framework used for the ORC use case.

storage size on waste heat utilisation and the operational flexibility of the integrated energy recovery system.

As shown in Figure 1.3, thermal energy storage plays a key role in enhancing the operational flexibility of the energy recovery system. By storing excess waste heat when it is available and releasing it during periods of higher electricity prices, the storage system improves the temporal alignment between waste heat availability and electricity generation. However, the results also reveal that a significant proportion of the available waste heat cannot be utilised and must be rejected. Heat rejection occurs when periods of sustained waste heat generation exceed the combined storage capacity of the thermal buffer and the heat conversion capability of the ORC. Although increasing both the thermal storage capacity and the ORC capacity reduces the amount of rejected heat, it does not eliminate it entirely. The analysis shows that the ORC remains the primary bottleneck of the system, as its maximum thermal conversion capacity ultimately limits the amount of waste heat that can be converted into electricity, while the thermal buffer mainly provides short-term operational flexibility.

Overall, the process model confirms the technical feasibility of integrating thermal energy storage with ORC technology to recover industrial waste heat while demonstrating the importance of jointly sizing the ORC and thermal storage system. The resulting operational profiles provide the necessary input for the market model, which evaluates the economic value of the recovered electricity and the flexibility that the integrated system can provide under different market conditions.

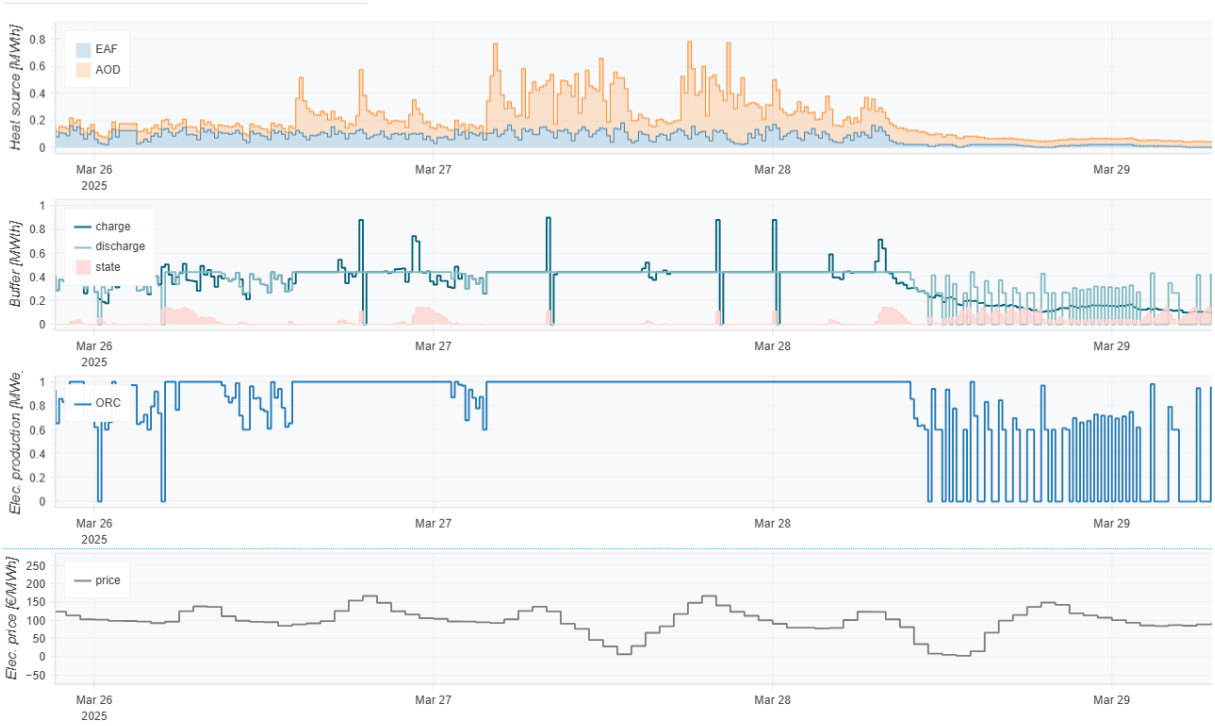


Figure 1.3: Representative dispatch schedule of the integrated ORC-thermal storage system (with buffer size 8 MWh and 5 MW ORC electrical output), illustrating the temporal evolution of ORC power output, thermal buffer charging, discharging and state of charge, and electricity price over a 72-hour representative period. Process variables are presented in normalized form.

1.3.2 Market Model Results

Scenario Design and Technical Configurations

A scenario-based framework is used to evaluate how the technical design of the ORC system affects its ability to provide operational flexibility and participate in electricity markets. The analysis focuses on two main design parameters: the minimum and maximum electrical outputs of the ORC and the capacity of the thermal buffer. These parameters influence the amount of upward and downward flexibility available, the duration for which this flexibility can be sustained, and the economic value that can be obtained through market participation.

Two alternative ORC configurations are considered. The first configuration operates between 3 and 5 MW, while the second operates between 4 and 6 MW. These alternatives represent two different turbine capacities. For each ORC configuration, several thermal buffer capacities are investigated. The 3–5 MW ORC is combined with buffer capacities ranging from 8 to 40 MWh, whereas the 4–6 MW configuration is evaluated with buffer capacities ranging from 8 to 40 MWh. The difference in the maximum feasible buffer capacity reflects the technical design scenarios provided by the industrial partner.

In total, fourteen asset configurations are evaluated, as summarised in Table 1.1. This set of scenarios enables the effects of ORC electrical capacity and thermal storage

size to be examined both independently and jointly.

Scenario	Maximum ORC output (MW)	Minimum ORC output (MW)	Buffer capacity (MWh)
1–7	5	3	8, 15, 20, 25, 30, 35, 40
8–14	6	4	8, 15, 20, 25, 30, 35, 40

Table 1.1: Summary of the ORC and thermal buffer scenarios.

The ORC is represented as a dispatchable generation unit that converts recovered waste heat into electricity. Its output can be adjusted within its technical operating range, while the thermal buffer decouples the timing of heat recovery from the timing of electricity production. When electricity production is reduced, thermal energy can be stored in the buffer. This energy can subsequently be used to increase electricity production during periods in which market prices or balancing-service revenues are more attractive.

The market model as shown in Figure 1.2 determines the optimal operating and market participation strategy by jointly coordinating the allocation of available flexibility across the DA, balancing, and imbalance markets. The balancing markets include both upward and downward aFRR and mFRR participation. For each market participation strategy, the model optimises the ORC generation schedule and the corresponding market bids while respecting the technical and operational constraints of the ORC system and thermal buffer described in the previous section. The available upward and downward flexibility is dynamically allocated among the enabled market segments to maximise the overall economic value of market participation while ensuring the feasibility of all process operations and previously established market commitments.

The market model evaluates the economic value of this flexibility through several participation strategies. The DA market serves as the basic market configuration. Additional strategies progressively introduce upward and downward aFRR, mFRR, and imbalance market participation. The resulting configurations represent increasing levels of revenue stacking and market complexity. The investigated strategies include DA participation alone; DA participation combined separately with aFRR-up (also denoted as aFRR+), aFRR-down (aFRR–), mFRR-up (mFRR+), or mFRR-down (mFRR–); participation in both upward and downward aFRR or mFRR; combined participation in the DA, aFRR, and mFRR markets; and full participation in the DA, balancing, and imbalance markets. For each strategy, only the explicitly selected market segments are enabled. The optimisation model therefore determines the optimal operating schedule and bidding strategy for the permitted market combination. An overview of the investigated market strategies is shown in Table 1.2.

In the DA market, the model schedules ORC electricity production using forecast prices. The objective is to sell electricity during economically attractive periods while respecting the minimum and maximum output limits and the operational constraints of the thermal buffer. The DA schedule therefore establishes the reference operating point around which balancing flexibility can subsequently be offered. Upward balancing services, represented by aFRR+ and mFRR+, require the ORC to increase generation above the DA schedule when requested by the system operator. By contrast, downward

Strategy	Interpretation
Reference	Baseline operation according to a predefined ORC schedule, without optimised electricity-market participation.
DA	Electricity generation is scheduled in the DA market to maximise revenue while satisfying the ORC and thermal-buffer constraints.
DA + aFRR-up	The ORC provides upward aFRR by increasing generation relative to the DA schedule.
DA + aFRR-down	The ORC provides downward aFRR by decreasing generation relative to the DA schedule.
DA + aFRR	Both upward and downward aFRR services are included in the optimisation.
DA + mFRR-up	The ORC provides upward mFRR by increasing generation relative to the DA schedule when activated.
DA + mFRR-down	The ORC provides downward mFRR by decreasing generation relative to the DA schedule when activated.
DA + mFRR	Both upward and downward mFRR services are included in the optimisation.
DA + aFRR + mFRR	Available flexibility is allocated among the DA, aFRR, and mFRR markets.
DA + aFRR + mFRR + Imbalance	Any flexibility remaining after DA and balancing commitments may be allocated to the imbalance market.

Table 1.2: Market participation strategies considered in the analysis.

balancing services, represented by aFRR– and mFRR–, require the ORC to reduce its generation below the scheduled level.

The analysis also accounts for uncertainty in the activation of aFRR bids. Strategies involving aFRR are therefore evaluated using activation factors of 10%, 30%, and 100%. These factors represent different assumptions regarding the share of the reserve capacity required by the Transmission System Operator (TSO) that is actually provided by ORC and thermal buffer. Comparing these activation levels makes it possible to assess how reserve activation affects the thermal state of the system, the amount of remaining flexibility, and the resulting market revenues.

This market model ensures that commitments made at each market stage are respected. It also prevents the same physical flexibility from being allocated simultaneously to multiple markets. For example, scheduling the ORC close to its maximum output may increase DA revenue but reduce the remaining upward flexibility available for balancing market participation. Conversely, scheduling the ORC close to its minimum output may increase the available upward reserve capacity while limiting its ability to provide downward balancing services.

The simulation results are analysed from three complementary perspectives. First, the influence of thermal buffer capacity is assessed while the ORC electrical operating range is held constant. For the 3–5 MW configuration, Scenarios 1–7 allow buffer capacities between 8 and 40 MWh to be compared directly. This analysis determines whether additional storage increases the revenue to justify the larger storage capacity.

Second, the influence of ORC electrical output is examined at a fixed thermal buffer

capacity. Scenarios 3 and 10 both use a 20 MWh thermal buffer, but the former uses a 3–5 MW ORC and the latter a 4–6 MW ORC. This comparison isolates the impact of turbine capacity. The larger ORC provides a higher maximum electrical output, but it also has a higher minimum output. Consequently, it may increase electricity production and upward reserve capability while potentially limiting the downward regulation.

Third, the combined effects of ORC capacity, thermal buffer size, market strategy, and aFRR activation factor are evaluated. This combined assessment is important because the value of a technical design depends on the markets in which the asset participates. A larger buffer may provide limited additional value under DA-only operation but become more beneficial when the ORC participates in balancing and imbalance markets. Likewise, a larger ORC capacity generates additional value only when sufficient thermal energy and favourable market opportunities are available.

The overall comparative assessment identifies the relationship between investment in ORC and thermal storage capacity and the resulting improvements in flexibility and market revenue. Increasing the thermal buffer size may allow the ORC to sustain upward or downward activation for longer periods. However, once the buffer is sufficiently large to accommodate the economically useful shifts in thermal energy, additional capacity may produce diminishing economic benefits. Similarly, increasing ORC capacity may improve generation and reserve potential, but the larger configuration is not necessarily the most profitable option. Its economic performance depends on its utilisation, the availability of recovered heat, the operating schedule, and the prices and activation patterns in the relevant electricity markets.

The progressive introduction of DA, balancing, and imbalance market participation enables the incremental value of revenue stacking to be quantified. The DA market provides the basic production revenue, the balancing markets monetise upward and downward deviations around the scheduled operating point, and the imbalance market provides a final opportunity to use residual flexibility. At the same time, participation in multiple markets increases operational complexity and creates competition between alternative uses of the same flexibility.

Overall, the evaluation framework provides a systematic basis for assessing the economic performance of flexible ORC operation. By comparing all combinations of ORC size, thermal buffer capacity, market strategy, and aFRR activation factor, the analysis identifies the configurations that offer the most favourable balance between investment requirements, flexibility provision, and market revenue. The results therefore support the evaluation of the business case for using the ORC system and thermal buffer as a flexible waste-heat-to-power system participating in the DA, balancing, and imbalance markets. Unless stated otherwise, the results presented for the different market participation strategies correspond to maximum and minimum generation of 5MW/3MW and thermal buffer size of 8 MWh, with an aFRR bid activation factor of 30%.

Market revenue and revenue stacking

Figure 1.4 compares the normalized annual revenues and total profits obtained under the different market participation strategies considered in this study, using the revenue of the reference case as the normalization basis. The stacked bars show the contribu-

tion of each electricity market segment to the total normalized revenue, while the line represents the corresponding normalized total profit. All values are normalized relative to the reference case, which represents the current ORC operating strategy without market-based scheduling. In this case, electricity generation follows the existing operating schedule, and the associated revenue is calculated using historical DA prices over the considered simulation horizon.

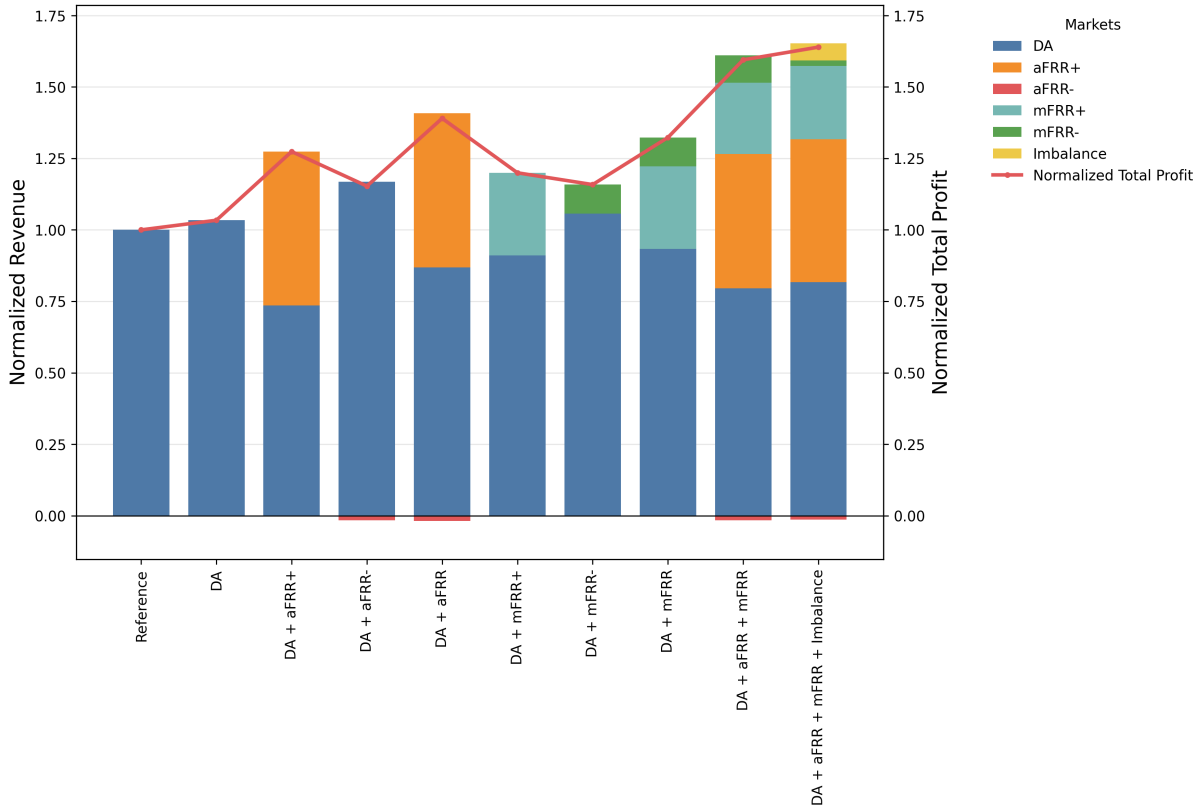


Figure 1.4: Comparison of normalized annual revenues and total profit for different electricity market participation strategies.

The results show that optimised participation in the DA market increases the normalized total profit slightly above the reference case. However, DA-only participation provides the smallest improvement among the optimised market strategies, with a normalized total profit of approximately 1.03. This indicates that market-based scheduling in the DA market creates additional value, but the largest economic benefits are obtained when the ORC also provides balancing services.

Participation in aFRR-up produces a substantial increase in profitability, resulting in a normalized total profit of approximately 1.27. In contrast, the DA + aFRR-down strategy reaches a lower normalized total profit of approximately 1.15. The direct aFRR-down contribution is slightly negative, although the corresponding change in the DA schedule increases DA revenue relative to the DA-only strategy. When both upward and downward aFRR participation are enabled, the normalized total profit increases further to approximately 1.39. This result indicates that coordinated allocation of flexibility between upward and downward aFRR provides greater economic value than participation in either direction alone.

A similar pattern is observed for mFRR participation. The DA + mFRR-up strategy achieves a normalized total profit of approximately 1.20, while the DA + mFRR-down strategy results in a value of approximately 1.16. Simultaneous participation in both upward and downward mFRR increases the normalized total profit to approximately 1.32. Although upward mFRR provides the larger individual contribution, combined participation allows the market model to use the available flexibility more effectively across both balancing directions.

The highest economic performance is achieved through coordinated participation in multiple markets. Combined DA, aFRR, and mFRR participation results in a normalized total profit of approximately 1.60, representing an increase of around 60% relative to the reference case. The corresponding revenue stack includes substantial contributions from aFRR-up and mFRR-up, together with a smaller contribution from mFRR-down. The direct aFRR-down contribution remains slightly negative, but its inclusion supports the coordinated optimisation of the ORC schedule and the allocation of flexibility across the enabled markets.

Adding the imbalance market produces the highest normalized total profit, approximately 1.64, corresponding to an improvement of around 64% relative to the reference case. The imbalance-market contribution is comparatively small, indicating that most of the available economic value is already captured through coordinated DA, aFRR, and mFRR participation. Nevertheless, the imbalance market provides an additional revenue opportunity by utilising flexibility that remains available after the DA and balancing-market commitments have been satisfied.

Overall, the results demonstrate that the DA market remains the principal source of revenue in all strategies, while balancing-market participation creates substantial additional value. Upward reserve provision is generally more profitable than downward reserve provision when considered individually. However, the greatest economic benefit is obtained when upward and downward flexibility are jointly allocated across aFRR and mFRR, followed by the use of residual flexibility in the imbalance market. The close agreement between the stacked normalized revenues and the normalized total-profit line further indicates that the additional market revenues translate directly into improved economic performance.

Annual flexibility potential

This section compares the normalized annual balancing and imbalance energy activated and the normalized reserve capacity contracted over the one-year simulation horizon. The results show how the available ORC flexibility is allocated among the DA, aFRR, mFRR, and imbalance markets under the different market combinations. Figure 1.5 presents the normalized annual activated balancing and imbalance energy. It shows how the market model distributes the available operational flexibility among the enabled services.

No balancing energy is activated under the DA-only strategy. For the individual aFRR strategies, the DA + aFRR-up configuration reaches a normalized upward activation of approximately 0.32, while the DA + aFRR-down strategy results in a downward activation of approximately 0.20. When both directions are enabled, the DA + aFRR strategy provides approximately 0.33 of upward activation and 0.20 of downward acti-

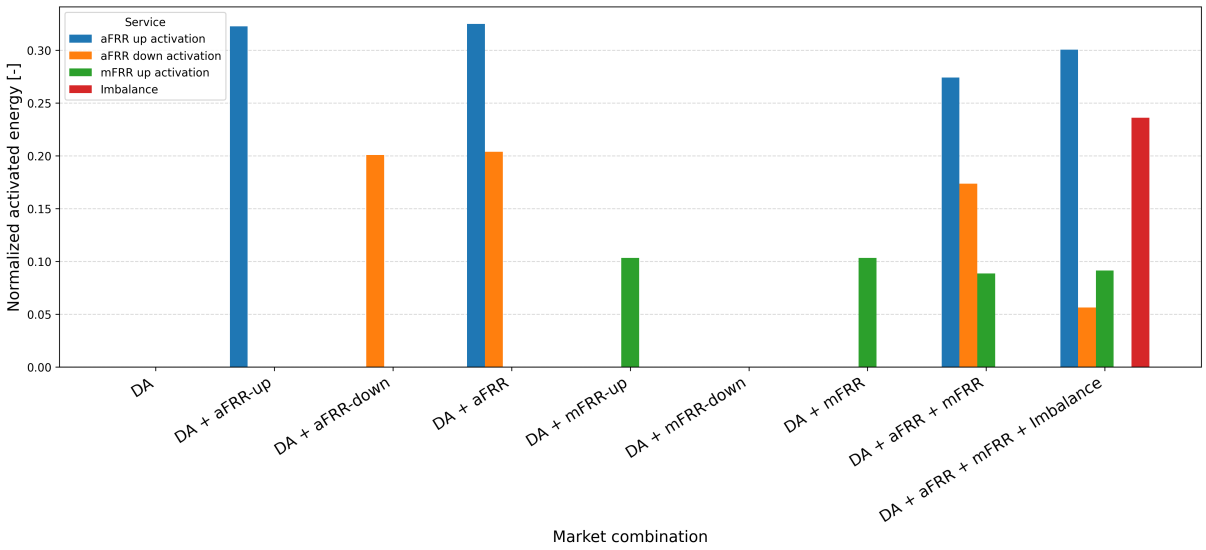


Figure 1.5: Normalized annual activated balancing and imbalance energy for the different electricity market participation strategies for ORC.

vation. Thus, enabling both directions does not substantially reduce the upward aFRR activation.

For the individual mFRR strategies, the DA + mFRR-up configuration produces a normalized upward activation of approximately 0.10. DA + mFRR-down results in a negligible activation volume. Similarly, the DA + mFRR strategy allocates activation almost entirely to mFRR-up, indicating that mFRR opportunities are concentrated in the upward direction under the considered market conditions.

When aFRR and mFRR are enabled simultaneously, the available flexibility is distributed among several services. Under DA + aFRR + mFRR, the normalized activated energy is approximately 0.27 for aFRR-up, 0.17 for aFRR-down, and 0.09 for mFRR-up. Relative to the individual aFRR strategies, part of the available flexibility is reallocated to mFRR-up. With imbalance-market participation, the normalized activated energy is approximately 0.30 for aFRR-up, 0.06 for aFRR-down, 0.09 for mFRR-up, and 0.24 for the imbalance market. The imbalance contribution shows that a substantial share of the residual flexibility is allocated to this market after the DA and balancing-market commitments are satisfied.

Overall, the market model reallocates the available physical flexibility according to the economic value of the enabled services and the operational state of the ORC system and thermal buffer. Upward aFRR is the largest activated balancing component, while mFRR participation is concentrated in the upward direction. The imbalance market provides an additional opportunity to utilise residual flexibility.

Figure 1.6 presents the normalized annual reserve capacity contracted in the balancing markets. In contrast to Figure 1.5, which shows the balancing and imbalance energy activated, this figure represents the flexibility committed in advance as reserve capacity. No reserve capacity is contracted under the DA-only strategy. For the individual aFRR configurations, the reserved capacities are comparatively small. The DA + aFRR-up strategy reserves approximately 0.011 of upward capacity, while DA + aFRR-down reserves approximately 0.010 of downward capacity. When both directions are

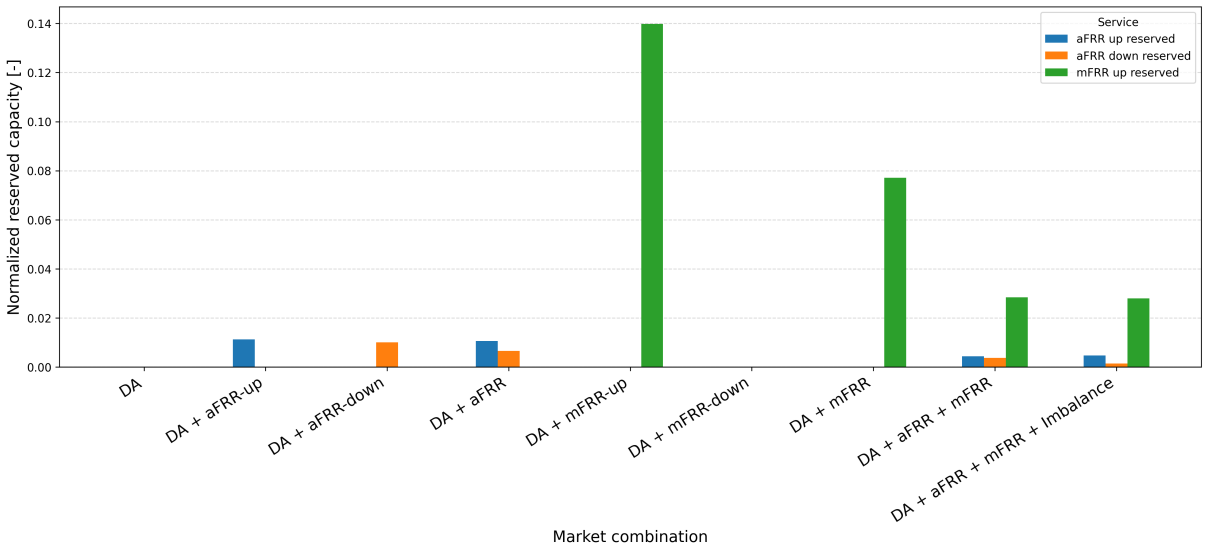


Figure 1.6: Normalized annual reserved balancing capacity for the different electricity market participation strategies for ORC.

enabled, approximately 0.011 of upward and 0.007 of downward aFRR capacity are reserved. These results indicate that the value of aFRR participation is associated more strongly with activated energy than with reserve-capacity commitments.

Substantially larger reserved capacities are observed for mFRR-up. The DA + mFRR-up strategy reaches the highest normalized reserved capacity, approximately 0.14. When both mFRR directions are enabled, approximately 0.08 of upward mFRR capacity is reserved, while no downward mFRR reserve capacity is observed (as mFRR-down capacity reservation is not carried out in Belgium). Under the DA + aFRR + mFRR strategy, the normalized reserved capacities are approximately 0.004 for aFRR-up, 0.004 for aFRR-down, and 0.029 for mFRR-up. The reduction in mFRR-up capacity relative to the individual mFRR strategies reflects competition among the enabled services for the same physical flexibility. Adding the imbalance market results in similar reserve allocations: approximately 0.005 for aFRR-up, 0.002 for aFRR-down, and 0.028 for mFRR-up. This indicates that imbalance-market participation has only a limited effect on reserve commitments and primarily influences the use of flexibility remaining after these commitments are established.

Overall, the market model reserves capacity in the products that provide the highest expected economic return. Upward mFRR is the dominant reserved service, whereas aFRR reserve commitments remain relatively small. Combined with the activated-energy results, this indicates that aFRR value is derived mainly from energy activation, while mFRR-up provides the main reserve-capacity opportunity.

Impact of thermal buffer capacity and aFRR activation factors

Figure 1.7 compares the normalized total annual revenue obtained for different thermal buffer capacities while maintaining a fixed ORC electrical output. The analysis considers buffer capacities ranging from 8 to 40 MWh and bid activation factors of 10%, 30%, and 100%. All values are normalized relative to the absolute DA revenue of the

reference case with an 8 MWh buffer.

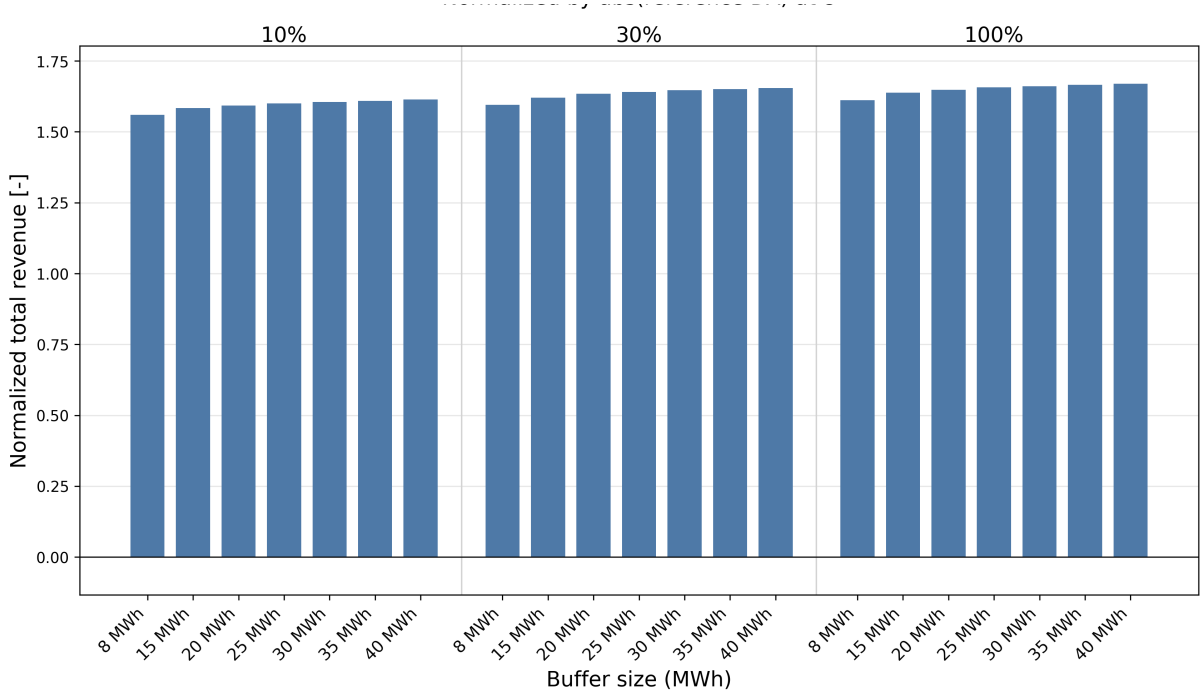


Figure 1.7: Variation of normalized total annual revenue with thermal buffer capacity for a fixed ORC electrical output (5MW) and different bid activation factors.

The results show that the normalized total annual revenue increases with both the bid activation factor and the thermal buffer capacity. For an 8 MWh buffer, the normalized revenue rises from approximately 1.56 at a 10% activation factor to around 1.60 at 30% and 1.61 at 100%. A similar trend is observed for all buffer sizes, indicating that higher activation levels increase the economic value captured from balancing-market participation. For each activation factor, increasing the thermal buffer capacity produces a gradual improvement in normalized revenue. At a 10% activation factor, the revenue increases from approximately 1.56 for an 8 MWh buffer to about 1.61 for a 40 MWh buffer. At 30%, the corresponding increase is from approximately 1.60 to 1.65, while at 100% the revenue rises from about 1.61 to 1.67.

The revenue increase is most pronounced when the buffer capacity is increased from 8 to approximately 20–25 MWh. Beyond this range, the incremental improvement becomes smaller, and the revenue curves begin to flatten. This indicates diminishing economic returns from further increases in thermal storage capacity once sufficient flexibility is available to exploit most of the profitable market opportunities.

The effect of the activation factor remains visible across all buffer sizes. Higher activation factors allow a larger share of the reserved flexibility to be converted into activated balancing energy and associated revenue. However, the difference between the 30% and 100% cases is relatively modest compared with the difference between the 10% and 30% cases. This suggests that a substantial share of the available economic value is already captured at the intermediate activation level.

The 40 MWh buffer achieves the highest normalized revenue for all three activation factors, although its advantage over the 30 and 35 MWh configurations is limited.

Overall, the results demonstrate that increasing thermal buffer capacity improves the economic performance of the ORC system by enabling more effective temporal allocation of thermal energy and electricity generation. Nevertheless, the diminishing revenue gains at larger buffer sizes indicate that the economically optimal storage capacity may be lower than the maximum technically feasible capacity.

Impact of ORC electrical capacity and aFRR activation factors

Figure 1.8 evaluates the influence of ORC electrical capacity on normalized total annual revenue at a fixed thermal buffer capacity of 20 MWh. The analysis is repeated for bid activation factors of 10%, 30%, and 100%, with all revenues normalized relative to the absolute DA revenue of the 5 MW reference configuration.

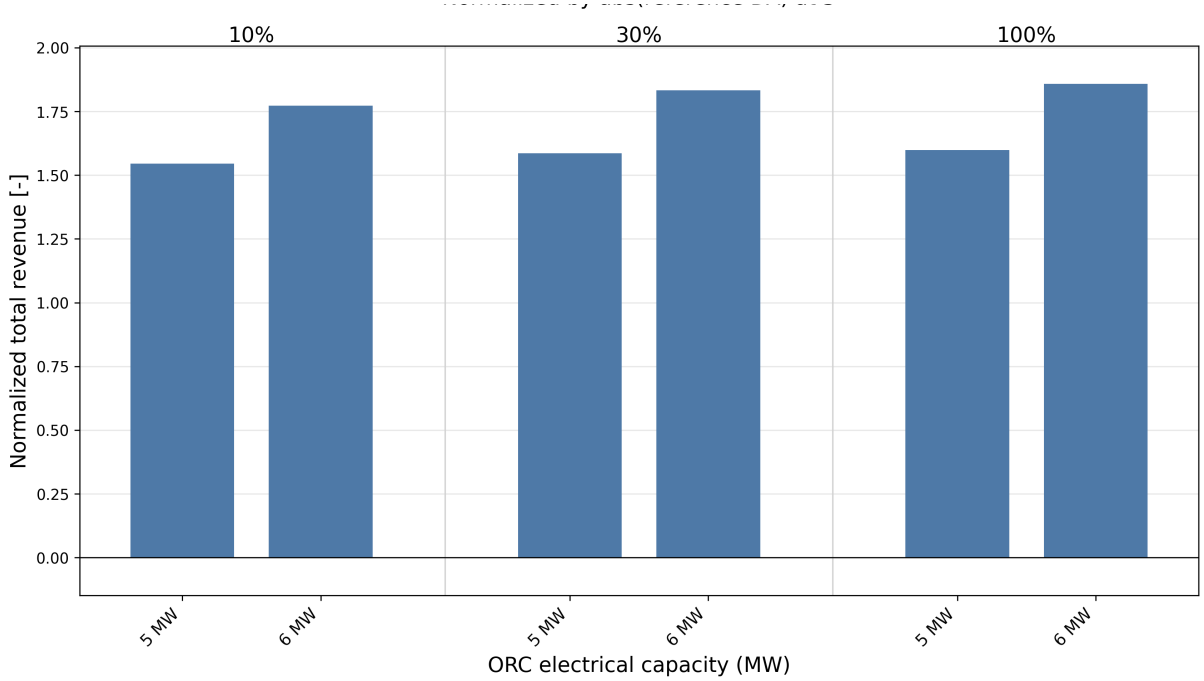


Figure 1.8: Variation of normalized total annual revenue for different ORC electrical capacities at a fixed thermal buffer capacity and different bid activation factors.

A clear revenue advantage is observed for the 6 MW ORC configuration. Its normalized total annual revenue increases from approximately 1.77 at a 10% activation factor to 1.83 at 30% and 1.86 at 100%. The corresponding values for the 5 MW configuration are approximately 1.55, 1.59, and 1.60. The effect of increasing the ORC electrical capacity is therefore larger than the effect of increasing the bid activation factor. Moving from the 5 MW to the 6 MW configuration raises normalized revenue by approximately 14% at 10%, 15% at 30%, and 16% at 100%, relative to the corresponding 5 MW results. By comparison, increasing the activation factor from 10% to 100% produces only a limited revenue increase within each ORC configuration.

The higher revenue of the 6 MW configuration indicates that the additional electrical capacity allows the market model to utilize a greater amount of generation and flexibility to profitable market opportunities. The slightly larger revenue difference at higher acti-

vation factors further suggests that the additional ORC capacity becomes more valuable when balancing-market activation increases.

Overall, the results identify ORC electrical capacity as a major determinant of economic performance at the fixed 20 MWh buffer size. Bid activation affects the revenue obtained from both configurations, but the larger ORC consistently delivers the greater economic benefit across all analysed activation levels.

Economic performance of the ORC and thermal buffer configurations

Figure 1.9 presents the sensitivity of the normalized total annual profit for the combined DA + aFRR + mFRR market participation strategy to the ORC electrical capacity, thermal buffer size, and bid activation factor. The three heatmaps correspond to activation factors of 10%, 30%, and 100%. For each activation factor, the normalized total profit is evaluated for ORC capacities of 5 and 6 MW and thermal buffer capacities ranging from 8 to 40 MWh.

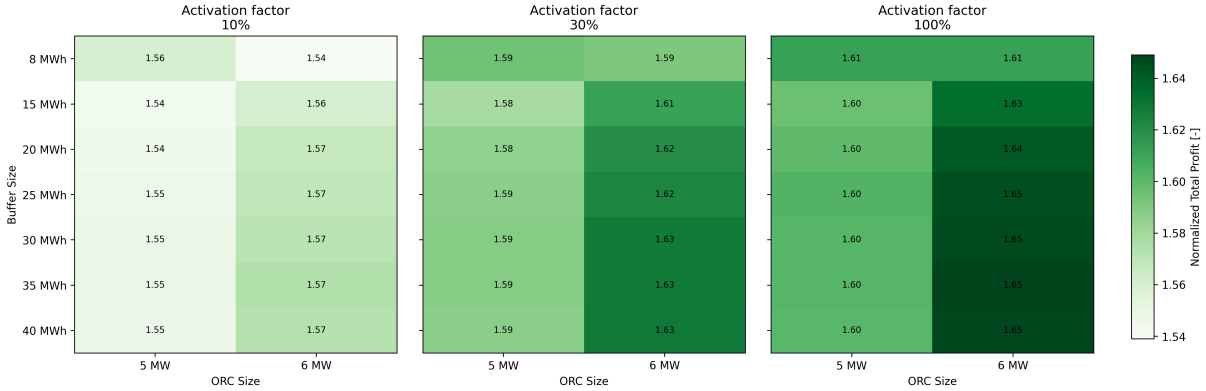


Figure 1.9: Sensitivity of the normalized total annual profit to ORC capacity, thermal buffer size, and bid activation factor for the DA + aFRR + mFRR market participation strategy.

The results show that the bid activation factor has a consistent positive influence on economic performance. For almost all combinations of ORC capacity and thermal buffer size, increasing the activation factor from 10% to 30% and subsequently to 100% leads to a higher normalized total profit. This reflects the additional economic value obtained when a greater share of the available aFRR flexibility is activated.

The influence of ORC electrical capacity depends on the available thermal buffer capacity. At an 8 MWh buffer size, the difference between the 5 and 6 MW configurations is negligible, and the 5 MW configuration produces a slightly higher normalized profit at the 10% activation factor. However, for buffer capacities of 15 MWh and above, the 6 MW ORC consistently outperforms the 5 MW configuration. The economic advantage of the larger ORC also becomes more pronounced as the activation factor increases.

For the 5 MW ORC, increasing the thermal buffer capacity has only a limited influence on normalized profit. Across the analysed buffer sizes, the values remain approximately 1.54–1.56 at a 10% activation factor, 1.58–1.59 at 30%, and 1.60–1.61 at 100%. These small variations indicate that the available flexibility of the 5 MW con-

figuration is not strongly constrained by thermal storage capacity under the combined market strategy.

A clearer storage effect is observed for the 6 MW ORC. At a 10% activation factor, the normalized profit increases from approximately 1.54 with an 8 MWh buffer to approximately 1.57 for buffer capacities of 20 MWh and above. At a 30% activation factor, it rises from approximately 1.59 to 1.63, while at 100% it increases from approximately 1.61 to 1.65. The improvement is concentrated mainly between 8 and 25–30 MWh, after which the values remain nearly constant. This indicates diminishing economic returns from further increases in thermal buffer capacity.

The highest normalized total profit, approximately 1.65, is obtained for the 6 MW ORC with buffer capacities between 25 and 40 MWh at a 100% activation factor. The lowest value, approximately 1.54, occurs for several configurations at the 10% activation factor. The relatively narrow range of results at low activation shows that the benefit of increasing ORC and buffer capacity is limited when only a small proportion of aFRR bids is activated.

Overall, the results demonstrate that coordinated participation in the DA, aFRR, mFRR, and imbalance markets enables the ORC system to allocate its available flexibility more effectively and achieve higher economic returns than DA-only operation. The combined DA + aFRR + mFRR strategy particularly benefits from the interaction between a larger ORC capacity, sufficient thermal storage, and a high bid activation factor. Upward balancing services provide the largest direct contribution to activated energy and revenue, while mFRR-up represents the dominant source of reserved capacity. The sensitivity analysis further shows that increasing ORC electrical capacity has the strongest positive effect on profitability, whereas increasing the thermal buffer provides additional value mainly up to approximately 25–30 MWh, beyond which the incremental benefit becomes limited. These findings indicate that ORC capacity, thermal buffer size, and market participation strategy should be considered jointly when evaluating the economic performance of flexible multi-market operation.

1.4 Technical Fit Summary

The technical fit exercise assesses whether the Aperam ORC installation and associated thermal buffer can technically provide flexibility services and which market requirements would need to change for additional services to become viable. The assessment maps the characteristics of the installation—including controllability, ramping capability, activation duration, availability and operational constraints—against the technical requirements of relevant Belgian flexibility mechanisms. It evaluates technical feasibility only and does not assess economic attractiveness, contractual risk or implementation cost.

The flexible asset configuration consists of an ORC unit, which recovers heat to produce electricity, and a thermal storage system, which buffers pressurised hot water. The installation has a limited but fast flexibility range: it can adjust its electric output within less than one minute, while upward flexibility is constrained by the availability of stored or excess heat. Downward flexibility is less energy-constrained, provided that the

bypass valve and heat-rejection route are available. Participation in balancing services may require aggregation or deliberate pre-positioning of the ORC operating point to create sufficient reserve capacity.

Table 1.3 summarizes the qualitative technical fit of the Aperam ORC installation with the main Belgian flexibility mechanisms.

Market / product	Technical fit	Main qualitative rationale
FCR (primary reserve)	**Poor**	Strict activation-time and symmetric delivery requirements cannot be reliably guaranteed by the ORC configuration.
aFRR up (secondary reserve)	**Moderate**	Upward activation is technically feasible, but depends on available stored or excess heat and requires deliberate pre-positioning of the ORC operating point.
aFRR down (secondary reserve)	**Good**	The ORC can reduce output within the required activation time, provided that storage and heat-rejection capacity are available.
mFRR up (tertiary reserve)	**Moderate**	Upward activation can be delivered when thermal storage or excess process heat is available, but sustained delivery remains energy-constrained.
mFRR down (tertiary reserve)	**Good**	The installation can reduce output within the required activation time and can sustain downward flexibility when the heat-rejection route is available.
Day-ahead market	**Good**	Thermal buffering enables spot market price arbitrage by shifting electricity production towards higher-price periods.
Intraday market	**Good**	The ORC can adjust its production schedule closer to delivery when updated market prices justify operational changes.
Imbalance settlement	**Good**	Fast response enables opportunistic deviations from the scheduled production profile when the thermal state of the system allows it.
Congestion management (TSO redispatch)	**Poor**	The ORC is technically controllable, but current redispatch access is constrained by the market framework and the relevant grid context.
Capacity Remuneration Mechanism (CRM)	**Good**	The baseload-oriented operating profile and high availability support CRM participation, although any flexible component should be treated as energy-limited capacity.

Table 1.3: Qualitative technical-fit summary for the Aperam ORC installation across Belgian flexibility mechanisms.

The assessment shows that downward flexibility products are the strongest technical fit. Downward aFRR and downward mFRR are good fits because the ORC can reduce output within the required activation times and can sustain downward activation

when sufficient storage and heat-rejection capacity are available. Upward aFRR and upward mFRR are moderate fits: activation is technically feasible, but depends on the availability of thermal storage or excess process heat and may require the ORC to be scheduled at a lower set-point during the reservation period.

Spot-market participation and imbalance settlement are also good technical fits. The ORC and thermal buffer can be used for spot market price arbitrage by shifting electricity production towards higher-price periods and reducing production during lower-price periods. The fast response time also allows opportunistic deviations from the scheduled production profile in response to imbalance prices, provided that the thermal state of the system allows such deviations.

Frequency Containment Reserve (FCR) and TSO redispatch are weak fits under the assessed conditions. FCR is constrained by the strict activation time and symmetric delivery requirements, which the ORC cannot reliably guarantee. TSO redispatch is technically possible from an operational perspective, but the current redispatch framework remains difficult to access because of the applicable minimum asset-size threshold and the absence of significant congestion in the relevant grid area. The CRM is a good technical fit because the ORC operates close to baseload conditions with high availability, although any flexible component would need to be treated as energy-limited capacity.

Chapter 2

Aperam BUC 1B: Summary of Key Findings

2.1 Introduction

Aperam Stainless Steel Belgium is an energy-intensive steel producer with major operations at its Genk site, where recycled scrap metal is processed into stainless steel products. Its operations depend on significant electricity and heat consumption across steel refining, rolling, and finishing processes.

Within GALILEO, Aperam's focus is on identifying how decarbonization investments and industrial energy assets can also support flexibility provision. The company is exploring ways to reduce exposure to energy price volatility, improve the integration of renewable electricity, and assess whether flexible operation can strengthen the business case for lower-carbon production.

2.1.1 BUC 1B description

In the cold rolling mill, steam is required for several downstream processes, including dryers in the annealing and pickling lines. Much of this demand is supplied by two steam recuperation units that recover heat from furnace exhaust gases, but these units cannot cover the full steam requirement under all operating conditions. The remaining demand is currently met by aging gas-fired boilers, which Aperam expects to replace in the coming years.

The replacement decision presents an opportunity to transition from fossil-based steam production to electric boilers (referred to as e-boilers in the rest of the deliverable). Although the average steam demand is relatively modest, the existing boilers are deliberately oversized because the plant occasionally needs high steam capacity to heat cold installations after long shutdowns. Any new e-boiler configuration must therefore serve both routine process demand and these less frequent peak requirements.

For GALILEO, the central question is how an e-boiler system, potentially combined with thermal storage, can be sized and operated to provide useful demand-side flexibility. Rather than generating electricity, as in BUC 1A, this case uses steam production as a controllable electrical load. The e-boilers could increase, reduce, or shift electricity consumption while continuing to meet process needs, making them relevant for

day-ahead and intraday optimization, aFRR and mFRR participation, imbalance management, and congestion management. The work also considers whether the resulting flexibility revenues and energy cost reductions can strengthen the business case for electrifying steam production.

Research questions

The following research questions are investigated within the scope of this BUC analysis across the different project tasks:

1. What is the correlation between changes in technical specifications (e-boiler and thermal buffer) and the flexibility that can be provided?
   (a) What is the optimal size of the e-boiler?
   (b) What are the benefits and optimal size of the thermal buffer unit?
   (c) What is the potential value of flexibility in the day-ahead, aFRR, mFRR, imbalance settlement market for this use case?
2. Which flexibility services can be provided by the e-boilers? What are limitations keeping it from being a viable option? What market requirements must change (and to what extent) for it to be a viable option?
3. How can an industrial e-boiler be operated using flexible matching strategies to maximise self-consumption of renewable electricity from existing and planned power purchase agreements (PPAs) (4 MW wind and 16 MWp solar, with solar capacity doubling next year), and what is the resulting economic value?

Research Questions 1 and 3 are addressed in the following sections, while research question 2 is addressed in two parts: the technical suitability of the e-boilers to provide different flexibility mechanisms (technical fit) is addressed in this chapter, while the market design changes required to enable additional flexibility are discussed in Deliverable D3: Market Design to Support Industrial Competitiveness and Flexibility [1]

2.2 Flexibility potential assessment

The flexibility potential of the proposed energy systems is assessed using a common modelling framework consisting of two interconnected models: a process model and a market model. This framework is applied to the e-boiler with a thermal storage system.

The process model provides a digital representation of the physical energy system and determines its optimal operation under representative industrial operating conditions. The model captures the interaction between the main energy conversion technologies, thermal energy storage, and the associated heat and electricity flows. The resulting operational dispatch profiles describe the technical behaviour of the system while respecting process constraints.

The operational profiles generated by the process model are subsequently transferred to the market model, which evaluates the economic performance of the system

under electricity market conditions. The market model optimizes the scheduling of electricity consumption according to market prices and quantifies the economic value of the operational flexibility provided by the system. The following sections describe the process model developed for this use case before presenting the corresponding market assessment.

2.2.1 Process Model

The process model represents the operation of an electric boiler with thermal energy storage. The objective is to enable flexible electricity consumption while maintaining continuous heat supply to the industrial process. The model captures the interaction between industrial heat demand, waste heat recuperation, electric boiler operation, and thermal storage under representative operating conditions.

The proposed system consists of three principal elements: the existing heat supply through waste heat recuperation, an electric boiler for flexible heat generation, and a thermal buffer that decouples heat production from heat demand, as illustrated in Figure 2.1. The modelling approach focuses on the operational coordination between these components rather than detailed modelling of individual industrial processes.

The assessment follows the same workflow as described in Section 2.2, with the process model determining the optimal operation of the electric boiler and thermal storage system based on heat demand and heat recuperation profiles. The resulting operational profiles are subsequently used as inputs to the market model.

2.2.2 Market model

The market model determines the optimal bidding and operating strategy for the e-boiler by maximising the economic value of electricity market participation while respecting all technical and operational constraints of the integrated energy system. The e-boiler is represented as a flexible electrical load whose consumption can be increased, reduced, or shifted over time according to the thermal requirements of the process and the operating limits of the system. The model jointly optimises electricity consumption in the DA market, participation in aFRR and mFRR, and imbalance settlement. Upward flexibility is provided by reducing electricity consumption relative to the scheduled baseline, whereas downward flexibility is provided by increasing consumption. The available flexibility is dynamically allocated among the enabled market segments to maximise total economic value while maintaining the feasibility of the thermal process and respecting all previously established market commitments.

The model therefore quantifies the load flexibility available to each market, evaluates the associated revenues and electricity procurement costs, and assesses the value of revenue stacking across the DA, balancing, and imbalance markets. These results provide the basis for the techno-economic assessment and business case evaluation of flexible e-boiler operation. Figure 2.2 illustrates the interactions between the market inputs, process model, and market model.

The simulations were performed using historical Belgian electricity market data for the 2025 calendar year with a temporal resolution of 15 minutes [2, 3, 4, 5, 6]. A perfect foresight assumption is applied, meaning that market prices and balancing activation

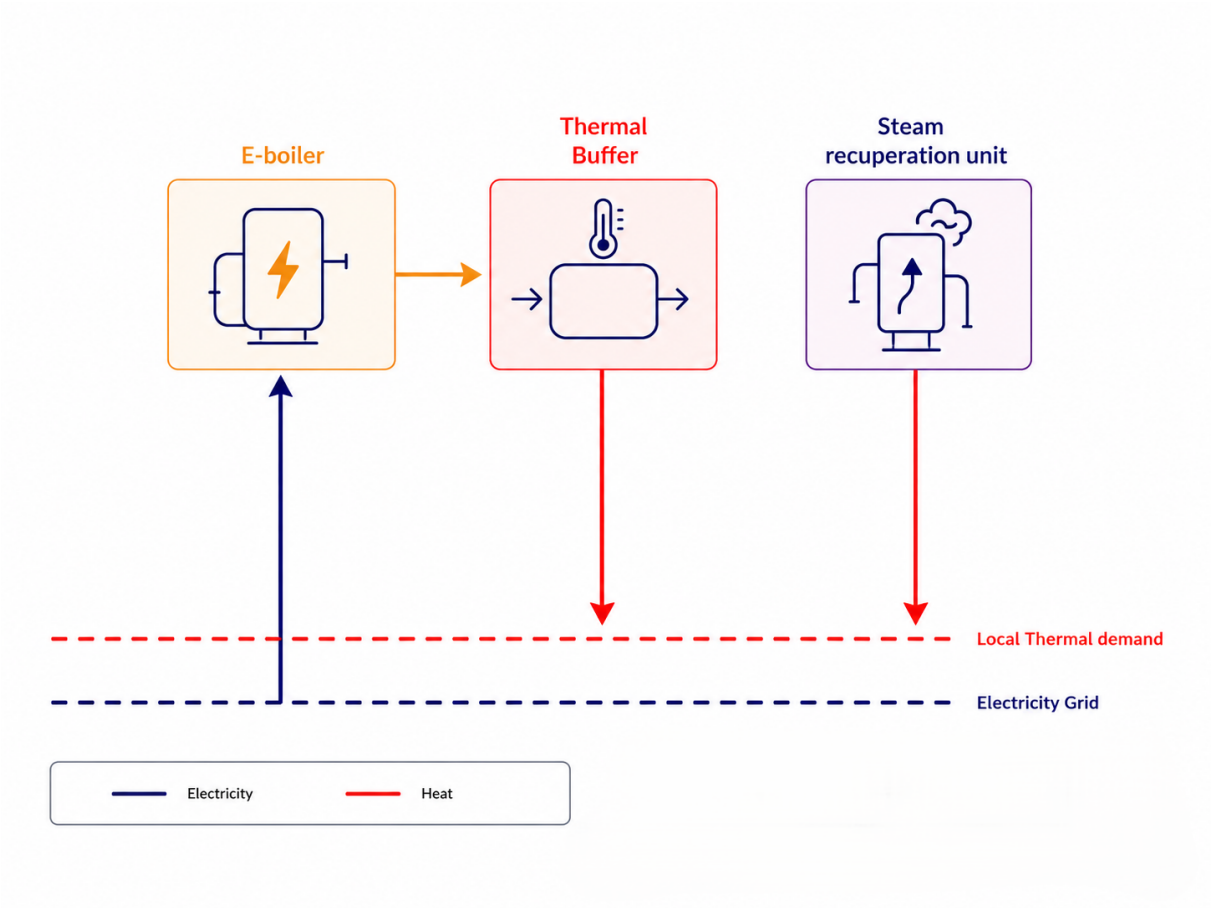


Figure 2.1: Schematic overview of heat demand coverage through heat recuperation, electric boiler operation, and thermal buffer integration for flexible heat supply.

requests are considered known in advance. Historical balancing activation volumes are used to determine when and to what extent the reserved flexibility is activated. Additional sensitivity scenarios vary the activation factor to represent future market conditions with increased competition among flexibility providers.

2.3 Results

2.3.1 Process Model Results

As shown in Figure 2.3, electric boiler operation is coordinated with thermal storage behaviour and electricity price variations. Thermal storage increases operational flexibility by enabling a temporal decoupling between electricity consumption and industrial heat demand. Consequently, electricity consumption can be shifted towards periods with lower electricity prices while maintaining uninterrupted heat supply.

This price-driven operating strategy is consistently observed throughout the analysed dispatch periods and demonstrates the ability of the integrated system to provide demand-side flexibility without compromising process heat requirements. The resulting operational profiles form the basis for the subsequent market assessment.

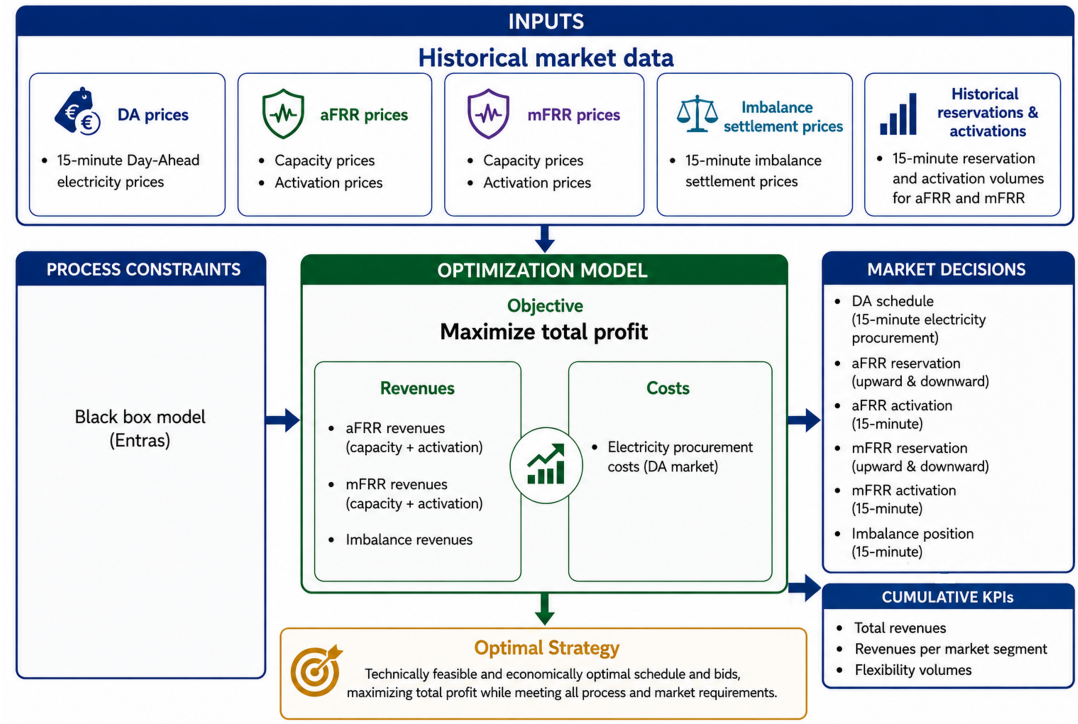


Figure 2.2: VITO's market optimization and flexibility valuation model (referred to as Market Model for short) used for e-boiler and thermal buffer flexibility potential assessment.

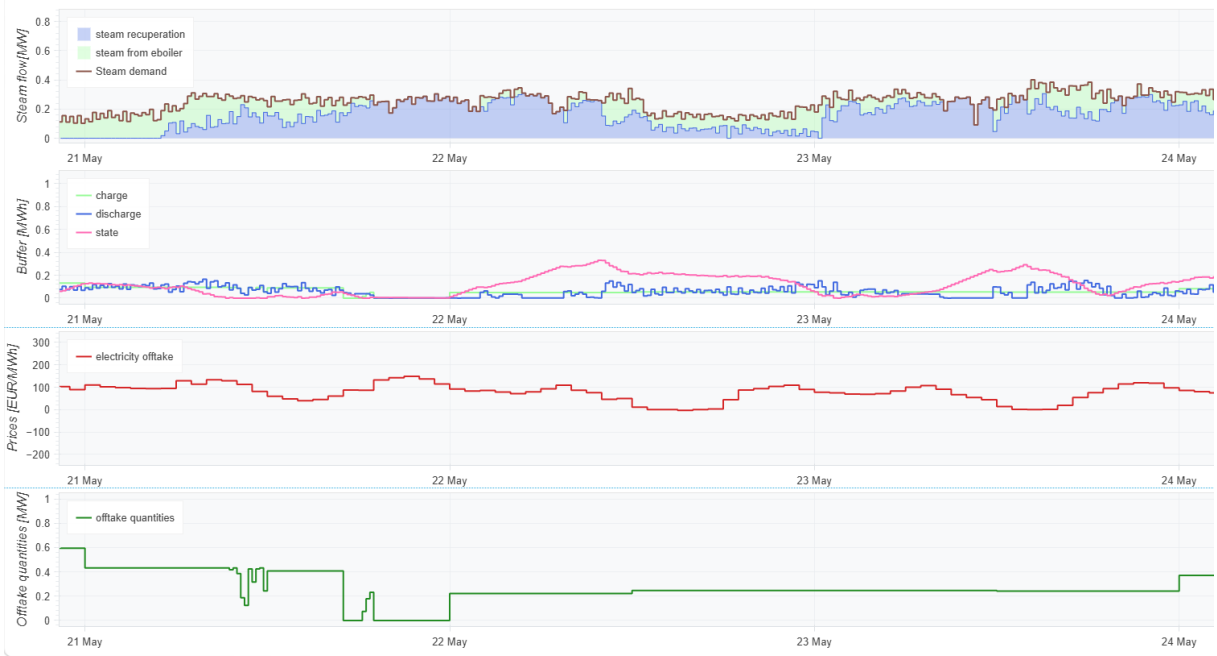


Figure 2.3: Dispatch schedule of the integrated e-boiler–thermal buffer system over a representative 72-hour period. Process variables are presented in normalized form.

2.3.2 Market Model Results

Scenario Design and Technical Configurations

A scenario-based framework is used to evaluate how the technical design of the e-boiler and thermal buffer affects operational flexibility and electricity market participation. Six e-boiler capacities between 10 and 20 MW are considered in steps of 2 MW, together with five thermal buffer capacities between 20 and 40 MWh in steps of 5 MWh. This results in a total of 30 sizing scenarios. The e-boiler is assumed to operate continuously between 0 MW and its rated electrical capacity, with no minimum operating power. Increasing the e-boiler capacity increases the maximum electrical flexibility that can be offered to the electricity markets, whereas increasing the thermal buffer capacity extends the duration for which this flexibility can be sustained. The complete set of sizing scenarios is presented in Table 2.1.

The selected scenarios enable the relationship between e-boiler size, thermal storage capacity, and electricity-market flexibility to be assessed systematically. The analysis quantifies the upward and downward flexibility available for each technical configuration while ensuring that the industrial heat demand is continuously satisfied.

The e-boiler is represented as a controllable electrical load that converts electricity into useful heat. The market model determines the optimal DA electricity-consumption schedule and allocates the available load flexibility across aFRR, mFRR, and the imbalance market. Upward flexibility is provided by reducing electricity consumption relative to the DA schedule, with the thermal buffer supplying the required heat during the activation period. Downward flexibility is provided by increasing electricity consumption and storing the additional thermal energy for later use.

Nine market participation configurations are considered. These range from DA-only operation to coordinated participation in the DA, aFRR, mFRR, and imbalance markets. For each configuration, only the corresponding market segments are enabled, and the market model determines the optimal operating and bidding strategy for the selected combination. Strategies involving aFRR are evaluated for bid activation factors of 10%, 30%, and 100%.

The market model ensures that commitments made at each market stage are respected and prevents the same physical flexibility from being allocated simultaneously to multiple markets. Any flexibility remaining after the DA and balancing-market commitments have been satisfied may be allocated to the imbalance market when this provides additional economic value. The simulation results are analysed from three complementary perspectives. First, the influence of thermal buffer capacity is evaluated at a fixed e-boiler capacity. Second, the influence of e-boiler capacity is evaluated at a fixed thermal buffer size. Third, the combined influence of e-boiler capacity, thermal buffer capacity, market strategy, and aFRR activation factor is assessed.

Table 2.2 presents the scenarios used to isolate the effect of thermal buffer capacity. The e-boiler capacity is fixed at 20 MW, while the thermal buffer is increased from 20 to 40 MWh. Table 2.3 presents the scenarios used to isolate the effect of e-boiler capacity. The thermal buffer capacity is fixed at 30 MWh, while the e-boiler capacity is increased from 10 to 20 MW.

The interpretation of the analysed market participation strategies is summarised in Table 2.4. Starting from the reference operation and DA participation, balancing ser-

Scenario	e-boiler capacity (MW)	Thermal buffer capacity (MWh)
Flex1	10	20
Flex2	12	20
Flex3	14	20
Flex4	16	20
Flex5	18	20
Flex6	20	20
Flex7	10	25
Flex8	12	25
Flex9	14	25
Flex10	16	25
Flex11	18	25
Flex12	20	25
Flex13	10	30
Flex14	12	30
Flex15	14	30
Flex16	16	30
Flex17	18	30
Flex18	20	30
Flex19	10	35
Flex20	12	35
Flex21	14	35
Flex22	16	35
Flex23	18	35
Flex24	20	35
Flex25	10	40
Flex26	12	40
Flex27	14	40
Flex28	16	40
Flex29	18	40
Flex30	20	40

Table 2.1: e-boiler and thermal buffer sizing scenarios considered in the analysis.

Scenario	e-boiler capacity (MW)	Thermal buffer capacity (MWh)
Flex6	20	20
Flex12	20	25
Flex18	20	30
Flex24	20	35
Flex30	20	40

Table 2.2: Scenario comparison for evaluating the impact of thermal buffer capacity at a fixed e-boiler capacity.

vices are progressively introduced through aFRR and mFRR, followed by participation

Scenario	e-boiler capacity (MW)	Thermal buffer capacity (MWh)
Flex13	10	30
Flex14	12	30
Flex15	14	30
Flex16	16	30
Flex17	18	30
Flex18	20	30

Table 2.3: Scenario comparison for evaluating the impact of e-boiler capacity at a fixed thermal buffer capacity.

in the imbalance market. This stepwise structure enables the incremental economic contribution of each market segment to be quantified while accounting for the operational constraints of the e-boiler and thermal buffer.

Strategy	**Interpretation**
Reference	Baseline operation according to a predefined e-boiler consumption schedule, without optimised electricity-market participation.
DA	Electricity consumption is scheduled in the DA market to minimise procurement costs while satisfying the e-boiler, thermal-buffer, and industrial heat-demand constraints.
DA + aFRR-up	The e-boiler provides upward aFRR by reducing electricity consumption relative to the DA schedule when activated.
DA + aFRR-down	The e-boiler provides downward aFRR by increasing electricity consumption relative to the DA schedule when activated.
DA + aFRR	Both upward and downward aFRR services are included in the optimisation.
DA + mFRR-up	The e-boiler provides upward mFRR by reducing electricity consumption relative to the DA schedule when activated.
DA + mFRR-down	The e-boiler provides downward mFRR by increasing electricity consumption relative to the DA schedule when activated.
DA + mFRR	Both upward and downward mFRR services are included in the optimisation.
DA + aFRR + mFRR	Available flexibility is allocated among the DA, aFRR, and mFRR markets while satisfying the e-boiler, thermal-buffer, and industrial heat-demand constraints.
DA + aFRR + mFRR + Imbalance	Any flexibility remaining after DA and balancing commitments may be allocated to the imbalance market.

Table 2.4: Market participation strategies considered in the analysis.

Overall, the evaluation framework considers all combinations of e-boiler capacity, thermal buffer size, market participation strategy, and aFRR activation factor. This enables the individual and combined effects of equipment sizing, thermal storage, and coordinated market participation on flexibility provision and economic performance to be quantified systematically. Unless stated otherwise, the results correspond to scenario, comprising a 14 MW e-boiler and a 20 MWh thermal buffer, with an aFRR bid

activation factor of 30%.

Market revenue and revenue stacking

Figure 2.4 compares the normalized annual market revenues and total profits obtained for the different e-boiler market participation strategies, using the absolute value of the reference-case result as the normalization basis. The stacked bars show the contribution of each electricity market segment to the normalized economic result, while the line represents the corresponding normalized total profit. The reference case represents the existing e-boiler operating strategy without market-based scheduling, in which electricity consumption follows the predefined operating schedule and the associated electricity cost is calculated using historical DA prices over the considered simulation horizon.

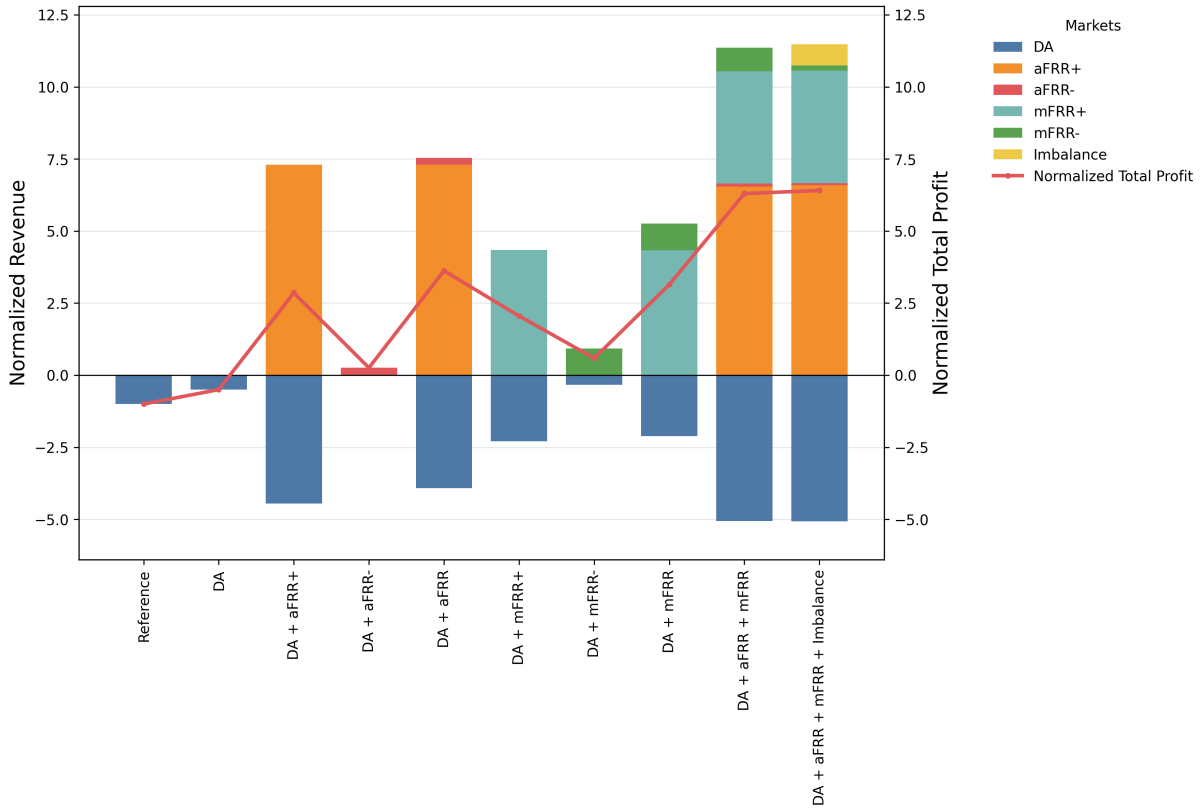


Figure 2.4: Comparison of normalized annual market revenues and total profit for different e-boiler market participation strategies.

The reference and DA-only strategies both result in negative normalized economic values because DA electricity procurement represents a cost for the e-boiler. Optimising the DA consumption schedule reduces this cost relative to the reference operation, increasing the normalized total profit from approximately -1.0 in the reference case to around -0.5 for the DA-only strategy. Nevertheless, DA-only participation remains economically less attractive than strategies that additionally provide balancing services. Participation in aFRR-up produces a substantial improvement in economic performance. Under the DA + aFRR-up strategy, the positive aFRR-up revenue more than compensates for the DA electricity cost, resulting in a normalized total profit of

approximately 2.9. In contrast, the DA + aFRR-down strategy provides only a small positive total profit of approximately 0.2. Although aFRR-down generates additional revenue, the associated increase in electricity consumption limits the overall economic benefit.

When both upward and downward aFRR participation are enabled, the normalized total profit increases to approximately 3.6. The result is dominated by the aFRR-up contribution, while aFRR-down provides a smaller additional revenue stream. Coordinated participation in both directions therefore improves the use of the available e-boiler flexibility compared with participation in either aFRR product alone. A similar pattern is observed for mFRR participation. The DA + mFRR-up strategy achieves a normalized total profit of approximately 2.0, whereas the DA + mFRR-down strategy results in a lower value of approximately 0.6. When both mFRR directions are enabled, the normalized total profit increases to approximately 3.2. The combined strategy benefits from a large mFRR-up contribution together with an additional, but smaller, mFRR-down contribution.

The highest economic performance is obtained through coordinated participation in multiple markets. The DA + aFRR + mFRR strategy achieves a normalized total profit of approximately 6.3. In this configuration, the DA electricity procurement cost is offset by substantial revenues from aFRR-up and mFRR-up, together with an additional contribution from mFRR-down. This result demonstrates the value of dynamically allocating the available load flexibility across several balancing products.

Adding imbalance-market participation produces the highest normalized total profit, approximately 6.4. The imbalance-market contribution provides a further increase in economic value, although the improvement relative to the DA + aFRR + mFRR strategy is comparatively modest. This indicates that most of the available flexibility value is already captured through coordinated participation in the DA, aFRR, and mFRR markets, while the imbalance market monetises part of the remaining flexibility.

Overall, the results demonstrate that DA electricity procurement remains the principal cost component for the e-boiler, while balancing-market participation creates substantial additional value. Upward balancing services are generally more profitable than downward balancing services because they allow the e-boiler to reduce electricity consumption relative to its DA schedule. The greatest economic benefit is achieved when upward and downward flexibility are jointly allocated across aFRR and mFRR, followed by the use of residual flexibility in the imbalance market.

Annual flexibility potential

This section compares the normalized annual balancing and imbalance energy activated and the normalized reserve capacity contracted over the one-year simulation horizon. The results show how the available e-boiler flexibility is allocated among the DA, aFRR, mFRR, and imbalance markets under the different market combinations. Figure 2.5 presents the normalized annual activated balancing and imbalance energy and illustrates how the market model distributes the available load flexibility among the enabled services.

No balancing energy is activated under the DA-only strategy. For the individual aFRR strategies, the DA + aFRR-up configuration reaches a normalized upward acti-

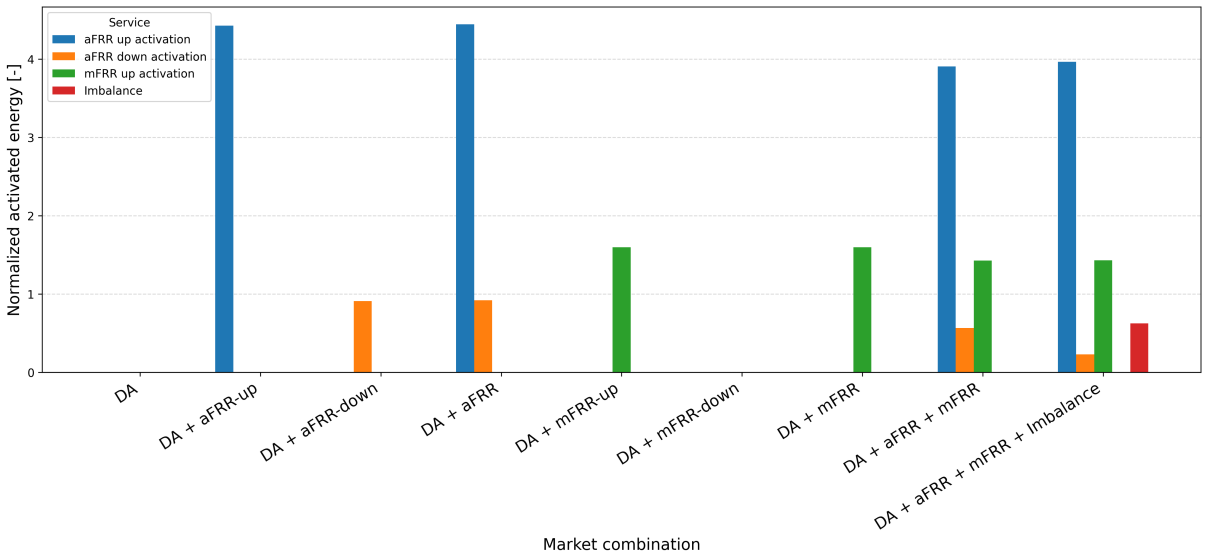


Figure 2.5: Normalized annual activated balancing and imbalance energy for the different electricity market participation strategies for the e-boiler.

vation of approximately 4.4, whereas the DA + aFRR-down strategy results in a normalized downward activation of approximately 0.9. When both directions are enabled, the DA + aFRR strategy provides approximately 4.4 of upward activation and 0.9 of downward activation. This indicates that enabling downward aFRR participation does not substantially reduce the upward aFRR activation.

For the individual mFRR strategies, the DA + mFRR-up configuration produces a normalized upward activation of approximately 1.6. No visible activation is observed for the DA + mFRR-down strategy. Similarly, the DA + mFRR strategy allocates activated energy almost entirely to mFRR-up, with a normalized value of approximately 1.6. Under the considered market conditions, the available mFRR opportunities are therefore concentrated in the upward direction. When aFRR and mFRR are enabled simultaneously, the available flexibility is distributed among several services. Under the DA + aFRR + mFRR strategy, the normalized activated energy is approximately 3.9 for aFRR-up, 0.6 for aFRR-down, and 1.4 for mFRR-up. Compared with the individual aFRR strategies, part of the available flexibility is reallocated from aFRR to mFRR-up.

With imbalance-market participation, the normalized activated energy is approximately 4.0 for aFRR-up, 0.2 for aFRR-down, 1.4 for mFRR-up, and 0.6 for the imbalance market. The imbalance contribution shows that part of the residual flexibility is allocated to this market after the DA and balancing-market commitments have been satisfied. At the same time, substantial participation in aFRR-up and mFRR-up is maintained.

Overall, the activated-energy results show that the e-boiler provides most of its balancing flexibility in the upward direction by reducing electricity consumption relative to the DA schedule. aFRR-up represents the largest activated component across the relevant strategies, while mFRR participation is also concentrated in the upward direction. The imbalance market provides an additional opportunity to utilise flexibility remaining after the balancing commitments have been established.

Figure 2.6 presents the normalized annual reserve capacity contracted in the balancing markets. In contrast to Figure 2.5, which shows the balancing and imbalance

energy activated, this figure represents the load flexibility committed in advance as reserve capacity.

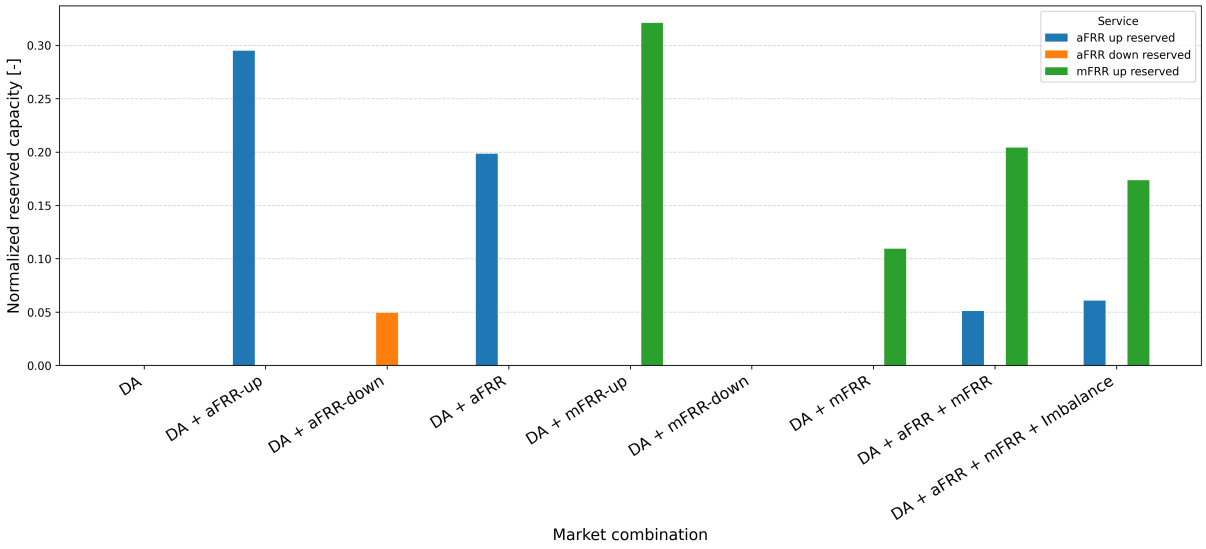


Figure 2.6: Normalized annual reserved balancing capacity for the different electricity market participation strategies for the e-boiler.

No reserve capacity is contracted under the DA-only strategy. For the individual aFRR configurations, the DA + aFRR-up strategy reserves approximately 0.30 of upward capacity, while the DA + aFRR-down strategy reserves approximately 0.05 of downward capacity. When both aFRR directions are enabled, the DA + aFRR strategy reserves approximately 0.20 of upward aFRR capacity, while the reserved downward capacity is negligible. For mFRR participation, the DA + mFRR-up strategy results in the highest normalized reserved capacity, approximately 0.32. When both mFRR directions are enabled, approximately 0.11 of upward mFRR capacity is reserved. No downward mFRR reserve capacity is observed.

Under the DA + aFRR + mFRR strategy, the normalized reserved capacities are approximately 0.05 for aFRR-up and 0.20 for mFRR-up. The reduction in the reserved capacity of the individual services relative to the single-market strategies reflects competition among the enabled balancing products for the same physical load flexibility. Adding imbalance-market participation produces a similar allocation, with approximately 0.06 of aFRR-up capacity and 0.17 of mFRR-up capacity reserved. This indicates that imbalance-market participation has only a limited influence on reserve-capacity commitments and primarily affects the use of flexibility remaining after the balancing-market positions have been established.

Overall, the reserve-capacity results show that the market model selectively commits e-boiler flexibility to the products providing the highest expected economic value. Upward mFRR is the dominant reserved service in the individual balancing strategies, while aFRR-up also represents a substantial reserve-capacity opportunity. In the combined strategies, the available load flexibility is shared between aFRR-up and mFRR-up, whereas downward reserve commitments remain limited.

Impact of thermal buffer capacity and aFRR activation factors

Figure 2.7 compares the normalized total annual revenue obtained for different thermal buffer capacities while maintaining a fixed e-boiler electrical capacity of 20 MW. The analysis considers thermal buffer capacities ranging from 20 to 40 MWh and bid activation factors of 10%, 30%, and 100%. All values are normalized relative to the absolute DA result of the reference case with a 20 MWh thermal buffer.

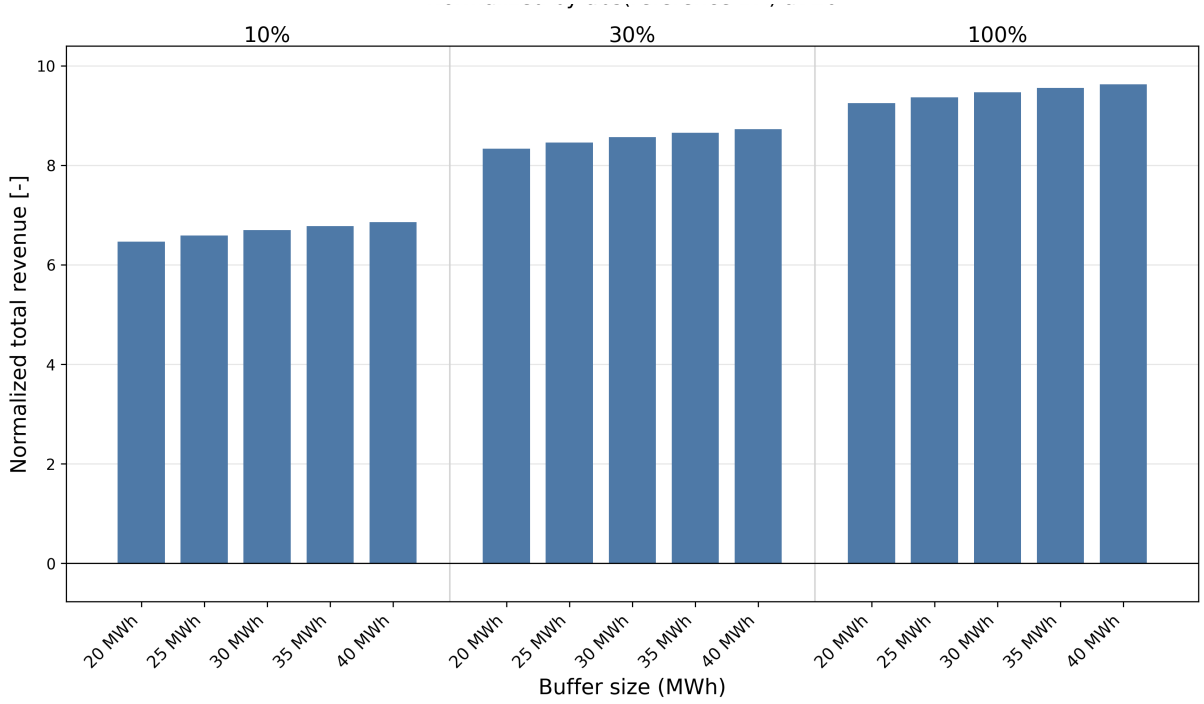


Figure 2.7: Variation of normalized total annual revenue with thermal buffer capacity for a fixed e-boiler electrical capacity of 20 MW and different bid activation factors.

The results show that the normalized total annual revenue increases with both the bid activation factor and the thermal buffer capacity. For a 20 MWh buffer, the normalized revenue rises from approximately 6.45 at a 10% activation factor to around 8.30 at 30% and 9.25 at 100%. A similar trend is observed for all buffer sizes, indicating that higher activation levels substantially increase the economic value captured through balancing-market participation. For each activation factor, increasing the thermal buffer capacity produces a gradual improvement in normalized revenue. At a 10% activation factor, the revenue increases from approximately 6.45 for a 20 MWh buffer to about 6.85 for a 40 MWh buffer. At 30%, the corresponding increase is from approximately 8.30 to 8.75, while at 100% the revenue rises from about 9.25 to 9.60.

The revenue gains associated with increasing the thermal buffer are relatively steady across the analysed range, although the incremental improvement becomes slightly smaller at the highest capacities. This indicates that additional thermal storage continues to create value by allowing the e-boiler to shift electricity consumption and heat production across time, but the marginal benefit gradually decreases as the buffer becomes larger.

The bid activation factor has a stronger influence on normalized revenue than the

thermal buffer size. Increasing the activation factor from 10% to 30% produces a substantial improvement for every buffer configuration, while the additional increase from 30% to 100% is smaller but still significant. This shows that the economic value of the e-boiler depends strongly on how much of the reserved flexibility is actually activated.

The 40 MWh buffer achieves the highest normalized revenue for all three activation factors, reaching approximately 9.60 at a 100% activation factor. However, its advantage over the 35 MWh configuration is limited. Overall, the results demonstrate that increasing the thermal buffer capacity improves the economic performance of the e-boiler by enabling more effective temporal shifting of electricity consumption and thermal energy. Nevertheless, the progressively smaller gains at higher buffer capacities indicate diminishing economic returns from further storage expansion.

Impact of e-boiler electrical capacity and aFRR activation factors

Figure 2.8 evaluates the influence of e-boiler electrical capacity on normalized total annual revenue at a fixed thermal buffer capacity of 20 MWh. The analysis considers e-boiler capacities ranging from 10 to 20 MW and bid activation factors of 10%, 30%, and 100%. All revenues are normalized relative to the absolute DA result of the 10 MW reference configuration.

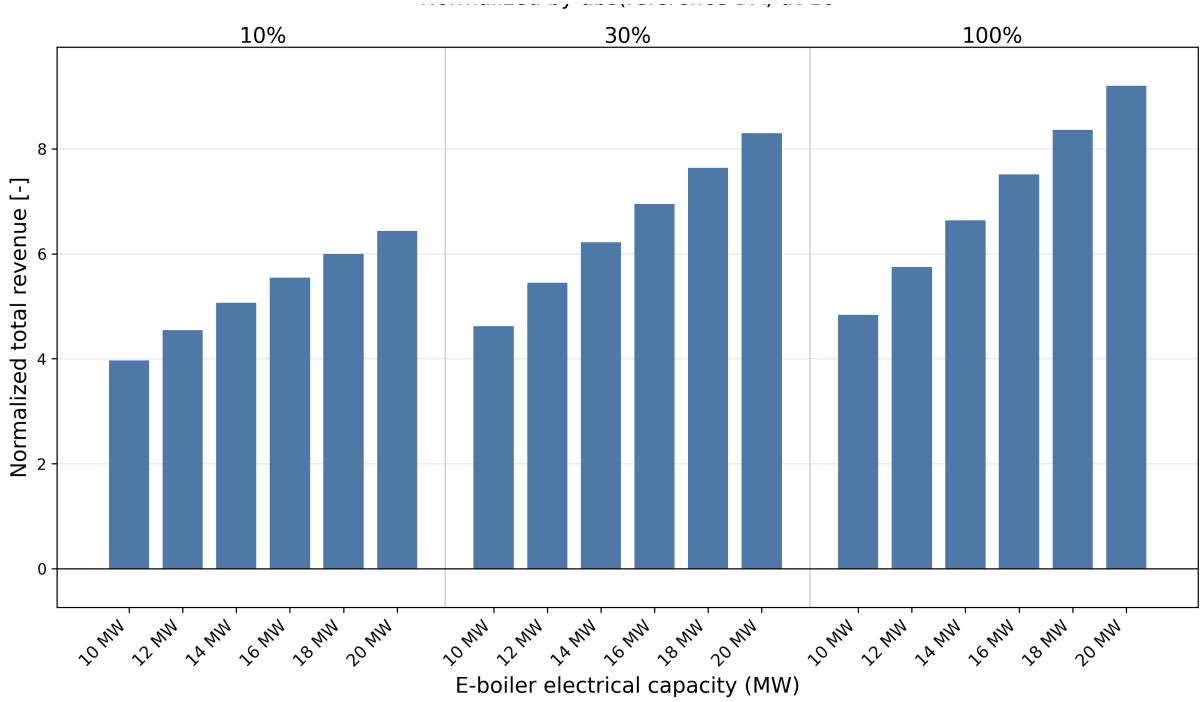


Figure 2.8: Variation of normalized total annual revenue for different e-boiler electrical capacities at a fixed thermal buffer capacity and different bid activation factors.

The results show a clear and consistent increase in normalized total annual revenue as the e-boiler electrical capacity increases. At a 10% activation factor, the normalized revenue rises from approximately 4.0 for the 10 MW configuration to around 6.4 for the 20 MW configuration. At 30%, the corresponding values increase from approximately 4.6 to 8.3, while at 100% the revenue rises from about 4.8 to 9.2.

The influence of e-boiler capacity is substantial across all activation factors. Increasing the electrical capacity from 10 to 20 MW raises normalized revenue by approximately 60% at a 10% activation factor, 80% at 30%, and more than 90% at 100%, relative to the corresponding 10 MW configurations. This indicates that the economic value of additional e-boiler capacity becomes more pronounced as balancing-market activation increases.

For every e-boiler size, increasing the activation factor also improves economic performance. However, the revenue increase associated with larger e-boiler capacity is greater than the increase obtained solely by raising the activation factor. This shows that installed electrical capacity is the dominant design parameter in this comparison, while the activation factor determines how effectively the available flexibility is monetized. The larger e-boiler configurations allow the market model to shift a greater amount of electricity consumption and thermal production across time. This increases the flexibility available for DA scheduling and balancing-market participation while maintaining the industrial heat demand through coordinated operation with the thermal buffer.

Overall, the results identify e-boiler electrical capacity as a key determinant of economic performance at the fixed 30 MWh buffer size. Higher activation factors provide an additional revenue increase for all configurations, but the largest benefits are obtained by combining a larger e-boiler with a high activation factor. The 20 MW configuration therefore achieves the highest normalized revenue under all analysed market conditions.

Economic performance of the e-boiler and thermal buffer configurations

Figure 2.9 presents the sensitivity of the normalized total annual profit for the combined DA + aFRR + mFRR market participation strategy to the e-boiler electrical capacity, thermal buffer size, and bid activation factor. The three heatmaps correspond to activation factors of 10%, 30%, and 100%. For each activation factor, the normalized total profit is evaluated for e-boiler capacities ranging from 10 to 20 MW and thermal buffer capacities ranging from 20 to 40 MWh.

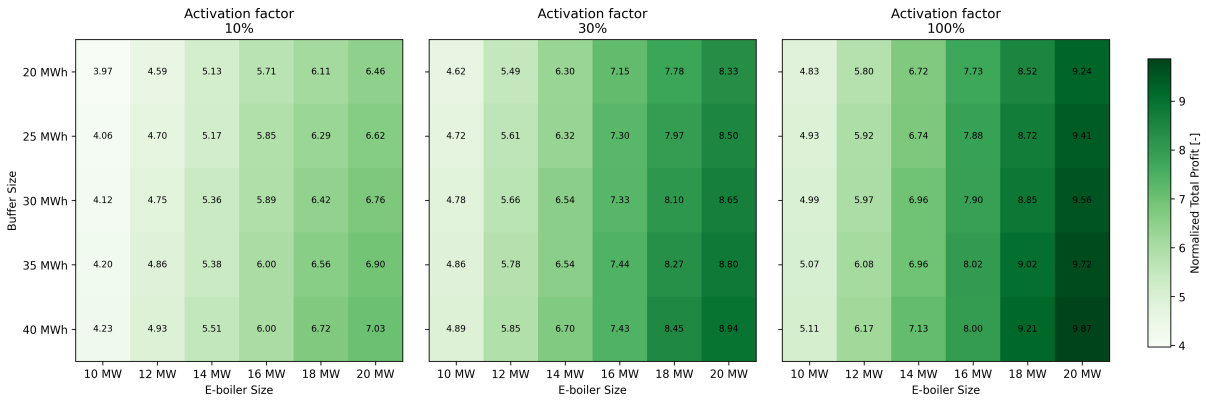


Figure 2.9: Sensitivity of the normalized total annual profit to e-boiler capacity, thermal buffer size, and bid activation factor for the DA + aFRR + mFRR market participation strategy.

The results show that the bid activation factor has a consistently positive influence on

economic performance across all e-boiler and thermal buffer configurations. Increasing the activation factor from 10% to 30% and subsequently to 100% results in progressively higher normalized total profits. This reflects the additional economic value obtained when a larger share of the available aFRR flexibility is activated.

The e-boiler electrical capacity has the strongest influence on normalized profit. For every thermal buffer size and activation factor, increasing the e-boiler capacity from 10 to 20 MW produces a substantial improvement in economic performance. At a thermal buffer capacity of 20 MWh, the normalized profit increases from approximately 3.97 to 6.46 at a 10% activation factor, from 4.62 to 8.33 at 30%, and from 4.83 to 9.24 at 100%. The economic advantage of increasing the e-boiler capacity therefore becomes more pronounced as the activation factor rises.

Increasing the thermal buffer capacity also improves normalized profit, although its influence is smaller than that of the e-boiler capacity. For the 10 MW e-boiler, increasing the buffer from 20 to 40 MWh raises the normalized profit from approximately 3.97 to 4.23 at a 10% activation factor, from 4.62 to 4.89 at 30%, and from 4.83 to 5.11 at 100%. For the 20 MW e-boiler, the corresponding values increase from approximately 6.46 to 7.03, from 8.33 to 8.94, and from 9.24 to 9.87, respectively. The results indicate that the value of additional thermal storage increases with e-boiler capacity. Larger e-boilers can shift a greater amount of electricity consumption and thermal production across time, allowing the additional buffer capacity to be used more effectively. Nevertheless, the profit increase associated with expanding the thermal buffer remains moderate compared with the effect of increasing the e-boiler electrical capacity.

The highest normalized total profit, approximately 9.87, is obtained for the configuration combining a 20 MW e-boiler, a 40 MWh thermal buffer, and a 100% activation factor. The lowest normalized profit, approximately 3.97, occurs for the 10 MW e-boiler with a 20 MWh thermal buffer at a 10% activation factor. The wide difference between these configurations demonstrates the combined importance of equipment sizing and balancing-market activation.

Overall, the sensitivity results show that the economic performance of the DA + aFRR + mFRR strategy benefits from the interaction between a larger e-boiler capacity, greater thermal storage, and a higher bid activation factor. Increasing the e-boiler capacity provides the largest improvement in profitability, while a larger thermal buffer provides an additional benefit by extending the duration and operational availability of load flexibility. These findings indicate that e-boiler capacity and thermal buffer size should be evaluated jointly when assessing the economic performance of coordinated multi-market participation.

2.4 Technical Fit Summary

The technical fit exercise assessed whether the Aperam e-boiler installation and associated thermal buffer can technically provide flexibility services and which market requirements would need to change for additional services to become viable. The assessment maps the characteristics of the installation—including controllability, ramping capability, activation duration, availability and operational constraints—against the technical requirements of relevant Belgian flexibility mechanisms. It evaluates technical feasibility

only and does not assess economic attractiveness, contractual risk or implementation cost.

The flexible asset configuration consists of an electric boiler, a thermal storage system and PV generation. The e-boiler provides a fast and controllable source of electrical flexibility by increasing or reducing electricity consumption while maintaining steam supply through the thermal buffer. Upward flexibility is delivered by reducing e-boiler consumption and using stored thermal energy to bridge steam demand, while downward flexibility is delivered by increasing e-boiler consumption when sufficient operating margin and thermal storage capacity are available. The installation can respond quickly, but the direction and duration of flexibility depend on the state of charge of the thermal buffer and the operating point of the e-boiler.

Table 2.5 summarizes the qualitative technical fit of the Aperam e-boiler installation with the main Belgian flexibility mechanisms.

The assessment shows that upward balancing services are the strongest technical fit among the reserve products. Upward aFRR and upward mFRR are good fits because the e-boiler can reduce consumption within the required activation times and the thermal buffer can sustain the resulting steam supply for the relevant reservation period when it is pre-filled. Downward aFRR and downward mFRR are moderate fits: activation is technically feasible, but sufficient part-load operating margin must be available because the e-boiler may already be operating close to its maximum power level.

Spot-market participation and imbalance settlement are also good technical fits. The combination of fast e-boiler modulation and thermal storage enables spot market price arbitrage by shifting electricity consumption towards lower-price periods and reducing consumption during higher-price periods. The same operational flexibility can be used in the intraday market and imbalance settlement, where the installation can adjust its consumption in response to updated price signals, provided that the thermal buffer state allows the deviation.

FCR is only a moderate fit. The e-boiler can potentially meet the fast response requirement when operated in a suitable standby or part-load mode, but the strict activation requirement and the need to keep symmetric reserve available make participation more demanding. TSO redispatch is a poor fit under the current framework because access is constrained by the current redispatch design and local grid context, even though the installation is technically controllable. The CRM is a good technical fit because the e-boiler can provide demand-response capacity through downward modulation of consumption, although the resulting capacity would be subject to derating and depends on the available thermal buffer state.

2.5 Flexible operation of E-boiler to maximise PPA self consumption

This study investigated the potential of enhancing the renewable electricity self consumption of Aperam Genk through the integration of an E-boiler and a thermal buffer. The flexibility solution was evaluated on top of an expanded renewable PPA portfolio with dynamic electricity contracts.

Market / product	Technical fit	Main qualitative rationale
FCR (primary reserve)	Moderate	Fast activation may be achievable in a suitable standby or part-load mode, but the strict response requirement and symmetric reserve obligation make participation demanding.
aFRR up (secondary reserve)	Good	The e-boiler can reduce consumption within the required activation time, provided that the thermal buffer has been sufficiently pre-filled.
aFRR down (secondary reserve)	Moderate	Increasing consumption is technically feasible, but requires sufficient part-load operating margin and available thermal storage capacity.
mFRR up (tertiary reserve)	Good	The e-boiler can reduce consumption well within the required activation time and sustain delivery when sufficient thermal energy has been buffered beforehand.
mFRR down (tertiary reserve)	Moderate	Activation is technically straightforward, but sustained downward flexibility depends on available headroom and thermal-buffer conditions.
Day-ahead market	Good	Thermal storage enables spot market price arbitrage by shifting e-boiler consumption towards lower-price periods.
Intraday market	Good	Fast modulation and thermal buffering allow the installation to adjust consumption closer to delivery when updated market prices justify it.
Imbalance settlement	Good	The e-boiler can react rapidly to imbalance price signals, provided that the thermal state of the system allows the deviation.
Congestion management (TSO redispatch)	Poor	The installation is technically controllable, but current redispatch access is constrained by the market framework and local grid context.
Capacity Remuneration Mechanism (CRM)	Good	The e-boiler can provide demand-response capacity through consumption reduction, although the available capacity is subject to derating and thermal-buffer constraints.

Table 2.5: Qualitative technical-fit summary for the Aperam e-boiler installation across Belgian flexibility mechanisms.

First, the analysis demonstrates financial loss of uncontrolled renewable injection, both for current PPA capacity and the future expansion plan. In the market nowadays, renewable energy fed to the grid brings topically lower revenue than the costs of procuring them through PPA.

Second, the e-boiler can effectively utilize renewable electricity surplus that would otherwise be exported to the grid. By adopting a flexible control strategy of e-boiler operation, excess renewable electricity is converted into steam, the system increases renewable energy self-consumption while reducing dependence on natural gas for in-

dustrial heat production. The thermal storage buffer further enhances flexibility by allowing heat production to be shifted in time and supplied when required by the process. Additionally, with increasing number of negative prices in the electricity market, simply charging the E-boiler is the low hanging fruit for activating flexibility and generating revenues.

Simulation results for 2025 show that the e-boiler can consume 10.45 GWh of electricity. Renewable self-consumption increased by 2.57 GWh, while renewable electricity exports were reduced to only 0.28 GWh. The system delivered 10.05 GWh of process heat and reduced natural gas consumption, resulting in significant economic benefit per year. In addition to increasing renewable energy utilization, the control strategy successfully exploited periods of negative electricity prices, allowing the e-boiler to charge the thermal buffer at very low or even negative electricity costs. The combined flexibility of the e-boiler and thermal storage improved the economic performance of the renewable PPA portfolio and saving large amount of fossil energy procurement costs.

Overall, the results indicate that e-boiler integration represents a technically feasible and economically attractive flexibility option for Aperam. The solution supports its industrial decarbonization objectives, increases the capacity of renewable PPAs, reduces exposure to fossil fuel consumption, and provides a pathway for further electrification of industrial heat demand.

Chapter 3

Nyrstar BUC 2: Summary of Key Findings

3.1 Introduction

Nyrstar Belgium operates a major zinc smelting facility where electricity is central to the production process. The site's electrolysis halls use large rectified electrical currents to deposit zinc onto cathodes from a purified zinc sulphate solution. This makes electricity consumption both a major cost driver and a potential source of operational flexibility. Nyrstar already participates in electricity markets, including the DA and continuous intraday markets, and also provides mFRR services.

Within GALILEO, Nyrstar is focusing on whether its electrolysis process can be operated as a large-scale flexibility asset through its "Virtual Battery" concept. The work examines how electricity demand can be shifted while protecting production quality, process safety, and profitability.

3.2 BUC 2 description

The work in GALILEO investigates how Nyrstar can expand the flexibility of its zinc electrolysis process by increasing electrolyte buffer capacity. In normal operation, a purified zinc sulphate solution is fed into electrolysis cells, where zinc is then deposited onto cathodes. The remaining zinc-poor electrolyte is then returned to the leaching process, where it is regenerated before being reused. Because these process steps are connected by physical flows, flexibility depends on the ability to decouple the electrolytic reaction from the upstream and downstream sections of the plant.

Nyrstar's Virtual Battery concept does this by using large hybrid buffer tanks for purified solution and spent acid. These tanks allow the electrolysis process to temporarily increase or decrease electricity consumption while the wider production system continues operating within acceptable limits. In effect, the site stores production potential in process buffers rather than in an electrochemical battery. This makes the concept especially relevant for long-duration flexibility, since the planned buffer capacity could allow operation at maximum capacity for roughly 120 hours or at minimum capacity for roughly 70 hours.

This use case will explore how Nyrstar Belgium can enhance energy flexibility by optimizing its participation in various energy markets, including DAM, aFRR, and mFRR, through innovative bidding strategies. It will investigate the feasibility of using Nyrstar's Virtual Battery, which leverages two conversion processes (using electrolysis), to shift production and respond quickly to market imbalances without compromising process safety. Additionally, the research will focus on value stacking, determining how to dynamically allocate the total volume of flexibility across markets to maximize returns and understand the impact on cleared market prices.

Research questions

The following research questions are investigated within the scope of this BUC analysis across the different project tasks:

1. What quantities of aFRR and mFRR can be activated without reducing zinc production volumes or profitability, and do these impacts differ between the two services?
2. How can existing and future CRM impact the value of the flexibility?
3. What flexibility mechanisms can be provided with the virtual battery? What market requirements must change (and to what extent) for other services to be an option for the virtual battery?

Research Questions 1 and 2 are addressed in the following sections, while research question 3 is addressed in two parts: the technical suitability of the virtual battery to provide different flexibility mechanisms (technical fit) is addressed in this chapter, while the market design changes required to enable additional flexibility are discussed in Deliverable D3: Market Design to Support Industrial Competitiveness and Flexibility [1]

3.3 Flexibility potential assessment

3.3.1 Market model and simulation framework

The market model determines the optimal market participation strategy (i.e., bidding strategy) for the Nyrstar virtual battery by maximizing the economic value of its participation in electricity markets while respecting all technical and operational constraints imposed by the zinc production process. The model simultaneously schedules electricity procurement in the DA market and participation in the balancing markets, namely the aFRR and mFRR. By co-optimizing these market opportunities, the model quantifies the flexibility that can be offered to each balancing service, compares their technical and economic performance, and evaluates value stacking by dynamically allocating the available flexibility across the considered markets to maximize overall revenues. This process of optimal market participation then allows the estimation of the economic value that can be realized by the industrial process via participation in DA, mFRR, and aFRR

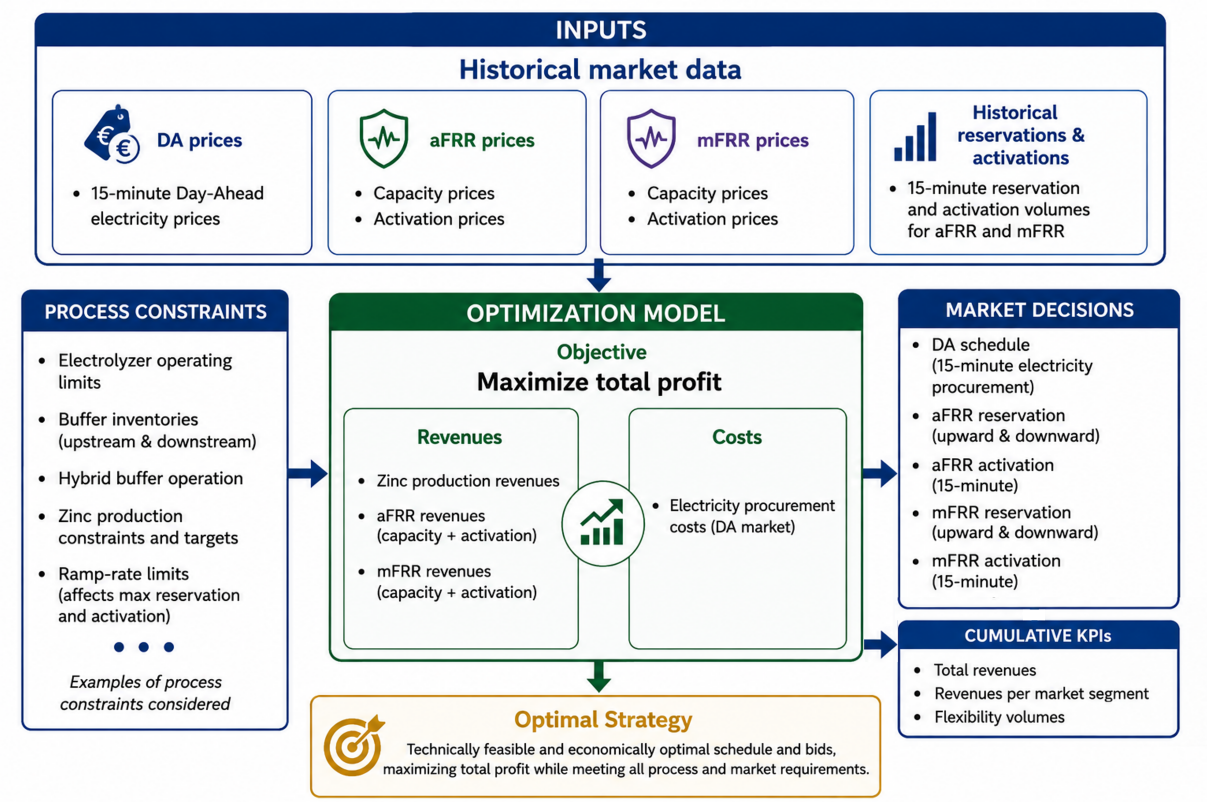


Figure 3.1: VITO's market optimization and flexibility valuation model (referred to as Market Model for short) used in the Nyrstar Use Case

markets, which can then feed into relevant business case calculations. Figure 3.1 provides an overview of the market model framework and the interactions between the market inputs, the process constraints, and the market model.

The simulations were performed using historical Belgian electricity market data for the 2024 calendar year with a temporal resolution of 15 minutes, matching the settlement period of the considered markets [2, 3, 4, 5, 6]. The model considers a setting of perfect foresight for the use case analysis and uses historical balancing activation volumes to determine when and how much reserved flexibility is activated. Under the perfect foresight assumption, all market prices and balancing needs are considered to be known in advance. Sensitivity scenarios were additionally evaluated in which the effective activation factor was reduced to represent future balancing markets with increased competition among flexibility providers. To reflect operational limitations, the number of balancing activations was limited to a maximum of 20 per day, as indicated by Nyrstar.

The electrolysis process was represented using the planned Virtual Battery configuration, allowing operation between the minimum stable load of 27.3 MW and the expanded maximum capacity of 151.1 MW. Throughout all simulations, the annual zinc production target was maintained, ensuring that any economic benefits resulted exclusively from shifting electricity consumption over time rather than changing total production.

3.3.2 Results

A total of twelve scenarios were evaluated to assess the technical feasibility and economic value of the Virtual Battery under different market participation strategies. The scenarios progressively investigate participation in individual balancing markets, combined participation through value stacking, and more conservative operating assumptions that account for reduced activation frequencies and practical operational constraints. This approach allows the assessment of both the technical flexibility potential and the corresponding economic performance of the Virtual Battery under representative Belgian market conditions. The complete set of scenarios is summarized in Table 5.1.

ID	Scenario	Description
S1	DA only	Baseline optimization considering only DA market participation.
S2	DA + aFRR$^+$	Participation in the DA market and upward aFRR.
S3	DA + aFRR$^-$	Participation in the DA market and downward aFRR.
S4	DA + aFRR	Participation in the DA market and both upward and downward aFRR.
S5	DA + mFRR$^+$	Participation in the DA market and upward mFRR.
S6	DA + mFRR$^-$	Participation in the DA market and downward mFRR.
S7	DA + mFRR	Participation in the DA market and both upward and downward mFRR.
S8	DA + aFRR + mFRR	Participation in (and optimized value stacking across) the DA, aFRR, and mFRR markets.
S9	DA + aFRR + mFRR (relaxed activation constraints)	Scenario in which the coupling constraints between contracted reserves and balancing activations are relaxed.
S10	DA + 1.0 mFRR + 0.3 aFRR	Value-stacking scenario with full mFRR activation needs and an aFRR activation factor of 0.3.
S11	DA + 1.0 mFRR + 0.3 aFRR (relaxed activation constraints)	Analysis combining an aFRR activation factor of 0.3 with relaxed activation constraints.
S12	DA + aFRR + mFRR (conservative high-risk flexibility)	Value-stacking scenario in which balancing activations are adjusted after the simulation.

Table 3.1: Simulation scenarios considered in BUC2 Nyrstar.

Market participation strategies

The DA only scenario serves as the reference case against which all other scenarios are compared. In this baseline configuration, the market model shifts electricity consumption from periods with high DA electricity prices to periods with lower DA prices while respecting all operational constraints and maintaining the annual zinc production target. The resulting operating strategy alternates predominantly between the minimum and maximum operating levels of the electrolysis process, with intermediate operating points occurring only during short transitions. The Virtual Battery therefore already

creates economic value through DA optimisation alone, demonstrating that increased process flexibility can reduce electricity costs without affecting industrial production.

Introducing participation in balancing markets fundamentally changes the optimal operating strategy. Rather than simply following DA price signals, the market model deliberately positions the electrolysis process to preserve upward and downward flexibility whenever reserve capacity or activation revenues are expected to outweigh the additional electricity procurement costs. Consequently, the optimal operating point is no longer determined solely by DA electricity prices, but by the combined value of all available market opportunities.

The simulations reveal clear differences between participation in aFRR and mFRR. Participation in aFRR leads the market model to select intermediate DA operating points more frequently, maintaining sufficient headroom to provide both upward and downward flexibility while remaining compatible with the production objectives. In contrast, participation in mFRR has a much smaller influence on the DA schedule because activations occur less frequently. As a result, the operating strategy remains closer to the DA only case, while still exploiting profitable balancing opportunities when activation requests occur.

The highest economic performance is obtained when the market model simultaneously considers all available markets. Under this value stacking strategy, the market model combines the bidding characteristics observed in the individual market scenarios and dynamically allocates the available flexibility to the market offering the highest expected value. Rather than prioritising a single balancing service, the result reflects a continuous trade-off between electricity procurement in DA, reserve provision and expected activation revenues, while maintaining sufficient operational flexibility for future activations and respecting all process constraints.

Annual flexibility provision

Figures 3.2 and 3.3 present the annual activated balancing energy and reserved capacity obtained under the different market scenarios. To facilitate comparison between scenarios, the results are normalised with respect to a reference scenario. Although the absolute values are omitted, the figures illustrate how the available process flexibility is allocated across the different balancing services under the evaluated market participation strategies.

Figure 3.3 shows clear differences in the reserve capacity allocated to the different balancing products. Capacity reservation remains negligible in the dedicated aFRR scenarios (S2–S4), confirming that the market model relies predominantly on free bids. This behaviour results from the combination of mandatory activation delivery during the reservation period and the assumed limit on the maximum number of daily activations, making aFRR capacity reservation economically unattractive. In contrast, upward mFRR capacity reservation becomes an important source of flexibility in the dedicated mFRR scenarios (S5 and S7). The lower expected activation frequency of mFRR allows reserve capacity to be offered while respecting the operational constraints of the zinc production process. As expected, no downward mFRR capacity is reserved in Scenario S6, reflecting the absence of capacity remuneration for this service in the considered market design.

The value stacking scenarios (S8–S12) further demonstrate how the market assumptions influence the allocation of reserve capacity. In Scenario S8, upward mFRR remains the dominant reserved product. Relaxing the coupling between reserve capacity reservation and mandatory activation in Scenario S9 substantially increases participation in the aFRR capacity market, whereas reducing the aFRR activation factor in Scenario S10 shifts the allocation back towards upward mFRR. When both assumptions are combined (Scenario S11), the market model simultaneously reserves substantial amounts of both aFRR and mFRR capacity, illustrating the strong influence of market design and activation assumptions on the allocation of industrial flexibility.

Figure 3.2 presents the annual activated balancing energy for the different scenarios. In the dedicated market participation scenarios, the activated energy follows the balancing service considered, with the dedicated upward mFRR scenarios exhibiting the largest activated energy volumes. This highlights the important role of mFRR in valorising the flexibility provided by the Virtual Battery under the considered market conditions. In the value stacking scenarios, the activated energy is distributed across both aFRR and mFRR according to their expected economic value, illustrating how the market model dynamically reallocates flexibility between balancing services.

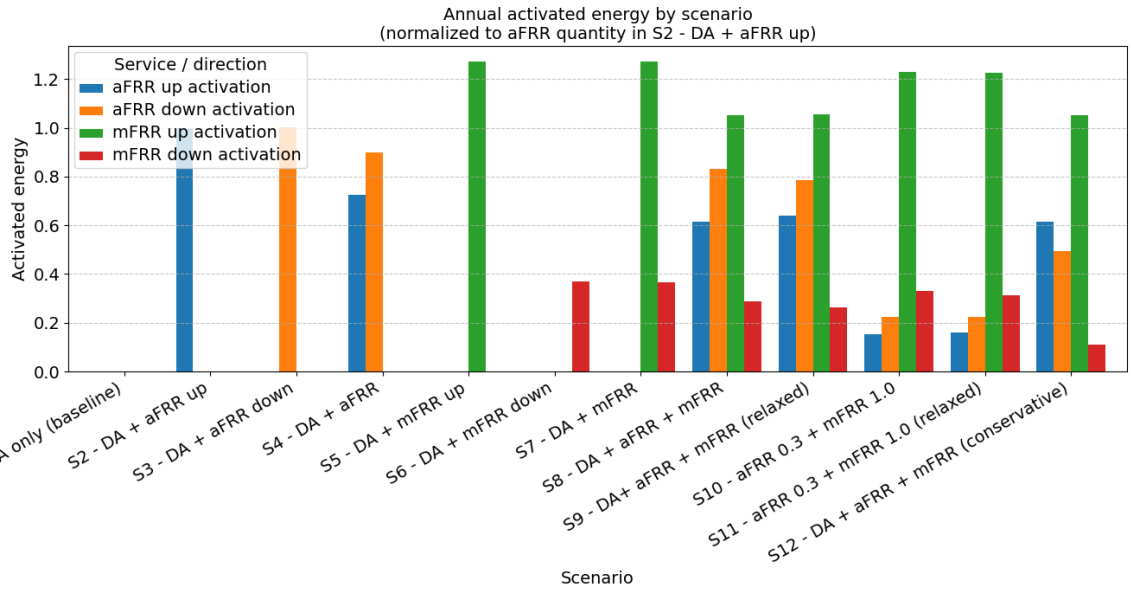


Figure 3.2: Annual activated energy by scenario - Normalized to aFRR up volume in S2

Impact on industrial operation

A key objective of the BUC was to verify that flexibility provision does not compromise the primary industrial objective of zinc production. Across all evaluated scenarios, the annual production target is maintained, demonstrating that the additional flexibility created by the Virtual Battery originates from shifting electricity consumption over time rather than reducing industrial output.

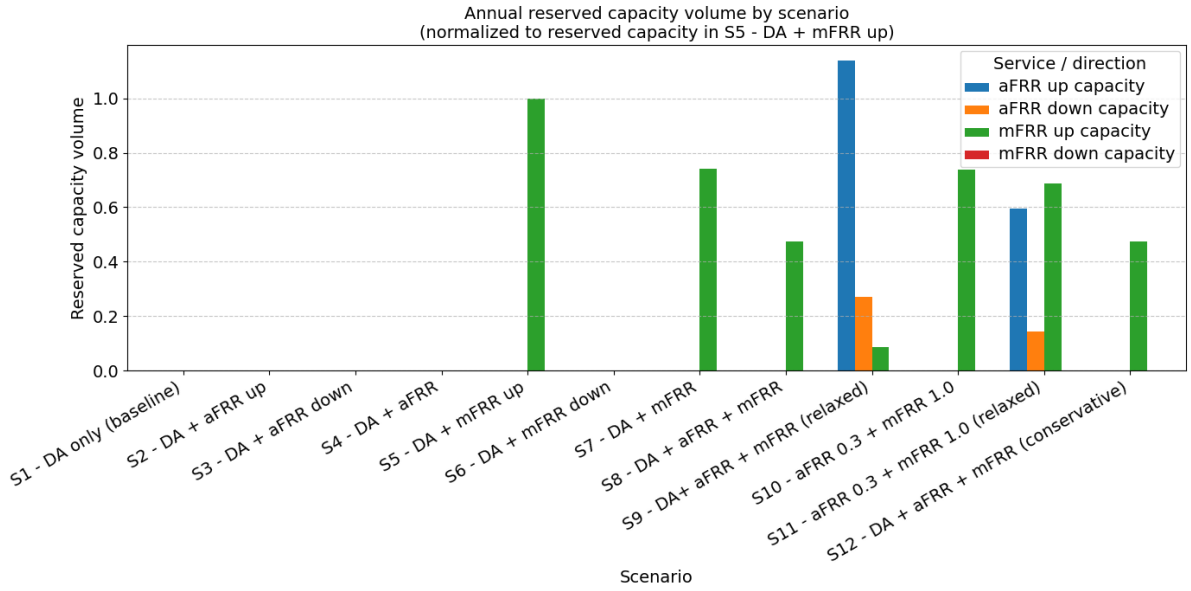


Figure 3.3: Annual reserved capacity by scenario - Normalized to S1

The production results further illustrate how the electrolyte buffer system absorbs short-term variations in electrolysis power. During periods of increased electricity consumption, the upstream and downstream buffers gradually compensate for the temporary imbalance between electrolysis and the surrounding process units. Conversely, periods of reduced electricity consumption are compensated later in the year as the electrolysers return to higher operating levels. The inventory trajectories remain within the available storage limits throughout all simulations, confirming that the proposed buffer capacity is sufficient to support the investigated flexibility strategies. This demonstrates that the Virtual Battery effectively decouples electricity consumption from the remainder of the production process while preserving stable plant operation.

Economic assessment

Figures 3.4 and 3.5 summarize the relative economic performance of the different market participation scenarios. To preserve the confidentiality of the industrial case study, the results are presented in normalized form. The figures therefore illustrate the relative differences between the evaluated scenarios rather than the absolute financial values.

The DA only scenario serves as the reference case where the Virtual Battery creates economic value by shifting electricity consumption from periods with high electricity prices to periods with lower prices. Participation in balancing markets further improves the economic performance in all evaluated scenarios, confirming that industrial flexibility can generate additional value beyond energy procurement optimisation.

The simulations reveal clear differences between the balancing products. Within the dedicated balancing market scenarios, downward aFRR provides a larger economic benefit than upward aFRR, whereas the opposite is observed for mFRR, where upward participation is the dominant contributor to the overall economic performance. Allowing participation in both activation directions (S4 and S7) further increases the economic

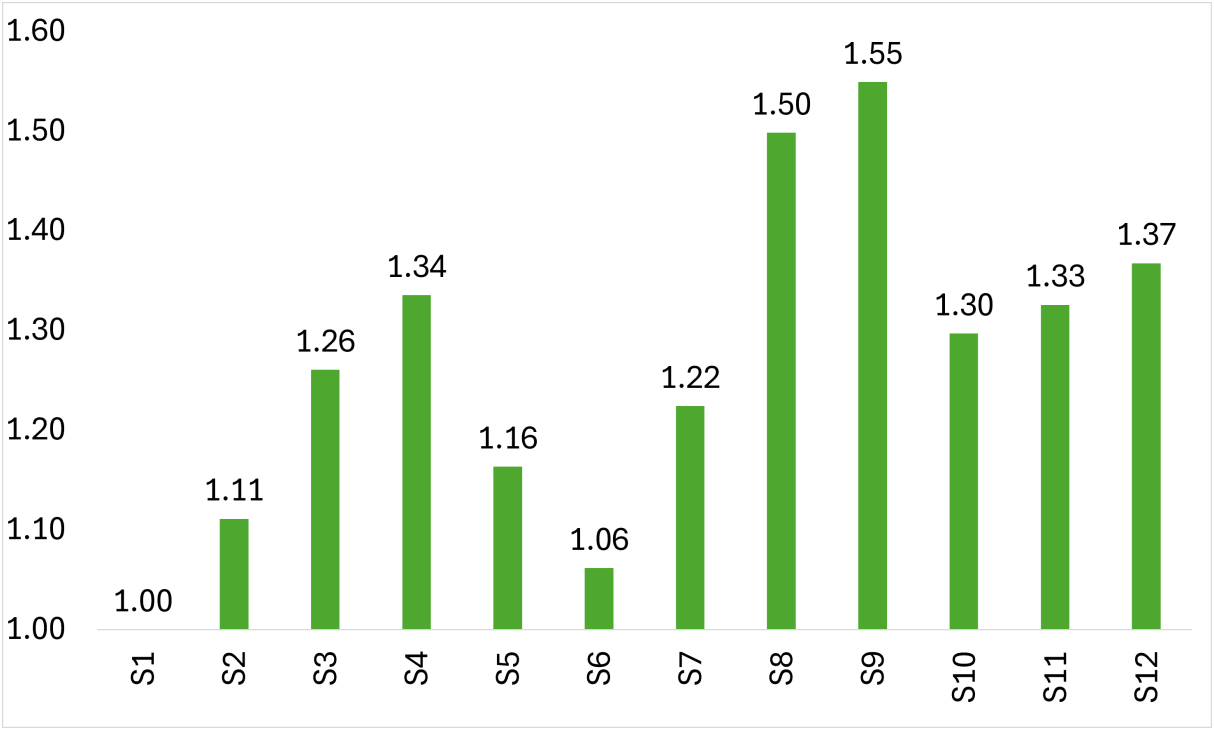


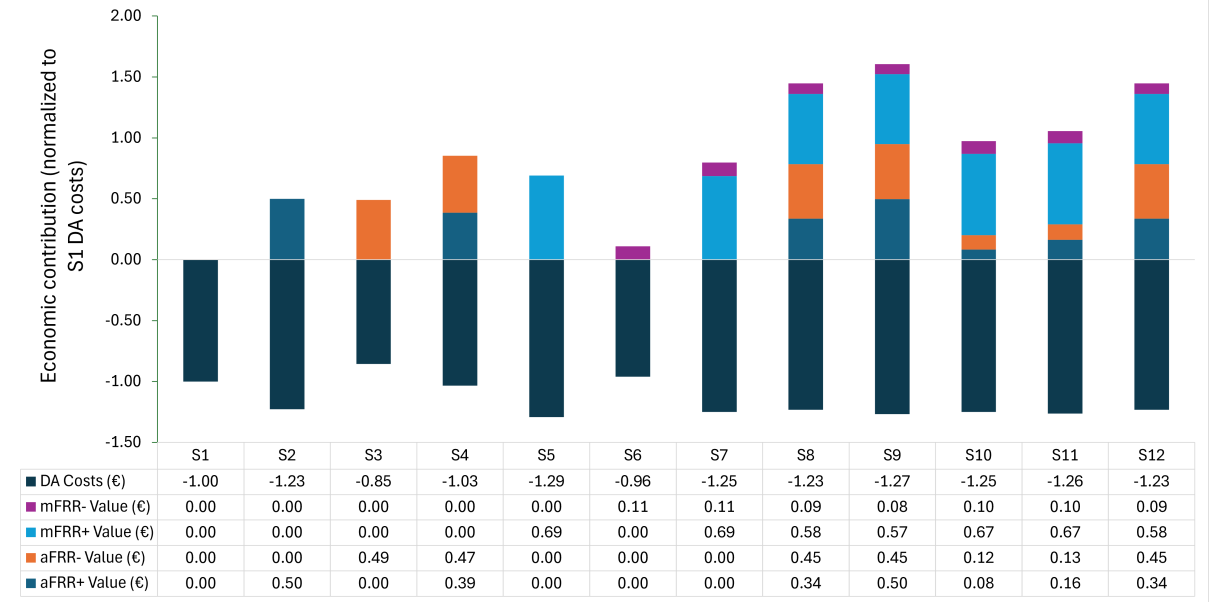
Figure 3.4: Estimated annual turnover of all scenarios (normalized values to S1).

value by providing the model with greater flexibility to position the process across the different market opportunities.

The highest economic performance is obtained when the Virtual Battery simultaneously participates in the DA, aFRR and mFRR markets (S8–S12). Rather than allocating the available flexibility to a single balancing service, the market model dynamically distributes the available flexibility across the considered markets according to their expected economic value. This demonstrates the benefit of integrated market participation for maximising the value of industrial demand-side flexibility.

The analyses further show that the achievable economic value depends on the adopted market and operational assumptions. Relaxing the coupling between reserve capacity reservation and mandatory activation results in the highest theoretical value by enabling more extensive participation in the reserve capacity markets. Conversely, reducing the assumed aFRR activation factor to represent increased competition between flexibility providers decreases the attainable turnover while maintaining a clear improvement over the DA only reference case. Applying a more conservative bidding strategy further reduces the theoretical value but continues to outperform the dedicated market participation scenarios, demonstrating that a substantial share of the economic potential can be retained while adopting more robust operating strategies.

Figure 3.5 shows that several of the scenarios with the highest turnover are not those with the lowest DA electricity procurement costs. Participation in balancing markets may require operating the electrolysis process at less favourable DA positions to preserve upward or downward flexibility. Although this increases electricity procurement costs, these additional costs are compensated by revenues from balancing market participation. The relative contribution of the different balancing products depends on the con-



	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
DA Costs (€)	-1.00	-1.23	-0.85	-1.03	-1.29	-0.96	-1.25	-1.23	-1.27	-1.25	-1.26	-1.23
mFRR- Value (€)	0.00	0.00	0.00	0.00	0.00	0.11	0.11	0.09	0.08	0.10	0.10	0.09
mFRR+ Value (€)	0.00	0.00	0.00	0.00	0.69	0.00	0.69	0.58	0.57	0.67	0.67	0.58
aFRR- Value (€)	0.00	0.00	0.49	0.47	0.00	0.00	0.00	0.45	0.45	0.12	0.13	0.45
aFRR+ Value (€)	0.00	0.50	0.00	0.39	0.00	0.00	0.00	0.34	0.50	0.08	0.16	0.34

Figure 3.5: Normalized contributions towards the estimated annual turnover for all scenarios of each market: DA costs, aFRR+, aFRR-, mFRR+, mFRR-.

sidered market participation strategy and the underlying modelling assumptions. These results demonstrate that the economic value of the Virtual Battery arises from the combined optimisation of electricity procurement, reserve provision and balancing market participation rather than from minimising DA electricity procurement costs alone.

Overall, the flexibility potential assessment demonstrates that the proposed Virtual Battery enables Nyrstar to provide both aFRR and mFRR services without compromising the annual zinc production target or violating the operational constraints of the electrolysis process. The analyses further show that the technical and economic characteristics differ between the balancing products, and that the achievable value depends on the adopted market participation strategy and modelling assumptions. Among the evaluated strategies, value stacking consistently provides the highest overall economic performance by dynamically allocating the available flexibility across the considered markets. These findings confirm that industrial process flexibility can be effectively valorised through balancing market participation while preserving production volumes and economic performance, thereby positively addressing the first research question of this use case.

3.4 Impact of CRM on the Virtual Battery use case

The proposed Virtual Battery can obtain a significant and stable revenue source from the CRM. With an activation time over 12h, which is longer than Belgium's scarcity periods, the Virtual Battery is not de-rated and can submit its full capacity to the CRM (category SLA unlimited). There is important uncertainty with regards to the exact net revenues from participation.

The first source of uncertainty is related to the capacity payments themselves. Currently, the Virtual Battery project is likely to fit in the single-year contract category. It would therefore have to participate to the CRM for every delivery year, and be subject to the intermediate price cap. Average weighted capacity prices are volatile across delivery years. They are also volatile across auction lead times. In particular, capacity prices appear higher in Y-4 than in Y-1 auctions. So, the exact price that the Virtual Battery project can receive is difficult to predict. The CREG [7] has published a study on industrial flexibility participation within the CRM, which proposed options for such investments to fit into the multi-year contracts category (and be subject to the higher price cap). This could enable more secure long-term revenues.

A second source of uncertainty is related to additional revenues and losses from operating the Virtual Battery in response to CRM signals. Since 2025, demand-response is exempted from the CRM reliability option payback obligation. This means that activating during high price periods, the Virtual Battery would also have significant savings from wholesale market procurement. The exact quantity of those savings depends on the exposure of Nyrstar's electricity purchases to short-term prices, and the marginal costs of activating (i.e., cost of "recharging", delaying consumption with the buffer). In addition, the Virtual Battery could be exposed to non-negligible over-delivery penalties.

Overall, the analysis suggests that the business case for the Virtual Battery participation in the CRM is favourable under a broad range of assumptions, while remaining sensitive to auction outcomes and the operational implementation of the project.

3.5 Technical Fit Summary

The technical fit exercise assessed whether the Nyrstar zinc electrolysis process and associated process buffers can technically provide flexibility services and which market requirements would need to change for additional services to become viable. The assessment maps the characteristics of the installation—including controllability, ramping capability, activation duration, availability and operational constraints—against the technical requirements of relevant Belgian flexibility mechanisms. It evaluates technical feasibility only and does not assess economic attractiveness, contractual risk or implementation cost.

The flexible asset configuration consists of a zinc electrolyser and upstream and downstream process buffers that decouple the electrolysis process from adjacent production steps. This creates a virtual battery: electricity consumption can be reduced to provide upward flexibility or increased to provide downward flexibility, while the process buffers preserve continuity of the wider industrial process. The installation combines a broad controllable operating range, relatively fast ramping and long-duration storage, making it technically suitable for both upward and downward modulation over extended periods.

Table 3.2 summarizes the qualitative technical fit of the Nyrstar zinc electrolysis process with the main Belgian flexibility mechanisms.

The assessment shows that balancing services are a strong technical fit, with the exception of FCR. aFRR and mFRR are good fits in both directions because the electrolysis process can change operating point within the required activation times and the

Market / product	Technical fit	Main qualitative rationale
FCR (primary reserve)	Moderate	The process can respond quickly, but only part of the available flexible capacity can reliably meet the strict full-response requirement.
aFRR up (secondary reserve)	Good	Consumption reduction can be delivered within the required activation time and sustained through the available process-buffer capacity.
aFRR down (secondary reserve)	Good	Consumption increase is technically feasible within the required activation time and can be sustained because of the available process-buffer capacity.
mFRR up (tertiary reserve)	Good	The process can reduce consumption within the required activation time and sustain upward flexibility for durations exceeding the reservation requirement.
mFRR down (tertiary reserve)	Good	The process can increase consumption within the required activation time and sustain downward flexibility over long activation periods.
DA market	Good	The virtual battery can shift consumption between off-peak and peak-price periods, enabling spot market price arbitrage.
Intraday market	Good	The broad modulation range and process-buffer duration allow the installation to react to updated near-real-time price signals.
Imbalance settlement	Good	The process can modulate consumption in response to imbalance price signals, provided that buffer state and production constraints allow the deviation.
Congestion management (TSO redispatch)	Good	The installation is technically controllable and aligns well with the operational timing and asset-size requirements of the current redispatch framework.
CRM	Very good	The process behaves as a long-duration demand-side flexibility resource with high availability, making it technically well suited for CRM participation.

Table 3.2: Qualitative technical-fit summary for the Nyrstar zinc electrolysis process across Belgian flexibility mechanisms.

process buffers can sustain activation for durations exceeding the relevant reservation requirements. FCR is only a moderate fit: the process can respond quickly, but only part of the available flexible capacity can reliably meet the strict full-response requirement.

Spot-market participation and imbalance settlement are also good technical fits. The virtual battery can shift electricity consumption between lower-price and higher-price periods in the DA and intraday markets, while the long process-buffer duration gives substantial operational freedom. The same flexibility can be used to respond to imbalance price signals, provided that the buffer state and production constraints allow the deviation. Full exploitation of multi-day storage would require robust multi-day price forecasting and is therefore more uncertain than daily or intraday optimization.

Congestion management through TSO redispatch is a good fit under the current framework because the installation is technically controllable, has sufficient flexible capacity and can comply with the operational timing of redispatch actions. The CRM is a very good technical fit because the process behaves as a long-duration demand-side flexibility resource with high availability. Classification and derating treatment remain relevant design considerations, but the long-duration virtual-battery characteristics are technically favourable for CRM participation.

Chapter 4

Tessenderlo BUC 3: Summary of Key Findings

4.1 Introduction

Tessenderlo Group's Ham site produces sulfuric acid using an exothermic process that releases substantial amounts of heat. Rather than wasting this heat, the site recovers it to produce steam, which is used to drive a steam turbine for electricity generation. The turbine has historically been operated mainly as a stable generation asset, supplying electricity to the plant and, when available, to the grid.

The work in GALILEO focuses on whether this existing steam and electricity generation system can be operated more flexibly. The main question is how far the site can move from base-load generation toward market-responsive operation while maintaining the conditions required for safe and stable sulfuric acid production.

4.1.1 BUC 3A description

This use case investigates the flexibility potential of the steam turbine at Tessenderlo's Ham facility. In the sulfuric acid production process, heat is released during the combustion of sulfur and the catalytic conversion of SO_2 to SO_3. This heat is recovered through a steam generation system, producing high-pressure steam that drives a turbine connected to the site's electricity system.

The central flexibility mechanism is the steam turbine bypass valve. When steam bypasses the turbine, electricity generation can be reduced quickly while the production process continues to receive the thermal conditions it requires. This creates a source of downward flexibility. Upward flexibility may also be possible in some conditions, but it depends on steam availability and the operating state of the sulfuric acid process. Initial testing indicated a ramp rate of approximately 1.75 MW/min and an operating range of about 4 MW to 12 MW.

The use case investigates how the steam turbine can be transformed from a conventional base-load generation asset into a market-responsive flexibility resource. An optimisation-based dispatch model is developed to evaluate participation in the DA, mFRR, and aFRR electricity markets without impacting the upstream operations of the

sulfuric acid production plant. The economic value of this flexibility is subsequently assessed in different scenarios. These scenarios include a sensitivity analysis on key asset and market parameters, as well as an evaluation of the market design changes required to enable additional flexibility services.

Research questions

The following research questions are investigated within the scope of this BUC analysis across the different project tasks:

1. How can the steam turbine be dispatched optimally in response to DA, and balancing market (aFRR, mFRR) given sulfuric acid production constraints? What is the valorisation of each flex service?

2. Which operational and market parameters most significantly impact the revenue generation and merit order of the plant, and how do variations in these parameters affect the economic viability of the investment under current market conditions?

3. What flexibility mechanisms can be provided with the steam turbine? What market requirements must change (and to what extent) for other services to be an option for the steam turbine?

Research Questions 1 and 2 are addressed in the following sections, while research question 3 is addressed in two parts: the technical suitability of the steam turbine to provide different flexibility mechanisms (technical fit) is addressed in this chapter, while the market design changes required to enable additional flexibility are discussed in Deliverable D3: Market Design to Support Industrial Competitiveness and Flexibility [1]

4.2 Flexibility Potential Assessment

The flexibility potential of the Tessenderlo sulfuric acid production site is assessed using a modelling framework consisting of two interconnected models: a process model and a market model.

The process model provides a digital representation of the site's electrical system and characterises the interaction between steam turbine electricity generation, on-site electricity demand, and grid exchange. Using representative operational data as inputs, the model reproduces the physical power balance of the system while respecting the technical characteristics of the steam turbine and grid connection.

The operational profiles generated by the process model are subsequently transferred to the market model, which evaluates the economic value of the available flexibility under Belgian electricity market conditions. Building upon the process model representation, the market model optimises the utilisation of the identified flexibility through participation in the DA, aFRR, and mFRR markets while ensuring consistency with the physical operation of the industrial process.

4.2.1 Process Model

The process model represents the electrical operation of the sulfuric acid production site. The system consists of three principal elements: the steam turbine, the site electricity demand, and the grid connection, as illustrated in Figure 4.1. Steam turbine generation and site electricity demand are represented as exogenous time series derived from operational measurements. At each time step, electricity generated by the steam turbine is first supplied to the on-site demand, while any surplus electricity is exported to the grid and any deficit is covered through electricity imports.

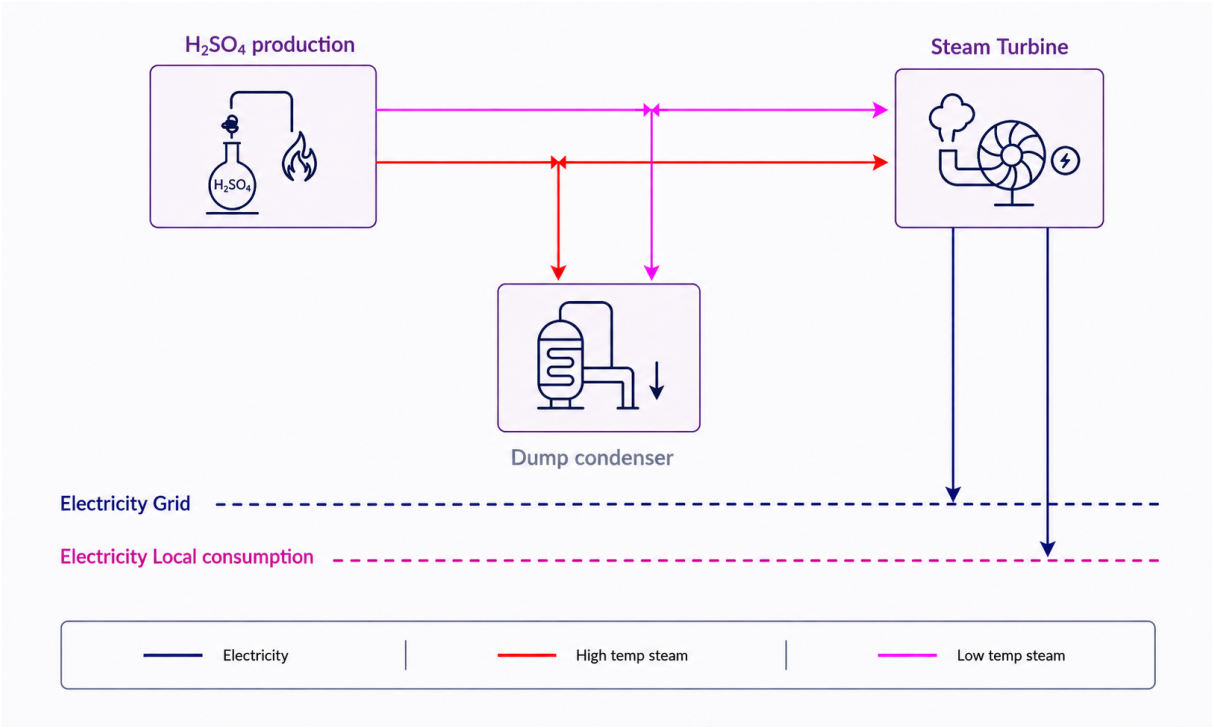


Figure 4.1: Schematic overview of the power balance representation of the steam turbine, site demand, and grid exchange system.

The process model establishes the physical power balance of the industrial system and determines the resulting grid import and export profiles. These operational profiles provide the basis for a mathematical representation of the system, which is subsequently transferred to the market model for economic evaluation of operational flexibility

Process Model results

The assessment focuses on the temporal evolution of electricity generation, on-site consumption, and the resulting grid exchange, which forms the basis for evaluating the flexibility potential of the steam turbine, as shown in Figure 4.2. The resulting import and export profiles provide the operational baseline for the subsequent market model, where the identified flexibility of the steam turbine is economically evaluated through participation in electricity and balancing markets.

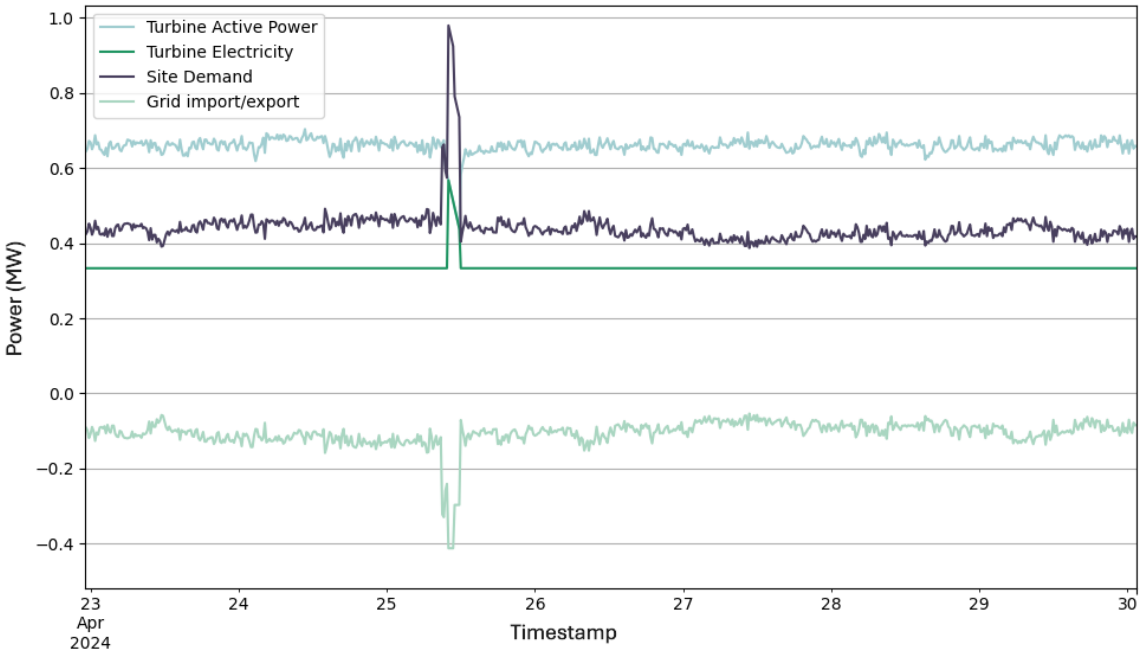


Figure 4.2: Representative weekly profile of steam turbine generation, site electricity demand, and resulting grid exchange. Process parameters are normalized.

4.2.2 Market model and simulation framework

The market model determines the optimal market participation strategy (i.e., bidding strategy) for the steam turbine by maximizing the economic value of the Tessenderlo site's participation in electricity markets while respecting all technical and operational constraints imposed by the LP formulation of the process model (i.e., the black-box model). The model simultaneously schedules site-level electricity generation or consumption in the DA market and participation in the balancing markets, namely aFRR and mFRR. By co-optimizing these market opportunities, the model quantifies the flexibility that can be offered to each balancing service, compares their technical and economic performance, and evaluates value stacking by dynamically allocating the available flexibility across the considered markets to maximize overall profits. This process of optimal market participation then allows the estimation of the economic value that can be realized by the industrial process via participation in DA, mFRR, and aFRR markets, which can then feed into relevant business case calculations. Figure 4.3 provides an overview of the market model framework and the interactions between the market inputs, the process constraints, and the optimization model.

The simulations were performed using historical Belgian electricity market data for the 2024 calendar year with a temporal resolution of 15 minutes, matching the settlement period of the considered markets [2, 3, 4, 5, 6]. The model considers a setting of perfect foresight for the use case analysis and uses historical balancing activation volumes to determine when and how much reserved flexibility is activated. Under the perfect foresight assumption, all market prices and balancing needs are considered to

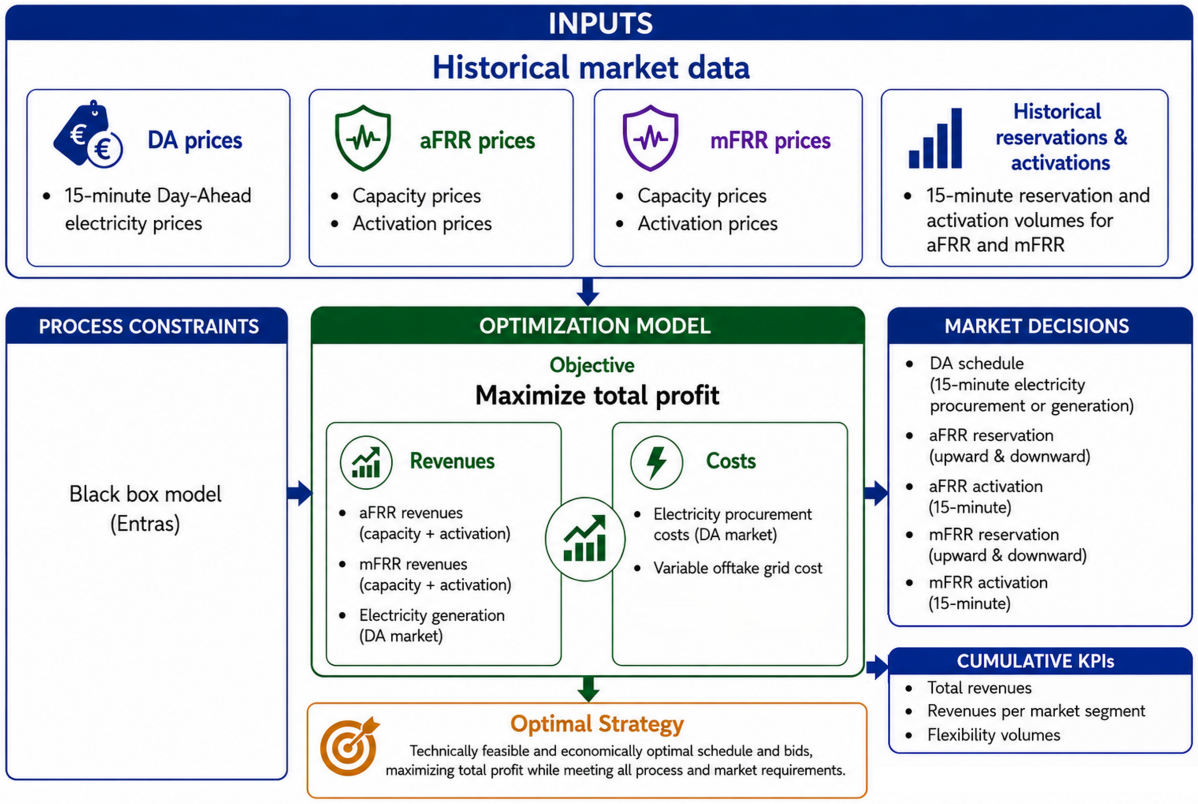


Figure 4.3: VITO's market optimization and flexibility valuation model (referred to as Market Model for short) used in the Tessenderlo Use Case

be known in advance.

The steam turbine is assumed to remain in operation throughout the simulations and cannot be completely shut down unless insufficient steam is available from the sulfuric acid production process. Similarly, the turbine is required to operate above its technical minimum load (7.5MW) whenever sufficient steam is available, reflecting the operational limitations of the asset. Finally, the feasible range of DA market bids is derived from two extreme operating simulations representing maximum electricity import and maximum electricity export, ensuring that all market schedules remain technically feasible.

4.2.3 Results

To evaluate the flexibility potential of the steam turbine under different market participation scenarios, a set of simulation scenarios is considered. These scenarios progressively increase the level of market participation, starting from the reference operation without market optimization, followed by a DA-only optimization, and finally simultaneous participation in the balancing markets. The complete set of scenarios is summarized in Table 5.1. Sensitivity analysis In addition to the market participation scenarios, a sensitivity analysis is performed to evaluate the impact of the steam turbine's minimum generation capacity on the eco- nomic value of the available flexibility. Three minimum generation capacities are con- sidered: 7.5 MW, representing the current operating condition of the turbine, and two hypothetical values of 6.5 MW and 5.5 MW. For each

minimum generation capacity, the complete set of simulation scenarios is evaluated.

ID	Scenario	Description
S1	No optimization	Baseline scenario.
S2	DA only	Participation in the DA market only.
S3	DA + aFRR^{+}	Participation in the DA market and upward aFRR.
S4	DA + aFRR^{-}	Participation in the DA market and downward aFRR.
S5	DA + aFRR	Participation in the DA market and both upward and downward aFRR.
S6	DA + mFRR^{+}	Participation in the DA market and upward mFRR.
S7	DA + mFRR^{-}	Participation in the DA market and downward mFRR.
S8	DA + mFRR	Participation in the DA market and both upward and downward mFRR.
S9	DA + aFRR + mFRR	Value stacking across the DA, aFRR, and mFRR markets.

Table 4.1: Simulation scenarios considered in this deliverable.

Market participation strategies

In the DA-only scenario, participation is driven solely by DA electricity prices. Under these conditions, the market model predominantly operates the steam turbine at its maximum feasible generation level, thereby maximizing electricity exports to the grid. Generation is only reduced towards the minimum permissible operating level during periods of low or negative electricity prices, where limiting electricity exports becomes economically advantageous. Intermediate operating points occur only during transitions between these operating regimes.

Participation in balancing markets modifies this baseline operating strategy by allowing the steam turbine to provide reserve capacity and balancing energy in addition to electricity trading. In the dedicated aFRR participation scenarios (S3–S5), the operating strategy is characterized by frequent adjustments of the turbine output to accommodate both upward and downward activation requests, with the market model selecting the balancing direction according to the prevailing market conditions and activation requests. Reserve capacity is only offered when its availability can be guaranteed throughout the reservation period.

In the dedicated mFRR participation scenarios (S6–S8), the operating strategy differs from that of aFRR. Compared to aFRR, mFRR activations occur considerably less frequently, allowing the turbine to remain closer to its economically optimal DA dispatch. While both upward and downward mFRR services can be provided, upward mFRR is utilised more frequently than downward mFRR under the considered market conditions.

In the value stacking scenario (S9), simultaneous participation in the DA, aFRR, and mFRR markets allows the available flexibility to be shared across the different balancing products. The market model dynamically allocates the steam turbine's flexibility to the market offering the highest expected economic value, resulting in coordinated participation across all considered markets. Under the considered market conditions, upward and downward aFRR remain the dominant balancing services, while mFRR is selected less frequently but continues to contribute when it provides a higher economic

value. This coordinated market participation enables the steam turbine to maximise the overall value of its available flexibility through value stacking.

Annual flexibility provision

Figures 4.4 and 4.5 summarize the annual reserve capacity and activated balancing energy for the different market participation scenarios. The results show clear differences in the way the steam turbine allocates its flexibility across the balancing products.

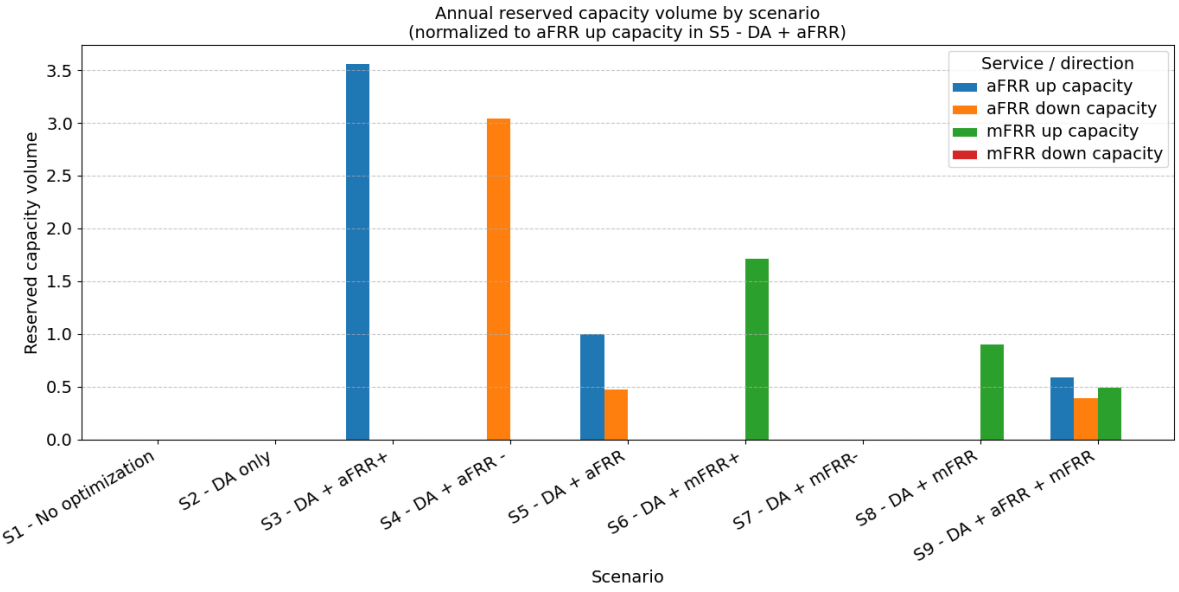


Figure 4.4: Annual reserve capacity by scenario Normalized to aFRR up volume in S3

Regarding reserve capacity, the highest reservation volumes are achieved in the dedicated balancing market scenarios. The largest upward and downward aFRR reserve capacities are obtained when the turbine participates exclusively in the corresponding aFRR product (S3 and S4, respectively), while the largest upward mFRR reserve capacity is obtained in the dedicated upward mFRR scenario (S6). When both directions of the same balancing product are allowed (S5 for aFRR), the available reserve capacity is distributed between upward and downward services. Finally, in the value stacking scenario (S9), the available flexibility is shared across both aFRR and mFRR markets, resulting in lower reservation volumes for each individual balancing product than in the dedicated market scenarios.

The annual activated balancing energy follows a similar pattern. The dedicated aFRR scenarios (S3–S5) provide substantially larger activated energy volumes than the corresponding mFRR scenarios (S6–S8), reflecting the considerably higher historical activation frequency of aFRR in the Belgian balancing market. Within the mFRR scenarios, upward mFRR (S6) delivers significantly more activated energy than downward mFRR (S7), consistent with the historical activation patterns considered in the simulations.

The value stacking scenario (S9) illustrates how the steam turbine's flexibility is allocated across competing balancing services. Rather than maximizing a single balancing

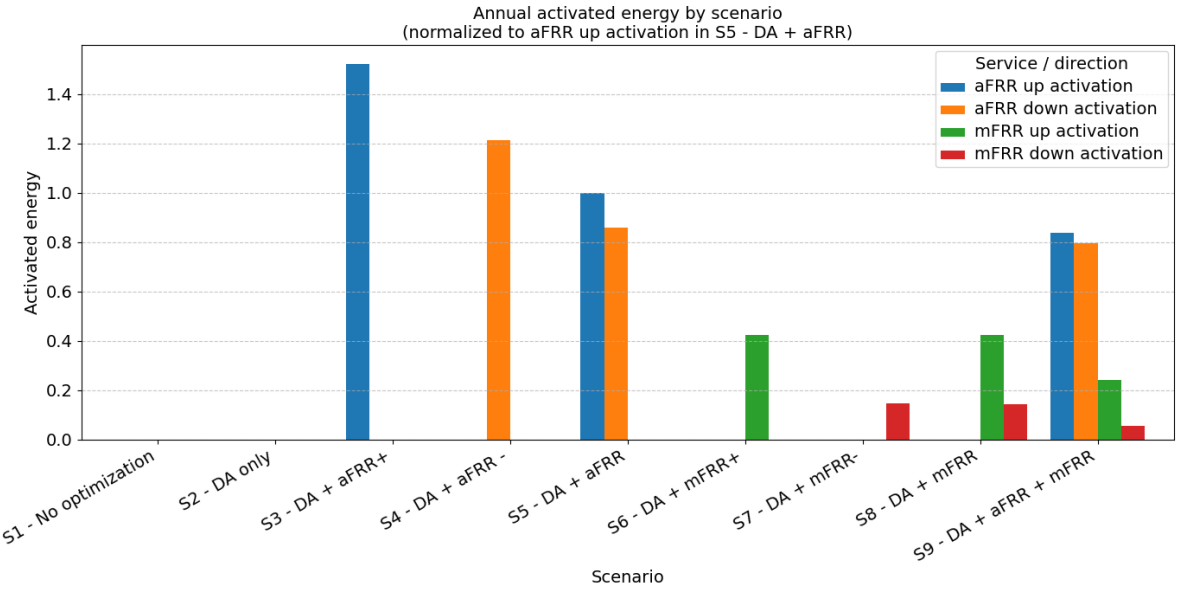


Figure 4.5: Annual activated energy by scenario - Normalized to aFRR up volume in S3

product, the market model distributes the available flexibility between aFRR and mFRR according to their expected economic value. Under the considered market conditions, aFRR remains the dominant service, while mFRR continues to receive a share of the available flexibility despite its lower activation frequency, owing to its higher remuneration when activated. This coordinated allocation enables the steam turbine to maximize the overall economic value of its available flexibility.

Profitability of the market participation scenarios

Figure 4.6 presents the normalized annual profit for each market participation scenario together with the contribution of the individual electricity markets. Optimizing participation in the DA market only (S2) provides only a marginal improvement over the reference operation (S1), indicating that the operational flexibility of the steam turbine has limited value when exploited exclusively through DA electricity trading. In contrast, participation in the balancing markets substantially increases the economic value of the asset. Among the dedicated balancing market strategies, the bidirectional aFRR scenario (S5) achieves the highest overall profit, outperforming all other single-market configurations. The normalized profit breakdown further shows that downward aFRR contributes more to the overall profit than upward aFRR. Although participation in the mFRR market (S6–S8) also increases profitability compared to DA-only participation, its economic contribution remains lower than that of aFRR. Within the mFRR scenarios, upward mFRR provides a larger contribution to the annual profit than downward mFRR.

The value stacking scenario (S9) achieves the highest overall profit by allowing simultaneous participation in the DA, aFRR, and mFRR markets. Rather than maximizing revenues from a single balancing product, the available flexibility is dynamically allocated across the different markets according to their expected economic value. As a

result, the combined revenues from aFRR and mFRR exceed those obtained in any dedicated market scenario.

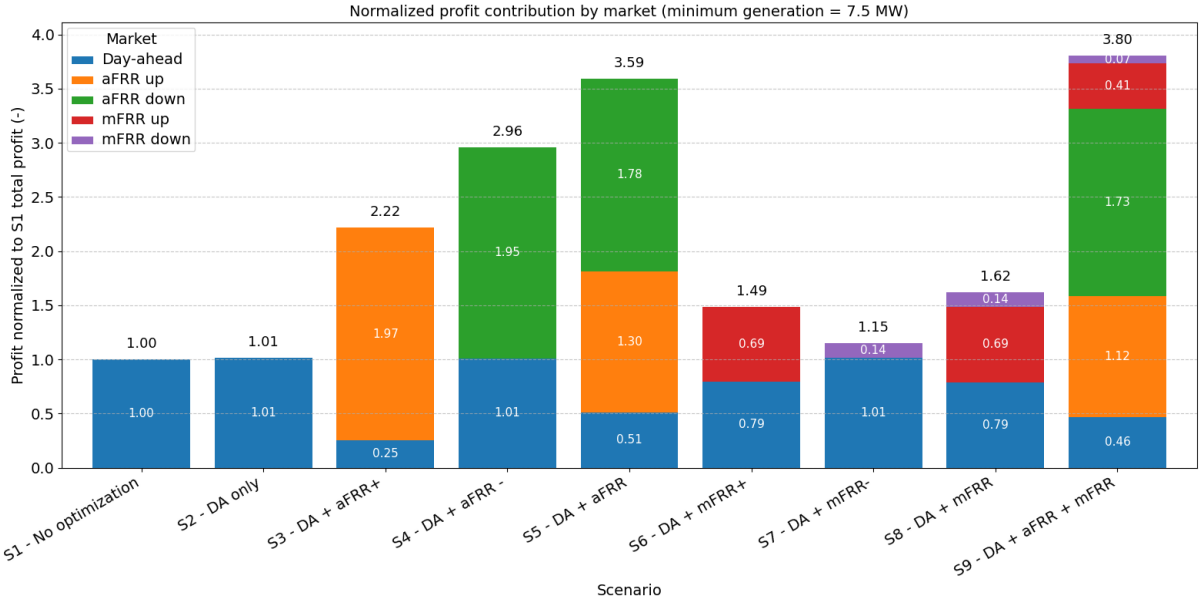


Figure 4.6: Annual profit breakdown by market for all simulation scenarios - Normalized to the DA profits in S1

Impact of the minimum generation capacity on market participation

A sensitivity analysis was performed to assess the impact of the steam turbine's minimum generation capacity on the economic performance of the different market participation scenarios. The results show that reducing the minimum generation level consistently increases the annual profit for all scenarios involving balancing market participation, whereas participation in the DA market alone remains largely unaffected. The largest improvements are observed for the DA + aFRR (S5) and value stacking (S9) scenarios. The sensitivity analysis shows that the largest absolute economic gains are achieved through aFRR, with both upward and downward aFRR revenues increasing as the operating range expands. In relative terms, upward mFRR exhibits the strongest increase, indicating that the wider operating range enables the steam turbine to exploit additional balancing opportunities that were previously unavailable.

The Tessenderlo case study demonstrates that the existing steam turbine can be transformed from a conventional base-load generation asset into a valuable flexibility resource through coordinated participation in electricity markets, while maintaining the operational requirements of the sulfuric acid production process. The results show that participation in the DA market alone provides only limited additional value, whereas balancing markets substantially enhance the economic potential of the asset. Among the individual balancing products, aFRR provides the highest economic value under the considered market conditions, while mFRR offers an additional revenue stream that further increases profitability when combined through value stacking (S9), which represents the most prof-

itable market participation strategy. Furthermore, the analysis identifies the minimum stable generation capacity as the key operational parameter influencing the economic value of the flexibility, with a wider operating range enabling greater participation in balancing markets and higher overall revenues. Overall, the study confirms that coordinated participation across multiple electricity markets, combined with operational improvements that increase the turbine's flexibility, provides the greatest potential for maximizing the economic value of the available industrial flexibility.

4.3 Technical Fit Summary

The technical fit exercise assessed whether the Tessenderlo steam turbine installation can technically provide flexibility services and which market requirements would need to change for additional services to become viable. The assessment maps the characteristics of the installation—including controllability, ramping capability, activation duration, availability and operational constraints—against the technical requirements of relevant Belgian flexibility mechanisms. It evaluates technical feasibility only and does not assess economic attractiveness, contractual risk or implementation cost.

The flexible asset configuration consists of a steam turbine whose electrical output can be reduced by bypassing steam around the turbine. This makes downward flexibility the most robust flexibility direction: generation can be reduced quickly and, if the bypass route is available, for long durations. Upward flexibility is more conditional because it requires the turbine to be operating below its maximum output and depends on the availability of excess steam. As a result, upward services may require deliberate pre-positioning of the turbine operating point during the reservation period.

Table 4.2 summarizes the qualitative technical fit of the Tessenderlo steam turbine installation with the main Belgian flexibility mechanisms.

The assessment shows that downward balancing services are the strongest technical fit among the reserve products. Downward aFRR and downward mFRR are good fits because the steam turbine can reduce generation within the required activation times through the bypass valve. Upward aFRR and upward mFRR are moderate fits: activation is technically feasible within the required timeframes, but the available flexibility depends on the operating point and the availability of excess steam.

Spot-market participation and imbalance settlement are also good technical fits. The steam turbine can reduce generation during periods of negative or otherwise unfavourable prices, making downward response particularly relevant for DA, intraday and imbalance-market optimization. Increasing generation during high-price periods is possible only when the turbine is not already operating close to its maximum output and when sufficient excess steam is available.

FCR is a poor fit because the turbine cannot reliably meet the strict activation-time requirement and cannot provide robust symmetric upward and downward delivery. TSO redispatch is also a poor fit under the current framework because access is constrained by the applicable minimum asset-size threshold, although the asset could become more relevant if future redispatch rules allow smaller installations to participate. The CRM is a good technical fit for baseload generation, although availability risk remains relevant

Market / product	Technical fit	Main qualitative rationale
FCR (primary reserve)	**Poor**	The turbine cannot reliably meet the strict activation-time requirement and cannot provide robust symmetric upward and downward delivery.
aFRR up (secondary reserve)	**Moderate**	Upward activation is technically feasible within the required activation time, but depends on the turbine operating point and the availability of excess steam.
aFRR down (secondary reserve)	**Good**	The turbine can reduce generation within the required activation time through the bypass valve and can sustain downward activation when the bypass route is available.
mFRR up (tertiary reserve)	**Moderate**	Upward activation can be delivered within the required timeframe, but sustained delivery remains conditional on excess steam availability.
mFRR down (tertiary reserve)	**Good**	The turbine can reduce output within the required activation time and sustain downward flexibility through steam bypass operation.
DA market	**Good**	Generation can be reduced during negative or low-price periods, while upward response during high-price periods is possible when excess steam is available.
Intraday market	**Good**	Rapid downward modulation allows the installation to adjust closer to delivery, especially during negative-price periods or updated market conditions.
Imbalance settlement	**Good**	The installation can respond opportunistically to imbalance prices, particularly by reducing generation during periods where downward response is valuable.
Congestion management (TSO redispatch)	**Poor**	The installation is technically controllable, but current redispatch access is constrained by the applicable minimum asset-size threshold and upward redispatch depends on excess steam availability.
CRM	**Good**	The baseload-oriented generation profile supports CRM participation, although steam availability and annual generation variability create availability risk.

Table 4.2: Qualitative technical-fit summary for the Tessenderlo steam turbine installation across Belgian flexibility mechanisms.

because steam availability and generation can vary over the year.

Chapter 5

Tiense Suiker BUC 4A: Summary of Key Findings

5.1 Introduction

Tiense Suiker is part of an international sugar production company headquartered in Germany, with production facilities in both Flanders and Wallonia. Its Belgian operations are shaped by a strongly seasonal production profile, where the main sugar beet campaign runs from September to January and creates a much higher energy demand than the rest of the year. This seasonality makes energy procurement, electrification, and flexibility planning more complex, especially because investment decisions and energy strategies are managed across regions with different regulatory conditions.

Within GALILEO, Tiense Suiker is investigating how its steam and energy systems can support decarbonization while improving the business case for flexibility. The work focuses on two linked areas: the coordinated operation of an upgraded steam network for market participation, and the development of a longer-term energy procurement and investment strategy that better matches the company's seasonal heat and electricity needs. This chapter focuses on the first aspect.

5.1.1 BUC 4A description

The first of Tiense Suiker's use cases investigates the flexibility potential of the site's integrated steam network, which is a critical component of the sugar production process during the beet campaign. The steam network consists of a 20 MW steam turbine, two smaller gas-fired boilers with potential partial electrification through electric boiler retrofits, and a planned Mechanical Vapor Recompression (MVR) system. Since these assets are interconnected through the site's steam balance, their coordinated operation creates opportunities to provide electricity system flexibility while maintaining stable production conditions.

The use case evaluates the flexibility contribution of each individual technology and compares this with the additional flexibility and economic value obtained when operating the steam network as a coordinated system. The analysis investigates how steam production, electricity generation, and electrified steam consumption can be optimized to provide flexibility services without compromising process requirements or product

quality. Both DA market optimization and participation in the mFRR market are considered, with the assessment accounting for the seasonal operating pattern of the sugar production process.

The study also examines the technical and market constraints limiting flexibility participation, including steam demand requirements, asset operating limits, and the seasonal availability of flexibility. The objective is to identify how market adaptations and improved coordination of industrial steam networks could increase the value of flexibility from seasonal industrial processes.

Research questions

The following research questions are investigated within the scope of this BUC analysis across the different project tasks:

1. How much flexibility can be provided through the coordinated activation of the plant's steam network? How much revenue can be obtained? (Focus on DA and mFRR)
2. What are the most important constraints limiting participation to flexibility services? How could the market be adapted to enable more flexibility?
   (a) How does the highly seasonal profile of the company change what services can be provided?

Research Question 1 is addressed in the following sections, while research question 2 is addressed in two parts: the technical suitability of the steam network to provide different flexibility mechanisms (technical fit) is addressed in this chapter, while the market design changes required to enable additional flexibility are discussed in Deliverable D3: Market Design to Support Industrial Competitiveness and Flexibility [1]

5.2 Flexibility Potential Assessment

5.2.1 Process Model

The process model represents the operation of the integrated steam and electricity system at the Tiense Suiker production site. The model captures the interactions between steam production, electricity generation, MVR, electric boilers, and the process steam demand of the evaporation and crystallization units. The approach focuses on the coordinated operation of the main energy conversion assets while preserving the technical and operational constraints that govern the steam network, as illustrated in Figure 5.1.

The model determines the optimal dispatch of the steam generation units, back-pressure steam turbine, MVR system, and electric boilers using historical process demand profiles together with electricity and natural gas prices as inputs. Operational decisions are obtained through a rolling-horizon optimization framework that schedules the available assets while ensuring continuous process steam supply and respecting all

operational constraints. The simulations cover both campaign and off-campaign periods to evaluate how seasonal variations in production influence the operational flexibility of the integrated steam network.

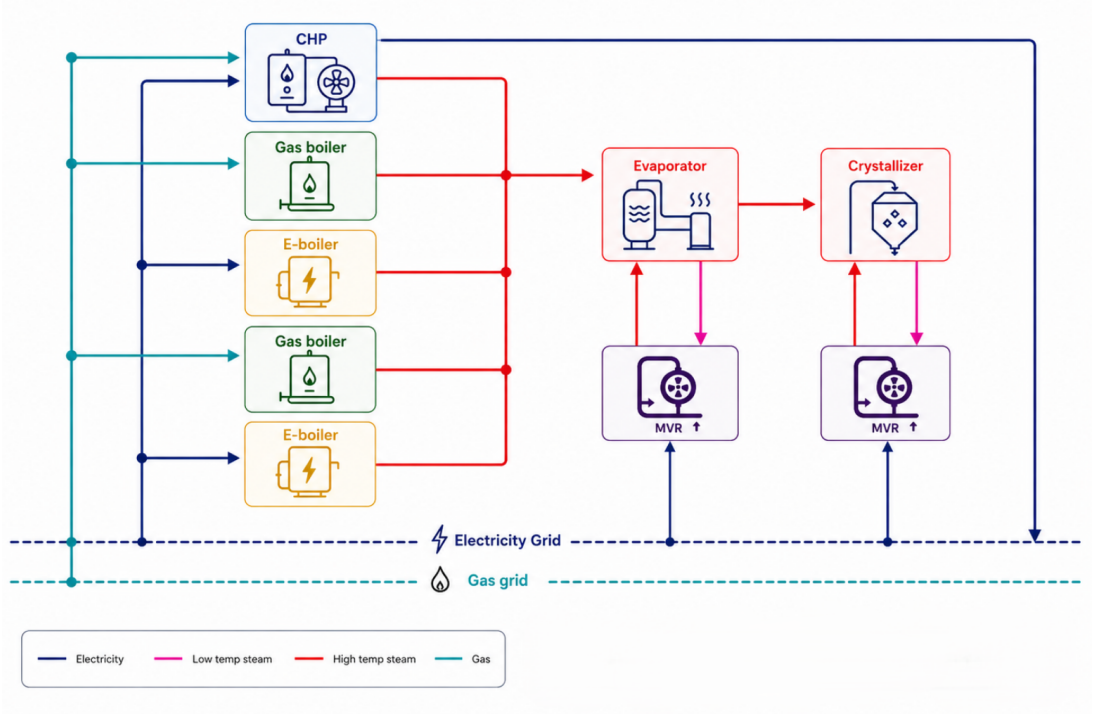


Figure 5.1: Schematic overview of the integrated steam and electricity system at Tiense Suiker, illustrating the interactions between steam generation units, the back-pressure steam turbine, MVR, electric boilers, process steam demand, and the electricity grid.

Process Model Results

The process model evaluates the coordinated operation of the integrated steam network over a full year using historical process demand and Belgian Day-Ahead electricity prices. The assessment focuses on the dispatch of the steam turbine, MVR, gas boilers, and electric boilers during both campaign and off-campaign operation, providing insight into the flexibility characteristics of the industrial steam system.

As shown in Figure 5.2, process steam demand remains the primary driver of system operation, while electricity price variations determine the optimal allocation between the available steam generation technologies. During the beet campaign, the high and relatively stable steam demand results in continuous utilisation of the MVR system and the steam turbine, with the MVR becoming the dominant source of steam production whenever sufficient process vapour is available. Gas boilers provide supplementary steam to satisfy residual demand, whereas electric boilers are mainly activated during periods of favourable electricity prices. During the off-campaign period (Figure 5.3), the lower steam demand reduces MVR utilisation and increases the ability of the system to respond to electricity market signals through greater substitution between the available steam generation technologies.

Overall, the process model demonstrates that coordinated operation of the integrated steam network enables economically optimal scheduling while maintaining continuous process steam supply. The results highlight the dominant contribution of the MVR system to steam generation, the complementary role of conventional gas boilers in ensuring operational reliability, and the additional flexibility provided by electrified steam production under favourable market conditions. These operational characteristics constitute the basis for the subsequent market model, which quantifies the economic value of the flexibility provided by the integrated steam network.



Figure 5.2: Representative dispatch schedule of the integrated steam network during the campaign period over a 7-day horizon, illustrating the coordinated operation of the steam turbine, MVR, gas boilers, electric boilers, and process steam demand. Process variables are presented in normalized form.

5.2.2 Market model and simulation framework

The market model determines the optimal bidding strategy for the steam network by maximizing the economic value of its participation in electricity markets while satisfying all technical and operational constraints defined by the LP process model (i.e., the black-box model). the market model simultaneously determines electricity generation and consumption schedules for the DA market, as well as participation in the mFRR market. This process of optimal market participation then allows the estimation of the economic value that can be realized by the industrial process via participation in DA, and mFRR, which can then feed into relevant business case calculations.

Figure 5.4 provides an overview of the market model framework and the interactions between the market inputs, the process constraints, and the optimization model. The following paragraphs describe each of these components in more detail.

The simulations were performed using historical Belgian electricity market data for the 2025 calendar year with a temporal resolution of 15 minutes, matching the settlement period of the considered markets [2, 3, 4, 5, 6]. The model considers a setting

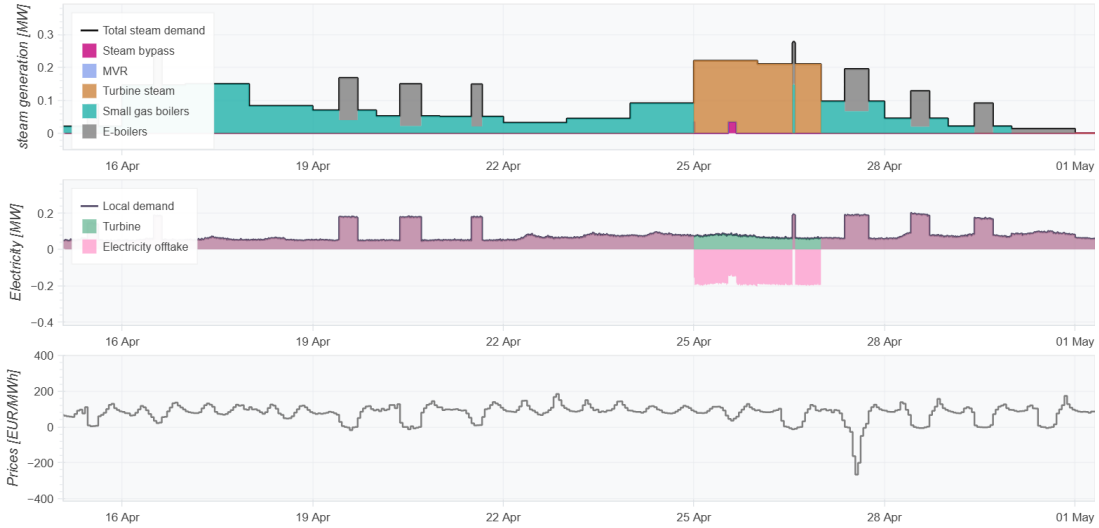


Figure 5.3: Representative dispatch schedule of the integrated steam network outside the campaign period over a 14-day horizon, illustrating the coordinated operation of the steam turbine, MVR, gas boilers, electric boilers, and process steam demand. Process variables are presented in normalized form.

of perfect foresight for the use case analysis and uses historical balancing activation volumes to determine when and how much reserved flexibility is activated. Under the perfect foresight assumption, all market prices and balancing needs are considered to be known in advance, providing an upper bound on the economic value of the available flexibility.

The feasible range of DA market bids was derived from extreme operating simulations representing maximum electricity consumption and generation, ensuring that all market schedules remained consistent with the operational limits of the steam network. The simulations cover both the sugar beet campaign and off-season periods to capture the site's strongly seasonal operating profile, with the off-season assumed to run from 11 April 2025 until 10 September 2025. Finally, the analysis focuses exclusively on operational optimization and therefore excludes investment costs and other long-term economic considerations.

5.2.3 Results

To evaluate the flexibility potential of the steam network under different market participation strategies, a set of simulation scenarios is considered. These scenarios progressively increase the level of market participation, starting from the reference operation without market optimization, followed by a DA-only optimization, and finally participation in the mFRR markets. The complete set of scenarios is summarized in Table 5.1.

Market participation strategies

In the DA-only scenario, the bidding strategy is strongly influenced by the seasonal steam demand of the sugar production process. During the campaign period, the high

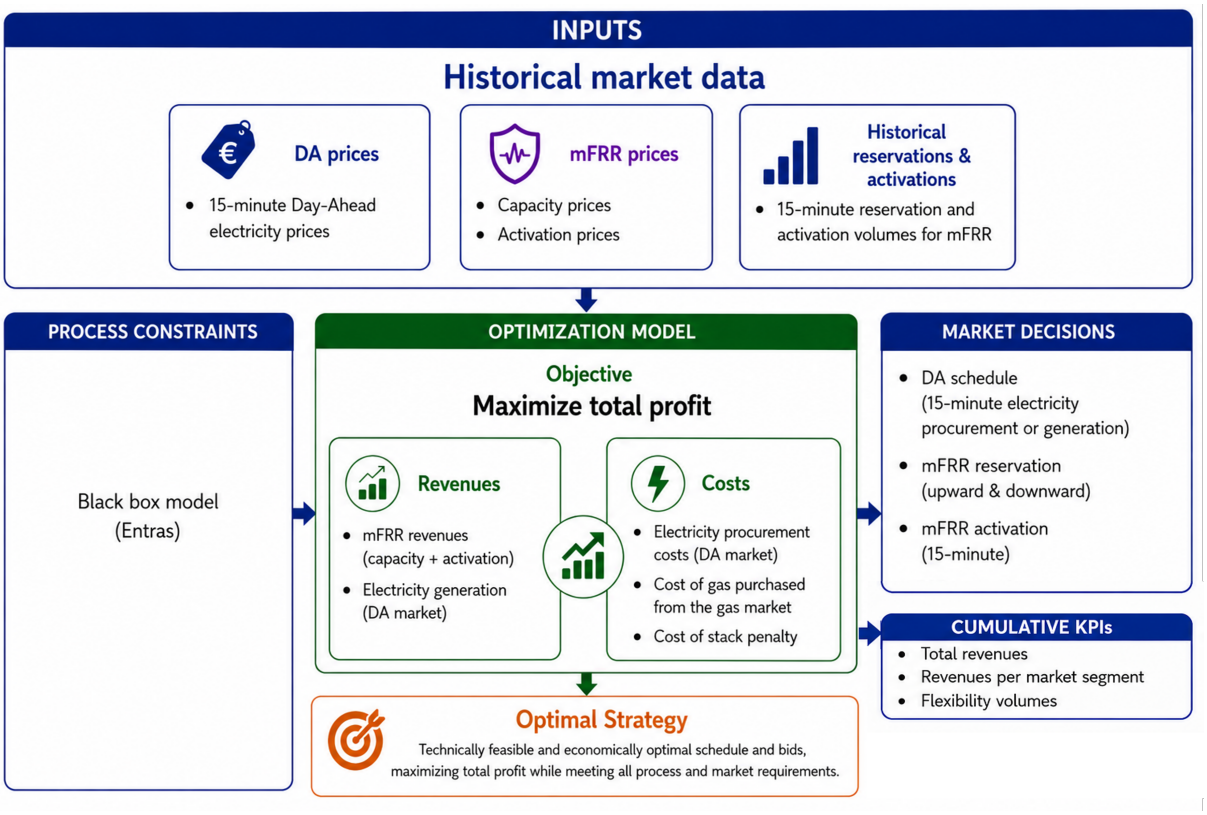


Figure 5.4: VITO's market optimization and flexibility valuation model (referred to as Market Model for short) used in the Tiense Suiker Use Case

ID	Scenario	Description
S1	No optimization	Baseline scenario.
S2	DA only	Participation in the DA market only.
S3	DA + mFRR^{+}	Participation in the DA market and upward mFRR.
S4	DA + mFRR^{-}	Participation in the DA market and downward mFRR.
S5	DA + mFRR	Participation in the DA market and both upward and downward mFRR.

Table 5.1: Simulation scenarios considered in this deliverable.

steam demand largely determines the operation of the steam network, with the MVR, large gas boiler and steam turbine operating to satisfy the process requirements. Consequently, the DA optimization mainly adjusts the balance between electricity procurement and on-site generation in response to electricity prices. During the off-season, the lower steam demand changes the operating configuration of the steam network. Steam production is primarily provided by the electric boiler and the smaller gas boilers, allowing electricity consumption to respond more directly to DA electricity price variations.

Participation in the mFRR market modifies the DA dispatch by allowing the integrated steam network to provide balancing services while respecting all process constraints. The results show that the seasonal production cycle also affects participation in the mFRR market. During the campaign period, upward mFRR reserve capacity is reserved during most of the operating period, reflecting the stable operating conditions

of the steam network under high steam demand. During the off-season, upward reserve capacity is reserved much less frequently, as the lower steam demand leads to a more dynamic DA dispatch of the available assets. Downward mFRR activations remain possible during both operating periods whenever sufficient operational headroom is available and balancing energy is requested.

Annual flexibility provision

Figure 5.6 summarizes the annual reserved upward mFRR capacity, while Figure 5.5 presents the corresponding annual activated balancing energy. Both figures show normalized values and distinguish between the campaign and off-season periods to illustrate the influence of the seasonal production cycle on the provision of flexibility. The annual flexibility provision differs between the investigated market participation scenarios. Scenario S3, which participates exclusively in upward mFRR, provides the largest annual upward reserve capacity and activated balancing energy. Scenario S4 delivers downward balancing energy, while Scenario S5, which combines upward and downward mFRR participation, achieves comparable activated energy in both directions. The results indicate that enabling simultaneous participation in both reserve directions has only a limited impact on the amount of balancing energy delivered compared with the dedicated upward and downward participation strategies.

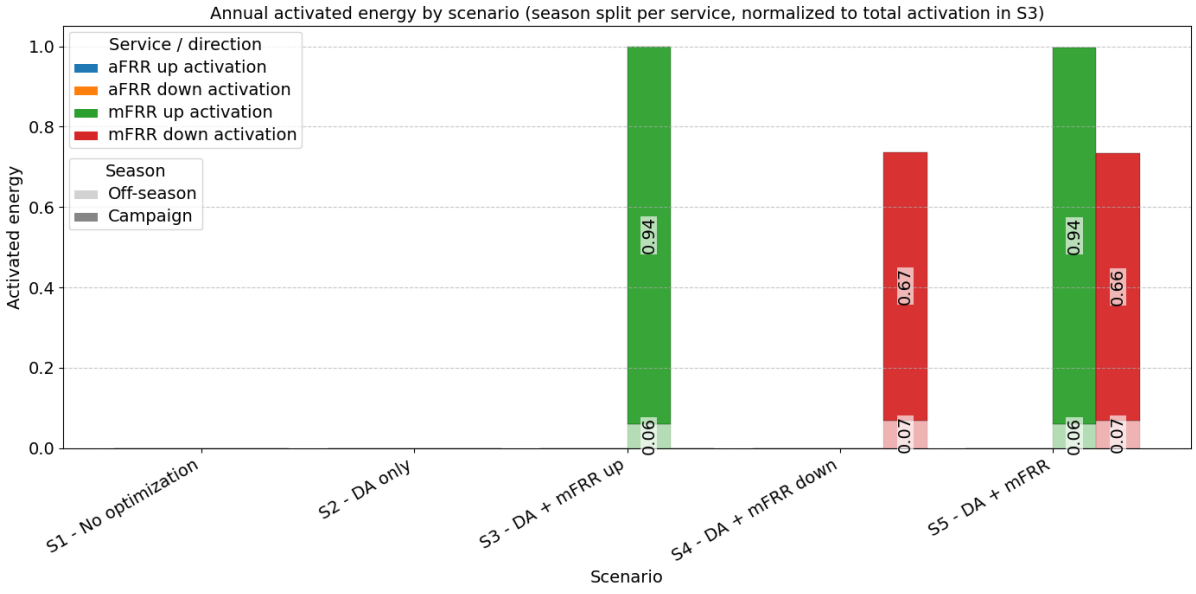


Figure 5.5: Annual activated energy by scenario - Normalized to total activation in S3

The flexibility provision is strongly concentrated during the beet campaign. In both S3 and S5, nearly all upward reserve capacity and the vast majority of upward activated energy are provided during the campaign period, whereas only a limited contribution originates from the off-season. Downward activated energy also occurs predominantly during the campaign, although the relative off-season contribution is larger than for upward balancing.

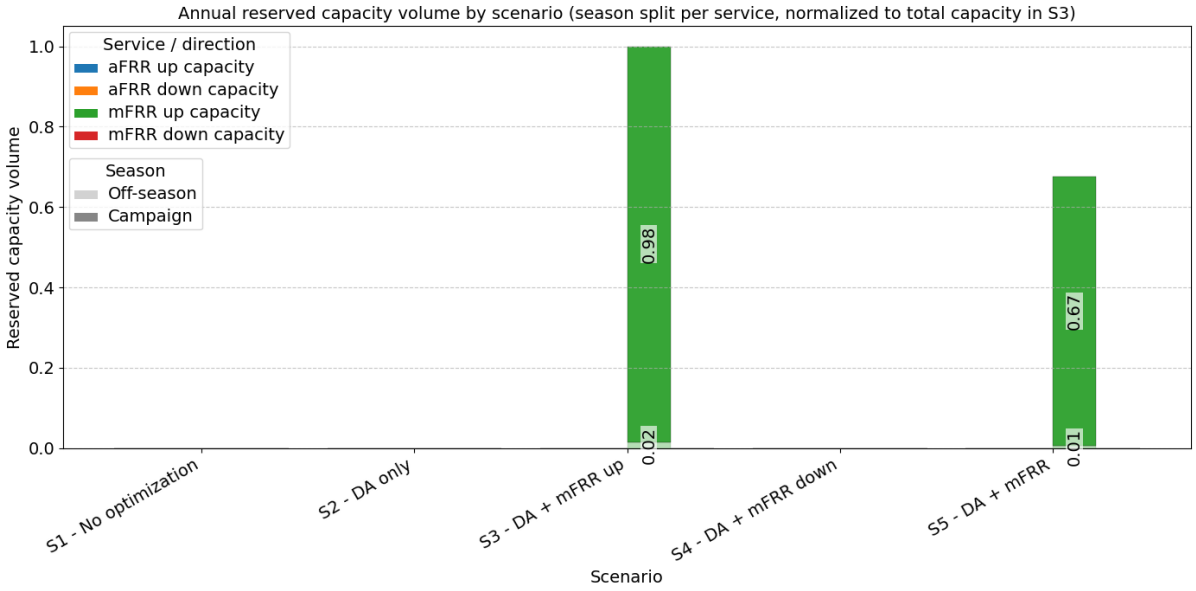


Figure 5.6: Annual reserve capacity volume by scenario - Normalized to total capacity in S3

Comparing S3 and S5 shows that allowing simultaneous upward and downward participation reduces the amount of upward reserve capacity reserved, as part of the available operational flexibility is allocated to support downward balancing services. Despite this reduction in reserved upward capacity, the annual upward activated energy remains largely unchanged, indicating that bidirectional participation enables a more balanced allocation of the available process flexibility without substantially reducing the upward balancing service delivered.

Profitability of the market participation scenarios

Figure 5.7 compares the normalized annual profits of the different market participation scenarios, distinguishing between the contribution from the DA market and the additional revenues obtained through upward and downward mFRR participation. Compared with the reference operation (S1), S2 (DA only) already substantially reduces the annual operating cost, demonstrating the economic benefit of optimizing the steam network operation according to DA electricity price variations.

Adding balancing market participation further improves the economic performance. Scenario S3 (DA + upward mFRR) achieves a considerably larger reduction in annual operating costs than S4 (DA + downward mFRR), indicating that upward mFRR participation provides significantly higher revenues than downward mFRR participation.

Scenario S5, which combines upward and downward mFRR participation, achieves the best overall economic performance. Although the DA market contribution is slightly lower than in Scenario S2, the additional balancing revenues more than compensate for this reduction, resulting in the lowest annual operating cost among all scenarios. The results further show that the profitability of the combined strategy is primarily driven by upward mFRR revenues, while downward mFRR provides an additional but smaller

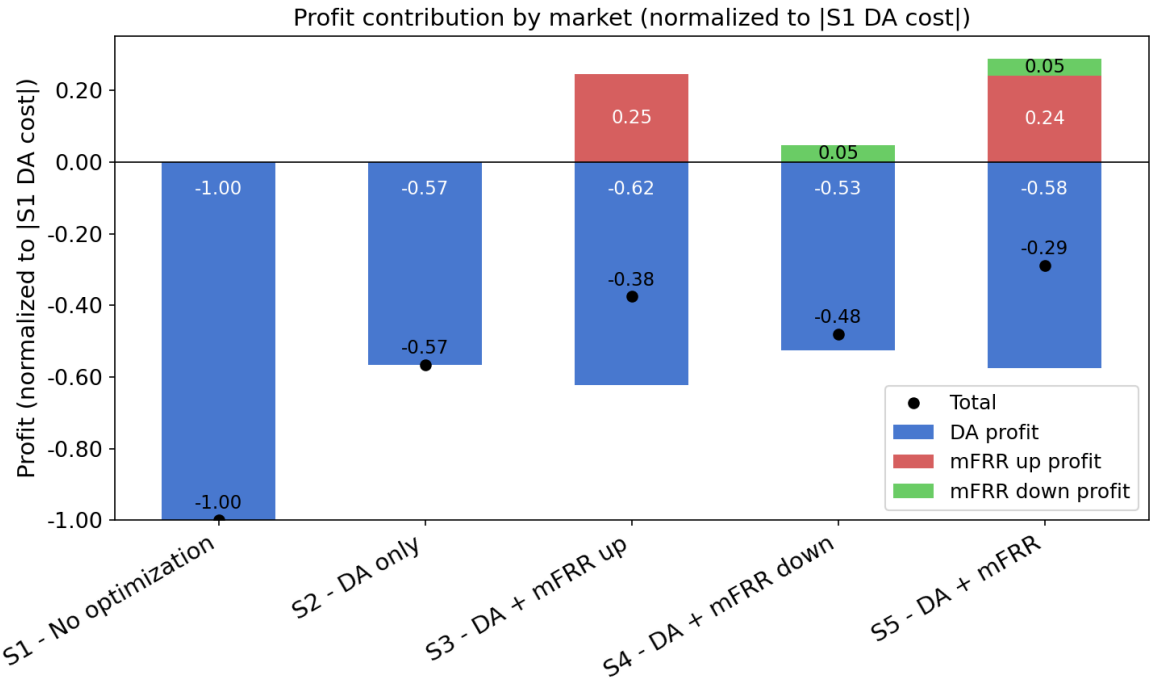


Figure 5.7: Annual profit breakdown by market for all simulation scenarios - Normalized to total profit in S1

economic contribution.

The results demonstrate that the integrated steam network can provide valuable flexibility to the electricity system while maintaining the steam requirements of the sugar production process. The seasonal production cycle strongly influences how this flexibility is deployed, with most upward reserve capacity and balancing energy provided during the beet campaign. Participation in the DA market already yields significant economic benefits by adapting the operation of the steam network to electricity price variations, while participation in the mFRR market further increases profitability. Among the investigated strategies, upward mFRR participation provides the largest additional economic benefit, and combining upward and downward mFRR participation achieves the best overall economic performance by efficiently allocating the available process flexibility across both balancing services.

5.3 Technical Fit Summary

The technical fit exercise assessed whether the Tiense Suiker integrated flexibility portfolio can technically provide flexibility services and which market requirements would need to change for additional services to become viable. The assessment maps the characteristics of the installation—including controllability, ramping capability, activation duration, availability and operational constraints—against the technical requirements of relevant Belgian flexibility mechanisms. It evaluates technical feasibility only and does

not assess economic attractiveness, contractual risk or implementation cost.

The flexible asset configuration consists of a steam turbine, gas-fired boilers, electric and hybrid boilers, and MVR units. Flexibility is mainly created by switching between gas-fired and electric heat production, changing steam-turbine output, and modulating MVR operation. Upward flexibility can be provided by reducing electric consumption and increasing gas-fired heat or steam-turbine generation, while downward flexibility can be provided by increasing electric heat production or reducing steam-turbine generation. The portfolio combines multiple technologies and therefore provides both upward and downward flexibility, but its availability and size vary between the beet campaign and the off-season.

The assessment shows that aFRR and mFRR are strong technical fits. The integrated portfolio can reach the required activation times for both aFRR and mFRR, and the combination of gas-fired generation, electric heating and steam-turbine operation can sustain activation over the relevant reservation periods. Upward reserve is supported by reducing electric heat production and increasing gas-fired heat or steam-turbine output. Downward reserve is supported by increasing electric heat production, reducing steam-turbine generation, or modulating MVR operation. The main operational uncertainty is whether all relevant assets can be controlled automatically and consistently within the required aFRR timeframe.

Spot-market participation and imbalance settlement are also good technical fits. The portfolio can shift electricity consumption and generation in response to day-ahead and intraday price signals, enabling spot market price arbitrage and fuel switching between gas and electricity. The relatively fast modulation capability also allows the installation to respond to imbalance prices, provided that process conditions and asset availability allow the required deviation.

FCR is a poor fit because the full integrated process cannot reliably provide continuous, symmetric and fully automatic response within the strict activation window, even though some individual electric heating assets may be fast enough. TSO redispatch is also a poor fit under the current framework because the site does not meet the current access conditions and the local grid context does not indicate strong redispatch relevance. The CRM is a moderate fit: generation and demand-response capacity could contribute technically, but seasonal availability, derating, autoconsumption and non-availability risk make participation less straightforward.

Table 5.2 summarizes the qualitative technical fit of the Tiense Suiker integrated flexibility portfolio with the main Belgian flexibility mechanisms. The strongest fits are aFRR, mFRR, spot-market participation and imbalance settlement; CRM is a moderate fit, while FCR and TSO redispatch are poor fits under the current technical and market-design conditions.

Market / product	Technical fit	Main qualitative rationale
FCR (primary reserve)	**Poor**	The full integrated process cannot reliably provide continuous, symmetric and fully automatic response within the strict activation window.
aFRR up (secondary reserve)	**Good**	Upward flexibility can be delivered by reducing electric heat production and increasing gas-fired heat or steam-turbine generation within the required activation time.
aFRR down (secondary reserve)	**Good**	Downward flexibility can be delivered by increasing electric heat production, reducing steam-turbine generation, or modulating MVR operation within the required activation time.
mFRR up (tertiary reserve)	**Good**	The portfolio can reduce electrical consumption or increase generation within the required activation time and sustain activation over the reservation period.
mFRR down (tertiary reserve)	**Good**	The portfolio can increase electrical consumption or reduce generation within the required activation time and sustain downward activation when the relevant assets are available.
Day-ahead market	**Good**	The asset combination enables spot market price arbitrage and fuel switching by shifting electricity consumption and generation in response to wholesale prices.
Intraday market	**Good**	The portfolio can adapt electricity consumption and generation closer to delivery as updated market signals become available.
Imbalance settlement	**Good**	Relatively fast modulation allows the installation to react to imbalance prices, provided that process conditions and asset availability allow the deviation.
Congestion management (TSO redispatch)	**Poor**	The portfolio is technically controllable, but current redispatch access is constrained by the applicable framework and the local grid context.
CRM	**Moderate**	Generation and demand-response capacity could contribute technically, but seasonal operation, derating, autoconsumption and non-availability risk complicate participation.

Table 5.2: Qualitative technical-fit summary for the Tiense Suiker integrated flexibility portfolio across Belgian flexibility mechanisms.

Chapter 6

Tiense Suiker BUC 4B: Summary of Key Findings

6.1 Introduction

Tiense Suiker is part of an international sugar production company headquartered in Germany, with production facilities in both Flanders and Wallonia. Its Belgian operations are shaped by a strongly seasonal production profile, where the main sugar beet campaign runs from September to January and creates a much higher energy demand than the rest of the year. This seasonality makes energy procurement, electrification, and flexibility planning more complex, especially because investment decisions and energy strategies are managed across regions with different regulatory conditions.

Within GALILEO, Tiense Suiker is investigating how its steam and energy systems can support decarbonization while improving the business case for flexibility. The work focuses on two linked areas: the coordinated operation of an upgraded steam network for market participation, and the development of a longer-term energy procurement and investment strategy that better matches the company's seasonal heat and electricity needs. This chapter focuses on the second aspect.

6.1.1 BUC 4B description

BUC 4B focuses less on a single flexible technology and more on Tiense Suiker's long-term energy strategy. The company's electricity demand is highly seasonal: during the campaign period, consumption can reach around 14 MW with continuous operation, while outside the campaign it falls to roughly 1.5 to 2 MW. This creates a mismatch with standard renewable PPAs, especially solar PPAs, because peak solar production occurs outside the period when Tiense Suiker has its highest demand.

The use case investigates how existing and future PPAs interact with electrification investments, heat demand, and potential long-duration energy solutions. Electrification is expected to increase campaign-period electricity consumption further, which strengthens the need for procurement strategies that are aligned with the production cycle. Due to the seasonal mismatch between renewable generation profiles and industrial electricity demand, the suitability of conventional procurement strategies and storage solutions needs to be evaluated.

The analysis therefore explores strategic options for addressing the mismatch between renewable electricity availability and seasonal industrial demand. These options include long-duration storage concepts and expanded onsite biomethanization using biowaste. Biomethanization is considered particularly relevant because it could reduce dependence on natural gas while fitting more closely with Tiense Suiker's long-term business strategy and seasonal energy needs. The purpose of the BUC is therefore to compare strategic options for reducing energy costs, improving procurement stability, and supporting the company's decarbonization pathway.

Research questions

The following research questions are investigated within the scope of this BUC analysis across the different project tasks:

1. How does the integration of flexibility activation impact the PPAs?
2. What are the potential technical and operational solutions to optimise Tiense Suiker's energy consumption, and how do these solutions, e.g., long-term thermal storage, power-to-(bio)gas conversion) compare in terms of financial impact?
3. Considering future process electrification, what is the optimal long-term strategy for energy procurement?

6.2 Long-term Energy Procurement Strategy and Decarbonisation Recommendations

Use Case 4B evaluated three decarbonisation pathways for Tiense Suiker: MVR, renewable electricity procurement through PPAs, and biomethanisation. The assessment was based on operational data from 2025 and considered both technical feasibility and economic performance.

Among the options analysed, MVR emerges as the most attractive decarbonisation measure. By electrifying the evaporation and crystallisation processes, MVR can replace the majority of the site's steam demand and significantly reduce natural gas consumption. Even under conservative assumptions, the technology delivers strong economic performance, with a short payback period. The main challenges remain the high upfront investment and the increased exposure to electricity market prices.

As electrification increases the site's dependence on electricity, long-term renewable electricity procurement becomes increasingly important. While PPAs do not necessarily reduce electricity costs under current market conditions, they provide protection against future electricity price volatility and can support the long-term operation of an electrified production system. Large off-site PPAs, financial PPAs, and other PPA structures are only recommended when there is clear economic potential, as they often deliver limited or even negative short-term cost savings. Risk premiums will need to be paid depending on the level of protection required by Tiense Suiker and its overall risk management strategy.

To supply the residual steam demand remaining after MVR implementation, the preferred option is the use of electric boilers. Biomethanization was found to be a less attractive primary decarbonisation pathway. Although it requires a lower initial investment than MVR, its economics depend heavily on operating costs, feedstock availability, biomethane certificate revenues, and future policy developments. Biomethane is therefore better suited as a complementary solution for residual gas demand that remains difficult to electrify, or where a small biomethanization facility can economically meet the remaining demand. It also requires the continued operation of gas boilers and CHP units, which may introduce additional operating costs while providing limited additional benefits.

Overall, the results indicate that process electrification through MVR offers the largest emissions reduction and the strongest economic potential. Renewable electricity procurement and long-term hedging should be considered important supporting measures to manage electricity price risks, while electric boilers and biomethane may play a role in supplying residual thermal demand and facilitating further decarbonisation in the longer term.

The results demonstrate that the choice of decarbonisation pathway should be evaluated from both a technical and an economic perspective. In this case study, electrification through MVR provides the largest emissions reductions and the most cost-effective long-term solution, although the associated capital investment and increased dependence on electricity prices remain important challenges. Biomethane, while not identified as the preferred decarbonisation pathway, represents a valuable complementary option due to its lower investment requirements and compatibility with existing thermal infrastructure. It can therefore contribute to supplying residual thermal demand and supporting applications that are more difficult to electrify. These findings highlight the importance of considering technology performance, investment costs, and future energy market conditions when selecting industrial decarbonisation strategies.

Chapter 7

LCL Data Centers BUC 5: Summary of Key Findings

7.1 Introduction

LCL Data Centers is a Belgian co-location data center operator providing critical digital infrastructure services with high requirements for reliability, up-time, and operational continuity. Unlike many industrial processes, like those presented in the other GALILEO use cases, the electricity demand of a data center is largely stable and continuous, with only limited variation linked to cooling requirements and external weather conditions. As digitalization, cloud computing, artificial intelligence, and high-performance computing continue to drive growth in electricity consumption, data centers are becoming increasingly important actors within the electricity system.

LCL Data Centers is investigating how battery storage, renewable generation, and energy management strategies can be integrated into its facilities to provide flexibility services without compromising the reliability of core IT operations. The company already operates on-site solar PV generation and is evaluating future expansions in both solar and wind capacity alongside increasing IT loads.

7.1.1 BUC 5A description

This use case assesses the potential contribution of a large-scale data center portfolio to electricity-system flexibility through battery storage and on-site renewable generation. LCL Data Centers operates several facilities in Belgium with a cumulative grid connection capacity of approximately 50 MW and existing PV generation, while future plans include the expansion of both solar and wind generation alongside growth in the underlying IT load. Because the computing infrastructure must operate continuously, the flexibility potential comes primarily from the interaction between the Battery Energy Storage System (BESS), renewable generation, cooling infrastructure, and grid management strategies.

The study focuses on how the size of the BESS and renewable installations affects the amount and duration of flexibility that can be provided. In particular, the technical capabilities of BESS are being evaluated for participation in balancing and ancillary

service markets such as FCR, aFRR, and mFRR, where fast response times are essential. The battery can absorb or inject power depending on the grid conditions, helping to manage renewable variability, reduce grid stress, and optimize electricity procurement in the day-ahead market.

A key part of the research is determining how these flexibility services can be activated without compromising the reliability requirements of the data center. While the IT systems themselves remain largely inflexible, the use case explores how supporting infrastructure and energy storage can allow the facility to participate more actively in electricity markets. The work also provides insight into how future data centers with larger AI and other high-performance computing workloads could integrate flexibility services alongside growing renewable energy deployment.

Research questions

The following research questions are investigated within the scope of this BUC analysis across the different project tasks:

1. How can BESS integrated with renewable energy maximize value in the day-ahead market and what system sizing and technological parameters ensure economic viability?
   (a) How can a BESS be operated to balance the renewable generation portfolio and perform energy arbitrage in the day-ahead market? A case study on peak-load shifting is considered.
   (b) For solar installations, how many hours should a battery be able to store in order to be economically viable?
2. What flexibility mechanisms can be provided by LCL Data Centers? What market requirements must change (and to what extent) for additional services to become viable for LCL Data Centers?
3. What are the operational and economic implications of implementing a flexible grid connection? Which measures would LCL Data Centers need to put in place to ensure 100% reliable operation of its data centers?

Research Questions 1 and 3 are addressed in the following sections, while research question 2 is addressed in two parts: the technical suitability of LCL Data Centers to provide different flexibility mechanisms (technical fit) is addressed in this chapter, while the market design changes required to enable additional flexibility are discussed in Deliverable D3: Market Design to Support Industrial Competitiveness and Flexibility [1]

7.2 Optimization Model

A techno-economic optimization framework was developed to determine the economically optimal BESS size and operational strategy. The optimization aims to maximize

the Net Present Value (NPV) of the battery investment over the project lifetime while satisfying battery operational constraints, grid connection limits, and renewable generation characteristics.

The optimization considers:

- Electricity procurement costs,
- Battery investment costs,
- Battery degradation effects,
- Charging and discharging efficiencies,
- Grid connection constraints,
- Renewable energy generation profiles, and
- Battery operational constraints.

The BESS charging and discharging schedule is optimized according to day-ahead electricity market prices. During low-price periods, the BESS charges either from excess renewable generation or from the grid. During high-price periods, the BESS discharges stored energy to reduce grid electricity offtake or increase electricity market revenues. The optimization framework also accounts for annual battery degradation, which reduces the usable battery capacity over the project lifetime and therefore affects the long-term economic performance of the storage system.

7.3 Optimal BESS Sizing Results

The analysis considered battery investment costs between 120 and 160 k€/MWh, discount rates ranging from 4% to 7%, and annual battery degradation rates between 0% and 1.8%. These sensitivity analyses provide insight into the key factors affecting the economic viability of BESS deployment in data centre applications.

7.3.1 Impact of Investment Cost and Discount Rate

Figure 7.1 illustrates the variation of the optimal BESS size with battery investment cost and discount rate for the case without battery degradation. The results show that both battery investment cost and discount rate strongly influence the economically optimal BESS capacity. Lower investment costs and lower financing costs result in larger economically viable BESS installations due to the increased value of operational savings obtained through energy arbitrage and renewable energy utilization.

For example, at an investment cost of 120 k€/MWh and a discount rate of 4%, the optimal BESS size is approximately 12.5 MWh. However, increasing the investment cost to 160 k€/MWh significantly reduces the optimal BESS size. At higher investment costs and discount rates, economically viable BESS investments are no longer obtained.

The results demonstrate that financing assumptions and battery capital costs are critical parameters influencing the economic feasibility of large-scale BESS deployment.

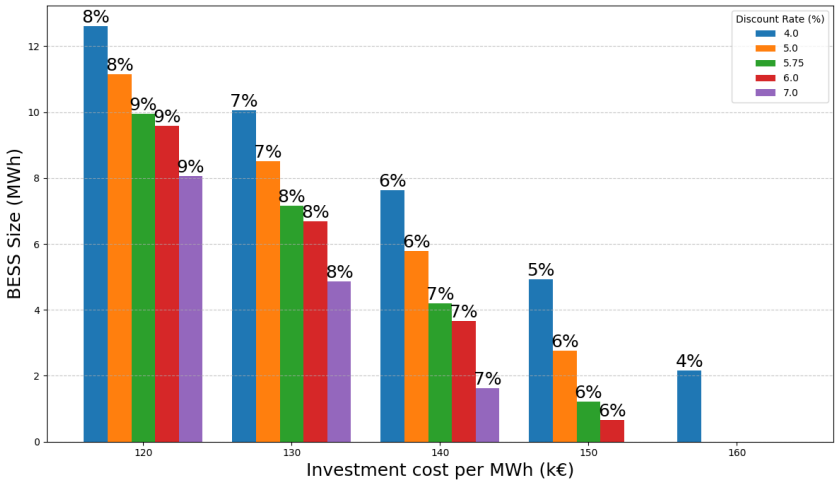


Figure 7.1: Variation of optimal BESS size with investment cost and discount rate

7.3.2 Impact of Battery Degradation

Figure 7.2 presents the variation of the optimal BESS size for different annual battery degradation rates. The results indicate that increasing battery degradation significantly reduces the economically optimal BESS capacity. Higher degradation rates reduce the usable battery capacity over time, thereby decreasing the long-term operational savings obtained from the storage system. For example, at an investment cost of 130 k€/MWh and a discount rate of 4%, the optimal BESS size decreases from approximately 10.1 MWh in the no-degradation case to nearly 7.6 MWh for an annual degradation rate of 1.8%.

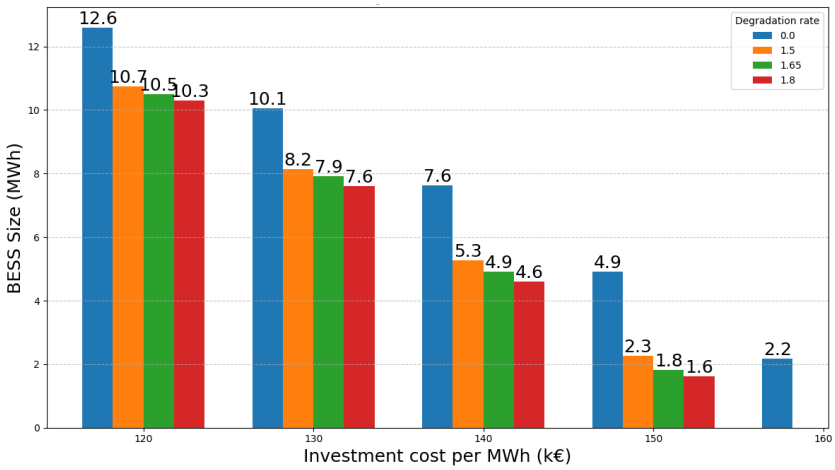


Figure 7.2: Variation of optimal BESS size with battery investment cost for different annual degradation rates

Overall, the results demonstrate that battery degradation has a substantial influence on the long-term profitability and feasible deployment size of battery storage systems.

7.4 Impact of BESS on Grid Offtake

The optimization results demonstrate that BESS operation significantly alters the grid electricity offtake profile by shifting electricity consumption from low-price periods to high-price periods. Figure 7.3 illustrates the difference between the grid electricity offtake with and without BESS operation under varying electricity market prices.

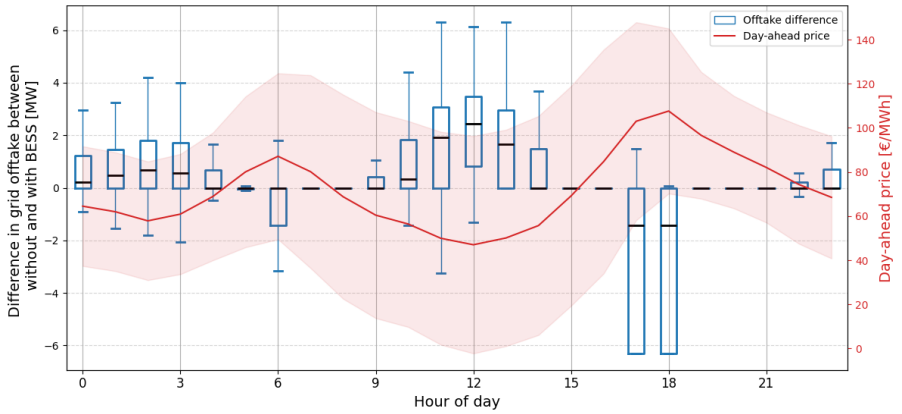


Figure 7.3: Impact of BESS operation on grid electricity offtake under varying day-ahead electricity prices

The results clearly demonstrate that the BESS performs energy arbitrage by shifting electricity consumption from low-price periods to high-price periods. During periods with low electricity prices, the BESS charges from the grid or excess renewable generation, resulting in an increase in grid electricity offtake. Conversely, during high-price periods, the BESS discharges stored energy to reduce electricity imported from the grid.

Significant reductions in grid electricity offtake are observed during evening peak-price periods, indicating that the BESS operation is strongly influenced by electricity market prices and optimized to maximize economic benefit. These results further demonstrate the capability of the BESS to perform peak shaving and improve the operational flexibility of the energy system.

7.5 Peak Generation Shifting Using PV and BESS

The study also evaluated the integration of BESS with PV generation systems located at different geographical locations in order to maximize revenue from participation in the day-ahead electricity market. Table 7.1 summarizes the considered PV locations together with the corresponding BESS capacities.

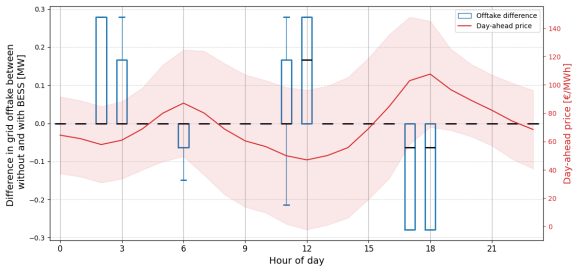
The economic analysis demonstrated that integrating BESS with PV generation systems significantly increases the market value of renewable electricity generation through peak-generation shifting and electricity market arbitrage. Across the considered locations, the integration of BESS increased annual revenues by approximately 15–27%, corresponding to additional annual benefits between 9.5 k€ and 14.2 k€ per year. The results demonstrate the capability of battery storage systems to increase the market

Location	PV Capacity [MWp]	BESS Capacity [MWh]
Zwevegem	0.877	0.558
Langemark-Poelkapelle 1	0.900	0.837
Langemark-Poelkapelle 2	0.890	0.837
Eeklo	0.717	0.837

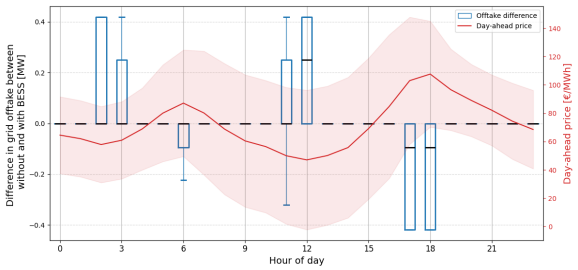
Table 7.1: PV generation locations and corresponding BESS capacities

value of renewable electricity by shifting generation from low-price periods to periods with higher electricity prices.

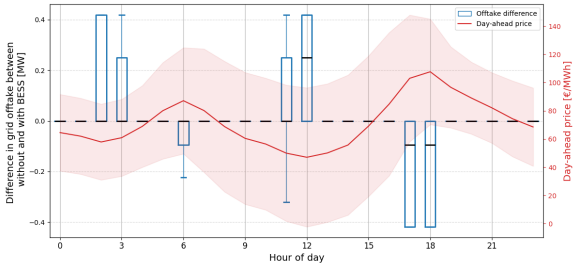
Figure 7.4 illustrates the operational behavior of the PV-integrated BESS systems for the considered locations. The results show that the BESS charges during periods with relatively low electricity prices and discharges during high-price periods, thereby increasing electricity injection into the grid when market prices are highest.



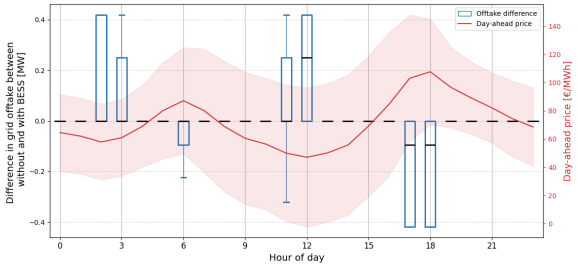
(a) Zwevegem



(b) Langemark-Poelkapelle 1



(c) Langemark-Poelkapelle 2



(d) Eeklo

Figure 7.4: Impact of PV-integrated BESS operation on electricity injection for different PV generation locations

Among the considered locations, the Langemark-Poelkapelle sites and Eeklo achieved the highest annual economic benefit due to their larger installed BESS capacities of 0.837 MWh. As shown in Table 7.2, the integration of BESS increased the annual revenue from 64.99 k€/year to 79.18 k€/year for Langemark-Poelkapelle 1 and from 64.27 k€/year to 78.46 k€/year for Langemark-Poelkapelle 2, resulting in an additional annual benefit of approximately 14.2 k€/year. Similarly, for the Eeklo location, the annual revenue increased from 51.78 k€/year to 65.96 k€/year, corresponding to the same annual benefit of approximately 14.2 k€/year.

For the Zwevegem location, which is equipped with a smaller BESS capacity of 0.558 MWh, the annual revenue increased from 63.33 k€/year to 72.79 k€/year, result-

ing in an additional annual benefit of 9.46 k€/year. Although the absolute benefit is lower than for the other locations, the results still demonstrate the economic value of integrating battery storage with PV generation.

Overall, Table 7.2 shows that the use of BESS increases the annual revenue by approximately 15–27% across the considered locations. These additional revenues are achieved by shifting PV generation from periods with lower electricity prices to periods with higher market prices. The results therefore demonstrate that integrating battery storage with renewable generation systems can significantly improve the profitability and market value of renewable electricity assets participating in the day-ahead electricity market.

Location	PV Size [MWp]	BESS Size [MWh]	Annual Revenue Without BESS [k€/year]	Annual Revenue With BESS [k€/year]	Annual Benefit [k€/year]
Zwevegem	0.877	0.558	63.33	72.79	9.46
Langemark-Poelkapelle 1	0.900	0.837	64.99	79.18	14.19
Langemark-Poelkapelle 2	0.890	0.837	64.27	78.46	14.19
Eeklo	0.717	0.837	51.78	65.96	14.19

Table 7.2: Economic performance of PV and BESS systems for peak-generation shifting without battery degradation

7.6 Technical Fit Summary

The technical fit exercise assessed whether LCL Data Centers' flexible assets can technically provide flexibility services and which market requirements would need to change for additional services to become viable. The assessment maps the key characteristics of the installation—such as flexible capacity, response speed, activation duration, availability and operational constraints—against the technical requirements of relevant Belgian flexibility mechanisms.

The flexible asset base considered in the assessment consists of on-site renewable generation and battery energy storage. The data center load itself is treated as non-flexible, as IT operations, cooling and auxiliary systems must preserve high availability and operational continuity. The main flexibility potential therefore comes from the BESS, which can provide both upward and downward flexibility, and from curtailable renewable generation, which can mainly contribute downward flexibility when production is available. Participation requires that renewable generation can be curtailed under the applicable PPA and that relevant assets can be controlled automatically.

Table 7.3 summarizes the qualitative technical fit of the LCL Data Centers flexible asset configuration with the main Belgian flexibility mechanisms.

The assessment shows that LCL Data Centers is best suited for spot-market participation and imbalance-related optimization. The BESS can perform spot market price arbitrage in the day-ahead and intraday markets by charging during low-price periods and discharging during high-price periods, while renewable generation can be curtailed during negative-price or otherwise adverse market conditions. Imbalance settlement is also a strong technical fit because the BESS can react opportunistically to imbal-

Market / product	Technical fit	Main qualitative rationale
FCR (primary reserve)	**Good**	Fast BESS response enables technical participation, but market saturation may limit commercial attractiveness.
aFRR up (secondary reserve)	**Moderate**	Technically feasible response speed, but upward capacity reservation is constrained by duration and minimum bid requirements.
aFRR down (secondary reserve)	**Moderate**	BESS and renewable curtailment can provide downward flexibility, but intermittency and forecasting requirements increase complexity.
mFRR up (tertiary reserve)	**Moderate**	Activation speed is sufficient, but upward capacity reservation remains constrained by the required reservation duration and minimum bid size.
mFRR down (tertiary reserve)	**Good**	BESS charging and renewable curtailment provide a good technical basis for downward activation, preferably via aggregation.
Day-ahead market	**Very good**	BESS can perform spot market price arbitrage and renewable generation can be curtailed during negative-price periods.
Intraday market	**Very good**	The asset configuration can adjust closer to real time through BESS operation and renewable curtailment.
Imbalance settlement	**Very good**	BESS operation and renewable curtailment can be used opportunistically to respond to imbalance price signals.
Congestion management (TSO redispatch)	**Poor**	The assets are technically controllable, but current redispatch access is limited by the applicable minimum asset-size threshold.
CRM	**Poor**	Derating, duration requirements and aggregation needs make participation difficult for the current flexible asset configuration.

Table 7.3: Qualitative technical-fit summary for LCL Data Centers across Belgian flexibility mechanisms.

ance prices and renewable generation can be curtailed to reduce exposure to adverse imbalance positions.

Balancing-service participation is technically possible but more constrained. FCR is a good technical fit because the BESS can meet the fast response requirements. Downward mFRR is also a good fit, as both the BESS and curtailable renewable generation can contribute downward flexibility. aFRR and upward mFRR are only moderate fits: the response speed and activation duration are technically adequate, but the capacity reservation duration and minimum bid requirements constrain participation, especially for upward services. Participation through aggregation is therefore likely to be preferable for several balancing products.

Congestion management under the current TSO redispatch framework and participation in the CRM are poor fits in the current configuration. For redispatch, the main barrier is the current minimum asset-size threshold, although future implementation steps under iCAROS may improve accessibility for smaller assets. For CRM, the combination of derating, duration requirements and aggregation needs makes participation difficult for the currently considered flexible asset configuration.

7.6.1 Impact of Flexible Connection Agreements on LCL Data Centers

Elia is moving from project-specific flexible access solutions to a structured contract framework. On the federal 110 kV and above grid, revised connection contracts and coordination rules are under public consultation, with a target go-live in Q2 2027. On the **Flemish 30–70 kV local transport grid**, the **temporary Fall-back flex PVN product** is already approved and can be used pending the implementation of a regional framework.

Flexible connection agreements are structured around **firm power, flexible power, an energy cap and a temporary period**. The setpoint is applied to a **congestion modulation group** rather than automatically to the whole site. Activation inside contractual limits can be **preventive** or **curative**. Activation beyond contractual limits is intended as a last-resort, curative action and is paired with cost-based remuneration in the federal design. The current Flemish temporary product does not provide remuneration and leaves imbalance risk with the grid user.

For LCL Data Centers, the main operational implication is the need to manage real-time, unpredictable curtailments with very limited notice. While existing firm demand is relatively well protected, flexible capacity can be curtailed frequently depending on local grid conditions and the site's impact on congestion. **As a result, data center reliability depends on the availability of fast-reacting, controllable on-site assets.**

The primary mitigation strategy is therefore the deployment and correct configuration of **on-site flexibility**. Existing batteries and generators could potentially be used – or new ones can be placed in the congestion modulation group – and are likely to be activated before pure demand. Sizing should be based only on the contracted curtailed power and energy cap, rather than on total site load. Existing uninterruptible power supply (UPS) systems are not suited for covering curtailments under flexible connection agreements, as they are designed to provide emergency support during full grid outages (blackouts) and can only do so for a duration of maximally 10 minutes. Contractual stipulations with its customers also oblige colocation data centers to use

UPS systems solely for this purpose, and not for other grid flexibility activations. Batteries could also bridge curtailments, but are energy-limited and require careful sizing for covering maximum-duration events. In cases where existing assets are insufficient to bridge curtailments, additional controllable and reliable generation assets may be required.

Flexible connection agreements enable faster grid connection capacity expansions or new grid connections, but transfer a significant share of grid congestion risk to the grid user. Reliable data center operation therefore requires clear agreements with Elia, assets capable of bridging curtailment periods, and robust operating procedures or automation. These measures may be costly. Previous simulations showed that BESS are not profitable under normal market conditions 7.3, while reserving capacity to manage FCA curtailments further restricts their participation in electricity markets. Diesel generators may offer a cheaper alternative but conflict with EU decarbonization objectives. FCAs may thus have an unintended consequence: while enabling electrification, they could incentivize additional fossil-fuel backup generation to maintain high operational availability. This highlights a fundamental tension between grid flexibility, data center reliability, BESS economics, and EU decarbonization objectives.

Chapter 8

Conclusion

The industrial BUCs presented in this deliverable demonstrate that industrial flexibility is highly site-specific and cannot be characterized by a single technology or market participation strategy. Across all investigated cases, the available flexibility depends on the interaction between process constraints, asset characteristics, operational objectives, and electricity market conditions. Nevertheless, several common observations emerge. First, all BUCs demonstrate that industrial assets can contribute flexibility while maintaining their primary industrial function. The investigated assets range from waste heat recovery systems, gas boilers, and electric boilers to an electrolysis process, steam turbines, integrated hot water and steam networks and battery energy storage systems. Although the source of flexibility differs between cases, the optimization results consistently show that flexibility can be activated without compromising the core industrial production process when operational constraints are explicitly represented in the optimization models.

Second, the industrial BUCs also show that the most profitable market participation strategy depends on the characteristics of the industrial process. For the Aperam ORC BUC, participation in aFRR-up in addition to the DA market provides the highest revenue potential, while coordinated participation across multiple markets further improves economic performance. For the Aperam e-boiler BUC, upward balancing services, particularly aFRR-up and mFRR-up, generate substantial additional revenues, with coordinated multi-market participation delivering the highest overall value. Nyrstar derives the highest economic value by stacking revenues across multiple electricity markets, exploiting the operational flexibility of the electrolysis process. Tessenderlo obtains most of its flexibility revenues through downward aFRR participation, while additional value can be realized by combining multiple market products. In contrast, Tiense Suiker already achieves significant savings through optimized participation in the day-ahead market, with upward mFRR providing the largest additional revenues. Unlike the other cases, the flexibility potential at Tiense Suiker is strongly influenced by its seasonal production cycle, with most balancing services being delivered during the beet campaign. For LCL Data Centers, the strategic use of BESS for peak-load and renewable-generation shifting produces significant economic gains by reducing high-price grid offtake and increasing the value of renewable electricity.

Third, the BUCs highlight an important trade-off between investment in additional flexibility capacity and the additional economic value that this capacity can unlock. In-

vesting in additional conversion, process-buffer or storage capacity can generate significant additional value when the increased capacity creates flexibility that can be effectively utilised across electricity markets. This is particularly evident for the Nyrstar Virtual Battery, where increased process-buffer and electrolyser capacity enables substantial long-duration demand flexibility and creates additional value through electricity procurement optimisation and participation across multiple balancing markets. At the same time, the Aperam cases show that the marginal value of additional capacity can differ substantially between asset components and may eventually exhibit diminishing returns, for example when additional thermal storage no longer enables significant additional market opportunities. The LCL Data Centers case further demonstrates that the economically attractive capacity depends strongly on investment cost, financing assumptions and asset degradation. Consequently, there is no general relationship whereby either larger or smaller flexibility assets are economically preferable. Asset dimensioning should instead balance the additional investment required against the additional revenues, cost savings and operational benefits that the incremental capacity can unlock. The economically appropriate investment is therefore site-specific and depends on process characteristics, technology costs, utilisation, and the range and expected value of accessible market opportunities.

Fourth, the BUCs reveal systematic differences in flexibility potential across technologies and industrial processes. These differences appear to be driven less by the industrial sector itself than by the physical characteristics and integration of the flexible assets within the production process. In particular, process and energy buffering can substantially increase flexibility by decoupling the timing of electricity consumption or generation from the requirements of the core industrial process. This is particularly evident at Nyrstar, where process buffers enable a continuous electrolysis process to provide long-duration upward and downward flexibility, and at Aperam, where thermal storage enables the ORC and e-boiler to shift electricity generation or consumption while respecting heat and steam requirements. Where such buffering is absent or limited, flexibility is more directly constrained by the instantaneous operating range and production requirements of the asset. The type and configuration of the technology also determine the speed, direction and duration of the flexibility that can be provided: batteries offer rapid bidirectional response, while thermal and process-based flexibility depends more strongly on storage state, heat availability and process operating conditions. Production patterns provide another important differentiator. Continuous processes can offer recurring flexibility when sufficient buffering or operational margins are available, whereas seasonal processes, as illustrated by Tiense Suiker, may provide substantial flexibility only during specific production periods. Finally, location becomes particularly relevant where flexibility interacts with grid constraints: local congestion and connection conditions can determine whether congestion-management services or flexible grid connections provide additional value. Overall, the results suggest that flexibility potential should therefore be assessed at the level of the integrated process and site rather than inferred primarily from the industrial sector or individual technology.

Fifth, the BUCs indicate that relevant industrial flexibility potential may remain untapped because identifying and monetising this potential is itself a complex task. A first challenge is the assessment of technically feasible flexibility within complex industrial processes. Flexibility cannot generally be inferred from installed electrical ca-

pacity alone, but requires an integrated understanding of process constraints, operating ranges, buffering possibilities, production schedules and interactions between energy and production assets. This challenge becomes particularly relevant when considering future investment and electrification pathways, as these can fundamentally change both electricity demand and the flexibility characteristics of an industrial site. A second challenge is translating the identified technical flexibility into participation in existing flexibility products. The technical-fit assessments provide a helpful tool for performing a quick and rough first scan of technical feasibility of delivering flexibility services. They show that not every source of industrial flexibility is suitable for every market product: response-time requirements, activation and reservation duration, minimum bid sizes, symmetry requirements, availability, aggregation requirements and process-specific constraints can all limit participation even where physical flexibility exists. The BUCs therefore demonstrate an important distinction between physical, market-compatible (technical), and economically attractive flexibility potential. Across the BUCs, day-ahead and intraday trading and imbalance settlement show the broadest technical potential, as their response-time and delivery requirements can be accommodated by all assessed installations. aFRR and mFRR also offer substantial potential, but participation is more installation- and direction-specific, with controllable headroom, automatic control capability, buffer state and process-dependent availability as the main constraints. FCR is the most technically demanding balancing product because its fast, automatic and symmetric response requirements can be met reliably only by highly controllable assets, while congestion management currently has limited potential due to locational eligibility and minimum bid-size constraints. CRM participation appears technically feasible for several installations, although derating, seasonal or process-dependent availability and service-level obligations require case-specific verification. Across the assessed installations, buffering and thermal storage emerge as important technical enablers because they decouple electricity use or generation from immediate production requirements and can extend the duration for which flexibility is delivered. Large electricity consumers are also more likely to meet minimum bid sizes, although installed capacity or total consumption alone is insufficient: participation depends on the controllable headroom that can be reliably made available at the prevailing operating point, potentially through aggregation. Further success factors include fast and automated control, operational redundancy, predictable availability and the ability to coordinate multiple assets or energy carriers. Conversely, tight process coupling, insufficient or asymmetric headroom, seasonal availability and product-specific requirements concerning response time, delivery duration and location remain the principal technical barriers.

Finally, the industrial BUCs illustrate that flexibility can also support broader industrial decarbonisation strategies, although the relationship differs between sites. At Aperam, the ORC supports decarbonisation by improving the utilisation of industrial waste heat, while the e-boiler enables greater renewable electricity self-consumption and reduces natural gas use for steam production, and creates additional operational flexibility. At Tiense Suiker, the strategic assessment identifies process electrification through MVR as the preferred decarbonisation pathway, while highlighting that increased electrification also increases exposure to electricity markets and therefore strengthens the importance of appropriate renewable electricity procurement strategies.

At LCL Data Centers, BESS supports decarbonisation by increasing the utilisation and market value of on-site renewable generation, reducing peak grid demand, and enabling more flexible integration of additional renewable capacity.

The GALILEO BUCs demonstrate that industrial flexibility can contribute to electricity-system operation and industrial decarbonisation, but that unlocking this potential requires consideration of process-specific constraints, investment decisions and the compatibility between industrial flexibility characteristics and market requirements. The findings presented in this deliverable provide an evidence base for subsequent GALILEO activities, which will further examine market-design barriers and develop a coherent set of recommendations and roadmap actions for facilitating industrial flexibility.

References

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