
Master Energy Science

Economic performance of BESS on the aFRR

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Abstract

In response to the urgent need to reduce global carbon dioxide emissions and mitigate climate change, the Netherlands has committed to significant reductions in CO_2 emissions by 2030 and 2050. This necessitates the rapid expansion of low carbon energy sources, including solar photovoltaic (PV) energy. However, the increase in intermittent renewable electricity supply poses challenges in managing the grid, leading to grid congestion and supply-demand mismatches. To address these challenges, Battery Energy Storage Systems (BESS) have emerged as flexible storage solutions. BESS offer various applications, including peak shaving and participation in markets such as the automatic Frequency Restoration Reserve (aFRR).

This thesis investigates the economic potential of BESS participating in the Dutch aFRR market. The research examines three key questions: how BESS deployment strategies can be modelled to optimize economic performance, what combination of strategies yields the highest economic performance, and how financial performance changes in response to fluctuating market prices. The methodology involves developing a Python model to simulate BESS operation and revenue potential based on market prices, battery costs, and other relevant variables. The model considers factors such as state of charge management, yearly revenues, and battery costs.

Results indicate that an intermediate deployment strategy, coupled with dynamic electricity bidding thresholds, offers optimal economic performance. The intermediate strategy demonstrates a balance between revenue generation and operational longevity, outperforming both conservative and aggressive approaches. Additionally, the study highlights the importance of considering factors such as capacity bid winning share and price fluctuations in assessing BESS profitability.

However, the research acknowledges certain limitations, including the simplification of capacity fee bidding processes and the exclusion of certain costs such as transport tariffs and network fees. Future research should address these limitations by incorporating detailed cost structures and exploring the impact of different connection configurations on project economics.

In conclusion, this study provides insights into the economic feasibility of BESS deployment in the Dutch aFRR market. The findings offer practical implications for battery operators and policymakers, emphasizing the attractiveness of the aFRR market as a business proposition for BESS deployment. By considering broader financial contexts and operational dynamics, this research aims to guide decision-making processes and contribute to the advancement of BESS deployment strategies in energy markets.

Contents

1. Introduction

To limit global temperature rise, it is crucial to reduce global carbon dioxide emissions. Therefore, in 2015, a deal was agreed upon by almost all countries to prevent global temperatures from increasing more than 2°C and to strive to limit this increase to 1.5°C (IPCC, 2021). If we fail to meet these goals, the consequences of climate change could have a widespread impact on both human and natural systems (IPCC, 2021). In line with this, the Netherlands has agreed to reduce CO_2 emissions by 49% by 2030 and 95% by 2050 compared to the levels in 1990 (Klimaatakkoord, 2019). Achieving these targets requires the rapid expansion of low carbon energy sources, such as solar photovoltaic (PV) (Klimaatakkoord, 2019). The installed capacity of solar PV energy has significantly increased in the Netherlands, from 1.5 GW in 2015 to 14.3 GW in 2021 (Solar Trendrapport, 2022). However, this increase in intermittent renewable electricity supply has led to challenges in handling the mismatch between supply and demand, as well as increased grid congestion (Liander, 2022; Enexis, 2022). To address these issues, flexible storage solutions are necessary to stabilize the grid during peak production and peak demand. One such solution is the deployment of Battery Energy Storage Systems (BESS).

BESS have a wide variety of applications, ranging from increasing self-consumption through peak shaving to providing ancillary services and participating in markets such as the day-ahead market. Due to their versatility, BESS have become increasingly attractive in the Netherlands, with an 87% price reduction over the last decade, and a total capacity of 185 MWh implemented in 2021 (Smart Storage Trendrapport, 2022). However, it is anticipated that the services that make BESS lucrative, such as the Frequency Containment Reserve (FCR), will become saturated in the near future (Smart Storage Trendrapport, 2022; CE Delft, 2022). Furthermore, the electricity markets and services that are currently provided mainly by conventional power plants need to decarbonize (Merten et al., 2020). It is therefore necessary to explore other markets to ensure that BESS remain profitable throughout their lifetime and continue to contribute to increasing flexibility in the energy system.

One market that presents untapped potential for batteries in the Netherlands is the automatic Frequency Restoration Reserve (aFRR), also known as the secondary control reserve. Although this market has entrance barriers and a more complex auction process compared to the FCR and passive imbalance market, changes made by the Dutch Transmission System Operator (TSO) TenneT have made aFRR participation more accessible for Balancing Service Providers (BSPs) that aggregate smaller scale assets, renewable generation, and/or demand response to provide flexibility (TenneT, 2021). For instance, assets are now only required to have a minimum capacity of 1 MW instead of 4 MW to join the aFRR market. Additionally, TenneT is modifying the restrictions so that assets are no longer required to provide full bid power for 24 hours, but rather only for 4 hours (CE Delft, 2023). While the aFRR market currently demands assets to provide full tendered power for longer time spans, which is typically not favourable for BESS, previous studies have shown promise in the economic potential of aFRR participation for BESS systems (Merten et al., 2020; CE Delft, 2022). Therefore, these changes could provide unprecedented opportunities for integrating BESS with the aFRR market.

This thesis aims to contribute to the existing research on the economic potential of BESS participating in the aFRR market in the Netherlands. To achieve this goal, the theoretical background and previous research is examined and relevant research questions are created. The methodology will then outline the approach to answering these questions, after which the results give an overview show the outcome of the methodology. These results are then discussed after which there will be a conclusion to summarize the findings of this thesis.

1.1 Theoretical Background

This section provides a theoretical background on the electricity markets relevant to Battery Energy Storage Systems (BESS) in the Netherlands. The primary objective of current energy markets is to ensure a continuous and dependable energy supply. To achieve this, several markets are operational, each active at different times. These markets are outlined below.

Day Ahead market

The Day Ahead (DA) market is a wholesale market that operates with a merit order system. The highest bid sets the electricity price for the entire market, which closes every day at 12:00 and sets the general electricity price for the day. During the day, trading on the intraday market is possible through energy arbitrage which allows BESS to purchase electricity and charge when prices are low and discharge during peak consumption moments.

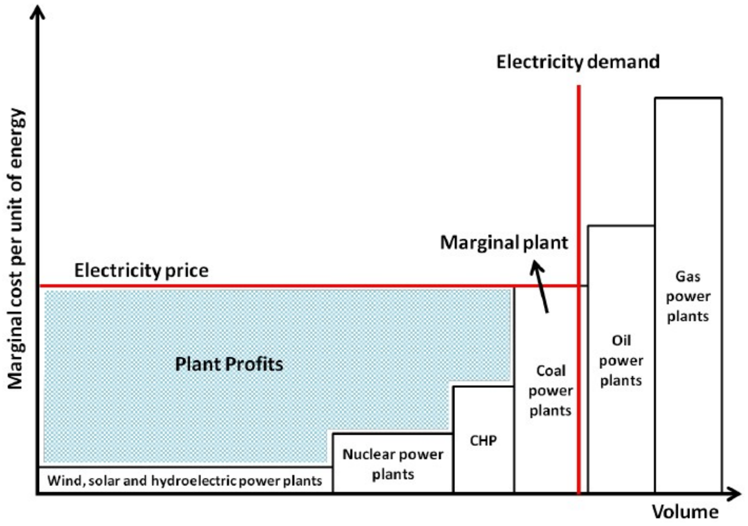

Figure 1: The Merit Order System of the day-ahead market, which shows that the electricity price depends on the electricity demand and the marginal costs per unit of energy (Bahar & Sauvage, 2013).

Passive imbalance market

The passive imbalance market works with time intervals of 15 minutes and presents an electricity price so production and consumption can be adjusted. When there is an imbalance between production and demand, it is represented in the electricity price. A low price incentivizes producers to reduce their production, whereas a high price incentivizes the flexible forms of energy production to be increased.

Balancing services

Balancing services are required to maintain the net frequency of 50 Hz in the Netherlands. The three balancing services that do so are the FCR, aFRR, and mFRR. These are also called the primary, secondary and tertiary control reserves which refers to the time that they are engaged in frequency control, as can be seen in Figure 2.

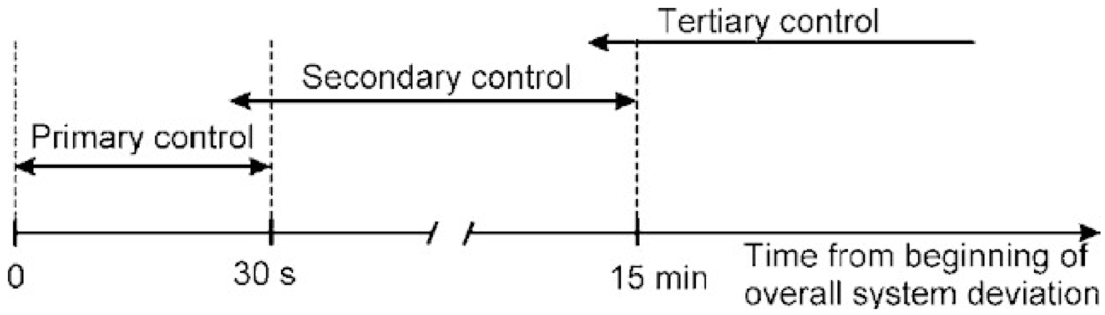

Figure 2: Balancing services and their timing (Merten et al., 2020).

The FCR is the first to respond when there is a deviation in net frequency of 200 mHz, and an asset is required to supply full power for the duration of 30 seconds after which aFRR takes over. This is to make sure that FCR capacity is available for the next frequency deviation. The aFRR on the other hand is required to supply full power to either upward or downward regulation for 15 minutes. These two balancing services usually maintain proper grid frequency, although sometimes significant system imbalances persist for longer periods of time (DNV & InvestNL, 2020). When this is the case, the manual Frequency Restoration Reserve (mFRR) is activated. As the name suggests, this happens manually as opposed to automatically with FCR and aFRR, and its purpose is to ensure that more aFRR capacity is free in the future for more minor disturbances. Although the FCR and aFRR markets both require a minimum bid size of 1 MW, the mFRR requires a minimum bid size of 20 MW. Furthermore, mFRR is only activated a few times per year, meaning that it is less suitable for BESS compared to the other two markets (CE Delft, 2022). Therefore, only the FCR and aFRR markets are considered in this section.

Frequency Containment Reserve (FCR)

The Frequency Containment Reserve is an international balancing service where each country is required to contribute capacity to maintain net frequency. In 2021, the Netherlands was required to supply 3.8% of synchronous Europe's total energy demand, which equals 113 MW (TenneT, 2021b). Since 2020, bidding is done in four hour timeslots, and the minimum required bid size is 1 MW compared to 5 MW before 2020 (DNV & InvestNL, 2021). This change caused a slight increase in FCR prices but have since been steadily decreasing again. This is because the available FCR capacity is growing whereas the demand for FCR capacity remains roughly the same (Smart Storage Trendrapport, 2022). This is also why the FCR market is expected to become saturated in the coming years, which means that BESS need another source of revenues to stimulate growth.

Automatic Frequency Restoration Reserve (aFRR)

As previously mentioned, the automatic Frequency Restoration Reserve is the secondary control reserve which is fully activated after 30 seconds since the original net frequency disruption. The asset is then required to be able to provide full power either upward (to the grid) or downward (from the grid) for 15 minutes. A Balancing Responsible Party (BRP) can access the aFRR market through a qualification process, in which the asset is assessed and it is decided whether it fulfils the requirements, the main one being that it can provide at least 1 MW (or multiples of 1 MW) for the full duration in which it is active on the aFRR market. Once the asset has been approved, the asset submits a capacity bid for each contracted period, which functions as paid-as-bid. If accepted, the asset is then required to bid for every Imbalance Settlement Period (ISP) of 15 minutes, which as with the day ahead market is decided through a merit order system in which the price is established through bidding (TenneT 2021c). This means that, unlike the capacity fee, the highest bid sets the price.

The main differences with the FCR market in the context of BESS are that the activation time is slower and the time required to supply full power is longer (currently 24 hours). BESS have the advantage compared to other energy sources or storage systems by being able to respond very quickly to a disruption in net frequency, which can be fully exploited for the FCR market but to a lesser degree for the aFRR market (DNV & InvestNL, 2021). On top of that, BESS have a limited energy pool compared to for instance a power plant. This means that a BESS cannot charge or discharge indefinitely, and this in turn results in a limited capacity to provide power. Therefore, the longer required time to supply full power currently proves to be a bottleneck for BESS participation in the aFRR market (Merten et al., 2020). However, TenneT has announced that it plans to reduce the contracted aFRR period from 24 hours to 4 hours, similar to the FCR (CE Delft, 2023). This means that this market will now become accessible to BESS, and specifically 4-hour batteries will be able to participate (e.g. 1 MW/4 MWh).

1.2 Previous Research

Previous research has focused on the aFRR market for BESS. DNV and InvestNL (2021) explored the opportunities for BESS on different markets in the Netherlands and concluded that aFRR could provide a relatively high income for BESS. However, the income potential is subject to high volatility and uncertainty due to the energy-limited nature of BESS, which can struggle to meet consecutive imbalance settlement periods with an upward or downward need.

Merten et al. (2020) considered three different configurations of virtual power plants, where BESS would be combined with wind, PV, and thermal generation on the German/Austrian market. They found that an economically feasible operation in 2019 would not be possible for any of these operations due to an insufficient price spread between the aFRR and intraday market prices. However, an economically feasible operation could be possible in 2025 for BESS in conjunction with a virtual power plant, although this is uncertain due to high energy price sensitivity.

Padmanabhan et al. (2022) proposed a mathematical model for simultaneously procuring primary and secondary regulation in the US while considering the degradation and operational costs for the specific BESS. The study focused on optimizing grid stability through simultaneous procurement of FCR and aFRR, as opposed to maximizing revenues. They found that social welfare was higher when a BESS was added to the system and that battery degradation management helped increase the years of operation and capture operational expenses.

CE Delft has published two main reports that focus on BESS in the Netherlands, one from 2022 and one from 2023. The report from 2022 estimated that current revenue streams for capacity fees and activation fees would lead to a total revenue of 228,000 €/MW/year on the aFRR market. Figure 3 shows the projected yearly revenues for BESS on various markets and market combinations for 2019, 2025, and 2030. The figure reveals that aFRR revenues are projected to remain constant due to a balance between the growth of the aFRR market and the number of BESS. However, the model did not consider the state of charge of the BESS, which may lead to skewed results.

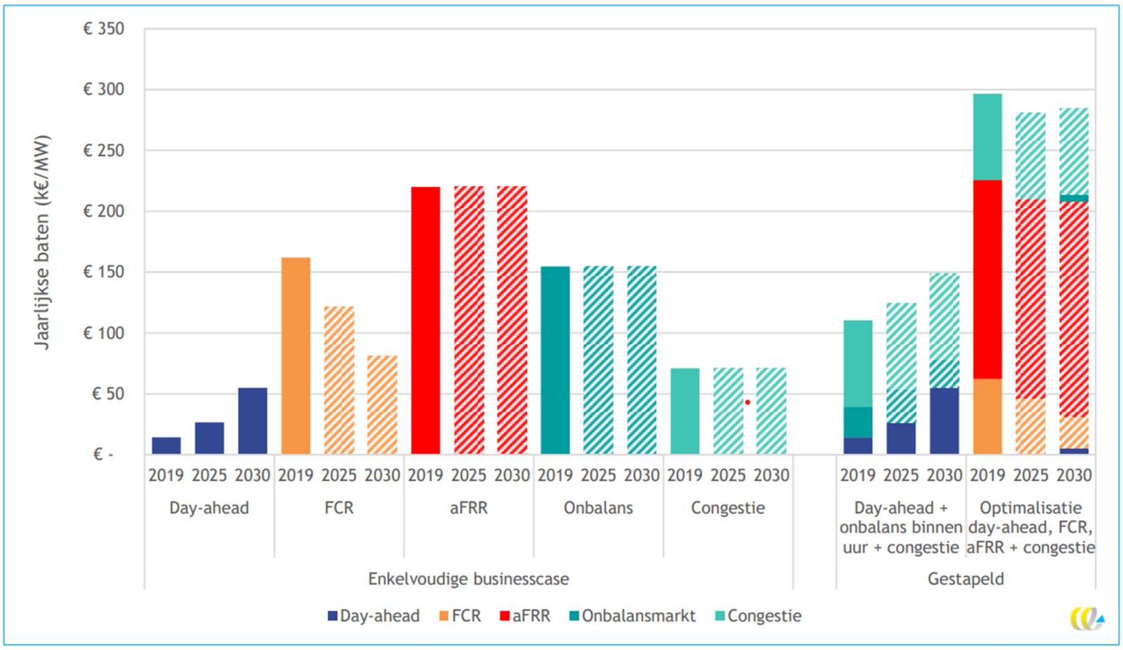

Figure 3: Projected yearly revenues for BESS on different markets. Note that "onbalansmarkt" and "congestie" translate to imbalance market and congestion. The section to the left shows the simple business cases, and the right section shows the layered business cases where different markets are combined (CE Delft, 2023).

CE Delft (2023) focused on the role that BESS are expected to play in congested areas and related policies. The report projects that BESS can be cost-effective near 2030, as currently, BESS would have to be able to provide full power for 24 hours in order to qualify for the lucrative capacity fee. This is only possible for BESS in combination with assets that have the capacity to supply full power for 24 hours such as thermal power plants, but in that case, it is mostly the power plant that provides the power.

Overall, there is a clear research gap on BESS participation in the aFRR market in the Netherlands due to restrictions put in place by TenneT. An in-depth model on BESS participation in the aFRR market in the Netherlands has not yet been developed. Although CE Delft's projections provide interesting insights, the limitations of the research show that there is a need for more research on BESS in the aFRR market.

1.3 Research Questions

The developments and gaps in literature as mentioned above lead to the following research question:

How can BESS be optimally operated in the Dutch aFRR market to maximize its economic performance?

In order to answer this question, this research is divided into the following three sub questions:

1. *How can a BESS strategy of deployment on the aFRR market be modelled to optimize economic performance?*
2. *What combination of strategies for deploying BESS in the aFRR market results in the highest economic performance?*

3. *How does the financial performance of BESS deployment in the aFRR market change in response to fluctuating market prices?*

The first sub question, "*How can a BESS strategy of deployment on the aFRR market be modelled to optimize economic performance?*", will be answered by creating a model to analyse the economic potential of battery participation in the aFRR market. The model will be developed in Python, and will incorporate data on market prices, battery costs, and other relevant variables as described in Methodology.

Using this model, the operation and economic performance will be simulated to identify the optimal deployment strategies for BESS in the aFRR market, thereby aiming to answer the second sub question, "*What combination of strategies for deploying BESS in the aFRR market results in the highest economic performance?"*. In this section, the economic potential in the aFRR market will be compared and different strategies will be explored.

The third sub question, "*How does the financial performance of BESS deployment in the aFRR market change in response to fluctuating market prices?"*, will include scenario analyses to test how different market conditions will affect the economic performance of different deployment strategies. The aim here is to find how different market prices in the future will affect the economic viability of BESS on the aFRR.

2. Methodology

This section outlines the methodology for assessing the economic potential of BESS participating in the aFRR market in the Netherlands.

2.1 Battery Model

The methodology involves developing a model in Python to identify optimal deployment strategies and analyse the impact of different market conditions on revenue potential. The different aspects of the model are split into an overview, the state of charge, the revenues and finally the costs.

2.1.1 Overview

The model combines data processing, conditional logic, and calculations to model the charging and discharging behaviour of the battery under various conditions. To build the model, a theoretical framework will be created to establish the underlying principles and assumptions of the aFRR market and facilitate the development of new theory and understanding of the market's challenges and opportunities.

Python was chosen as the programming language due to its open-source nature and ability to process large sets of data at a temporal resolution of 15 minutes, which matches the resolution of the aFRR market. Python also facilitates packages like Pandas and NumPy, which provide tools for data manipulation and analysis.

The research utilized data from ENTSO-E (European Network of Transmission System Operators for Electricity) as well as relevant data from battery manufacturers, ensuring compliance with GDPR regulations (ENTSO-E, 2024). These datasets include the electricity prices for the upward and downward bids, as well as the (currently) daily capacity fee. For the purposes of this research, electricity price data from 2021 is used, as it is more representative than 2022 electricity data as it was unusually high. The core of the methodology involves iterating through the dataset to calculate energy changes, revenue, and capacity fees. Specific conditions for charging and discharging are considered, taking into account dynamic price thresholds and varying time intervals. Revenue, capacity fees, and total energy flows are computed to assess the financial performance of the battery. In this model, different parameter categories are identified and are shown in Table 1 below.

Table 1: Parameters and decision variables relevant to the model.

Parameter categories
BESS parameters (size, efficiency)
Revenue parameters (energy price)
Investment cost
OPEX
Total life cycles

Decision variables
Electricity prices on the aFRR
BESS state of charge
Energy flows in and out of the BESS

2.1.2 State of Charge

A notable constraint for BESS is the State of Charge (SoC) management. Since BESS have a limited energy capacity, charging and discharging needs to be a conscious decision the battery management system makes. This energy constraint is shown in Equation 1, where E_t is the SoC of the battery at time t, E_{max} is the maximum capacity of the battery and E_{min} is the minimum SoC (all in MWh). SoC management is strongly dependent on the number of cycles the battery will run in its lifetime. More cycles per day means more short-term revenue gain, but long-term revenue loss due to degradation and its impact on the lifetime of the battery. The difficulty here is having the battery decide which actions to take per timestep whilst also taking into account the cost associated with the degradation caused by running cycles. The overall goal in this study is to find which strategy has the highest economic value over its lifetime, which will be further discussed in 3.1.5 Economic Performance.

$$E_{min} \leq E_t \leq E_{max} \qquad (1)$$

2.1.3 Yearly revenues

When measuring the revenue, two main sources are taken into account. The first is trading on the aFRR according to the electricity price. Every 15 minutes, the battery charges, discharges or idles, and based on the action it takes, the associated price in €/MWh is multiplied by the change in energy in MWh. This is summed up in the end and constitutes the electricity revenue.

The second source of revenue is the capacity revenue. This stems from the capacity fee that assets on the aFRR are granted when their initial bid is accepted. The capacity fee data is only available per day since the aFRR's timeslots are currently 24 hours long and is in €/MW/ISP. The ISP in this case means the fee for every 15 minutes that the asset is actively participating in the aFRR. This fee is paid as bid for every timeslot, and if the bid is not accepted, then the asset does not receive a capacity fee and is therefore not obligated to charge or discharge within the timeslot. However, it could still participate on the passive imbalance market which consists of the same electricity prices. In this case the asset would not receive the capacity fee.

The calculation of both revenue streams and the combination of both are shown in equations 2, 3 and 4, where R_{el} is the yearly electricity revenue from trading on the aFRR in €, ΔE is the amount of energy charged or discharged in MWh, p_t is the electricity price in € for the discharge (up) or charge (down) price at time t, R_c is the yearly capacity fee revenue in €, p_c is the daily capacity fee in €/MW/ISP, C_p is the power capacity of the battery in MW, N_{isp} is the number of ISPs per day and R_{tot} is the total yearly revenue in €.

$$R_{el} = \sum -\Delta E_{charge}\ p_{down,\ t} + \sum -\Delta E_{discharge}\ p_{up,\ t} \qquad (2)$$

$$R_c = \sum p_c\, C_p\, N_{isp} \qquad (3)$$

$$R_{tot} = R_{el} + R_c \qquad (4)$$

2.1.4 Battery costs

Aside from revenue, certain costs are assumed for the battery. For the investment costs, different suppliers of batteries were considered as there is a difference between small-scale battery systems compared to large-scale battery systems. Since the battery that this study considers is a 1 MW/4 MWh system, it is important to use an investment cost that is representative for its size. Investment costs from iWell and Alfen (theBattery elements) are considered (See Appendix 1). These costs are 350 €/kWh for 5 MW/10MWh and 370 €/kWh for 1 MW/2 MWh respectively. Therefore, the average of 360 €/kWh is used, which for our 4,000 kWh leads to an investment cost of €1,440,000.

The variable costs include the Operational Expenditures (OPEX) and grid fees. The OPEX differ per battery supplier, but in this study the OPEX are assumed to be 2.5% of total investment costs, as the NREL estimates in Cole et al. (2021). This leads to an OPEX of €36,000 per year.

The grid fees can be quite significant and can constitute about 30 to 50% of total yearly costs (CE Delft, 2023-B). These fees are also quite uncertain, considering that the maintenance costs of the Dutch grid are expected to increase, and the degree to which this will be translated to the owner of the asset is not yet determined (CE Delft, 2023-A; ACM, 2021). In 2022, the grid operators developed an integration framework for batteries (Netbeheer Nederland, 2022b). In it, they advocate for batteries to be connected to the grid in a grid-neutral manner in areas where grid congestion exists or threatens to occur. Grid operators also advocate for connecting batteries that provide system services to the TenneT network to relieve regional networks. Since the grid fees are a contentious point of debate as CE Delft (2023-B) points out, this research does not include these as part of the variable costs.

It is important to note that economic factors such as the time value of money, depreciation of assets and increasing OPEX as assets age are not considered in this research. This was decided as these factors can range significantly per asset as well as battery supplier. The purpose of this research is to present the results of a simplified economic model that can be easily adjusted based on differences in investment costs, OPEX and battery lifetime while ensuring a focus on the potential revenues that various strategies and scenarios can achieve for BESS on the aFRR.

2.1.5 Economic Performance

The economic performance is measured by several metrics, namely the following.

1. Total yearly revenue
2. Net revenue over the battery's lifetime
3. The payback time and lifetime of the battery
4. Rate of Return (ROR)

The total yearly revenue is used as a metric since it encompasses all revenue streams within a year and can be easily compared to other research on the aFRR. The net revenue over the battery's lifetime is calculated by subtracting the total investment cost and operational expenditures (OPEX) from the cumulative revenue generated over the battery's operational lifespan. This is a suitable metric to compare different strategies to one another, as yearly revenues may be higher for one strategy, but its overall lifetime may be significantly lower, thus decreasing the net lifetime revenue. Furthermore, the payback time compared with the lifetime of the battery can give insights into the number of years that the battery generates a profit. Finally, the Rate of Return (ROR) is used to give an indication of whether the BESS is likely to generate returns that exceed the cost of funding.

The lifetime of the battery is calculated according to specifications on a similar battery size, which is 10,000 cycles (BigASS battery, n.d.). As the model keeps track of the energy flows of the battery, it calculates how many cycles the battery has run and limits the battery's lifetime to where 10,000 cycles have been run. This is shown in Equation 5, where L is the battery's lifetime, N_{cycles} is the number of cycles in the battery's lifetime, E_{tot} is the yearly energy flows in MWh and C_e is the energy capacity of the battery in MWh.

$$L = \frac{N_{cycles}}{E_{tot} \ / \ 2C_e} \qquad (5)$$

The net revenue over lifetime and payback time is calculated as shown in Equations 6 and 7 below, where R_{net} is the net revenue over lifetime in €, I is the investment cost in €, O is the OPEX in €, PBT is the payback time in years and L is the battery's lifetime in years.

$$R_{net} = (R_{tot} - I - O) \, L \qquad (6)$$

$$PBT = \frac{R_{net}}{L} \qquad (7)$$

Finally, the Rate of Return provides a clear and concise measure of project profitability. The Rate of Return is calculated as shown in Equation 8, where the ROR is the Rate of Return in %, R_{net} is the net revenue over lifetime in €, I is the investment cost in € and L is the battery's lifetime in years.

$$ROR = \frac{R_{net}}{I\ /\ L} * 100\% \qquad (8)$$

These metrics are used to measure and compare the economic performance of the BESS for the various strategies and scenarios.

2.2 Operational Strategies

In this study, several strategies are explored:

1. Conservative, intermediate and aggressive timeslots.
2. Low, intermediate and high threshold values for prices
3. Capacity bid analysis

2.2.1 Timeslot strategies

The aFRR market is expected to change from timeslots of 24 hours to 4 hours, meaning that there will be 6 timeslots everyday. For the purpose of this research, it is assumed that this distribution is as presented in Table 2, which shows the six different timeslots as they are in the FCR market.

Table 2: Timeslot distribution if similar to the FCR distribution.

Number	Timeslot
1	00:00-04:00
2	04:00-08:00
3	08:00-12:00
4	12:00-16:00
5	16:00-20:00
6	20:00-24:00

This research explores which timeslots the BESS should participate in and when to idle. For the purpose of this, the following strategies are considered:

1. Conservative: Participation in 2 timeslots per day, in which the BESS charges in one timeslot and discharges in the other.
2. Intermediate: Participation in 4 timeslots per day, in which the BESS charges and discharges twice throughout the day.
3. Aggressive: Participation in 6 timeslots per day, in which the BESS participating in every single timeslot of the day, so is therefore always charging and discharging.

Firstly, the average prices during each timeslot throughout the year are examined to find which timeslots would be best used to charge and discharge. Since the dataset distinguishes between upwards and downwards prices, the prices for discharging and charging respectively, both are looked at separately. Furthermore, the SoC constraint imposes limitations on the battery's charging and discharging operations, ensuring that it cannot charge or discharge consecutively. This constraint is important in determining the optimal timeslots for the BESS to participate in charging or discharging activities. Specifically, it prevents scenarios where the battery may attempt to charge when already at full capacity or discharge when already depleted. Consequently, when evaluating the most favourable timeslots for BESS participation and determining the suitability of timeslots for charging or discharging, both the average prices for each timeslot and the SoC constraints are taken into account. Once the most favourable timeslots for charging and discharging are found, the different timeslot strategies are implemented in the model and presented.

2.2.2 Electricity bid strategies

This research aims to find at which price thresholds it is best to charge and discharge. To achieve this, a range of price thresholds relative to the mean upward and downward prices are used and implemented in a way that the battery will only charge/discharge if it meets the conditional price threshold. Simply put, the battery now not only looks at whether it has enough energy stored and whether they are in a timeslot of charging, discharging or idling, but now also looks at the electricity prices for each interval of 15 minutes to decide whether the price is worth it. In practice, the electricity price for each 15 minutes are also not known beforehand, and so the battery must make a bid. If the actual price is higher than the bid, then the bid has been accepted, and the highest possible bid dictates the electricity price which is then paid to all who participate. When managing a battery system, one can decide to make the threshold values dynamic to best fit the time of day or season. However, dynamic threshold values are not implemented.

The chosen thresholds range from 0.1 until 1.1 in increments of 0.1. These thresholds are then multiplied by the mean prices. This ensures that the BESS will only charge or discharge at the prices that are somewhat favourable.

2.2.3 Capacity bid analysis

As mentioned before, the BESS participates in the aFRR market by submitting bids for each timeslot, which occur at intervals of every four hours, with the intention of qualifying for the capacity fee. Notably, this fee is remunerated based on the bid submitted, and in the event of unsuccessful bids, no capacity fee accrues to the BESS. Unfortunately, data regarding bid outcomes and the corresponding capacity fee for 4-hour timeslots is presently unavailable, as 4-hour timeslot system has yet to be established. Consequently, this study adopts the assumption that the capacity fee is consistently secured and equal to the bid amount for a given day. This approach is necessitated by the absence of data pertaining to capacity fee outcomes, coupled with the absence of insights into bid success rates.

Integrating the capacity fee bidding process into the model would necessitate several assumptions, primarily concerning the potential distribution of the aFRR capacity fee bids and the feasible winning amounts. This entails determining a plausible distribution of aFRR capacity fee bids and estimating the likelihood of securing these bids. A decision would have to be made regarding whether to adopt a singular aFRR bid value and apply it uniformly throughout the year or implement a complex approach enabling the battery to anticipate and adjust its capacity fee bid for each subsequent timeslot.

Speculating on the distribution of aFRR capacity fee bids and predicting winning outcomes would necessitate numerous assumptions, rendering the modelling process intricate and prone to inaccuracies. There is currently not enough data available to build a statistically significant model for the aFRR capacity fee distribution and calculating a win % based on the bid price. Furthermore, such assumptions lack empirical validation until BESS are actively participating in the aFRR market and empirical data becomes available. Therefore, this approach is not implemented in this study.

Nevertheless, in order to provide an understanding of the potential ramifications of varying bid success rates on economic performance, an analytical examination was undertaken to delineate the impact of differing proportions of bid successes on economic outcomes. This analytical endeavour involved evaluating the economic performance across a spectrum of scenarios representing varying proportions of bid successes, with each scenario representing incremental adjustments of 10% in the share of total yearly capacity fee revenue (e.g., 100%, 90%, 80%, etc.). The objective of this analysis is to provide an understanding of the influence exerted by capacity fee bids on economic performance, thereby affording insights into the potential consequences should bids fail to secure the capacity fee in every instance.

2.3 Scenario Analysis

In this section, we delve into a scenario analysis to assess the ramifications of fluctuations in electricity prices on the economic viability of BESS. Electricity prices have exhibited considerable volatility in recent years, with notable disparities observed between 2020, 2021, and 2022 (PBL, 2022). Such volatility underscores the inherent uncertainty surrounding future electricity prices, attributed in part to fluctuations in energy production and demand, as well as unpredictable trends in fuel and CO2 prices (PBL, 2022). Notably, PBL's (2022) research explored the impact of various electricity price scenarios projected for 2030, encompassing low, moderate, and high price scenarios with deviations of approximately -10% to +10% compared to baseline prices.

Drawing inspiration from these findings, our study investigates the effects of price differentials ranging from -10% to +10%, as well as more moderate fluctuations of -5% and +5%, to elucidate the influence of smaller price variations on the economic performance of BESS. This is accomplished by multiplying the electricity price dataset by the appropriate price fluctuation to find what the effect is on the economic performance of BESS.

Table 3 provides an overview of the mean "Upwards" (discharge) and "Downwards" (charge) prices for the year 2021, the focal year of our analysis. Additionally, it illustrates the projected mean prices resulting from adjustments applied to all prices through multiplication factors aimed at increasing or decreasing the prices.

Table 3: The discharge and charge prices for different price fluctuations

	-10%	-5%	Reference	+5%	+10%
Discharge	67.842	71.611	75.38	79.149	82.918
Charge	18.918	19.969	21.02	22.071	23.122

3 Results

The Results section is structured according to the three research questions. The first section shows charging mechanics of that the model produced, where the second section will present the different strategies and their economic performance parameters. Finally, the scenario analysis shows the impact price fluctuations have on the economic performance of BESS.

3.1 Economic Model

Since many aspects of the economic model were explained in the Methodology section, this subsection shifts focus towards the charging and discharging behaviours of the different strategies. This includes the reference strategy and the electricity bidding strategy with the conservative, intermediate and aggressive timeslots. Figures 4, 5, and 6 depict the charging and discharging operations of the BESS during the initial five days of 2021.

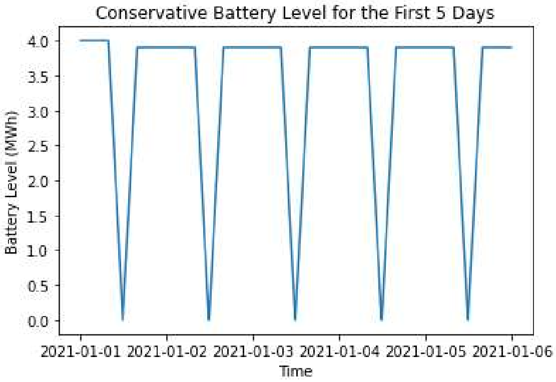

Figure 4.1 Battery level for the first 5 days of 2021 in MWh for the conservative reference strategy.

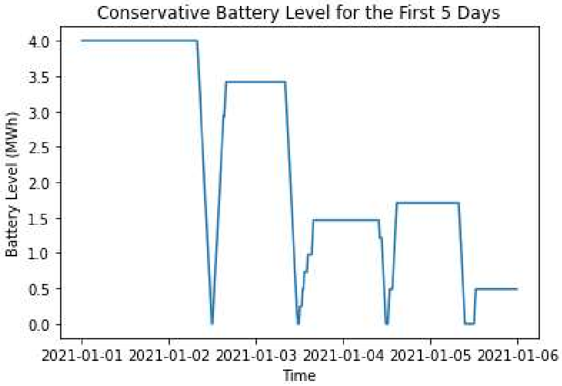

Figure 4.2: Battery level for the first 5 days of 2021 in MWh for the conservative electricity bidding strategy.

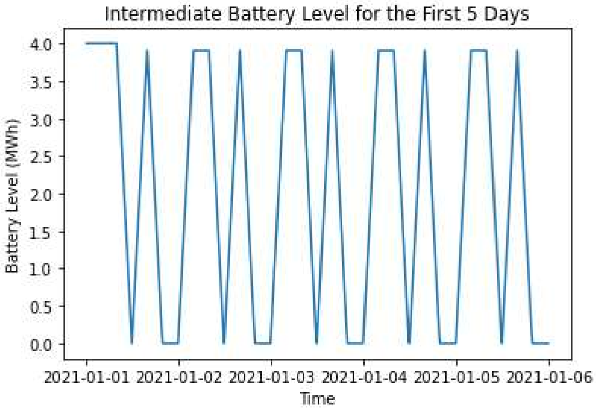

Figure 5.1: Battery level for the first 5 days of 2021 in MWh for the intermediate reference strategy.

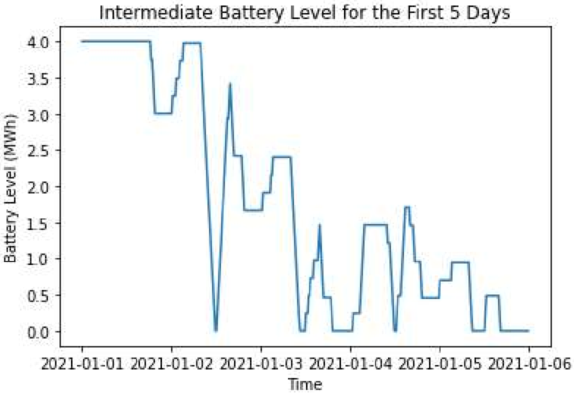

Figure 5.2: Battery level for the first 5 days of 2021 in MWh for the conservative electricity bidding strategy.

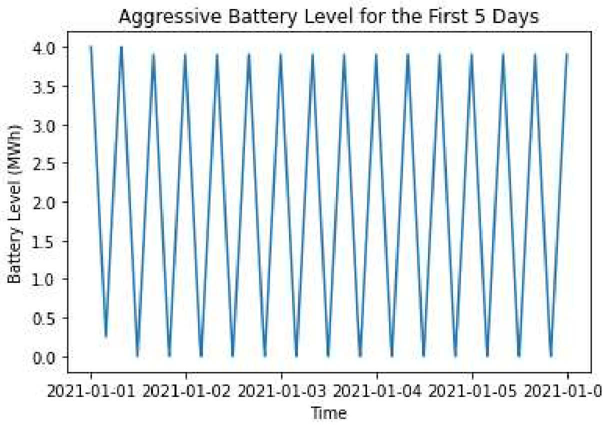

Figure 6.1: Battery level for the first 5 days of 2021 in MWh for the aggressive reference strategy.

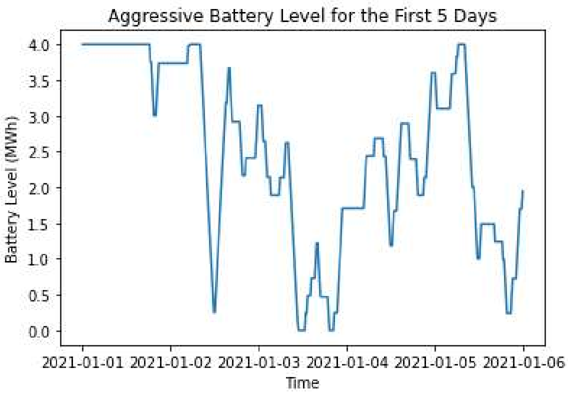

Figure 6.2: Battery level for the first 5 days of 2021 in MWh for the aggressive electricity bidding strategy.

Figure 4 illustrates the conservative timeslot strategy, where 4.1 denotes the reference strategy and 4.2 the electricity bidding strategy. Evidently, in both instances, the BESS undergoes a single charge and discharge cycle daily, remaining idle throughout the remainder of the timeslots. Notibly, a discernable difference between the reference and electricity bidding strategy emerges, as the reference fully charges and discharges whereas the electricity bidding strategy predominately discharges suggesting unfavourable charging conditions in accordance with the predefined threshold during the initial five days.

Figures 5 and 6 depict the intermediate and aggressive timeslot strategies, respectively. While the reference strategy adheres to a consistent charging and discharging schedule, the electricity bidding strategy is much more dynamic. Additionally, periods of idleness are evident within the initial timeslots. This can be attributed to several factors. In the conservative and intermediate strategies, the timeslot spanning 00:00-04:00 is excluded, thereby preventing charging or discharging. This timeslot is incorporated in Figure 6.1 where the BESS discharges during this time. However, despite discharge occurrences during this interval in Figure 6.1, Figure 6.2 refrains from discharging during the corresponding timeslot, as the prices do not warrant such action. Consequently, during the ensuing timeslot, i.e., the charging timeslot spanning 04:00-08:00, the BESS remains idle in Figure 6.2 owing to its already full 4 MWh capacity, rendering it ineligible for participation. The specific timeslots designated for charging and discharging are outlined in Chapter 3.2.1.

In the reference scenario figures, slight disparities in charging and discharging behaviours are discernible. This discrepancy is particularly pronounced in Figure 6.1, where the BESS initializes with a full 4 MWh capacity, subsequently failing to attain this value thereafter.

This is due to the 97.6% efficiency of the BESS, which ensures that the BESS cannot fully fill up according to the charging and discharging timeslots that alternate one another. This is not necessarily the case for the electricity bidding strategy, however, since the BESS is not required to fully charge or discharge, thereby affording it more time to charge back up to 4 MWh as can be seen on days 2021/01/02 and 2021/01/05 in Figure 6.2.

Figures 4, 5 and 6 emphasize the differences that the various strategies have on the charging habits of the BESS. The next chapter explores the economic performance that results from these decisions.

3.2 Operational Strategies

In this study, several different strategies were explored:

- Conservative, intermediate and aggressive timeslots.
- Low, intermediate and high threshold values for prices
- Capacity bid analysis

This chapter presents the economic performance of these strategies, starting with the timeslot strategies, followed by the electricity bidding based on thresholds, and concluding with an analysis of the impact of different capacity bid winning shares.

3.2.1 Timeslot strategies

This section presents the outcomes of the three timeslot strategies, beginning with the selection of timeslots, followed by the total yearly revenue, net revenue over the BESS lifetime, payback time and lifetime, Rate of Return, and concluding with an overview.

3.2.1.1 Choice of timeslots

The decision whether to charge or discharge during specific times is dictated by the mean timeslot prices during those timeslots. Figure 7 illustrates the mean timeslot prices observed throughout 2021.

Figure 7: Mean electricity prices during each timeslot in 2021.

As depicted in Figure 7, there is a substantial disparity between the mean Up price (or discharge price) and the mean Down price (or charge price), indicating that the revenue obtained from discharging is notably higher than the cost of charging. This discrepancy underscores the efficacy of Battery Energy Storage Systems (BESS) in dynamic trading within electricity markets. Additionally, approximately 10.7% of the time, the mean charge price is negative, signifying that revenue is earned during charging rather than expenditure for the electricity consumed. Overall, the mean discharge prices during timeslots 2, 3, 4 and 5 are relatively uniform, while those of timeslots 1 and 6 are notably lower. For the charge price however, the mean price at timeslot 4 is very low and timeslots 5 and 6 are significantly higher. These observations were taken into account when deciding the timeslot strategies, as seen in Table 4.

Table 4: The different timeslots and whether the BESS charges or discharges in for the conservative, intermediate and aggressive strategies.

Number	Timeslot	**Conservative**	**Intermediate**	**Aggressive**
1	00:00-04:00		Charge	Discharge
2	04:00-08:00			Charge
3	08:00-12:00	Discharge	Discharge	Discharge
4	12:00-16:00	Charge	Charge	Charge
5	16:00-20:00		Discharge	Discharge
6	20:00-24:00			Charge

Table 4 outlines the decisions for each timeslot strategy. Since timeslot 3 exhibits the highest mean electricity price, a decision was made to consistently discharge the BESS during this period. Similarly, since timeslot 4 has the lowest mean price and occurs immediately after the peak mean price, it was opted to charge the BESS during this timeframe. Notably, as timeslot 4 falls in the afternoon when solar energy generation is at its zenith, it is anticipated to witness the highest frequency of negative charge prices. Such occurrences during charging times enable the BESS to garner positive revenue opportunities.

It is important to highlight that the charging and discharging protocols differ for the intermediate and aggressive strategy during timeslot 1. This discrepancy arises from the intermediate strategy's higher flexibility, allowing for the BESS to remain idle during any two timeslots as desired. This is not desirable for the aggressive timeslot strategy, as discharging during timeslot 3 and charging during timeslot 4 is prioritized over charging during timeslots 1 and 2.

With these decisions established, the subsequent chapter will delve into the economic performance of each timeslot strategy.

3.2.1.2 Total yearly revenue

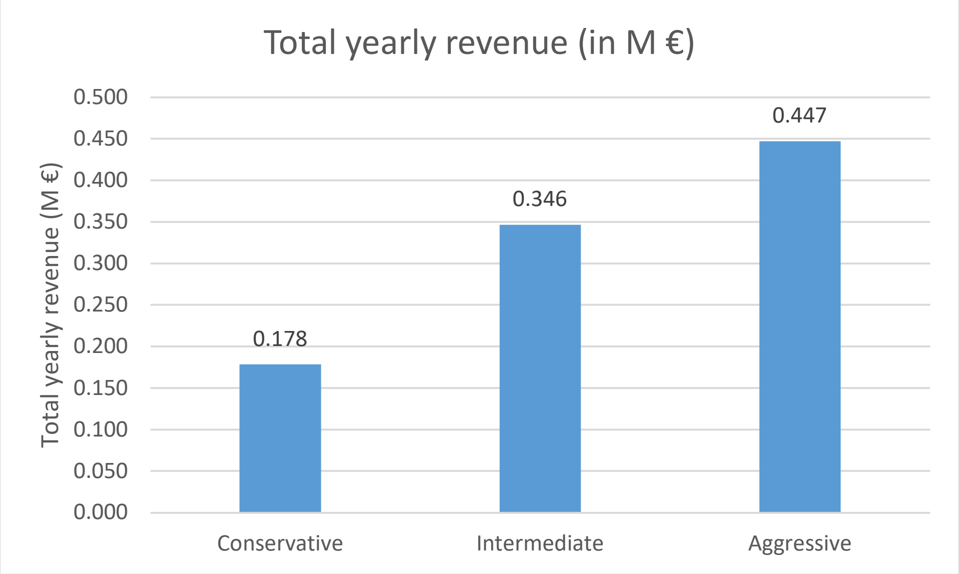

Figure 8: Total yearly revenue for the conservative, intermediate and aggressive timeslot strategies in million €.

Figure 8 illustrates the total yearly revenue in millions of euros (M €) for each timeslot strategy. There are some noteworthy differences between the total yearly revenue in Figure 8. Specifically, it is evident that the conservative strategy yields the lowest revenue, whereas the aggressive strategy attains the highest revenue. This discrepancy can be attributed to the increased participation of the aggressive strategy in the aFRR compared to the conservative strategy. Based on this finding, to optimize annual revenue generation, it is advisable to engage in all timeslots.

3.2.1.3 Net revenue lifetime and PBT/lifetime

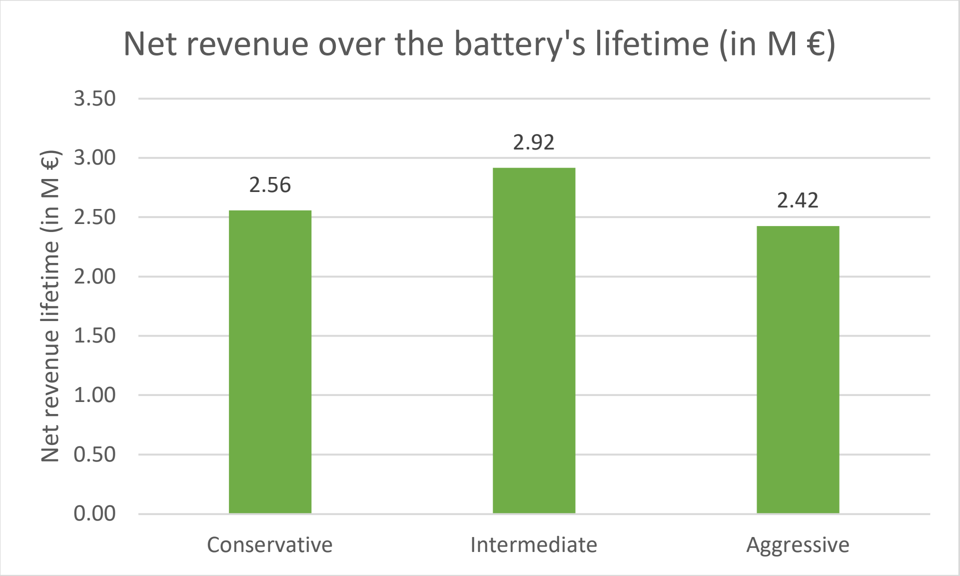

Figure 9: Net revenue over the battery's lifetime for the conservative, intermediate and aggressive timeslot strategies in million €.

Figure 9 presents the net revenue over the lifetime of the battery in millions of euros. It is noteworthy that despite the aggressive strategy yielding the highest total yearly revenue, as evidenced in Figure 8, the intermediate strategy demonstrates the highest net revenue over its lifespan. This phenomenon can be explained by the considerably shorter lifespan under the aggressive strategy due to the increased number of operational cycles per day compared to the intermediate and conservative strategies, as indicated in Table 5. However, please note that the time value of money (which favours short term gains) is not factored into the economic model.

Additionally, it is observed that although the conservative strategy boasts a lifespan nearly twice as long as that of the intermediate strategy, it fails to achieve a higher net revenue over its lifetime compared to the intermediate strategy. This discrepancy can be attributed to the combination of lower total yearly revenue and increased Operational Expenditure (OPEX) costs incurred due to an extended lifespan which increases lifetime maintenance costs. Table 5 further illustrates that each strategy, under these specified conditions, achieves a payback time within its respective lifespan.

Table 5: The payback time and lifetime (in years) for the conservative, intermediate and aggressive timeslot strategies.

	Conservative	**Intermediate**	**Aggressive**	Unit
Payback time	10.11	4.64	3.50	Years
Lifetime	28.06	14.04	9.40	Years

3.2.1.4 Rate of Return

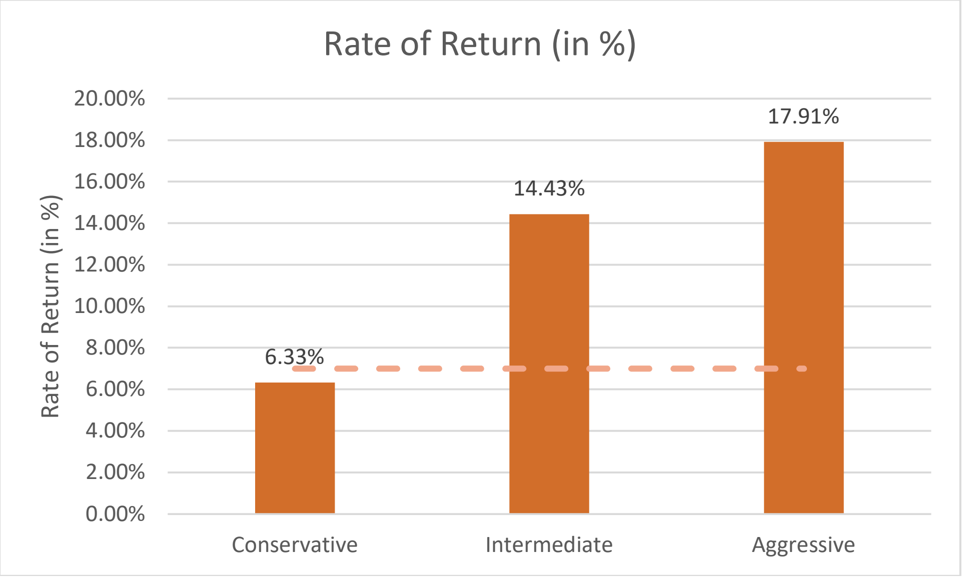

Figure 10: Rate of Return in % for the conservative, intermediate and aggressive timeslot strategies in %.

Figure 10 illustrates the Rate of Return (ROR) for each of the three timeslot strategies. The dashed line signifies the 7% mark, typically considered indicative of a profitable investment, with ROR values at or above this threshold signalling favourable economic viability. Furthermore, ROR values below 7% are indicative of comparatively less profitable investments.

As depicted in Figure 10, the ROR for the conservative strategy stands at 6.33%, falling below the 7% threshold. While this does not inherently imply that the conservative strategy is unprofitable, it does suggest suboptimal economic performance, rendering it less enticing for potential stakeholders. In contrast, both the intermediate and aggressive strategies exhibit excellent RORs, with values of 14.43% and 16.51% respectively. Notably, despite the aggressive strategy yielding the lowest net revenue over its lifetime, it boasts the highest ROR. This discrepancy can be attributed to the timing and magnitude of revenues, as the aggressive strategy generates higher returns earlier in its operational lifespan compared to the other strategies.

3.2.1.5 Overview

Table 6 shows an overview of the main results that were presented in this section. Overall, the aggressive timeslot strategy yields the highest total yearly revenues, the highest ROR and the lowest payback time. However, it also has the lowest net revenue over the battery's lifetime. In all other metrics, the intermediate strategy outperforms the conservative strategy, except on lifetime.

Table 6: Overview of the economic performance for the conservative, intermediate and aggressive timeslot strategies.

	Conservative	**Intermediate**	**Aggressive**	Unit
Total yearly revenue	0.178	0.346	0.447	M €
Net revenue lifetime	2.56	2.92	2.42	M €
PBT/Lifetime	10.11/28.06	4.64/14.04	3.5/9.4	years
ROR	6.33%	14.43%	17.91%	%

3.2.3 Electricity bid strategies

In this section, the economic performance of the electricity bid strategies will be presented. The different threshold values will be explained, and then the economic performance per timeslot strategy will be shown.

3.2.3.1 Electricity bid threshold values

Table 7 presents the various threshold values outlined in the Methodology, wherein the "discharge price threshold" and the "charge price threshold" align with the corresponding prices linked to these thresholds. Specifically, the discharge price threshold signifies the minimum revenue threshold below which the BESS refrains from discharging. This precautionary measure prevents the BESS from engaging in discharging activities when the revenue generated falls below the specified threshold, thereby averting potential losses associated with negative or suboptimal pricing conditions.

Conversely, the "Charge price threshold" denotes the upper limit of expenditure for energy acquisition by the BESS. This threshold ensures that the BESS does not procure energy at excessively high prices, mitigating the risk of incurring substantial costs that could diminish profitability. The results of implementing these thresholds are depicted within this chapter.

Table 7: Threshold values and their corresponding prices for the electricity bidding strategy.

Threshold value	**Discharge price threshold**	**Charge price threshold**	Unit
0.1	7.54	2.10	€/MWh
0.2	15.08	4.20	€/MWh
0.3	22.61	6.31	€/MWh
0.4	30.15	8.41	€/MWh
0.5	37.69	10.51	€/MWh
0.6	45.23	12.61	€/MWh
0.7	52.76	14.72	€/MWh
0.8	60.30	16.82	€/MWh
0.9	67.84	18.92	€/MWh
1	75.38	21.02	€/MWh
1.1	82.91	23.13	€/MWh

3.2.3.2 Total yearly revenue

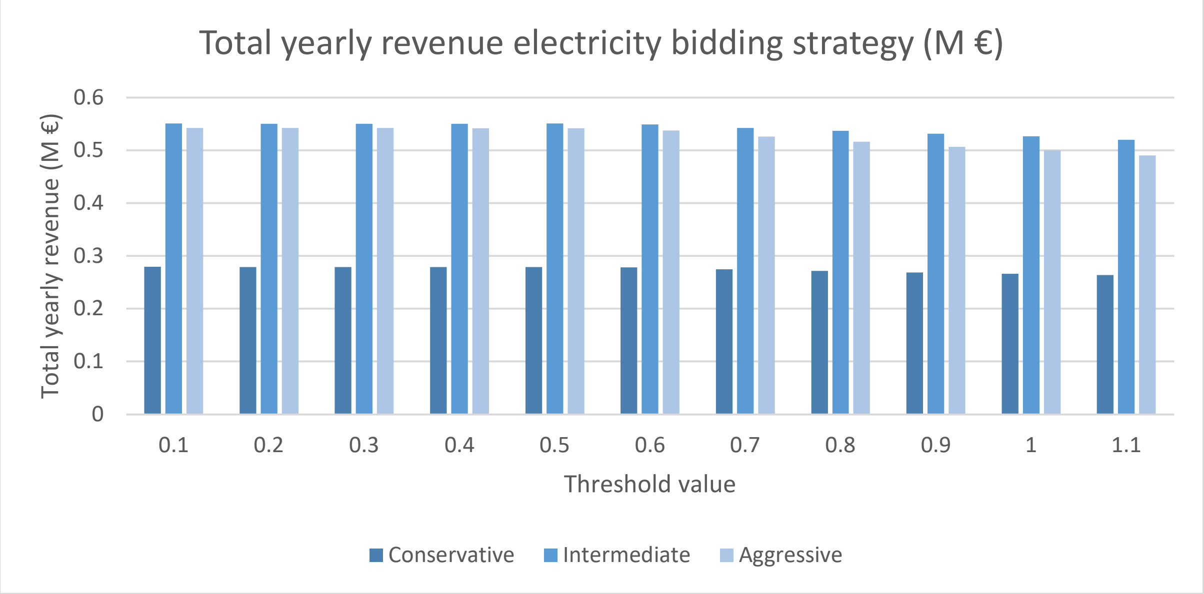

Figure 11: Total yearly revenue resulting from the electricity bidding strategy for the conservative, intermediate and aggressive timeslot strategies in million euros.

Figure 11 illustrates the conservative, intermediate, and aggressive electricity bidding strategies for the intervals outlined in Table 7. Upon initial inspection, it's evident that all three strategies exhibit a similar trend: lower thresholds result in higher revenues. From 0.6 to 1.1, there's a slight decrease in revenue yield across the board. Notably, this decline is most pronounced in the aggressive strategy, with a 9.6% revenue difference between thresholds 0.1 and 1.1. The conservative and intermediate strategies also show disparities, with differences of 5.6% and 5.5% respectively over the same range.

For each strategy, a threshold of 0.1 leads to the highest revenue, albeit by a small margin. This trend can be attributed to the fact that a lower threshold facilitates easier trading on the aFRR, thereby resulting in higher revenue. Despite this similarity, the intermediate strategy emerges as the most lucrative in terms of total yearly revenue, while the conservative strategy lags behind.

3.2.3.3 Net revenue lifetime and PBT/lifetime

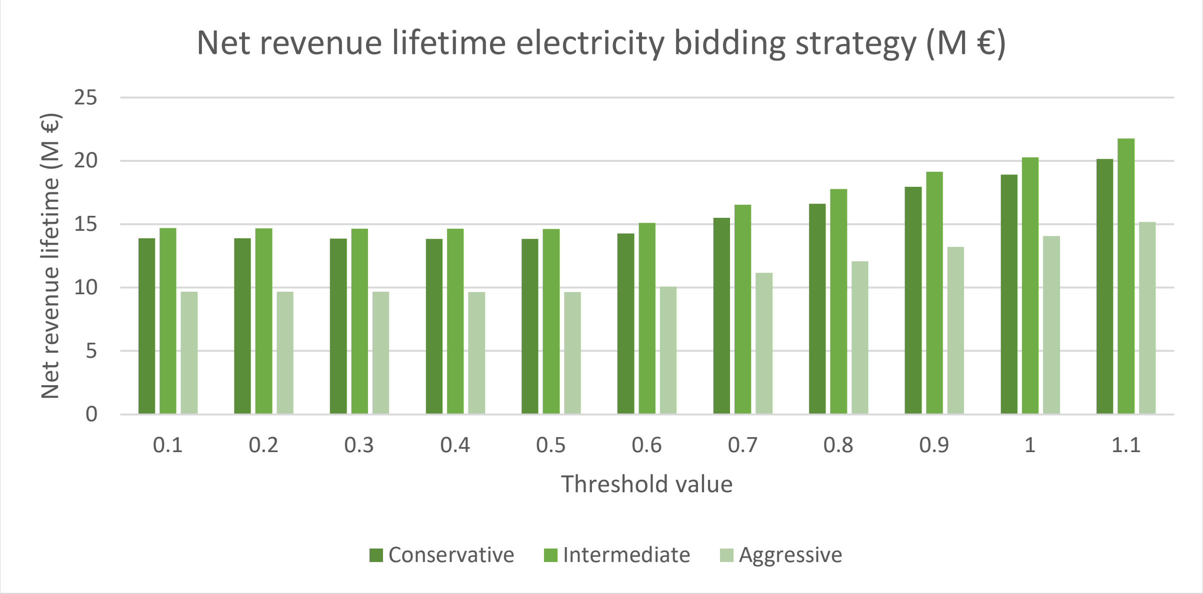

Figure 12: Net revenue lifetime resulting from the electricity bidding strategy for the conservative, intermediate and aggressive timeslot strategies in million euros.

Figure 12 illustrates the net revenue over the battery's lifespan in millions of euros for each timeslot strategy. Observing the figure reveals that the intermediate strategy exhibits superior performance, followed by the conservative and aggressive strategies. Furthermore, Figure 12 shows that at higher thresholds, the net revenue lifetime is higher as well. This phenomenon arises from the considerably longer lifespan of the BESS under the conservative and intermediate strategies, attributed to reduced energy flows. Consequently, the intermediate strategy emerges with the most favourable net revenue over the lifetime of the BESS.

3.2.3.4 Rate of return

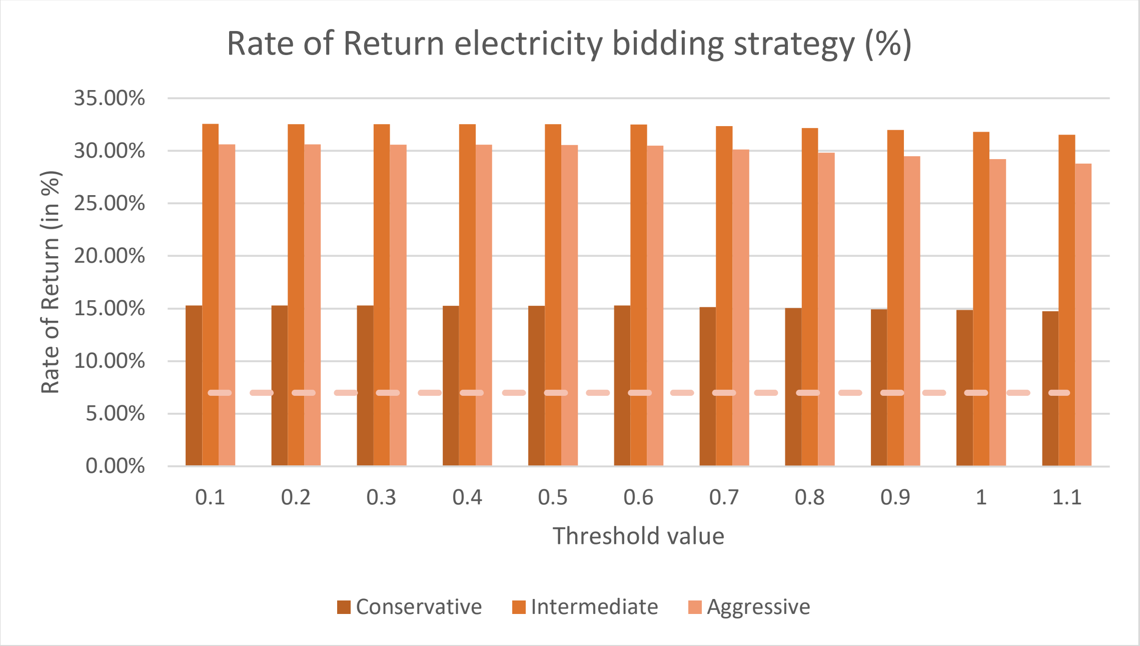

Figure 13: Rate of Return for the conservative, intermediate and aggressive electricity bidding strategies in %.

Figure 13 presents the Rate of Return (ROR) for the various electricity bidding strategies. Notably, it is evident that the ROR for each strategy surpasses that of the reference strategy. Upon closer examination, we observe that the conservative strategy consistently yields RORs exceeding 7% when incorporating the price thresholds, in contrast to the reference strategy where the conservative ROR stood at 6.33%. Conversely, the intermediate strategy demonstrates the highest ROR among all strategies, peaking at 32.55%.

Moreover, the trend in ROR does not exhibit a linear progression akin to previous economic performance parameters. Instead, across all three graphs, the ROR remains relatively stable between thresholds 0.1 and 0.7 before exhibiting a gradual decline. Nonetheless, the overall ROR values underscore a good economic performance across the various strategies.

3.2.3.5 Overview

In this overview, the electricity bidding strategy that has exhibited the most favourable outcomes across most metrics is discussed, namely the 0.1 threshold. Full data of all electricity bidding strategies can be found in Appendix 2.

Table 8 provides an overview of the economic performance metrics for the conservative, intermediate, and aggressive electricity bidding strategies utilizing the 0.1 threshold. Compared to the reference strategy, there are some notable differences. Firstly, the total yearly revenue is higher for each of the three strategies. Most notably, the BESS lifetime is much longer compared to the reference strategy, whilst the payback time (PBT) is lower. Furthermore, the ROR is significantly higher for the electricity bidding strategy. This may be attributed to potential instances of charging or discharging at suboptimal rates, consequently reducing the ROR for the reference strategy. Furthermore, whereas the aggressive strategy performed best in the reference strategy, here it is the intermediate strategy that performs best across all metrics. Overall, the economic performance is better for the electricity bidding strategy for all timeslot strategies compared to the reference.

Table 8: Overview of the economic performance for the conservative, intermediate and aggressive electricity bidding strategy with threshold 0.1.

	Conservative	**Intermediate**	**Aggressive**	Unit
Total yearly revenue	0.279	0.551	0.542	M €
Net revenue lifetime	13.90	14.69	9.69	M €
PBT/lifetime	5.92/63.06	2.80/31.34	2.84/21.98	years
ROR	15.30%	32.55%	30.61%	%

3.2.4 Capacity bid analysis

Up to this point in the study, the assumption has been that every bid placed by the BESS results in a successful outcome. However, this ideal scenario diverges from reality where bids are not always victorious. Unlike the electricity market bidding during timeslots, which operates on a system where compensation aligns with the highest available bid, capacity fee bidding adheres to a "paid-as-bid" structure. In this context, we explore the implications of scenarios where the capacity bid is not consistently secured. Specifically, the focus is on evaluating the effects on total yearly revenue and the Rate of Return (ROR).

3.2.4.1 Total yearly revenue

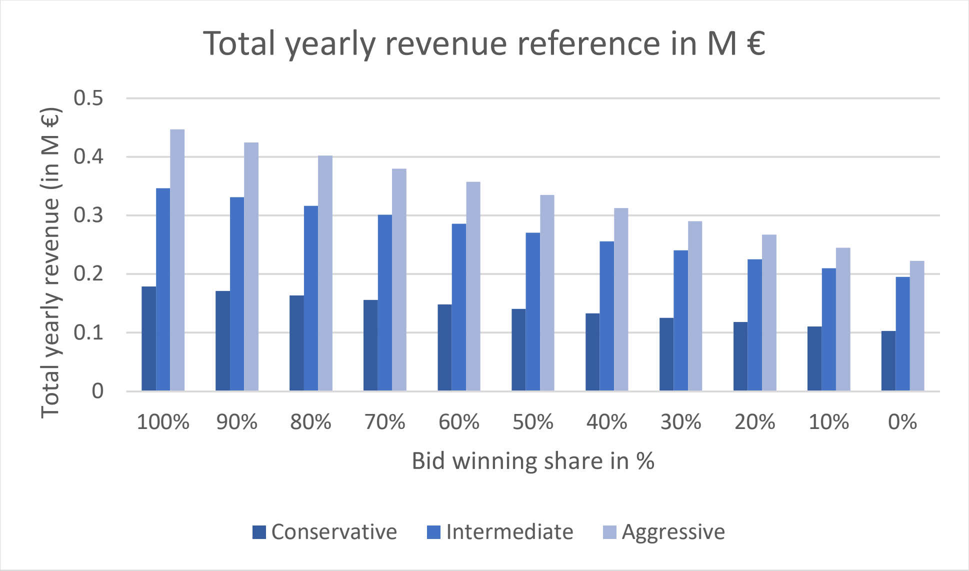

Figure 14: Total yearly revenue of the reference strategy for each capacity bid winning share in %.

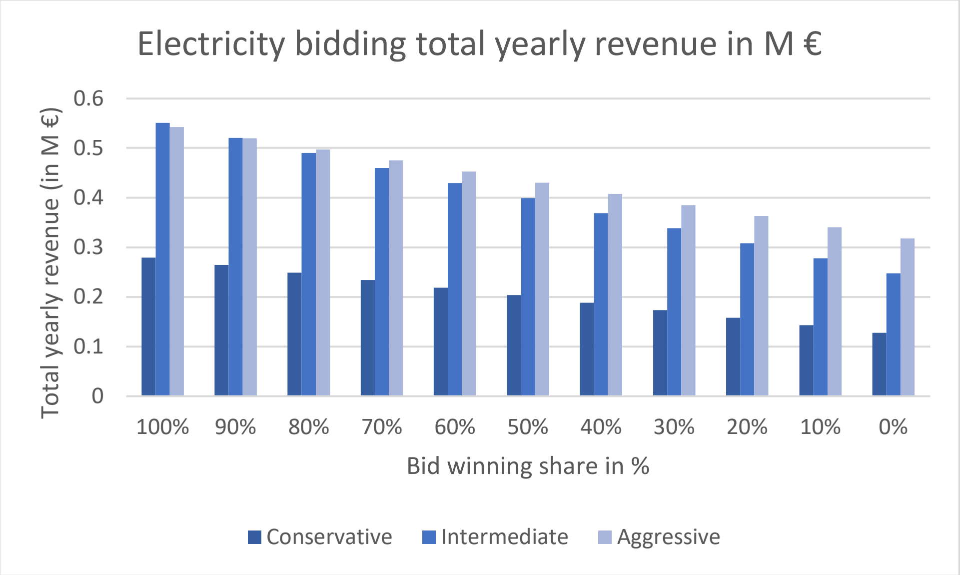

Figure 15: Total yearly revenue of the 0.1 electricity bidding strategy for each capacity bid winning share in %.

Figures 14 and 15 show the total yearly revenue for the reference and electricity bidding strategy respectively for bid winning shares between 0% and 100%. It can be seen that a lower capacity bid winning share leads to a significant reduction in total yearly revenue, especially in the reference scenario. It also shows a steeper decline than the electricity bid strategy, suggesting that the reference strategy is more dependent on the capacity fee. Specifically, a 50.2% reduction in total yearly revenue for the aggressive reference strategy between 100% and 0%, whereas the aggressive electricity bidding strategy only has a 27.7% reduction in revenue. As the reference case does not check for profitability before taking part in a bid, this clearly results in lower returns.

3.2.4.2 Net revenue lifetime

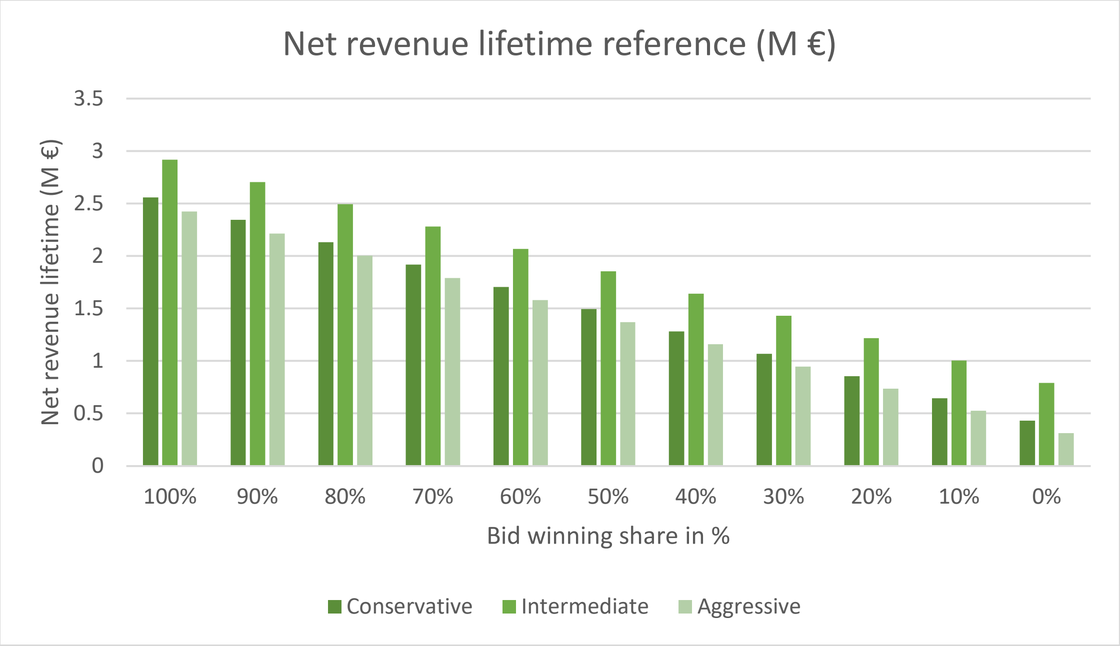

Figure 16: Net revenue lifetime of the reference strategy for each capacity bid winning share in %.

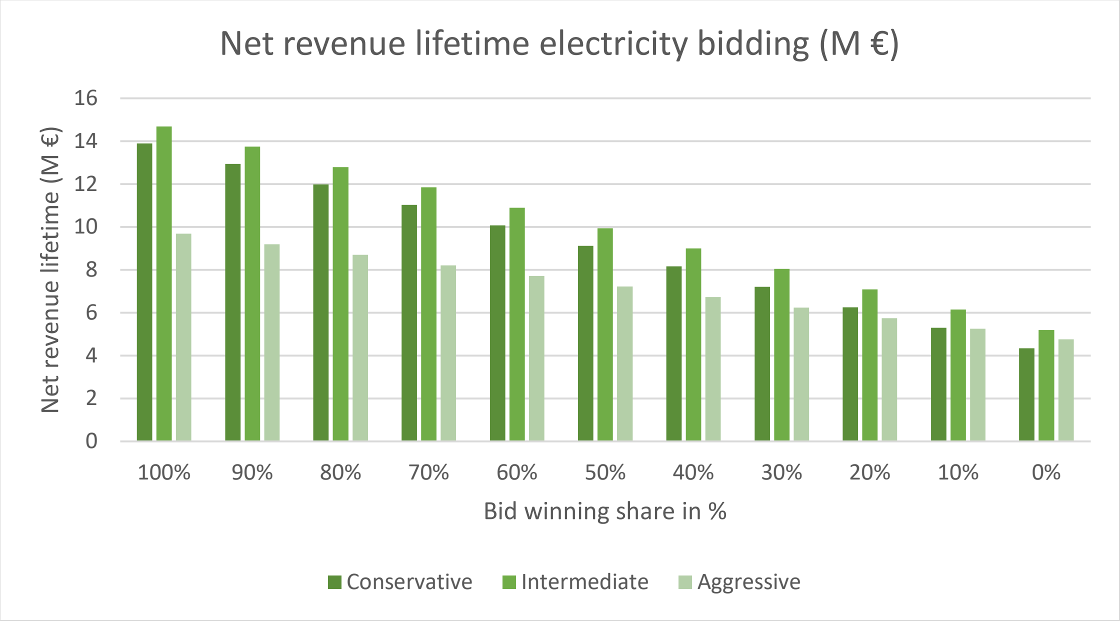

Figure 17: Net revenue lifetime of the 0.1 electricity bidding strategy for each capacity bid winning share in %.

Figures 16 and 17 present the net revenue trajectories over the Battery Energy Storage System (BESS) lifetime under conditions where the capacity bid winning share falls below 100%. Notably, the intermediate strategy consistently exhibits the highest net revenue lifetime across both scenarios. Despite similar overall trends observed in both figures, a discernible disparity arises in the aggressive scenario for electricity bidding, particularly evident at high bid winning shares. However, it is noteworthy that while the aggressive strategy may demonstrate inferior performance under these conditions, its decline in net revenue is less pronounced compared to that of the conservative and intermediate strategies as the capacity bid share decreases.

3.2.4.3 Rate of Return

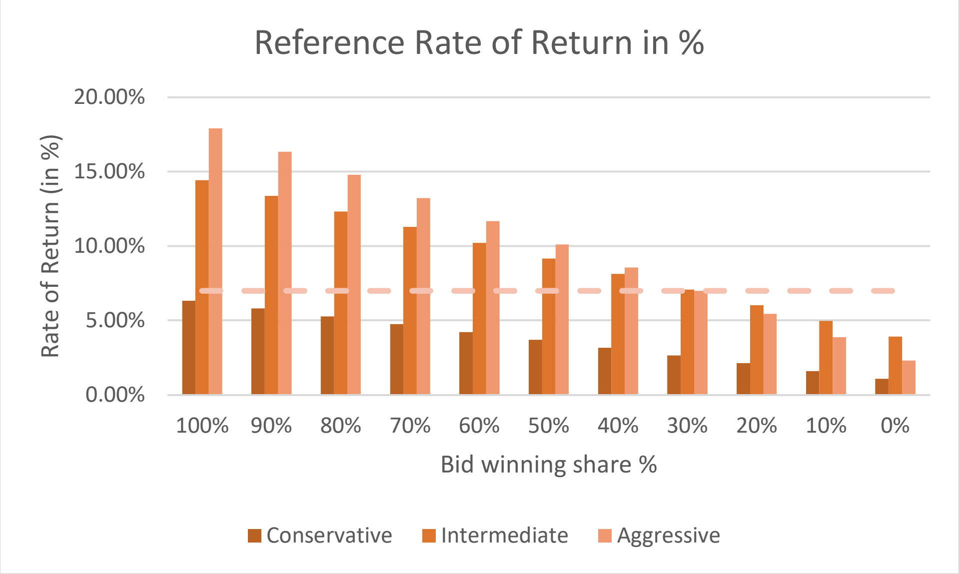

Figure 18: Rate of Return of the reference strategy for each capacity bid winning share in %. The dashed line is a reference ROR of 7%.

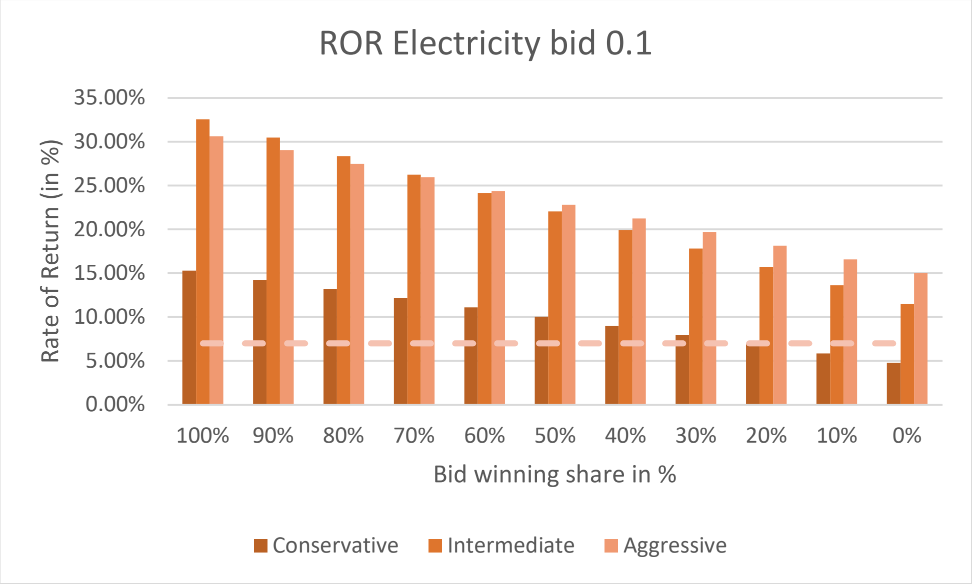

Figure 19: Rate of Return of the electricity bid strategy at a threshold of 0.1 for each capacity bid winning share in %. The dashed line is a reference ROR of 7%.

Figures 18 and 19 show the ROR when the bid winning share is lower than 100%. It is clear that a reduction in the capacity bid revenue has a significant impact on the ROR of both strategies, but again, mostly on the reference strategy. As Figure 16 shows, a bid winning share of 30% or lower leads to an ROR of 7% or lower for each timeslot strategy. It once again shows a steeper decline on the reference scenario compared to the electricity bidding scenario. Furthermore, from a 60% bid winning share or less, the aggressive strategy performs best.

3.2.4.3 Overview

Tables 9 and 10 provide a summary of the economic performance metrics for both the reference and 0.1 electricity bidding strategy under the condition where the capacity bid winning share stands at 50%. This scenario denotes a situation where 50% of the capacity bids are accepted. Analysis of the tables reveals that, in both scenarios, the conservative strategy yields the lowest performance, while the intermediate and aggressive strategies demonstrate comparable outcomes. Particularly noteworthy is the significantly higher net revenue lifetime observed in the electricity bidding strategy compared to the reference. According to the data presented, only the conservative reference strategy falls short of meeting the typical 7% ROR benchmark, suggesting potential underperformance.

Table 9: Overview of the economic performance for the conservative, intermediate and aggressive reference strategy with capacity bid winning share of 50%.

	Conservative	**Intermediate**	**Aggressive**	Unit
Total yearly revenue	0.141	0.271	0.335	M €
Net revenue lifetime	1.49	1.85	1.37	M €
PBT/lifetime	13.77/28.06	6.14/14.04	4.82/9.4	years
ROR	3.70%	9.17%	10.11%	%

Table 10: Overview of the economic performance for the conservative, intermediate and aggressive 0.1 electricity bidding strategy with capacity bid winning share of 50%.

	Conservative	**Intermediate**	**Aggressive**	Unit
Total yearly revenue	0.203	0.399	0.430	M €
Net revenue lifetime	9.12	9.94	7.22	M €
PBT/lifetime	13.77/28.06	6.14/14.04	4.82/9.04	years
ROR	10.04%	22.03%	22.81%	%

3.3 Scenario Analysis

This section presents the results of the scenario analysis, aimed at assessing the influence of electricity price fluctuations on the economic performance and robustness of both the reference and the 0.1 electricity bidding strategy. Specifically, the analysis explores the effects of price fluctuations ranging from -10% to +10%. By examining these variations, we aim to gain insights into the strategies' resilience and adaptability to changing market conditions.

3.3.1 Total yearly revenue

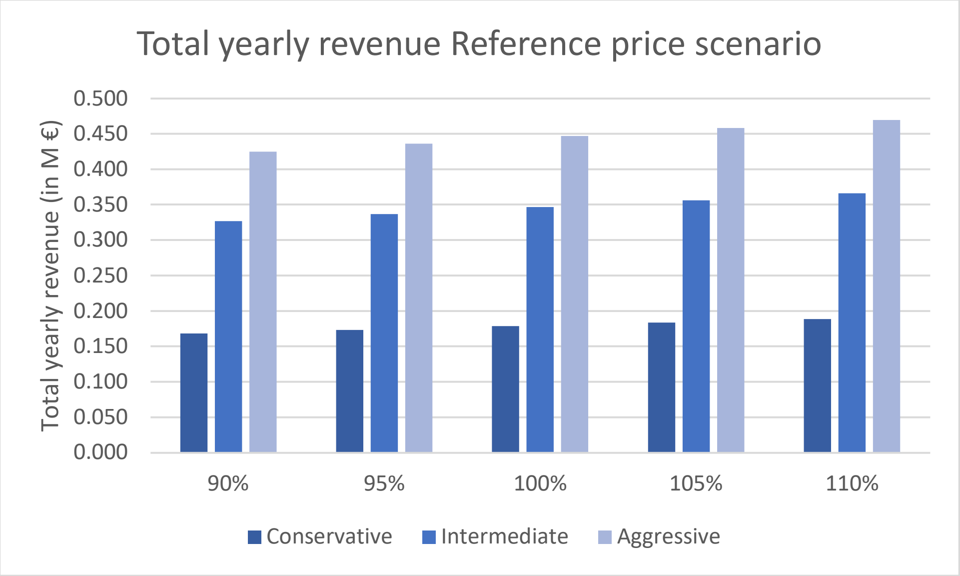

Figure 20: Total yearly revenue of the reference strategy for each price scenario in million euro.

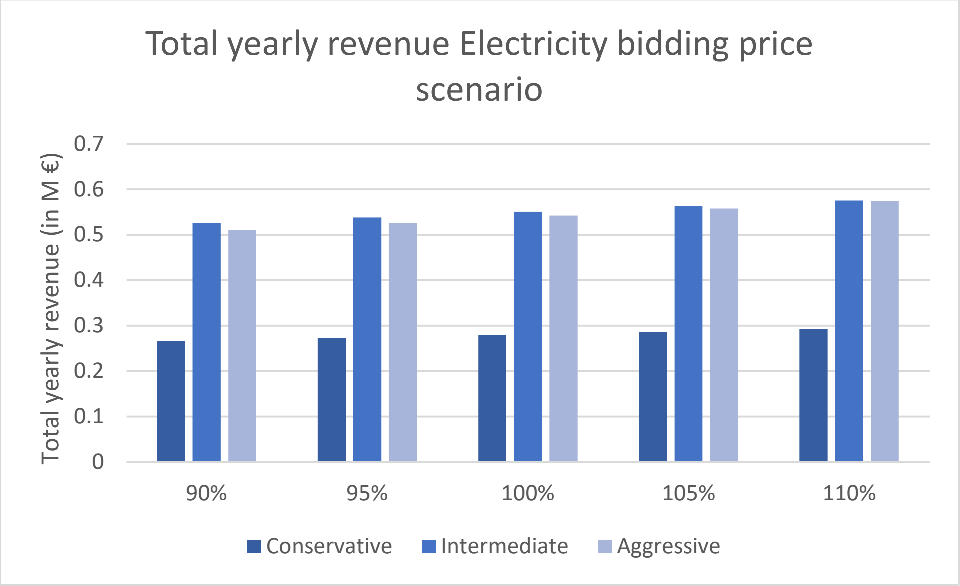

Figure 21: Total yearly revenue of the 0.1 electricity bidding strategy for each price scenario in million euro.

Figures 20 and 21 depict the total yearly revenues generated by both the reference and 0.1 electricity bidding strategies across various price scenarios. Surprisingly, the observed impact of fluctuations in electricity prices seems to be less pronounced compared to the effects of strategy variations discussed in Chapter 3.2. Notably, there exists a difference of approximately 12% in total yearly revenue for the aggressive electricity bidding strategy between price fluctuations of 90% and

110%, with a similar trend observed for the aggressive reference strategy, showing an approximately 11% difference. While discernible differences are evident, they appear to be relatively moderate in magnitude. Additionally, it is notable that the conservative strategies exhibit a lesser susceptibility to the effects of price fluctuations in comparison to the intermediate or aggressive strategies.

3.3.2 Net Revenue Lifetime

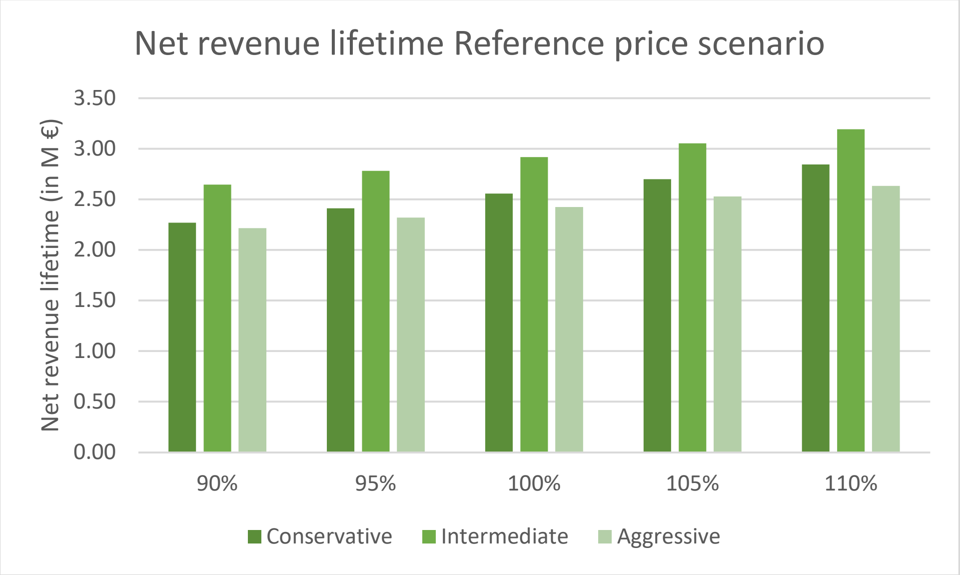

Figure 22: Net revenue lifetime of the reference strategy for each price scenario in million euro.

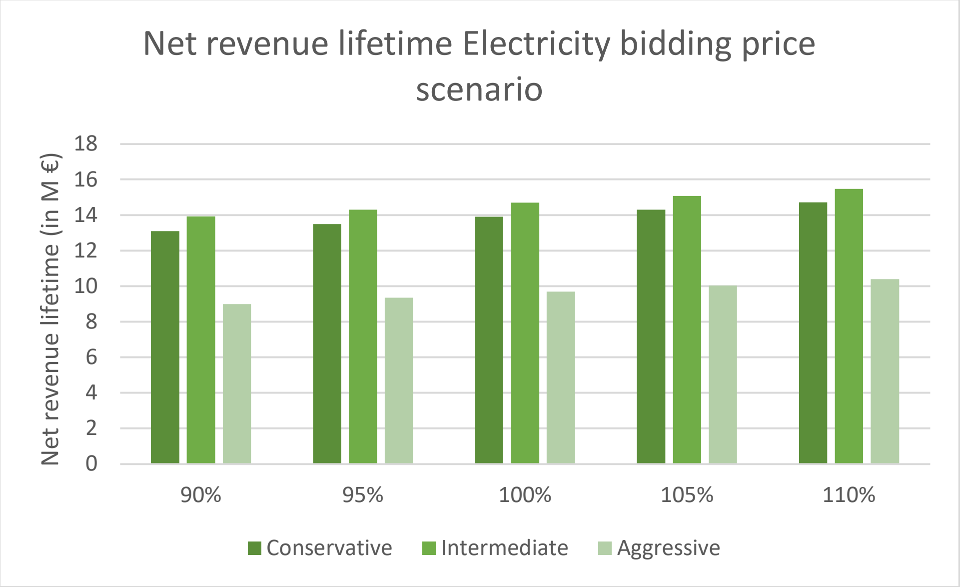

Figure 23: Net revenue lifetime of the 0.1 electricity bidding strategy for each price scenario in million euro.

Figures 22 and 23 portray the net revenue lifetime generated by both the reference and 0.1 electricity bidding strategies across different price scenarios. A notable observation is the discernible impact of the price scenarios on the reference strategy compared to the electricity bidding strategy, indicating a greater sensitivity of the former to changes in prices.

3.3.3 Rate of Return

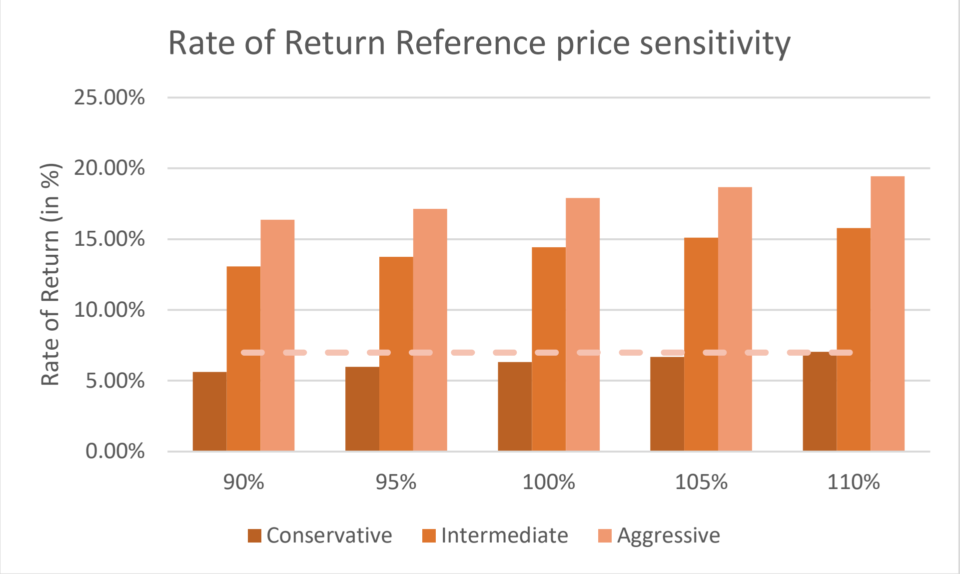

Figure 24: ROR of the reference strategy for each price scenario in %.

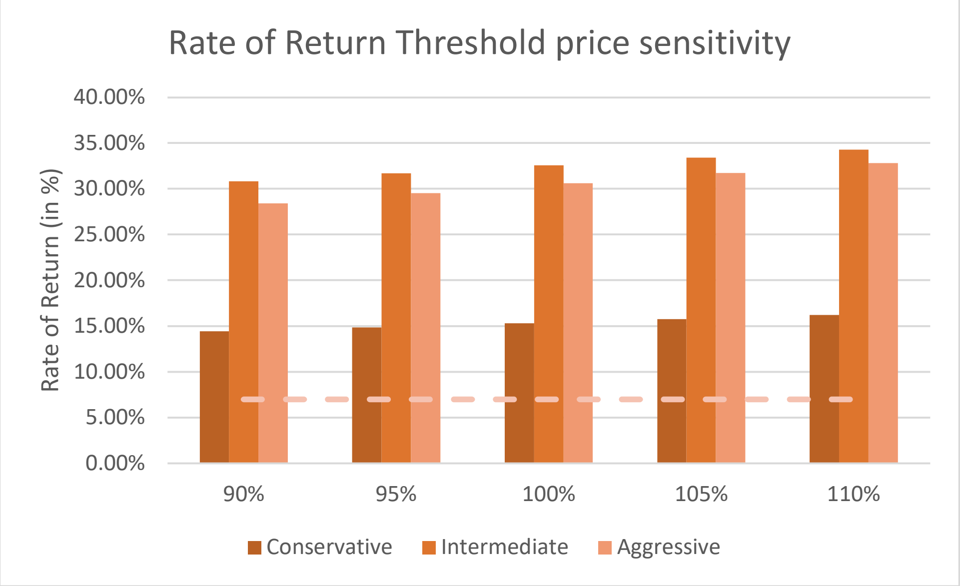

Figure 25: ROR of the 0.1 electricity bidding strategy for each price scenario in %.

Figures 24 and 25 depict the ROR generated by both the reference and 0.1 electricity bidding strategies across various price scenarios. Much like the total yearly revenue and net revenue lifetime, the ROR does not exhibit a significant response to these price fluctuations. Notably, the ROR tends to increase with rising electricity prices, in line with expectations.

Discussion

In this section, the results presented in the previous section will be discussed. At first the results will be briefly reviewed and summarized, followed by an exploration of the corresponding implications. Key limitations will be identified, and recommendations for future research will be made.

Reference strategy

The reference strategy, implemented with conservative, intermediate, and aggressive timeslot strategies, yielded markedly diverse outcomes. Notably, while the aggressive strategy demonstrated the highest total yearly revenue and Return on Revenue (ROR), the net revenue over the Battery Energy Storage System (BESS) lifetime peaked with the intermediate strategy, and the BESS lifetime itself was longest with the conservative approach. Despite the longer lifetime observed with the conservative and intermediate strategies, it's crucial to consider that this is contingent upon the number of cycles the BESS undergoes, with factors like age potentially impacting the actual lifespan of the BESS. Nevertheless, the aggressive strategy stands out for its superior performance and notably shorter payback time.

Moreover, the ROR for both the intermediate and aggressive strategies was economically attractive, with even the conservative ROR proving relatively favourable. An intriguing avenue for further research lies in exploring dynamic timeslot strategies, such as employing an intermediate strategy during periods of low electricity prices and transitioning to an aggressive approach during high-price periods. This approach could potentially optimize revenue generation by aligning bidding strategies with fluctuating market conditions.

Electricity bidding strategy

The utilization of different price thresholds within the electricity bidding strategy significantly enhanced the economic performance of the Battery Energy Storage System (BESS), surpassing that of the reference strategy. This improvement is attributed to the mitigation of discharging during periods of negative electricity prices, thereby averting revenue losses experienced in the reference strategy. Notably, the intermediate strategy emerged as the most effective. Among the range of thresholds examined in this study (ranging from 0.1 to 1.1), the lowest threshold yielded the optimal performance.

Future research could explore expanding these thresholds, including the consideration of negative thresholds, to evaluate whether occasional revenue losses could contribute to an overall improved economic performance. Additionally, there is potential for implementing dynamic thresholds, whereby periods or timeslots characterized by high prices could be assigned higher price thresholds compared to those with lower prices. Such dynamic adjustments could potentially further optimize the economic performance of the BESS bidding strategy.

Capacity bids

The main advantage for the aFRR market as opposed to the passive imbalance market is the capacity fee that BESS can receive for trading on the aFRR. This is a significant part of the profitability as Chapter 3.2.4 has shown, where for the intermediate bidding strategy, the capacity bidding encompasses 55% of total revenue. So far in this study, it was assumed that each capacity bid was accepted and perfectly bid to gain the maximum revenue out of it. In reality, this is not the case. As we saw before, especially the reference strategy experienced a significant reduction in profitability when the bid winning share was low.

Future research could expand the capacity bidding strategy further, where the paid-as-bid aspect of the capacity fee could be explored further to add dynamic bidding for the capacity bid depending on the time of year or time of day.

Scenario analysis

The scenario analysis looked at how resilient the economic performance of BESS is depending on different price fluctuations. It can be concluded that in the range of -10% to +10% compared to the 2021 prices, the difference in price has an impact, albeit a smaller one than one might expect. A difference of 20% in price led to a difference in total yearly revenue of 10.4% and 12.5% for the reference and electricity bidding strategies respectively. Although this is not insignificant, it is clear that different factors such as the capacity bid winning share have a bigger impact on the economic performance of BESS. It must be noted that in this analysis, only the electricity prices were affected, not the capacity bid prices. Since these two are inextricably linked, it could be interesting to see what the impact of lower or higher capacity fees would be on the profitability of BESS.

Future research could also conduct a sensitivity analysis on the price variability (volatility). In this case it is recommended to maintain the same average price but increase the standard deviation to see what the effect could be on BESS.

Overview

This study provides insights into the economic performance of BESS on the aFRR. Based on these results, it appears that the aFRR offers an attractive business proposition for battery operators which can deliver high rates of returns, although some fairly optimistic assumptions have been made (see the section on limitations below). A conservative strategy is not recommended as it clearly does not utilize the short- and medium-term earning potential of the battery. Its low participation rate clearly does not pay off.

BESS are optimally operated in the Dutch aFRR market when the battery participates in an intermediate number of thresholds, bids according to a threshold value of 0.1*mean price and at least 70% of capacity bids are won (ideally 100%). However, as bid winning success rates drop below 70%, then the aggressive strategy provides a better rate of return. The aggressive strategy also realizes the highest gains in the short term. If a full economic model that takes discount rates (time value of money) into account, it may well prove that the aggressive strategy yields the best overall result in all cases.

It should be noted that the further we forecast into the future, the larger the uncertainties will be regarding pricing assumptions. The intermediate strategy is more susceptible to such uncertainties. Another factor that should be taken into account is the rapid rate of battery innovation. This means that batteries of today may find it hard to compete with batteries of the future, which will be able to economically bid at lower rates than current batteries. In that case, a strategy that maximizes short-term returns makes more business sense. This factor also favours the aggressive strategy. When conducting a sensitivity analysis on the general pricing, it did yield different results, but the change in revenue, was less than the change in the pricing that was assumed. This is probably due to the fact that it is the variability of the pricing that plays a large role in the revenue.

Limitations

This study has several limitations, each of which will be detailed below.

The lack of data available on the capacity fee bidding process led to a simplified approach in which all bids were won aside from the capacity bidding section. Because data on the 4-hour timeslot system in aFRR and bid winning odds was unavailable, it was not possible to insert such an approach into the core of the model and have it have a meaningful impact. Several approaches to this were considered previously, including a set bid for the aFRR capacity fee that would dictate whether the capacity fee was accepted, or even a dynamic approach depending on the average capacity fee per month or season. However, these approaches were more complicated and require calibration with data. Since the aFRR market is still new for BESS, there is insufficient data to perform such calibration. Furthermore, a comparison to prices on the FCR, a market that does run in 4-hour timeslots, was considered. This approach would have compared the distribution of prices on the FCR to the capacity fee. This was yet again discarded as there was no way to validate that the distribution on the FCR and aFRR would be similar. Furthermore, there was unfortunately no way to validate the results and compare them to an actual BESS on the aFRR, as there currently do not exist any standalone BESS on the aFRR.

Perhaps the largest limitation and part of the reason why the rate of return was so high for certain strategies, has to do with the grid fees. To maintain flexibility and accommodate varying business contexts, the model was designed to focus solely on revenue potential and operational dynamics within the aFRR market framework. By omitting additional costs such as transport tariffs and network fees, users are afforded the opportunity to incorporate these expenses into the model as needed, thereby tailoring the analysis to their individual business cases. Additionally, the inclusion of connection costs may vary significantly depending on whether the BESS operates as a standalone entity or is integrated into the network connection of another asset.

It's important to acknowledge that while the exclusion of these costs may result in optimistic rate of return estimates, it does not diminish the validity of the study's findings regarding optimal strategies for aFRR participation. Instead, it underscores the importance of considering the broader financial context and incorporating relevant costs into the analysis to develop a comprehensive understanding of the economic feasibility of BESS deployment in specific scenarios.

In future research, expanding the model to include these omitted costs could provide a more nuanced assessment of the financial implications of BESS deployment. This would involve allowing users to input detailed cost structures for transport tariffs, network fees, and connection expenses, thereby enabling a more customized analysis tailored to individual business contexts and regulatory environments. Additionally, exploring the impact of different connection configurations on overall project economics could further enhance the utility and relevance of the model in real-world decision-making scenarios.

By focusing on assessing strategies for participating in the aFRR market, this study extends current theoretical insights and contributes to the literature by providing insights into the economic performance of BESS. The findings offer avenues for further research as mentioned throughout this chapter. Furthermore, the findings of this research offer valuable insights for battery operators and policymakers seeking to optimize revenue generation and operational efficiency in energy markets. The study highlights the attractiveness of the aFRR market as a business proposition for BESS operators, with potential for high rates of return.

Conclusion

This research aimed to address the question of how Battery Energy Storage Systems (BESS) can be optimally operated in the Dutch frequency restoration reserve (aFRR) market to maximize their economic performance. Three key sub-questions were explored:

Modelling BESS Deployment Strategies

The study investigated various strategies for deploying BESS in the aFRR market, considering conservative, intermediate, and aggressive timeslot strategies. Results indicated diverse outcomes, with the aggressive strategy demonstrating the highest total yearly revenue and Return on Revenue (ROR). However, the net revenue over the BESS lifetime peaked with the intermediate strategy, while the conservative approach exhibited the longest BESS lifespan. These findings underscore the importance of selecting an appropriate strategy that balances revenue potential with operational longevity.

Optimal Combination of Deployment Strategies

By examining the combination of strategies for deploying BESS in the aFRR market, the study revealed that the utilization of different price thresholds within the electricity bidding strategy significantly enhanced economic performance. Particularly, the intermediate strategy emerged as the most effective, suggesting that bidding according to a lower threshold value yields optimal results. Future research avenues include exploring dynamic threshold adjustments to further optimize revenue generation in response to fluctuating market conditions.

Impact of Price Fluctuations

The scenario analysis examined the resilience of BESS economic performance to fluctuating market prices. While price changes had an impact, the study highlighted that factors such as the capacity bid winning share had a more substantial influence on economic performance. Future research could further explore the impact of price variability on BESS profitability through sensitivity analysis.

Overall, this study contributes to theoretical insights by providing valuable insights into the economic performance of BESS in the aFRR market. The findings offer practical implications for battery operators and policymakers, emphasizing the attractiveness of the aFRR market as a business proposition for BESS deployment. However, it's essential to acknowledge the limitations of the study, including the exclusion of certain costs such as transport tariffs and network fees. Future research should focus on addressing these limitations by incorporating detailed cost structures and exploring the impact of different connection configurations on overall project economics.

In conclusion, this study underscores the importance of considering broader financial contexts and operational dynamics in assessing the economic feasibility of BESS deployment in energy markets. By providing insights and recommendations, this research aims to guide decision-making processes and contribute to the advancement of BESS deployment strategies in the aFRR market.

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Appendix 1: Investment costs

Supplier / Project	**Type**	**Power [kW]**	**Capacity [kWh]**	**C-rating [-]**	**Price [€]**	**Price / kWh [€/kWh]**	**Maintenance and Service [€/year]**
iWell (small)	price indication	800	1,600	0.5	€ 720,000	€ 450.00	n.a.
iWell (large)	price indication	5,000	10,000	0.5	€ 3,500,000	€ 350.00	n.a.
Big Ass Battery	price indication	425	800	0.53	€ 714,000	€ 892.50	€ 8,925.00
Alfen (TheBattery Elements)	price indication	1,000	2,000	0.5	€ 740,000	€370.00	n.a.
RWE Eemshaven 2023	investment	35,000	41,000	0.85	€ 24,000,000	€ 585.37	n.a.
2023 CE delft report 4 hr (small)	report assumption	20,000	80,000	0.25	€ 20,400,000	€ 255.00	€ 510,000.00
2023 CE delft report 2 hr (small)	report assumption	20,000	40,000	0.5	€ 12,400,000	€ 310.00	€ 310,000.00
2023 CE delft report 4 hr (large)	report assumption	400,000	1,600,000	0.25	€ 337,600,000	€ 211.00	€ 8,400,000.00
2023 CE delft report 2 hr (large)	report assumption	400,000	800,000	0.5	€ 205,600,000	€ 257.00	€ 5,100,000.00
Hornsdale Power Reserve / Tesla Big Battery (Australia, 2018)	investment	100,000	129,000	0.78	€ 56,000,000	€ 434.11	n.a.

Appendix 2: Electricity bidding results

Table 11: Conservative strategy.

Threshold	Total Revenue (euro)	Payback Time (years)	Lifetime (years)	Net Revenue (euro)	Electricity revenue (euro)	Total Capacity fee revenue (euro)	Energy Per Day (MWh)	Cycles Per Day	Total Revenue Lifetime (euro)	Net Revenue Lifetime (euro)	Rate of Return (%)
0.1	171172.6	10.65	63.06065	135172.6	127721.4	43451.26	3.48	0.43	8524074	7084074.01	7.80%
0.2	170867.4	10.68	63.08732	134867.4	127405.2	43462.14	3.47	0.43	8508422	7068421.88	7.78%
0.3	170873.7	10.68	63.01459	134873.7	127374.9	43498.78	3.48	0.43	8499012	7059011.83	7.78%
0.4	170805	10.68	62.93823	134805	127293	43512.07	3.48	0.44	8484390	7044390.2	7.77%
0.5	170851.7	10.68	62.93853	134851.7	127274.6	43577.09	3.48	0.44	8487367	7047366.65	7.78%
0.6	170075.1	10.74	64.8261	134075.1	126762.8	43312.33	3.38	0.42	8691567	7251566.74	7.77%
0.7	165550.9	11.12	71.04261	129550.9	122916.9	42633.94	3.09	0.39	9203632	7763631.62	7.59%
0.8	161976.9	11.43	76.74773	125976.9	119848.8	42128.15	2.86	0.36	9668441	8228440.98	7.45%
0.9	158498.5	11.76	83.42362	122498.5	116861.6	41636.96	2.63	0.33	10219272	8779271.52	7.31%
1	155947.5	12.01	88.38559	119947.5	114731.7	41215.73	2.48	0.31	10601626	9161626.18	7.20%
1.1	152727.1	12.34	94.83801	116727.1	112096	40631.1	2.31	0.29	11070164	9630163.7	7.05%

Table 12: Intermediate strategy.

Threshold	Total Revenue (euro)	Payback Time (years)	Lifetime (years)	Net Revenue (euro)	Electricity revenue (euro)	Total capacity fee revenue (euro)	Energy Per Day (MWh)	Cycles Per Day	Total Revenue Lifetime (euro)	Net Revenue Lifetime (euro)	Rate of Return (%)
0.1	333101.6	4.85	31.34302	297101.6	247714.9	85386.68	6.99	0.87	9312062	7872061.51	17.44%
0.2	332934.7	4.85	31.317	296934.7	247520.5	85414.21	7	0.87	9299102	7859101.92	17.43%
0.3	332997.9	4.85	31.28735	296997.9	247533.8	85464.11	7.01	0.88	9292275	7852275.45	17.43%
0.4	332809.6	4.85	31.27586	296809.6	247300.3	85509.31	7.01	0.88	9282976	7842976.41	17.41%
0.5	333355.8	4.84	31.23201	297355.8	247739.9	85615.89	7.02	0.88	9287019	7847019.18	17.45%
0.6	330960.6	4.88	32.28486	294960.6	245826	85134.6	6.79	0.85	9522764	8082763.5	17.39%
0.7	323139.3	5.01	35.51473	287139.3	239390.3	83748.98	6.17	0.77	10197674	8757673.91	17.12%
0.8	316438.7	5.13	38.40396	280438.7	233736.1	82702.54	5.71	0.71	10769954	9329954.13	16.87%
0.9	309963.4	5.26	41.57097	273963.4	228321.8	81641.52	5.27	0.66	11388923	9948922.9	16.62%
1	304464.4	5.36	44.24782	268464.4	223681.2	80783.25	4.95	0.62	11878966	10438966.09	16.38%
1.1	296707.3	5.52	47.94102	260707.3	217170.7	79536.54	4.57	0.57	12498572	11058572.02	16.02%

Table 13: Aggressive strategy.

Threshold	Total Revenue (euro)	Payback Time (years)	Lifetime (years)	Net Revenue (euro)	Electricity revenue (euro)	Total capacity fee revenue (euro)	Energy Per Day (MWh)	Cycles Per Day	Total Revenue Lifetime (euro)	Net Revenue Lifetime (euro)	Rate of Return (%)
0.1	439671.8	3.57	21.98222	403671.8	317733.4	121938.4	9.97	1.25	8873600	7433600.41	23.48%
0.2	439638.2	3.57	21.97586	403638.2	317669.9	121968.3	9.97	1.25	8870298	7430297.73	23.48%
0.3	439629.8	3.57	21.96129	403629.8	317550.4	122079.5	9.98	1.25	8864233	7424232.7	23.48%
0.4	439500.6	3.57	21.94176	403500.6	317352.9	122147.7	9.99	1.25	8853513	7413512.55	23.46%
0.5	439343.5	3.57	21.94162	403343.5	317065.3	122278.3	9.99	1.25	8850008	7410008.37	23.45%
0.6	434512.2	3.61	22.94863	398512.2	313087.1	121425.1	9.55	1.19	9145310	7705309.52	23.32%
0.7	420402.2	3.75	25.72375	384402.2	301214.8	119187.3	8.52	1.07	9888265	8448264.51	22.81%
0.8	409669	3.85	28.1191	373669	292072.7	117596.2	7.79	0.97	10507235	9067235.25	22.39%
0.9	398119.2	3.98	31.11686	362119.2	282292.2	115827	7.04	0.88	11268011	9828011.27	21.93%
1	389661.7	4.07	33.45296	353661.7	275147.9	114513.9	6.55	0.82	11831034	10391033.55	21.57%
1.1	378190.7	4.21	36.57924	342190.7	265495.3	112695.5	5.99	0.75	12517078	11077078.4	21.03%