Master's Thesis – master Energy Science

BUSINESS CASE EFFECTS OF A BATTERY ACTING ON THE AFRR MARKET COMBINED WITH INTRADAY CHARGE MANAGEMENT

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Summary

The increasing penetration of renewable energy sources for electricity generation has made it increasingly difficult to match supply and demand on the grid. This creates an increasing demand for flexible power to respond to grid needs. A battery energy storage system (BESS) is an example of a flexible asset.

First, the added value of BESS for the electricity system was investigated. It can be concluded that adding BESS for grid stabilization reduces the imbalance price and thus makes renewable energy projects more financially attractive due to lower imbalance costs. A BESS can contribute to imbalance cost reduction in two ways: actively or passively balancing. Active means that participation is preselected through bidding, with the transmission system operator (TSO) providing the connection and activation. Passive balancing means a voluntary contribution to grid imbalance, stimulated by live publication of imbalance prices. The entry of BESS reduces imbalance costs for both forms of balancing, compared to a scenario where batteries do not enter. In the general sense of grid stabilization, it can be said that active balancing is more efficient way of balancing, however, creates a smaller supply of available power overall.

The provision of active balancing power, is done through the automatic frequency restoration reserve market (aFRR). However, the choice deployment for BESS should not only be made on the basis of grid stabilization, there should also be responsible financial compensation in return.

This thesis research investigates how a BESS can bid into the aFRR market with its full power and the added value of this market on a battery's business case. Using literature and published documents from TenneT, the conditions a BESS must meet to be able to bid its full power have been identified. It has been found that a BESS can offer its full power by applying charge management supported by an intraday energy transaction Next, this study examines the data flows required in Scholt Energy organizational structure to make this possible. From this, it appears that the current organizational structure allows for the control of aFRR combined with intraday charge management, but means that data communication of purchased intraday deals goes through Scholt Energy. Technical simplification and the added value of market stacking occurs the moment it is possible to connect to the extended crowd balancing platform (CBP) for aFRR delivery. Here the involved parties for aFRR delivery, intraday charge management and BESS control are all connected.

After having established how a BESS can legally and organizationally participate with its full capacity in the aFRR market, the possible financial outcome has been investigated. This involved investigating the returns of different battery dimensions (being different power to storage ratios) on the aFRR market. This was done by modelling four bidding strategies. The models were run based on the historical revenue achieved in 2021, 2022 and 2023, where 2023 outcomes were based on the first quarter and extrapolated. From the outcome it can be indicated that in 2022, BESS revenues on aFRR were highest, followed by 2023 and lastly 2021.

Revenue from just the aFRR market needs to be put into perspective against other markets to which the battery has access. The comparison model compares the revenues of the aFRR revenue model with historically achieved revenues of a battery in the Frequency Restoration Reserve (FCR) and imbalance market. This shows that the aFRR market does give a significant increase on a battery's revenues, even when the balance Service Provider (BSP) does not have perfect foresight on the profitability of each market. For a future scenario, this effect is even greater.

This same effect can be seen for payback period of the BESS. Here, it has been found that the payback time of a BESS in the future scenario decreases from 8-13 years to 3-10 years when the

battery also has access to the aFRR market, depending on different battery sizing. Besides the fact that adding the aFRR market, makes the battery more robust to market developments, it also ensures that the battery gives a higher fee yield for Scholt Energy. Since Scholt Energy receives a fee dependent on the revenue, it is financially attractive for both the investor/owner of the battery and Scholt Energy to achieve the highest possible revenue. For this reason, trading on the aFRR market is recommended. This not only gives a financial advantage to a Scholt Energy and the battery investor, but also reduces the cost of balancing energy in general and thus increases the financial viability of renewable energy projects such as wind and solar.

List of abbreviations

aFRR	automatic Frequency Restoration Reserve
APFAS	Auction Platform For Ancillary Services
BESS	Battery Energy Storage System
BRP	Balance Responsible Party
BSP	Balance Service provider
CBP	Crowd Balancing Platform
CID	Continuous Intraday
e-program	Energy program
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
FVR	Frequentie Vermogens Regeling
ISP	Imbalance Settlement Period
k	Kilo (abbreviation of a thousand)
LER	Limited Energy Reserve
mFRR	manual Frequency Restoration Reserve
RPG	Reserve Providing Group
RSU	Reserve Supply Unit
TI	Technical Installation
TSO	Transmission System Operator
UER	Unlimited Energy Reserve

Contents

1. Introduction

1.1 Problem definition

The Dutch government has great ambitions in terms of sustainability, reliability and available energy. This ambition translates into the strong increase of renewable sources. In 2021, between 12.0% and 13.4% of all energy in the Netherlands came from renewable energy sources (CBS, 2022); By 2030, this must be at least 27%. By 2050, almost all energy consumed in the Netherlands must come from renewable energy sources (Rijksoverheid, 2022). Renewable sources for electricity, such as wind and solar, are a lot less harmful to the environment than its fossil alternatives such as coal and gas. The disadvantage of these sources, however, is that renewable production varies greatly by season and even during the day.

This is a disadvantage because electricity has the physical characteristic of being difficult to store. This is why the power grid is built so that supply and demand are always in balance. This is done in Europe at a high-voltage frequency of 50Hertz. If the production on the grid is larger than consumption, or vica versa, this disturbs the grid frequency. This can lead to a power outage or even a blackout. (Energids, 2023). The rapid transition to renewable and flexible energy sources have increased the demand for flexibility on the power grid. Flexibility refers to power that can respond to the grid's control needs. This means that it can increase production power at times of high demand and/or decrease production power at times of high electricity supply. To fill the growing demand for electricity in the future with renewable energy sources, the grid must have sufficient flexible power to balance supply and demand.

Flexible power assets may be made up of interconnected power systems, demand or supply controlled management, or through flexible fossil sources of energy supply (Lund, 2015). In addition, battery Energy Storage Systems (BESS) can also provide this form of flexibility to balance the grid by providing balancing services.

When more BESS, and thus flexibility, are added to the grid, demand can be more easily matched with supply, ultimately leading to the fact that the energy transition from fossil to more sustainable sources can take place more quickly. In practice, investments BESS will only be made when it has a closed business case. A closed business case considers the costs against the benefits over its lifetime, taking into account the risks.

Current BESS deployed, acts in the short term (up to 1 day). This means that the BESS helps to balance the daily differences between supply and demand. This also means that the BESS cannot be offered in long-term markets. The other components of the electricity market are theoretically suitable for BESS to trade on. Here the BESS can load energy on the supply markets when the price is low and sell the same energy again when the price is higher. In addition, the battery can be offered on balancing markets to TenneT to actively remedy imbalance. CE-Delft research shows that the earning model of large-scale battery storage (+500kW) is greatest when it stacks business cases from different markets, or in other words: is deployed on different electricity markets over a year (Jongsma, van Cappellen, & Vendrik, 2021) (Zwang, 2022). Choosing the right market at the right time is done by an aggregator. Scholt Energy is such a aggregator party.

1.2 Scholt Energy

Scholt Energy is an energy supplier primarily for large business customers. In addition, the flexibility of its customers offers the ability to trade on electricity markets. Since 2016, Scholt Energy uses this knowledge of trading on the electricity markets with flexibility to control batteries. Here, Scholt Energy is convinced that choosing the right market not only ensures that it is the best choice financially, but also socially, since the price represents the greatest need for electricity. Therefore, if the price is very high for providing balancing power, it means that TenneT needs this power very badly. Putting a battery on the market that yields the most is therefore not only financially important, but also socially beneficial to the grid.

1.3 Thesis scope & objective

One market that Scholt Energy has only recently access to, is the automatic frequency restoration reserve (aFRR) balancing market. aFRR power can be supplied in two directions, but not simultaneously. This means that the battery receives compensation for either up-regulating the grid (supplying power) or down-regulating the grid (taking power). Scholt Energy believes that batteries in the future are only suitable for providing aFRR for up-regulating power. For this reason, this research focuses only on the provision of aFRR up-regulation power by a battery. Because not every type of asset is suitable for providing the necessary balancing power, TenneT sets requirements that this power must meet. One example used by TenneT is that batteries must include charge management in their baseline when contracted for aFRR power. In other words, when the battery wants to start charging, TenneT must have received a signal that this charging was planned. This charge scheduling can be achieved by buying volume on the intraday market. The application of how this charge planning can best be applied and its effect on the business case is not yet known to Scholt Energy.

It is of interest to Scholt Energy to add the aFRR market to their battery dispatch because this additional market can provide additional revenue and in addition it reduces the dependence on a single market which makes the business case more robust to market developments.

Scholt Energy would like to gain insights into the impact of bidding the aFRR up regulation power (battery discharge) by their BESS Therefore, the purpose of this internship at Scholt Energy is: (1) To provide insight into the legal frameworks governing aFRR up power by a battery and intraday trading to meet contractual obligations. (2) The effect of bidding the maximum allowed power of a battery on the aFRR up balancing market on the business case of a BESS by Scholt Energy. And lastly, (3) to provide insight into the organizational necessities for the control of a BESS by Scholt energy when using the intraday market for aFRR up supply.

Existing literature has been published on applying a BESS to the aFRR market (Gitis, Leuthold, & Sauer, 2015) (Olk, Sauer, & Merten, 2019). From these studies, it is concluded that they are not economically viable to act as stand-alone setups for aFRR delivery. However, this study does not consider the intraday market for meeting the contracted obligations and is outdated for the current market situation. Another study does consider a BESS that takes the intraday into account (Olk, Merten, Schoeneberger, & Sauer, 2020). This research indicates that the intraday market is only useful to apply at a pool of batteries in combination with other assets of production. Here, trading on the intraday market is seen as exchanging energy internally (i.e., within the pool) and selling excess energy through intraday. Instead, Scholt Energy wants to know the effect trading on the intraday that uses the energy outside its own pool to meet the contracted obligations for aFRR balancing power. To fill this gap in the existing literature the following research question has been formulated:

What is the effect on a battery's business case by bidding the full power into the aFRR balancing market where contractual obligations are met through trading on the intraday market?

To be able to answer the main research question, the following sub-questions were identified.

1. How do legal regulations from TenneT limit the trading opportunities within the business case of a battery?

2. What is the financial effect of bidding the full battery power into the aFRR balancing market where contractual obligations are met through trading on the intraday market?
3. What is the effect of bidding the full power into the aFRR balancing market for different battery assets dimensions and their business cases?
4. How can Scholt Energy integrate intraday market trading for the security of aFRR balancing power by a battery asset into its own organizational structure?
5. What (beneficial) effect does the new business model have for grid stability and the effectiveness with which assets are used?

To answer the questions, this thesis is structured as follows.

Chapter two, the methodology gives an overview of the method used for completing this thesis.

Chapter three, theoretical background, further explains different parts of the topic. The purpose of this chapter is to better understand the components of the problem. Here, additional explanations are first given on the trading markets and then more extensive explanations are given on the balancing markets.

Chapter four provides a literature review of the added value of battery for aFRR. Here the added value of batteries participating in the aFRR market for the need of grid stabilization is explained in more detail.

Then in chapter five, further explanation is given on the key requirements for trading in the aFRR and intraday market. This chapter explains how trading on the intraday market can be used by a battery to meet TenneT's requirements for aFRR delivery.

Chapter six describes how aFRR can be integrated into the Scholt Energy organization. Here, it visually demonstrates how communication between differences involved and what the potential danger of this might be. It also explains how data flows should ideally run for a robust and verifiable approach that can also be verified by TenneT.

Chapter seven describes the operation and results of the aFRR yield model. This model was created to calculate what revenue the battery would earn when it receives energy fees for aFRR activation and recharges the battery through intraday purchased volume. This was done by using four trading strategies and applied to three battery dimensions (ratio of power to storage capacity). These are a 1c , 0.5c and 0.25c battery.

Chapter eight describes the operation and results of the revenue comparison model where the achieved aFRR revenue is compared with the historical achieved battery revenue in the FCR and imbalance market. The results are then corrected for the lack of perfect prior knowledge and finally, this chapter tests the effect of aFRR on the business case of different battery dimensions.

Chapter nine, the discussion, considers the limitations of this study. Here, the limitations are further explained and a recommendation is made about future research.

Finally, chapter 10 concludes the study in the conclusion. This answers the various subquestions and ultimately the main question.

2. Method

To answer the main question, a mix-method research method is needed. This means conducting both qualitative and quantitative research. The beginning of the research deals with qualitative part in which existing literature on the application of a BESS in the aFRR market and intraday is examined. In addition, TenneT documents on rules and requirements of aFRR power are also examined. The qualitative part also examines Scholt Energy's bidding strategy and business case for their BESS. This will be primarily through internal documents & meetings. Finally the organization structure that Scholt Energy currently uses for the steering its batteries is investigated. The quantitative part of this study consist of a model development phase in which a model is created that can indicate the financial effect of intraday trading to meet the contracted obligation for aFRR delivery by a BESS. These results are then incorporated into Scholt Energy's current business case. The full method is visualized in the figure below.

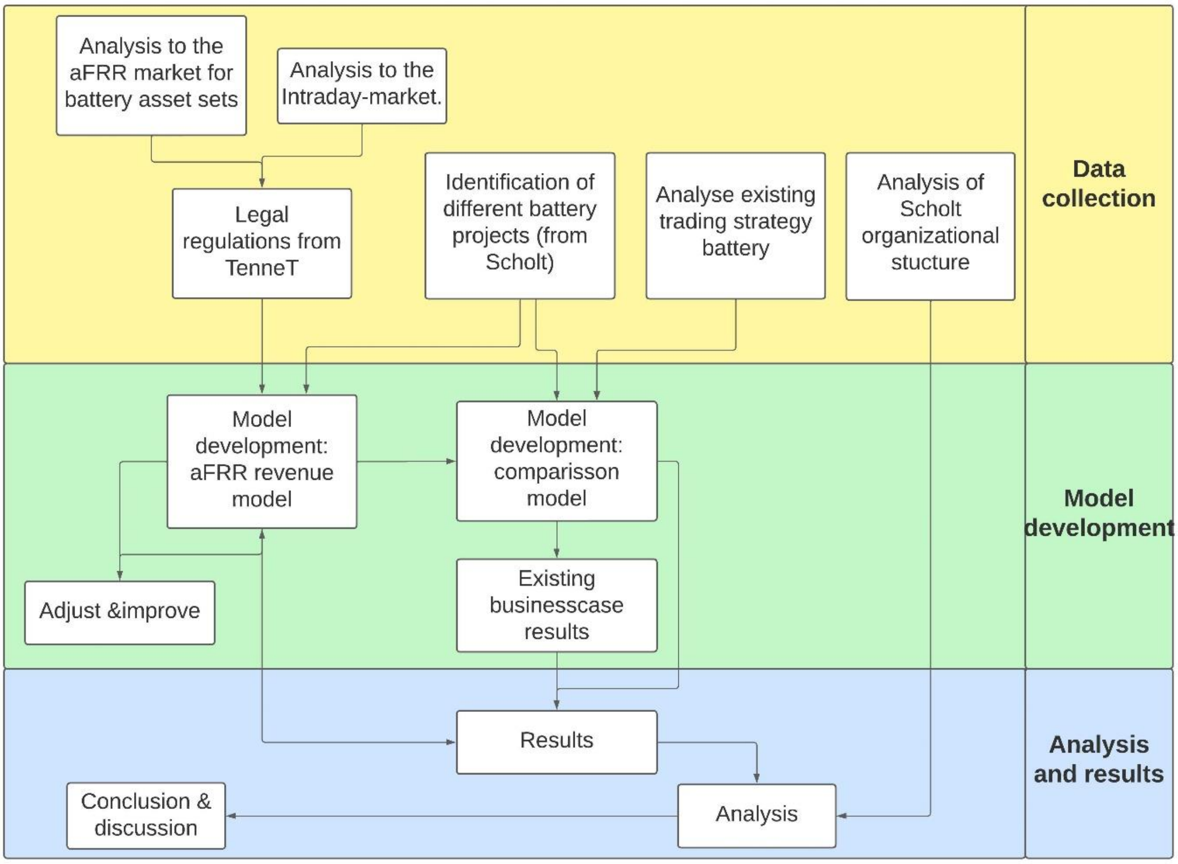


Figure 1 Visual representation of the method

The method can be divided into 3 sub topics:

- Part 1: Data collection
- Part 2: Model development
- Part 3: Analysis and results

In the rest of this chapter, these parts are explained in more detail.

Data collection

The first component is data collection. This is mainly done in two parts. (1) investigating the legal possibilities of aFRR delivery with purchased intraday trading. And (2) Investigating organization Scholt Energy in terms of bidding strategy & business case for their batteries, which includes the identification of different battery dimensions and the organizational structure for the steering of the batteries.

The first part will be analyzed mainly by analyzing product documents from TenneT. These documents often explain what the requirements are from TenneT for supplying the aFRR power. In addition, these documents are also used for a comprehensive explanation of the aFRR market. The same is also done for the intraday market. All this information is obtained through desk research and in particular TenneT websites used as a source. In addition, other studies on these markets are also used to provide information on how these markets work and how a battery acts on them. Because TenneT's publications are often generic for all suitable sources of supply, it is wise to use other studies for the application of a battery in these markets. Once these markets are clearly described, it can be determined to what extent a battery can use the intraday market for meeting aFRR contracted obligations. Because the battery is still a very new asset for providing balancing energy, some descriptions are not quite in line with the characteristics of a battery. To clarify these rules, small meetings were scheduled with TenneT employees. This was done using the existing relationships Scholt Energy has with TenneT.

The second part relates primarily to Scholt Energy's organization. Scholt Energy already manages BESS. This steering is done using a certain strategy. In order to later apply the new market, it is important to understand this current strategy. Existing studies by Scholt Energy are also being examined. For example, that of average activation time on the aFRR. Once the current operation of the bidding strategy, and from that the business case, is known, it can then be expanded to include the new market. Therefore, this data comes primarily from internal sources such as process descriptions and mathematical models. Furthermore, internal meetings are planned with employees to better understand certain processes. In addition, desk research is used to better understand general information from business cases. Scholt Energy's various battery projects are also analyzed. The goal is to identify different characteristics that distinguish projects from each other. These different properties that distinguish a project can later be used to identify whether the impact of a new market is different by battery dimension. Finally the organizational structure for steering the battery is investigated. These imply the platforms that Scholt Energy currently uses for trading with the batteries.

Model development

The next phase is the development of a model that calculate the financial effect of full power for aFRR delivery. From a practical standpoint, the model should be able to be made in a limited time. From Scholt Energy's point of view, the model must be user-friendly and adaptable if needed (allowing people from Scholt to use and understand the model as well). These requirements led to focus on developing an Excel-based model. Within Scholt Energy's department, Microsoft Excel is widely used for calculation models. Because of this, many colleagues working in the department are familiar with the program and its applications. For this reason, Microsoft Excel Office 2021 will be used. In the "model development phase", an aFRR revenue model is developed, then this data is used for the “revenue comparison model”. The results can then be used in Scholt Energy's existing business case model to determine the impact of adding aFRR in a battery's business case.

The aFRR revenue model aims to determine the financial effect of trading on the aFRR. The model is based on the historical data of 2021, 2022 and the first quarter of 2023. The revenue model is for aFRR is based on only the aFRR up fee, both the energy fee and the capacity fee. The model acts on input data from the "data collection phase" in which the rules of aFRR are known. The model follows these rules and calculates the annual revenue achieved. This is done by executing a trading strategy determined through internal consultation with experts at Scholt Energy. From this came four trading strategies that can be used in practice for driving a battery on the aFRR. The aFRR revenue model is described in detail in Chapter 6.

Once the revenue of aFRR was calculated, it was compared with historical achieved revenue of batteries in the FCR and imbalance market. Large-scale batteries are now deployed in this market combination. Scholt Energy has the historical achieved turnover of batteries in these markets. The model compares on a daily basis which market would have had a higher achieved turnover. In this way, it can be determined what the maximum achieved turnover would have been for different years if the battery had the choice of the calculated values from the aFRR revenue model and the historical turnover. This is also called the perfect foresight revenue. To correct for the fact that in reality there is not perfect foresight, a simplified trading strategy is used to calculate a realistic turnover in which batteries could trade on the aFRR, FCR and imbalance market, based on historical achieved revenue. The same is done for a future scenario in which market trends and expectations shape the market situation. This forecast provides insight into the impact of aFRR on a business case for future scenario.

These future revenues combined with aFRR are then applied in the existing business case model that Scholt Energy uses for battery projects. The outcomes are compared with the situation where aFRR is not applied to reveal the effect of aFRR on the business case.

Analysis and results

The final part of the study consists of compiling results. The results of the different models are presented in graphs and tables. This is then analysed and from this, conclusions can be drawn that can answer the various sub-questions and together answer the main question. Based on this analysis, a discussion can also be formed on the assumptions and uncertainties of this study. In doing so, the discussion considers follow-up research.

3. Theoretical background

Before conducting the research, it is important to have a good basic knowledge of the electricity market. This chapter serves to further explain two parts of the electricity market. These are the "wholesale markets" and the " balancing markets". These two parts consist of several sub-markets. A simplified representation of the markets is shown in Figure 2

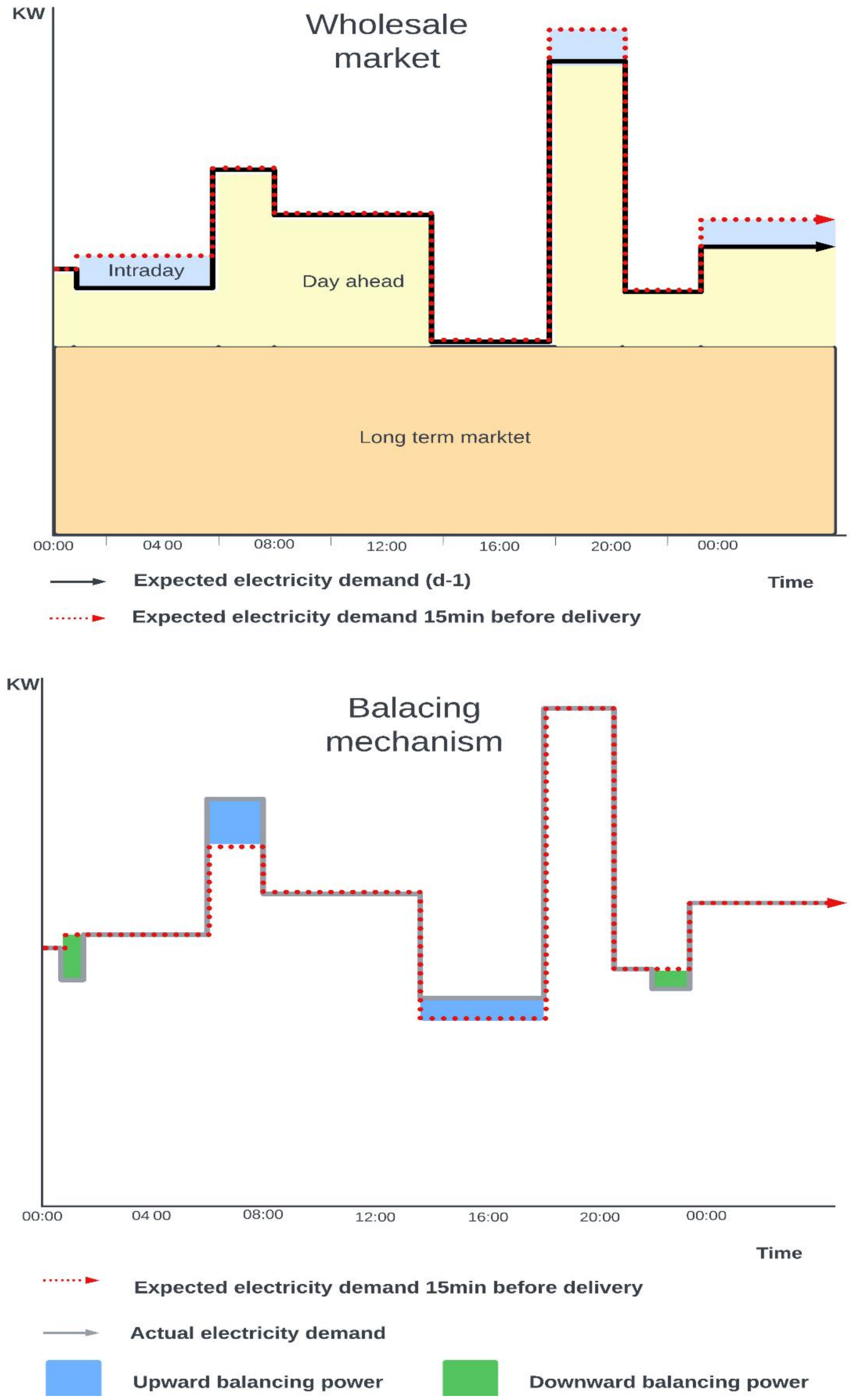


Figure 2 Visual presentation of wholesale market composition and balancing mechanism.

The top graph of Figure 2 shows the wholesale market. The baseload of demand, is sourced from the long term market. The daily fluctuations are traded on the day-ahead market. A day before delivery, it is therefore possible to determine what the offtake of electricity on the grid is. This is also visible with the black arrow line. During the day, the forecast may change, e.g. due to a forecast error. This is made visible with the red dotted line arrow. The difference between these two arrows, is the volume still being traded on the intraday market. This market closes 5min before delivery.

The bottom chart shows how the balancing mechanism works. Here, the red dotted line arrow is the quantity the TSO expects to be taken from the grid. This volume can be different in reality, this is made visible with the grey arrow line. To compensate for the mismatch between predicted an actual grid offtake, the TSO activates balancing power. Here, the TSO can activate upward and downward power. Upward balancing power is activated when in reality more power is taken from the grid than expected, while downward balancing power is activated the other way around, when there is less offtake from the grid than expected. In parallel, the TSO is also required to have various types of balancing power available. For example, for the time when a major power plant fails.

The functioning of the two markets and their associated sub-markets is further explained in the sections below.

3.1 Wholesale markets

Wholesale markets are "normal" markets in which suppliers offer electricity and customers buys electricity. Supply and demand determine the price of electricity. Any party supplying or taking energy from the grid must be registered with a Balancing Responsible Party (BRP). The role of a BRP is to fulfill the predicted values (i.e. if one buys 1 MW, also consumes it from the grid). There are several wholesale markets. They differ in terms of time frame. These are:

1. Long-term market: This is where electricity is traded in large blocks. These can be years, quarters or months. So a seller can sell 1 MW for every hour of the year for a fixed price (TenneT 7, 2023).
2. Day-ahead markt: In the day-ahead market, participants can sell and buy electricity for the next day's 24 hours in (hourly) blocks. Thus, hourly supply and demand determines the price of electricity. This market closes at noon the day before delivery (TenneT 7, 2023).
3. Intraday markt (ID). The intrday opens after the day-ahead market and is meant for market participants to adjust their market position (i.e., how much MW you are buying or selling at that time) because your forecasts have changed (it may not be as sunny as you predicted a day earlier) (TenneT 7, 2023).

Finally, TenneT publishes the live imbalance price. This is the price TenneT pays for resolving the imbalance. TenneT recovers this price from BRP’s. Example: a consumer has bought 100MW for an hour on the day-ahead market. Ultimately, the consumer consumes 98MW. This consumer thus creates 2MW of imbalance in the grid. To restore the total imbalance in the grid, TenneT has paid €20/MW (for adjustment capacity). The customer now has to pay its imbalance (2MW) x the imbalance price (€20/MW) = €40 to TenneT for causing the imbalance. TenneT publishes the live imbalance price to get market participants to passively participate from processing the imbalance in the grid. Namely, if there is a high imbalance price, this stimulates the market to adjust its volume in favor of TenneT. The imbalance price is determined by the energy fee of FRR power (both aFRR and mFRR) deployed at that time. In other words, the balancing market determines the price BRP must pay for causing the imbalance.

As indicated in the introduction, a battery trades in the short-term markets (up to 1 day). For this reason, the long-term market is excluded from this report and not explained further. The other components of the electricity market are further explained below, as well as the implementation of a battery on this market. Finally the future outlook of this market is discussed.

3.1.1 Day-ahead market

Up to one day before delivery, electricity can be traded on the day-ahead market. This market operates through a bidding mechanism. Until noon the day before delivery, suppliers can automatically submit their bids. After this happens, supply and demand are matched, and the market prices for the next day are set, varying by hour. TenneT records these bids for each party in its "e-program." This program then establishes what each party will deliver and/or purchase the next day. Trading takes place on the EPEX-SPOT (TenneT 1, 2023).

A battery can be used to make money in the day-ahead market by charging at times when prices are low and discharging at times when prices are higher. Since this trading on the day-ahead market happens a day before delivery, the buy bids and sell bids be submitted by 12:00. In short, the operator or whoever performs this service must make a prediction of prices the next day to determine the best time to charge and discharge the battery. Added to this, the difference between charging and discharging must be greater than the cost per cycles to obtain a profit. Contracted agreements have a time period of one hour. This means that if you want to deploy 1MW in the day-ahead market, you must have at least a storage capacity of 1MWh (efficiency not included). It also means that the same energy cannot be deployed to another market at the same time.

The DNV Power Price forecast for the Netherlands predicts that by 2025, gas-fired power plants will still be the most dominant source of electricity price. Subsequently, the share of renewable electricity generation will have increased and the share of fossil will have decreased. As a result, the baseload price of electricity will decrease, but volatility will increase. It is therefore expected that from 2025 to 2030 the baseload will decrease from an average of 46€/MWh to 43€/MWh. As indicated, the daily volatility of the market is particularly important for battery revenues. From 2025, the variation between high and low prices is expected to increase. This is caused by the increasing influence of renewable sources in the Netherlands and its neighboring countries, and the decrease in adjustable power supply. This higher variation between prices means that the battery can achieve higher revenues (DNV, 2021). However, it is also expected that the increasing variation of prices in the day-ahead market will create a more participants than today. Therefore, it is expected that in the future more participants will use the price differences on the day-ahead market for a business case. Examples include smart charging of electric vehicles and smart charging of small-scale (households) or large-scale consumers (industry). It is also expected that in the future renewable generation will be more predictable than today. Where today renewable generation is based on weather forecasts, in the future this is predicted to change to specific and detailed generation forecasts (DNV, 2021). So, according to DNV, there are developments that will make the day-ahead market more favorable for batteries in the future, but at the same time there are developments that will make the price more unfavorable. The DNV report does not make concrete predictions of future sales that a battery can make on the day-ahead market but predicts that the difference between charging and discharging will eventually increase. The CE Delft report however does this by making expectations for 2025 and 2030 by comparing prices with historical 2019 prices as shown in table 1.

Table 1 Day-ahead prices & predicted revenue of a battery (Jongsma, van Cappellen, & Vendrik, 2021)

Parameter	Unit	2019	2025	2030
Average day-ahead price	€/MWh	€ 41	€ 59	€ 65
Average price charging	€/MWh	€ 35	€ 48	€ 48
Average price discharging	€/MWh	€ 47	€ 68	€ 78
Yearly revenue day-ahead	€/MWh/year	€ 14k	€ 27k	€ 55k

3.1.2 Intraday market

Energy suppliers and large customers have balancing responsibilities, this is also why they are called Balancing Responsible Parties or BRPs. Any party that supplies or takes energy from the grid must be registered with a BRP. BRPs help balance the grid. If the actual production or offtake differs from the established e-program, then there is an imbalance in the system. This imbalance occurs because off-take and production are based on predicted values, which may differ in reality. TenneT takes care of preventing the imbalance, but charges for this. These costs are recovered from the BRPs that were (partly) responsible for the imbalance. It is therefore financially attractive for a BRP to reduce its own caused imbalance. This can be done through the intraday market. On the intraday market, trading can be done today for tomorrow's and today's energy. From 3 p.m. on the day before delivery until 5 minutes before delivery, trading on the intraday market can be done in blocks of 15,30 or 60 minutes. Trading is done on the EPEX spot intraday market.

Because relatively long trades can be made before delivery occurs, a spread can occur between the highest and lowest price for the same quarter. A battery can be used to buy quarters at cheap times and sell these same quarters at times when the price is higher. The advantage of the intraday market over the day ahead market is that there is a lot more certainty about the expected price. In addition, trading can be done in shorter time blocks, which increases the flexibility of battery deployment. The specific market mechanisms that allowed intraday trading are further explained in chapter x.

The intraday market is expected to increase in trading volume. This is because this market is excellent for use by BSP with renewable resources to correct forecast errors. The trading volume of the intraday market in 2022 was 753 GWh. This volume is expected to continue growing to +1GWh in 2030 (Jongsma, van Cappellen, & Vendrik, 2021). The effect this growth has on the average spread between the highest and lowest bid is unknown and not previously studied (Terpstra, 2020). Used techniques that other studies employ in their simulation of the future imbalance price is by using the same day-ahead price developments and trends (Slooff, 2019) (Alberizzi, Zani, & Barba, 2022). In other words, a growth in the future spread of intraday volume, similar to that of the day-ahead market.

3.1.3 Imbalance

The imbalance price is the price BRPs have to pay to TenneT for having imbalance that contributes to the total imbalance in the system. The imbalance is determined as follows:

$$Imbalance_{ISP} = P_{ISP} * MW_{imb}$$

In which:

$Imbalance_{ISP}$	The imbalance price for a specific Imbalance Settlement Period (ISP) in €
P_{ISP}	The price that TenneT pays the BSP for restoring the balance
MW_{imb}	The amount of imbalance that contributes to the total imbalance in the gird.

So it is also possible that a BRP causes an imbalance but is opposite to the national imbalance. In that case, the BRP thus receives compensation from TenneT. The imbalance price is (usually) equal to the price of energy/activation bid ladder for FRR energy.

Because the bid ladder operates according to marginal pricing, BRP can passively influence the imbalance price. Namely, when a BRP reduces the overall imbalance in the system with its volume, less FRR power is needed, so it can be solved with cheaper reserves. This passive balancing, as it is called, is possible because TenneT shares live volumes and prices of active balancing power on its website. As a result, TenneT encourages BRPs to deviate from their portfolio to solve the general imbalance.

A battery can be deployed on the passive imbalance. Because a battery can import or withdraw energy from the grid very quickly, it is very suitable for trading on the passive imbalance. When trading on the imbalance market with perfect insider information, some 210-230 k€/MW/year can be earned in 2021. In practice, battery trading on the imbalance market is done through an algorithm that controls the battery to start charging and discharging. Experts estimate that a good algorithm should achieve 50-75% of the maximum yield, which amounts to 110-165 k€/MW/year (Jongsma, van Cappellen, & Vendrik, 2021).

The future trend of the imbalance market is similar to that of the day-ahead market and the intraday market. Namely, when more (unpredictable) variable energy sources are added to the electricity mix, it becomes more difficult to balance the grid and fluctuations during the day will increase. On the other hand, when more flexible power is added to the grid (e.g., from batteries), these fluctuations in the grid decrease. For this reason, it is difficult to predict whether the future yield of a battery trading on the imbalance market will be higher or lower in the future. For this reason, the yields through imbalance trading are considered constant over time. (Jongsma, van Cappellen, & Vendrik, 2021) (Hartman, 2022).

3.2 Balancing markets

Balancing markets are the markets where TenneT buys power to actually activate to restore balance in the system. TenneT buys the balancing power by Balancing Service Providers (BSP).

There are three types of balancing reserves that TenneT purchases every day. These are:

1. Frequency Containment Reserve (FCR).
   The Transmission System Operator (TSO),for the Netherlands this is TenneT, monitor the frequency continuously. If it deviates from 50 Hertz, the FCR is activated within seconds to stabilize the frequency. FCR, also called primary reserve, operates across borders and for the entire synchronous network of continental Europe (TenneT 1, 2023). TenneT pays the BSP a fee for having the power available during the contract period.
2. Automatic Frequency Restoration Reserve (aFRR)
   aFRR power, also called secondary reserve, occurs as a result of sending delta setpoints calculated by the Frequency Power Regulation or in Dutch " Frequentie Vermogens Regeling" (FVR). The main purpose of the FVR is to quickly (within 15 minutes) and effectively restore extensive imbalance in the Netherlands. The FVR activates aFRR energy by sending aFRR activation signals to the BSP's. The BSP can receive a capacity fee for making the power available during the contract period and an energy fee for the actual power delivered (TenneT 2, 2022).
3. Manual Frequency Restoration Reserve (mFRR)
   Through a manual procedure, TenneT can activate mFRR, also called tertiaries reserves. mFRR is activated if the available aFRR falls below a threshold and/or the outage is expected to remain for a long time. (+30min) (TenneT 1, 2023).

An overview of the main features of the three balancing products is shown in figure 3. Figure 3 shows the purpose of the different balancing products, for which area the energy is used to balance the grid. In addition, figure 3 shows the size of the total market now and in the future, what the average capacity fee is and what are example plants that are now supplying this energy. These features are explained in more detail later in this chapter

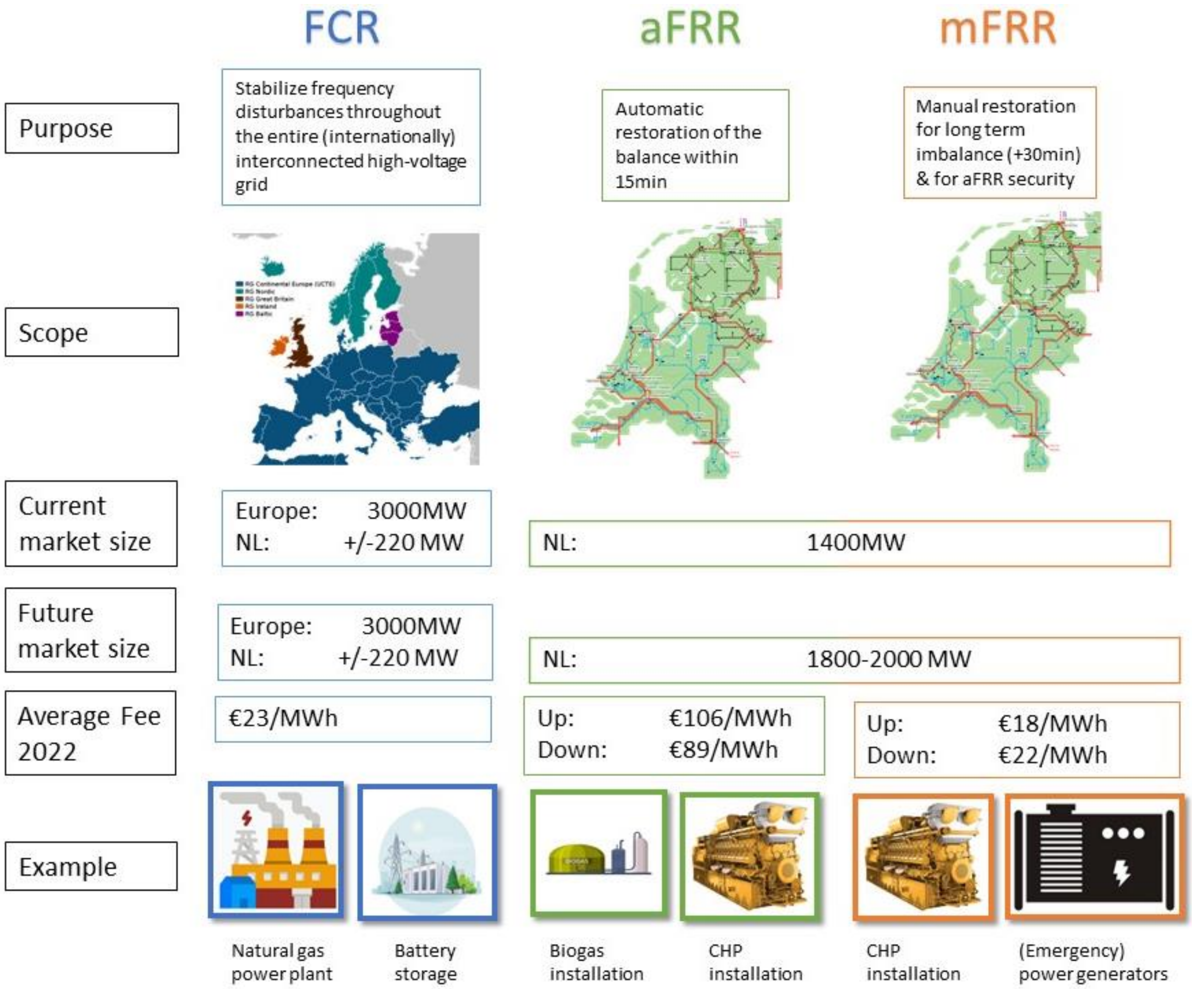


Figure 3 overview of the most important characteristics of the thee balancing reserve power that is used in the Netherlands

The deployment of balancing reserves during a power plant outage is shown in Figure 4. First, the FCR power responds within a few seconds. Within 2 seconds of the frequency drop, the FCR asset must show a linear activation of its contracted power. Then, after about 30 seconds, aFRR should show a visible power change and takes over from FCR for restoring the imbalance. The aFRR power must be capable of delivering the full contracted power within five minutes. If the imbalance is than still not solved, mFRR will be activated. mFRR will get a activation signal within 5 minutes of the imbalance occurrence and must deliver its full contracted power within 15 minutes after activation (TenneT 1, 2023) (TenneT 2, 2022) (TenneT 3, 2022).

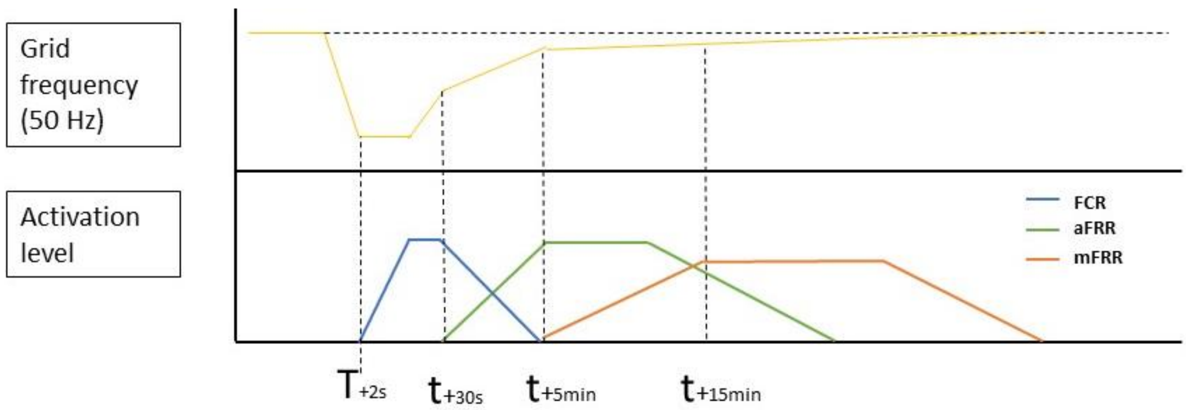


Figure 4 Overview of the balancing process used by TenneT. In case of a grid frequency disturbance, first the FCR is activated with a very fast response time, then if the disturbance is not solved right away, aFRR power takes over which responds a little slower and if the grid is still not recovered by then, mFRR takes over.

3.2.1 FCR

FCR power is used to stabilize the entire synchronized grid of continental Europe. FCR operates across borders and international agreements have been made for the supply of this product on the European grid. TenneT must also meet these international obligations. For 2023, the frequency constant for the Netherlands has been set at 3.685%. This then means that a Dutch contribution of 36.85 MW is expected in the event of an outage of 1000MW somewhere in continental Europe. However, a total outage of 3000 MW is taken into account. This means that the Netherlands must have an FCR reserve capacity of 110.55 MW available in both control directions at all times (TenneT 6, 2023). The distribution of FCR obligation among TSOs is based on the sum of net production and net consumption of its control zone divided by the sum of net production and net consumption of the synchronous zone during one year expressed in %, and is also called frequency constant. In addition, power in the Netherlands are still allowed to supply 100 MW of FCR to neighboring countries. This is done to increase FCR competition. Thus, the total market size for FCR is about 210 MW. This market size is expected to remain the same in the coming years (Jongsma, van Cappellen, & Vendrik, 2021).

For FCR reserve, TenneT applies strict requirements. An example of such a requirement is as follows: "*Limited plants(which include batteries) deployed as stand-alone units for FCR delivery shall have a power to pre-qualified power ratio of at least 1.25: 1 or an alternative solution with similar effect, for example through active charge management".* For a battery, this would mean that when 1 MW is offered on the FCR, there is a minimum of 1.25 x 15/60 x 1MW = 312.5 kWh in storage, or 250 kWh of charging power available (efficiencies not included). When an asset can meet all FCR requirements, it can participate in the FCR mark. FCR power for a day is offered in six four-hour blocks. The auction takes place on the day before delivery (d-1) at 8 a.m. The price of a "block" is set by marginal price formation. That is, all bids are sorted by price: the price per MW that covers demand is the price TenneT compensates all participant. In 2021, the average compensation for FCR were around 23 euros per MW per hour. This results in about 200k euros per MW per year that was available 100% of the time for providing FCR (Next Kraftwerke, 2023) (ENTSOE, 2023).

TenneT assumes that the contracted power is always available. It may happen that the power is (temporarily) not available or not fully available. The period during which this occurs is known as an incident. To prevent these incidents, TenneT applies a penalty. The penalty for failure to deliver FCR power is calculated as follows.

$$Penalty_{GBR} = Period_{deficient}\ x\ MW_{deficient}\ x\ fee\ x\ 20 \qquad (3.1)$$

In which:

Penalty GBR	The penalty in €
$Period_{deficient}$	The time when the power could not deliver (fully) in hours
$MW_{deficient}$	The power under-delivered in MW
Fee	The FCR fee received by the BSP for providing FCR power in €/MWh

So the fine a BSPer receives is 20x higher than the fee the BSP would receive. The reason for this high penalty is to maintain more security of supply. (Namely, the BSPer now receive a higher financial incentive to actually deliver the contracted power) (TenneT 3, 2022).

Figure 5 shows the average FCR price as of 2021. In this it is easy to see that the years 2021 and 2022 were relatively high prices compared to the first six months in 2023. In 2020, the contract period of 24 was replaced by blocks of 4 hours. This had the effect of increasing the price somewhat. Next to that, the overall electricity price in the Netherlands in 2021 and 2022 increased due to the high gas price. This (temporary) increase in the power price during 2021 and 2022 caused the average FCR price to increase in these years because the flexibility can be economically better used in other markets, reducing the supply of FCR power. (DNE, 2022). The FCR price in the near future is expected to be similar to the German FCR price, about €10/MWh. The reason is that the German electricity market is a forerunner to the Dutch in terms of the share of renewable energy and (battery) storage. For this reason, several studies expect the German FCR price to be a good proxy for the Dutch FCR price of +2-3 years (Jongsma, van Cappellen, & Vendrik, 2021) (Zwang, 2022) (DNV, 2021).

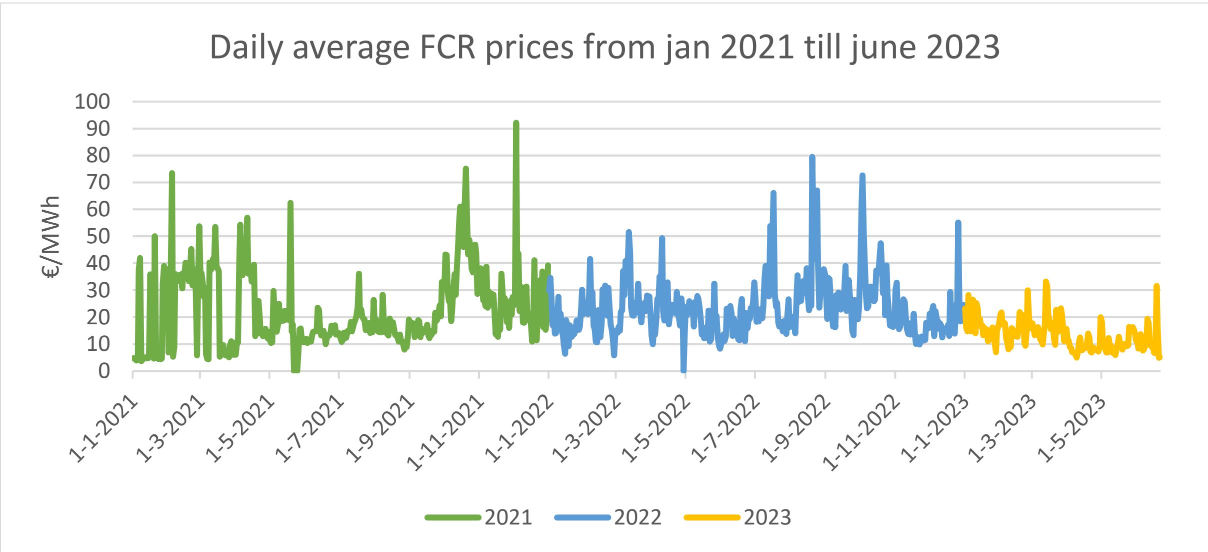


Figure 5 Price development of the daily average FCR price in the Netherlands from 2021 till June 2023

3.2.2 aFRR

TenneT uses the Frequency Power Regulation (FVR) for national balance enforcement. The main purpose of the FVR is to restore the extensive imbalance in the Netherlands within 15 minutes. The FVR continuously calculates the instantaneous control error of the Netherlands and based on this how much aFRR should be activated to maintain the power balance. Technically, the FVR operates separately from the BRP. However, in the balance sheet process, the two schemes do affect each other. The FVR responds to an imbalance by activating assets, to which the BRP itself may also respond. (TenneT 2, 2022). The aFRR product has two directions.

1. Upwards regulation: supplying to the grid. This can be done by producing more electricity or consume less electricity.
2. Downwards regulation: Taking (additional) power from the grid. This can be done by producing less electricity or by consuming more electricity.

For both directions, power can receive compensation for being on standby and for actually delivering energy. Every six months, TenneT calculates how much FRR power is needed and purchases this amount in daily capacity bids (i.e., this is aFRR and mFRR). These bids are held on the Auction Platform For Ancillary Services (APFAS) and take place the day before delivery (d-1) at 9 a.m. aFRR and mFRR capacity bids are selected simultaneously. An award algorithm then chooses the lowest-cost combination that meets the minimum aFRR and minimum FRR capacity requirements. After a bid is won, the BSP receives the capacity fee as bid (pay as bid). The aFRR capacity fee in 2021 averaged 29 euros per MW per hour for upward regulation and 21 euros per MW per hour for downward regulation (Jongsma, van Cappellen, & Vendrik, 2021).

The amount of FRR reserve capacity needed is based, among other things, on historical imbalance values and the size of a reference outage situation. A reference outage situation herein is the largest imbalance that can occur in the Netherlands as a result of an instantaneous change in active power due to failure of one power generation unit, consumer plant, HVDC interconnector or AC line. With the arrival of several offshore wind farms with a connection to land via a 2GW cable, the probability of failure of such a cable will also increase. For this reason, TenneT expects that from 2030 the largest outage that the required FRR up regulating power has to take into account will be 2GW this is considerably more than the current 1304MW that TenneT takes into account today. For up regulating power, this change is somewhat lower, at around 1800MW, this is mainly based on incremental historical growth of large consumers.

When a capacity contract is won, the BSP is required to submit an activation bid for each Imbalance Settlement Period (ISP). An ISP lasts 15 minutes.

The activation bid is equal to the fee a BSP wants to receive for supplying energy for a specific ISP. This price can vary by time during the contract period. For example, a BSP may be able to provide aFRR power cheaper in the first hours of the day than in the afternoon. For this reason, the cost that TenneT has to pay for restoring the same imbalance can differ greatly during the day.

The activation price is set by marginal pricing. This means that the price per MWh per ISP per direction is the same for all FRR energy that is activated, and equal to the most expensive bid. This merit order for determining activation power consists of the following energy bids:

- Contracted aFRR capacity
  All power receiving aFRR capacity fee are required to make an energy bid for all ISP of the contract period.
- Contracted mFRRda capacity

For mFRRda, the contracted capacity fee is the only fee that TenneT needs to pay and therefore, it can sometimes be financial attractive for longer activation periods.

- Free bids from the BSP's
  BSP that are qualified for aFRR but did not win the capacity bids have the opportunity to submit "free" bids. These are energy bids for specific ISP that increase competition.

The resulting bid ladder is shown in figure 6. The bid ladder allows TenneT to restore the balance in the cheapest way possible. The larger the imbalance, the more TenneT has to pay the BSP for correcting it. The price TenneT pays is settled per quarter-hour and recovers these costs from the BRPs.

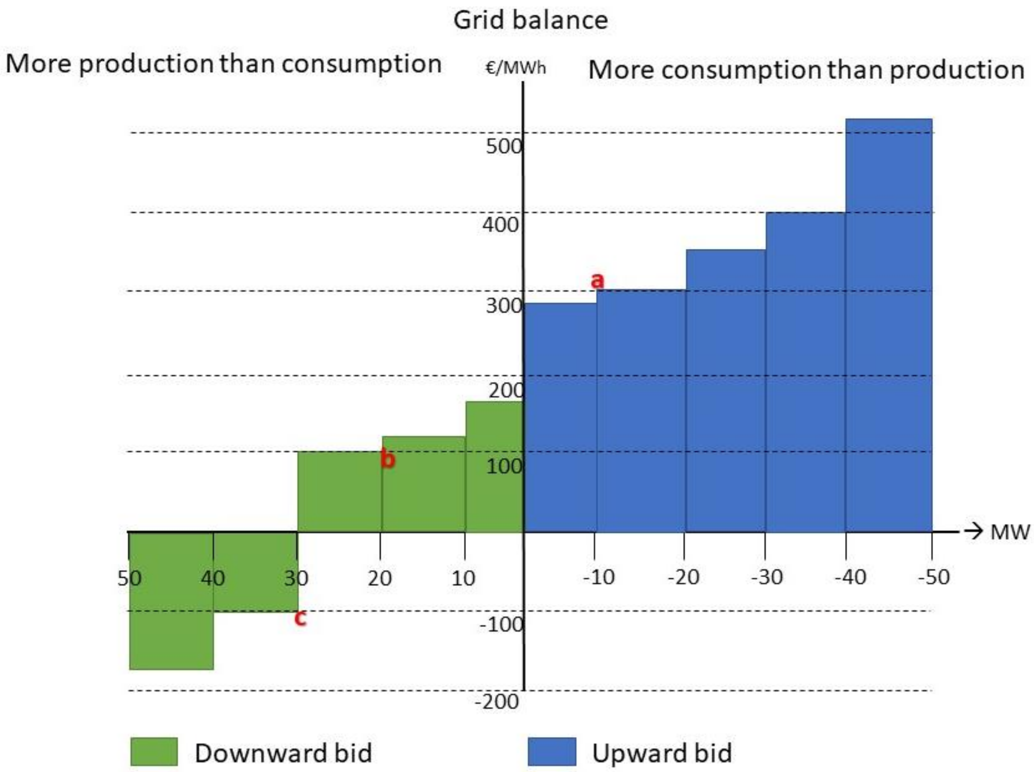


Figure 6 Visual representation of the FRR bid ladder for energy fee.

Figure 6 shows on the left side what happens when more electricity is produced than taken and on the right side it the opposite situation. Three situations are depicted in figure 6:

a. There is 10MW more consumption than production. TenneT therefore has to activate 10MW of upward regulating energy. This can be power that is going to produce extra (a battery that discharges), or power that is going to consume less (a freezing house going out temporarily). For all activated energy TenneT pays around €300/MWh.
b. There is 20MW more production than consumption. TenneT has to activate 20MW of downwards regulating energy. This can be power that is going to decrease its production (gas-fired power plant running at a slower rate) or power that is going to consume more (battery charging). Because the price is positive, the BSP has to pay TenneT for the activated energy. This are mostly assets that save money in another production process when they deliver downwards power (e.g., by saving fuel costs).

c. Situation c is similar to situation b, the difference is that there is now 30MW imbalance instead of 20MW. The price has become negative. This means that TenneT has to pay the BSP for activating the downwards regulation energy. So all activated power now receives a fee for the delivered power, also the power who is whiling to pay TenneT because they save on fuel cost, now receive a fee.

Looking at the price trend of aFRR capacity fee, we see that it has a very similar trend to the gas price. Figure 7 shows what the capacity fee for providing aFRR up has been. Note that because the price is pay-as bid, it means that this is the highest distributed fee visible, this does not mean that all contacted capacities received this price.

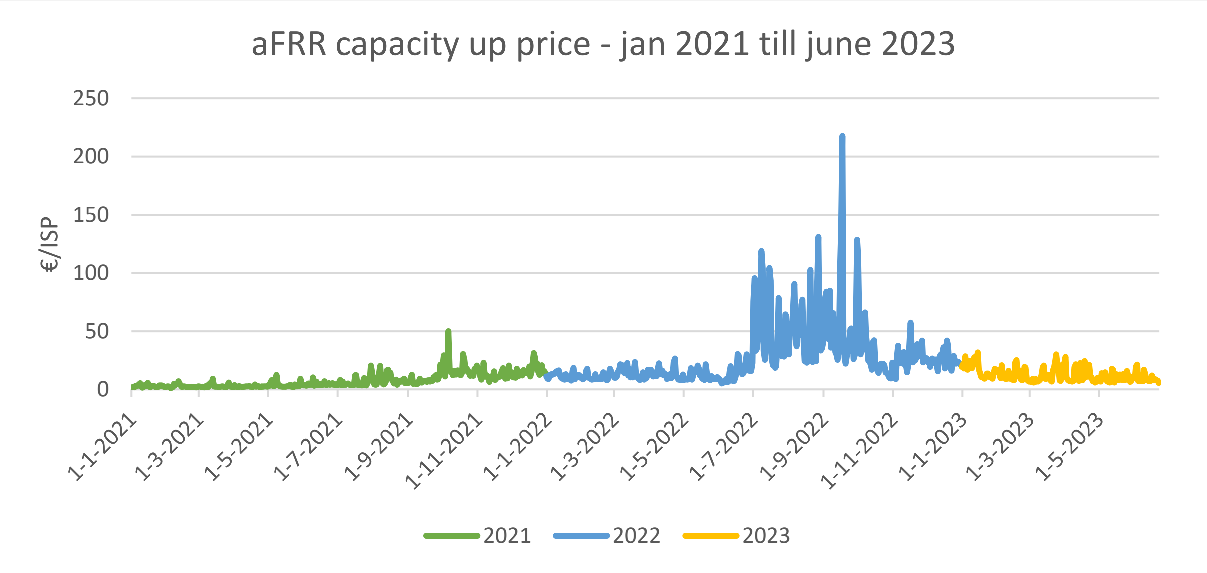


Figure 7 Highest paid aFRR capacity up price from January 2021 till June 2023

It can be seen that the price for aFRR up has a strong similarity with the gas price, to clarify the development of the price, figure 8 shows the same graph but here the vertical axis is fixed at €50/MW/ISP, this to make trends more visible.

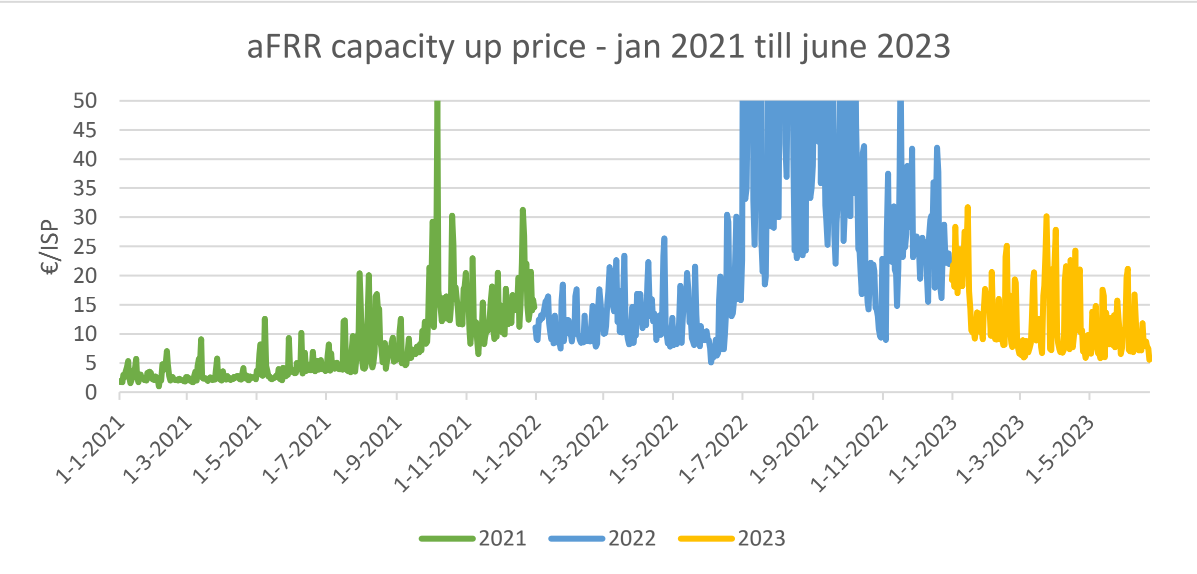


Figure 8 Highest paid aFRR capacity up price from January 2021 till June 2023, fixed at a price of €50/MW/ISP

Figure 8 shows that the price for aFRR up power is decreasing (because the gas price is also decreasing). The future price development of aFRR up power is similar to that of the imbalance whereby the demand for aFRR up will increase, but this at the same time also creates a greater supply of aFRR up power. Therefore, the aFRR up fee is expected to remain similar to 2021 (Jongsma, van Cappellen, & Vendrik, 2021).

3.2.3 mFRR

The FVR restores the imbalance as much as possible with the deployment of aFRR power. However, if the available imbalance falls below a certain standard and/or the imbalance will persist for a long period of time (for example, due to the loss of a power plant), additional power is required. Through a manual operation, mFRR power can be deployed until sufficient aFRR power is available or until the imbalance is restored (TenneT 4, 2023). The mFRR product has two directions. The up-regulation and the down-regulation of power. Both are contracted separately. Offering mFRR capacity is done through the same capacity auctions where aFRR capacity auctions take place. mFRR only receives a fee for the capacity and thus does not receive an additional energy fee for an actual activation. For this reason, in the event of a long-awaited imbalance, it may be financially attractive to deploy mFRR capacity. mFRR capacity has a start-up period of about 15minutes. This means that after calling for activation, the power should be fully activated within 15minutes (TenneT 4, 2023). The contract period of mFRR is 24 hours. This means that the power must be available all day to provide balancing energy. The power must be able to provide power for at least 1 hour upon activation. After activation, the power is allowed time to recover. This period may mean, for example, for a battery to recharge. The maximum recovery time for mFRR power is 6 hours. Other requirements set by TenneT for providing mFRR power are described in the TenneT Emergency Power Manual.

The fees for mFRR volume is a lot lower than that of aFRR power. For example, the fee in 2021 was about 5 euros per MW for up control (discharging the battery) and 2.5 euros for down control (charging the battery). We can also see this in figure 9. Here we can see that the fee is a lot lower than that of aFRR, shown in figure 7 and 8. Besides the fact that the capacity fees of mFRR are lower than those of aFRR, power also does not get an extra fee for actually delivering energy. So for this reason, mFRR is always less attractive for a battery to trade on, as it can earn more for the same power in the aFRR market (Zwang, 2022).

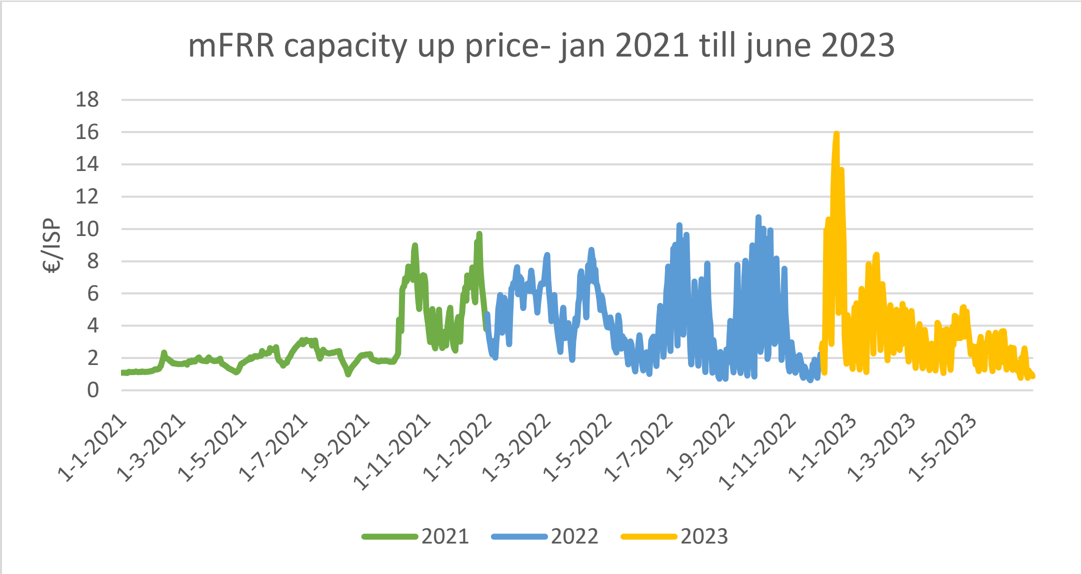


Figure 9 mFRR capacity up fee for January 2021 till June 2023

4. The beneficial effect of aFRR capacity for net stability

The forecast errors of renewable energy sources in power generation are causing more imbalance. For this reason, the demand for aFRR is increasing in the coming years. The deployment of batteries in the aFRR market leads to an increased supply of this power, this growth in supply is expected to be accompanied by increasing demand which will maintain prices (Jongsma, van Cappellen, & Vendrik, 2021). The prices of the deployed aFRR also determine the imbalance price. Deploying batteries on the aFRR market and thus imbalance market leads to lower grid frequency maintenance costs than in a situation without batteries (Jongsma, van Cappellen, & Vendrik, 2021). These costs are passed on pro rata by TenneT to all users causing imbalance. The use of batteries for grid balancing therefore contributes to lower imbalance costs. This ensures higher profitability of existing projects than in a situation without batteries. Batteries therefore make new (renewable) projects more attractive from a financial perspective.

However, when passive supply capacity increases, this causes the price for balancing capacity to decrease and therefore has the same effect on the profitability of existing and new renewable energy development projects (Schittekatte, 2022). The two ways in which batteries can contribute to reducing the imbalance price is shown in figure 10. Here it can be seen that the blue line is the supply of reserve supply power (FRR). As batteries increase in the supply of aFRR, the line decreases and the price per quantity decreases. Batteries can also passively balance which causes the red line to decrease and the price idem ditto to decrease per quantity of balancing power (Eicke, Ruhnau, & Hirth, 2021). For the battery, therefore, there are two ways to contribute in need of real-time grid stability: active and passive.

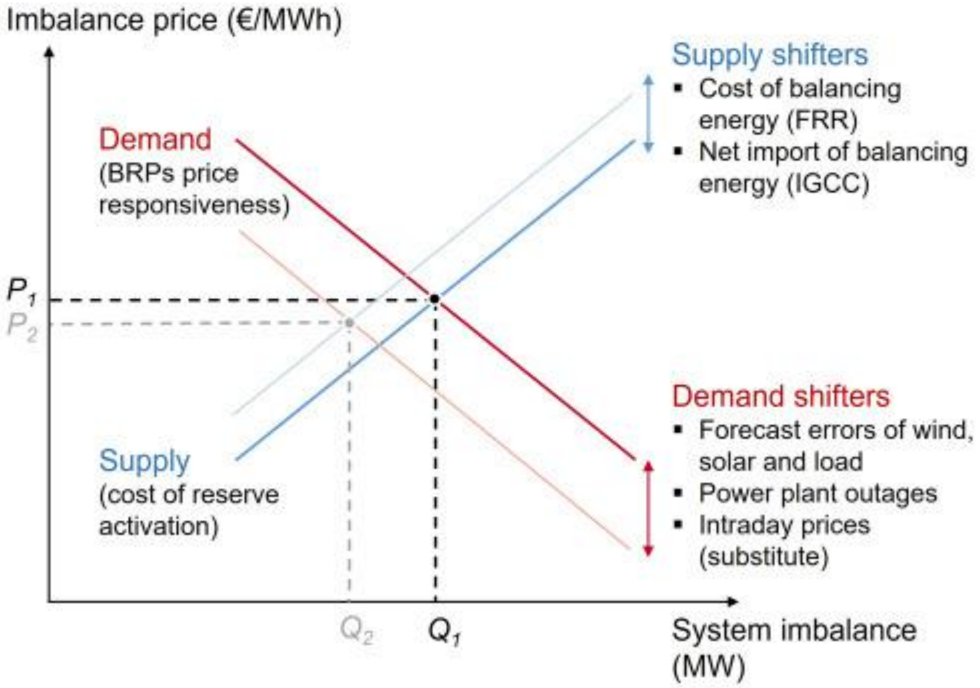


Figure 10 Overview for the "imblance energy market" where the equilibrium quantity (system imbalance) and price (imbalance price) emerge from the intersection of the demand and supply curves (Eicke, Ruhnau, & Hirth, 2021)

Active vs passive balancing

For active balancing the grid, power is contracted and it is obliged to make energy bids. Passive balancing does not have this obligation and responds to the grid's current balancing needs. Voluntary aFRR energy bids for the purpose of grid stabilization are not included here as in practice this form of bidding is not utilized by batteries due to limited financial security vis-à-vis obligations/penalties. Looking at the literature, the two forms of balancing are described differently. Passive balancing is seen in the sources (Zande, Saguan, Meeus, Clachant, & Belmans, 2009) (Datta, Kalam, & Shi, 2021) (Hu, Harmsen, Crijns-Graus, Worrell, & van den Broek, 2018), as a means that reduces overall balancing costs and reduces the available balancing capacity aFRR. Therefore less contracted balancing power is necessary to maintain grid stability which in turn is beneficial for the price.

However, based on the analysis of empirical data in Germany, Weber and Just observed that passive balancing also creates a system where incentives for strategic behavior between day ahead market price and imbalance price is encouraged. Here, a strategic over or under market position is taken in the day-ahead market at low or high day ahead prices, when the system equilibrium is expected to be long and short, respectively. This strategic behavior can move the system imbalance in the unfavorable direction resulting in higher demand for balancing energy and additional balancing costs (Hu, Harmsen, Crijns-Graus, Worrell, & van den Broek, 2018) (Prakash, et al., 2022) . In (Just, 2011), it even conclude that these increasing costs for strategic purposes outweigh the savings from passive balancing. However, these studies are based on the German balancing market, which is different from the Dutch balancing market. The main difference is that passive balancing is not allowed and BRP only have to balance their own portfolio, regardless of whether they help the national grid in doing so. The effects of passive balancing on strategic amount between day-ahead and imbalance for the Dutch market has not been investigated before.

In the research of van der Veen and Hakvoort (Veen & Hakvoort, 2016), active and passive balancing power is examined for the Dutch market. Passive balancing can provide a significant reduction in balancing demand, but on the other hand can provide a reduction in available FRR power to the TSO. This is because these assets are now not bid into aFRR but passively deployed in the imbalance market. As a result, the quality of balance maintenance can be affected as BRP overreact to a system imbalance and thus cause frequency surpluses. For this reason, Veen & Hakvoort concludes that passive balancing trades schedulable for availability. This does not mean that one is better than the other. It concludes that with active power, there is a lower supply of balancing power, but the power deployed is used more effectively.

5. TenneT legal framework for aFRR delivery

This section below examines what the legal frameworks of aFRR delivery by applying intraday charge management are. To do this, it first examines what distinctions TenneT makes for the provision of balancing power by different assets. Next, the requirements for delivering aFRR power and specifically the delivery of aFRR power by a battery are examined.

5.1 Providing balancing power

Balancing ability can be divided into two different types of groups. These are:

1. Reserve Supply Unit (RSU).
   A single connection point is connected to an asset or group that can meet all the requirements needed for the particular balancing product (FCR, aFRR or mFRR).
2. Reserve providing groups (RPG).
   A reserve providing group has multiple connection points of units or groups that together can meet the requirements of the relevant balancing product.

Technical installations (TI) behind one connection that collectively meet all requirements form a (RLE). RLEs can be bundled together into an RPG, see figure 11.

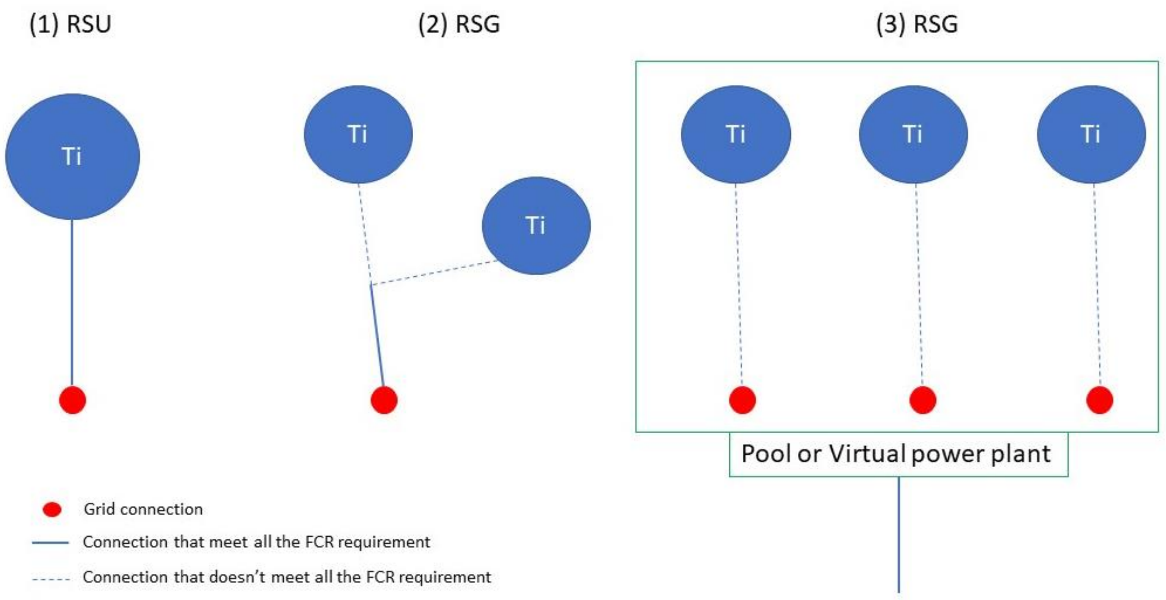


Figure 11 Visual representation of (1) a technical installation that is connected to the grid and can meet all requirements for delivering the balancing power. (2) Two technical installation that are connected with one connection point to the grid, that can meet the requirements for delivering the balancing power, and (3) multiple technical installations that are all individual connected to the grid and together fulfill the needed requirements for delivering balancing power.

Figure 11 shows that there are different ways possible for providing balancing energy. Option 1 shows that, a technical installation can meet the requirements individually, option 2 that, multiple installations behind 1 connection can meet the requirements. And finally option 3 that, multiple connections bundled together can meet the requirements.

TIs can also differ from each other. For example, TenneT distinguishes between Limited Energy Resevoirs (LER) and Unlimited Energy Resevoirs (UER). TenneT defines the LER in the handbook for FCR power as follows: " *FCR-supplying RLEs/RLGs are considered LER for FCR if a full continuous activation during a two-hour period in positive or negative direction, without taking into account the effect of active charge management, leads to a limitation of their ability to achieve a full FCR* *activation, taking into account the Effective Energy Reserve effectively available*. " (TenneT 3, 2022) This definition is the same for delivering aFRR power.

5.2 Managing aFRR data flow

For activating aFRR, the FVR sends a power target value, also called 'delta-setpoints'. A delta-setpoint represents the requested aFRR volume rounded in 1MW increments. A delta setpoint will never exceed the power offered by the BSP, and the delta setpoint change will never exceed the specified ramping rate of the power bids, as the powers have an activation period during which they are given time to (de)activate the power to the contracted power. This ramping rate is at least 20%. In other words, upon activation, the power delivered between two delta set points must be at least 20% higher (if the contracted power has not yet been reached). The FVR continuously keeps track of how much balancing energy has been activated. This information is then recorded per energy bid for the purpose of settlement. The delta setpoints can change every four seconds, but only when the value of the delta setpoint changes, or in other words, if there is no change in needed power, no new setpoint is sent.

The BSP must send power measurements from its portfolio real-time to TenneT with a resolution of 4 seconds. In the future possibly 1 second (TenneT 2, 2022). Here, the BSP is allowed to prepare an aggregated power measurement because not all technical installations are capable of performing a power measurement in such a resolution. TenneT uses this power measurement to check the "reference signal" of the BSP

The reference signal is intended to establish the quality of the aFRR supplied when an energy bid is activated by TenneT. The reference signal is the expected value of the power that will be delivered/purchased one minute later without the aFRR power activated by TenneT. With the reference signal, TenneT can determine whether the contracted power actually follows delta setpoint as agreed.

A battery is supposed to follow the same rules as those of other sources who deliver aFRR. For both voluntary bids and contracted bids, a BSP must be able to supply the requested power for the entire period of the energy bid. This means for a portfolio of only batteries (or other LER connections), the BSP must ensure that units can consume/produce enough energy as if the entire ISP will be requested for its full power. This means that when a battery wants to participated with its full power on the aFRR capacity market that it:

1. Has enough storage that can sustain it throughout the contract period (current 24 hours and in future 4 hours).
2. Can charge/discharge without creating imbalance in the system balance sheet. In practice, this means that when the battery wants to charge, this is based on an intraday transaction. This also means that when aFRR is activated, no intraday deals can be taken place.

This study delves into the further results of the second scenario on the battery business case.

5.3 Intraday market

The intraday market allows participants to adjust their market position to better forecasts of renewable energy demand or production or unexpected power plant outages. The intraday market is therefore only accessible to BRPs. A BSP thus depends on a BRP to make intraday transactions. On the intraday market it is possible to trade power continuously in intervals of fifteen minutes, an hour or longer. Once a buy offer matches a sell offer, a trade is closed. A trade must be completed at least 5 minutes before the time of delivery. Intraday prices are determined according to the "pay as bid" principle. This means that the trading transaction is completed once a sell bid is accepted by a buyer. While national markets can only trade on 1 trading area, linked markets can do so for different areas. Since 2018, there has been the single intraday coupled market (CID). This centralized the intraday market of the countries Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Latvia, Lithuania, Norway, the Netherlands, Portugal, Spain and Sweden. In 2019, this platform was extended to the countries of Bulgaria, Croatia, Czech Republic, Hungary, Poland and Slovenia. Then in 2021 Italy joined and lastly in 2022 Greece and Slovakia were added (Nemo committee, 2023). The CID collects all orders in a large combined order book. How this works is shown in figure 12. Figure 12 describes the CID flow of the Dutch, Belgian and French markets.

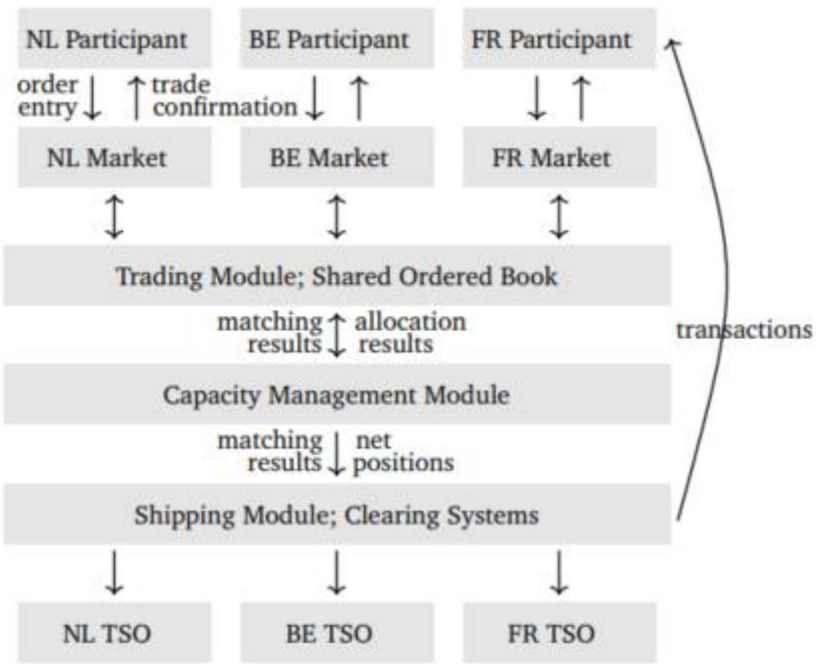


Figure 12 Visual representations of the CID operation of the Netherlands, Belgium and France. Participants from the different countries exchange bids with each other that are processed both technically and communicatively. (Demir, 2023)

Figure 12 shows that when participants submit their orders to the market. If an available capacity is found , this order is removed from the register. Then the joint order book is updated with the changed capacity. The matched order is sent to the dispatch module of the joint order book, starting the post linking process and informing the TSO of the exchange taking place.

The CID is a continuous market. The CID opening time may vary by period, for example, in Belgium it opens at 2 p.m. the day before delivery and in the Netherlands at 3 p.m. the day before delivery. The closing time is 60 minutes before delivery. In other words, up to an hour before delivery, volumes can be traded on the intraday market across much of Europe, within the hour in the Netherlands can be traded on the intraday only with Dutch volumes. Electricity traded on the intraday market has the characteristics.

- Order type: description of electricity is being sold or bought.
- Quantity: The amount of electricity that is being sold or bought.
- Price limit: De maximum price in €/MWh
- Location: The participants country of delivery (so for example the Netherlands)
- Expiry: The time and duration of the deal. (so for example between 13.00 and 14.00 on 01-01-2023)
- Validity restriction. Orders can be for 1 session, (e.g. valid for 1 quarter of an hour) or "good till date" which means the bid will remain until the expiration date is reached.

5.4 aFRR & intraday

Because Scholt Energy's battery pool does not have enough storage to supply the full power for the entire contract period, it must implement charge management on the aFRR market to receive the full available capacity fee. In other words, the reference input of charging the battery must be compensated with an opposite registered response. This can be the purchase of intraday volume, or could be, for example, by means of switching off production within the pool. For the use of intraday volume for the purpose of charge management, TenneT writes the following in its handbook: "If charge management affects actual aFRR delivery, it cannot be deployed at the time of actual delivery of aFRR. It is then considered the responsibility of the BSP to take this into account in its bidding strategy." (TenneT 2, 2022) It is possible to take this into account in the bidding strategy because energy bids are adjustable up to two ISPs. For contracted bids this means the price is adjustable, for voluntary bids it means the price and volume are adjustable. In other words, when applying charge management to recharge the battery, at those times it is wise to offer an energy bid that either has a volume of 0MW , or is very high making the probability of activation very low (with a maximum of €100k/MWh) (TenneT 5, 2022). This also means that the volume purchased on the intraday should be earlier than 30 minutes before delivery. This because a decision can than still be made in time to adjust the energy offer.

In addition, this "adjustability" in the energy bids ensures that when the battery is in danger of running out, the energy bid can be adjusted so that the battery will (probably) not be activated and thus not be called out at the time it runs out.

6. Interne analysis

The following section explores in more detail how Scholt Energy can best integrate intraday trading into its own organization. This is done by first analyzing what the current control of a battery is. It then identifies how this can be improved and what communication should be distributed between different parties and in what area they are matched in terms of information.

6.1 Current structure

When Scholt Energy would like to drive its battery into the aFRR market, it has to deal with the following involved parties.

1. Crowd balancing platform (CBP)
   A CBP facilitates the registration, bidding and activation of aggregators' flexible services for aFRR. The CBP enables flexible, balancing power to be provided while the market operates within its grid limits (Equigy, 2023). Equigy is the CBP used by TenneT for aFRR delivery in het Netherlands
2. CID platform
   Scholt Energy has the unique position of both BSP and BRP. This means they are allowed to trade the intraday market themselves. They currently trade on intraday via Nordpool's CID platform. Nordpool is Europe's leading energy market and offers trading, clearing, settlement and related services in both day-ahead and intraday markets in 16 European countries (Nordpool, 2023).
3. Software
   The batteries are controlled by a control software. For this, Scholt Energy is currently using Enervalis. Enervalis is in direct contact with TenneT true the CBP.
4. TSO
   In the Netherlands, the TSO is TenneT and responsible for the balancing process. Activation, (adjustments of) bids and verification happens at this party.

As described in chapter five, Scholt Energy can bid its full power into the aFRR market when it applies charge management through transactions in the intraday market. Supplying aFRR power is done by BSP parties while buying intraday volume can only be done by BRPs. This makes it very difficult for BSPs that are not also BRPs to validate to TenneT that charge management is correctly applied. Scholt Energy is both BSP and BRP and could therefore correctly demonstrate that it applies charge management properly. The necessary data streams required for proper charge management is shown in figure 13. Arrows 1 to 4 show the communication signals that take place for the qualification of the energy. Arrows 5 through 7 show the signals taking place constantly. Arrows 8 to 13 are the signals that take place when a battery wants to recharge. In the current structure, no communication takes place between Enervalis and Nordpool. As a result, any operation done on intraday for the purpose of charging a battery must be passed through Scholt Energy to Enervalis so that TenneT does not detect a deviation and give a penalty.

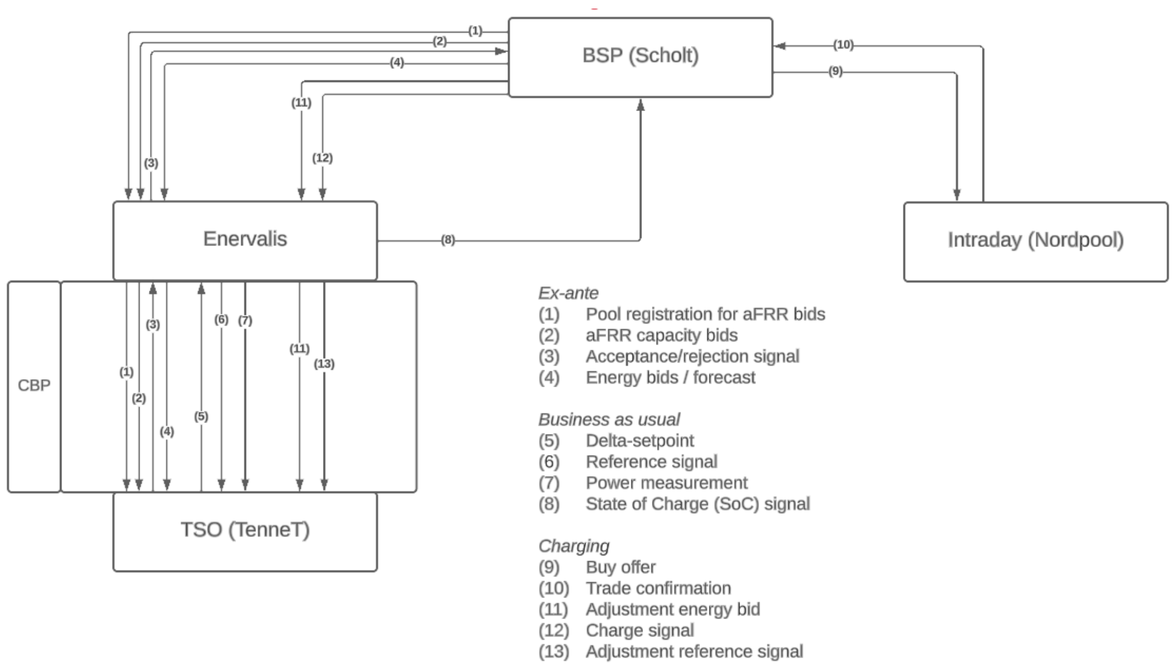


Figure 13 Visual presentation of the data communication flow required in the current organizational structure of Scholt Energy to participated on the aFRR capacity bids with the full power of a battery.

De information flows that occur are further explained in table 2.

Table 2 Explanation of the data flows required for the application of full aFRR bidding in combination with charge management.

Data flow number	Objective	Characteristics
1	Scholt Energy should communicate which power will participate in the aFRR (capacity) bids. This power must be registered by TenneT to provide aFRR power.	EAN-code
2	A capacity bid includes the volume for which a BSP will be required to make energy bids (contracted energy bids) for.	- EAN-code of the participated connections - Power in multiples of MW - Bid price (EUR/MWh)
3	Acceptance or refusal of the capacity bid	- Contracted power in multiples of MW - Capacity price
4	A separate energy bid must be submitted for all ISP of the contract period.	- ISP number - Bid price
5	To activate energy bids aFRR, TenneT sends (via the FVR) a power direction value, also called 'delta setpoints', to the BSPs that submitted these energy bids.	- Required aFRR volume in multiplies of MW
6	The reference signal represents the planned capacity of the portfolio of the BSP. It is the expected net power over 1 minute in the	- expected delivered power 1 minute in the future in multiplies of MW.

	future, without the aFRR activation by TenneT	
7	A real-time power measurement so TenneT can monitor the aFRR delivery	- Power delivered in multiples of MW
8	The level of charge of an electric battery relative to its capacity	- percentage of the capacity
9	Specific bid on the intraday market	- Quantity in MW - Price limit in €/MWh - Location - Expire (time an duration)
10	Confirmation that the delivery is made.	Confirmation that the bid is matched
11	To secure aFRR delivery, once an intraday deal is made (and the battery will be charging at a specific time), the energy bids must be adjusted to a high value to prevent an aFRR activation to ultimately avoid a fine from TenneT	See data flow number 4
12	Information that ensures that the battery will charge at the time of the intraday deal	See data flow number 9
13	Information that ensures that the reference signal is adjusted for the charging of the battery. This to ultimately avoid a fine from TenneT	See data flow number 9

6.2 New structure

The ability to apply charge management on intraday for the sake of energy security has only been possible since Q2 2023. At the time of writing, therefore, no battery is yet using this capability in practice. Currently, Equigy, TenneT's CBP for aFRR delivery, is expanding it’s current CBP platform n which proper validation of charge management could be applied. This platform would be a CID platform linked to aFRR's existing CBP platform. In this way, BSP parties could make intraday deals via the same platform (if necessary via a linked BRP) and TenneT would have insight into all deals taking place for the purpose of charge management. Scholt Energy is currently involved in the development of this platform. It is likely that when Scholt Energy decides to offer full power to the aFRR market, it will do so on the yet-to-be-developed platform. This new platform is shown in figure 14.

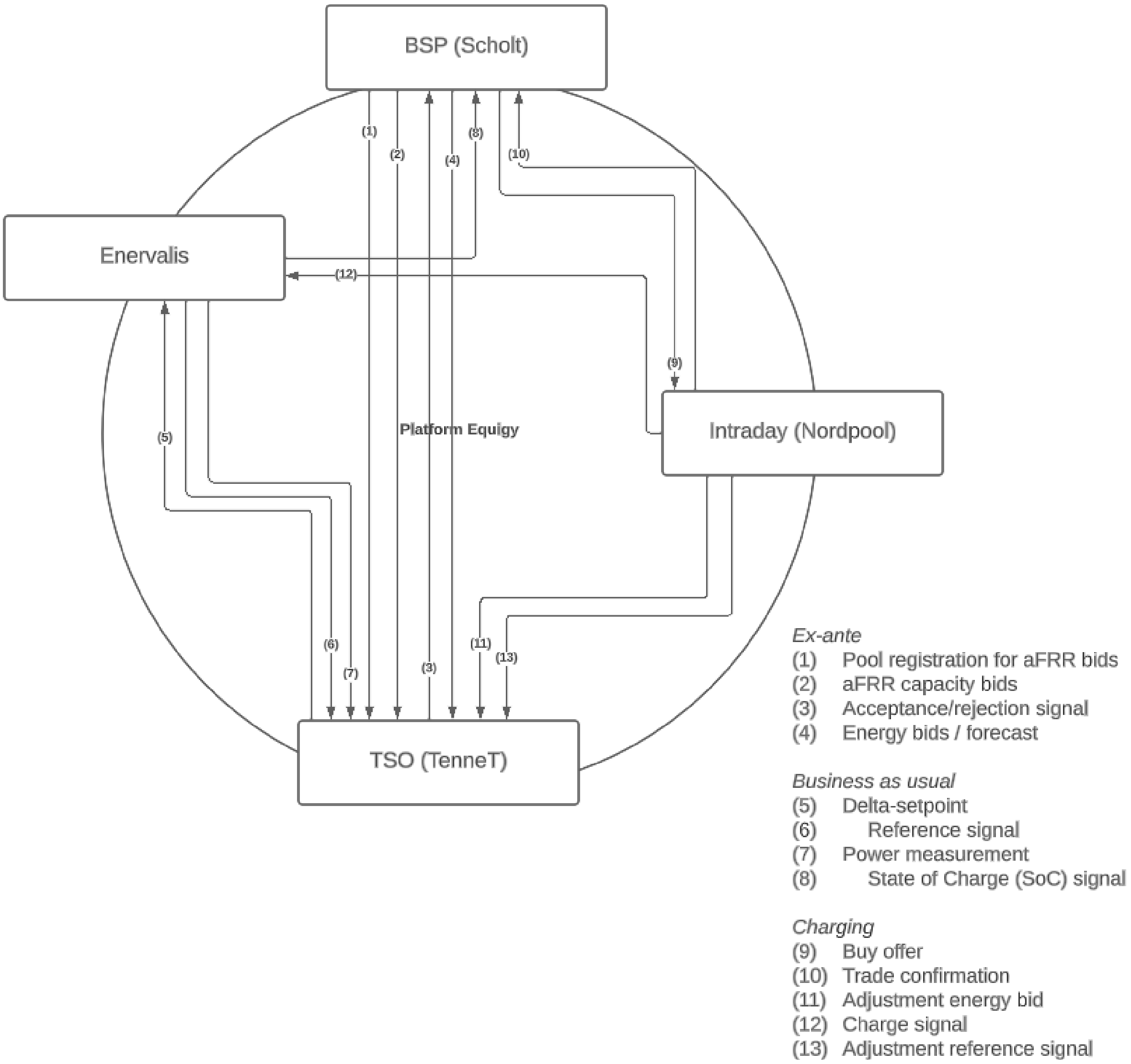


Figure 14 Visual presentation of the data communication flow required in the future organizational structure of Scholt Energy to participated on the aFRR capacity bids with a battery's full power of a power.

No such platform exists today. It is currently still in the development/exploration phase and the intention is to have it operational to trade on before the end of the year. The development of this platform gives the added value:

1. Technical added value
   Technical added value is created by now requiring only a single (easy) connection. This reduces IT development and maintenance.
2. Value staking of multiple markets
   Having access to multiple markets within 1 platform makes it easier to stack value from different markets. Assets can be more easily offered in different markets which increases flexibility. In addition, the transparency of data streams makes it easier to demonstrate compliance with product requirements. For example, a party like Scholt Energy can more easily demonstrate that it has met the requirements of aFRR through deals on intraday.

In short, Scholt Energy can bid in the full power of a battery for the aFRR within its current organizational structure. To facilitate this, Scholt Energy needs to send all communication streams from the intraday deal itself to the battery's control software, which in turn needs to clarify with the data stream to TenneT that a transaction underlies battery charging.

Under the current structure, this would mean that the BSP is responsible for ensuring that all closed deals on the CID platform are properly implemented. Once the existing CBP platform is extended, these data flows can proceed directly. This would technically simplify data flows, and also provides the opportunity for value stacking of different markets. Especially value stacking adds monetary value for Scholt Energy

7. Financial effect of aFRR trading

To determine the financial effect of trading a battery on the aFRR market, a model has been developed that determines the historical financial outcome of a battery deployed on the aFRR market. In the section below, the developed model is explained, then the trading strategies used are explained and finally the results are explained.

7.1 Model development

The revenue model aFRR calculates what the revenue achieved is for aFRR delivery. The scope of this study focuses on delivering aFRR up power. Meaning: delivering energy for the benefit of grid balancing. (discharging the battery).

7.1.1 Time and scope

The model uses time intervals of fifteen minutes. The reason for this is because the imbalance price is settled based on 15-minute time blocks(1 ISP). This means that the settled imbalance price is the same for all minutes in one ISP. Thus, this also applies to the balancing delivered aFRR power of the battery. The time period over which the model is run is one year. One year was chosen because one year provides enough insights into battery activation, and annual revenue and costs, but is still small enough to run on a standard laptop without crashing or becoming very slow.

7.1.2 Reference signal

An important parameter of the model is the reference signal. The reference signal must be zero at all times (including a call-off signal/ correction from TenneT for aFRR delivery). The reference signal is a check on the operation of the model. When the reference signal is not zero, there is something wrong somewhere in the model. The reference signal is calculated in the model as follows.

$$S_{ref} = S_{bat} + S_{aFRR} - S_{intra} \qquad (7.1)$$

In which:

S_{Ref}	Reference signal
S_{bat}	Battery signal
S_{aFRR}	aFRR singal
S_{intra}	intraday signal.

The battery signal is calculated using:

$$S_{bat} = Capacity\ bat_{t-1} - Capacity\ bat_t \qquad (7.2)$$

In other words, the difference in storage capacity between the battery 1 time interval ago and the current time interval. When a battery discharge in that 15-minute interval, this will be negative; when the battery recharges, this number is positive. So when a battery discharges, an aFRR activation must also occur at that same time to ensure that the reference signal remains zero. The same applies to the intraday signal at the moment the battery wants to recharge. In short, the reference signal of the battery remains zero if the battery discharges at times when aFRR is triggered and charges at times when intraday is supplemented. Visually, this is shown in figure 15. Figure 15 shows the different signals, In which the reference signal is grey and must always be equal to zero. The reference signal of the battery can be positive (the battery charges) or negative (the battery discharges), this is shown by the orange line. When the reference signal of the battery deviates from zero, it should at the same time show an opposite reaction of either an aFRR signal or an intraday deal.

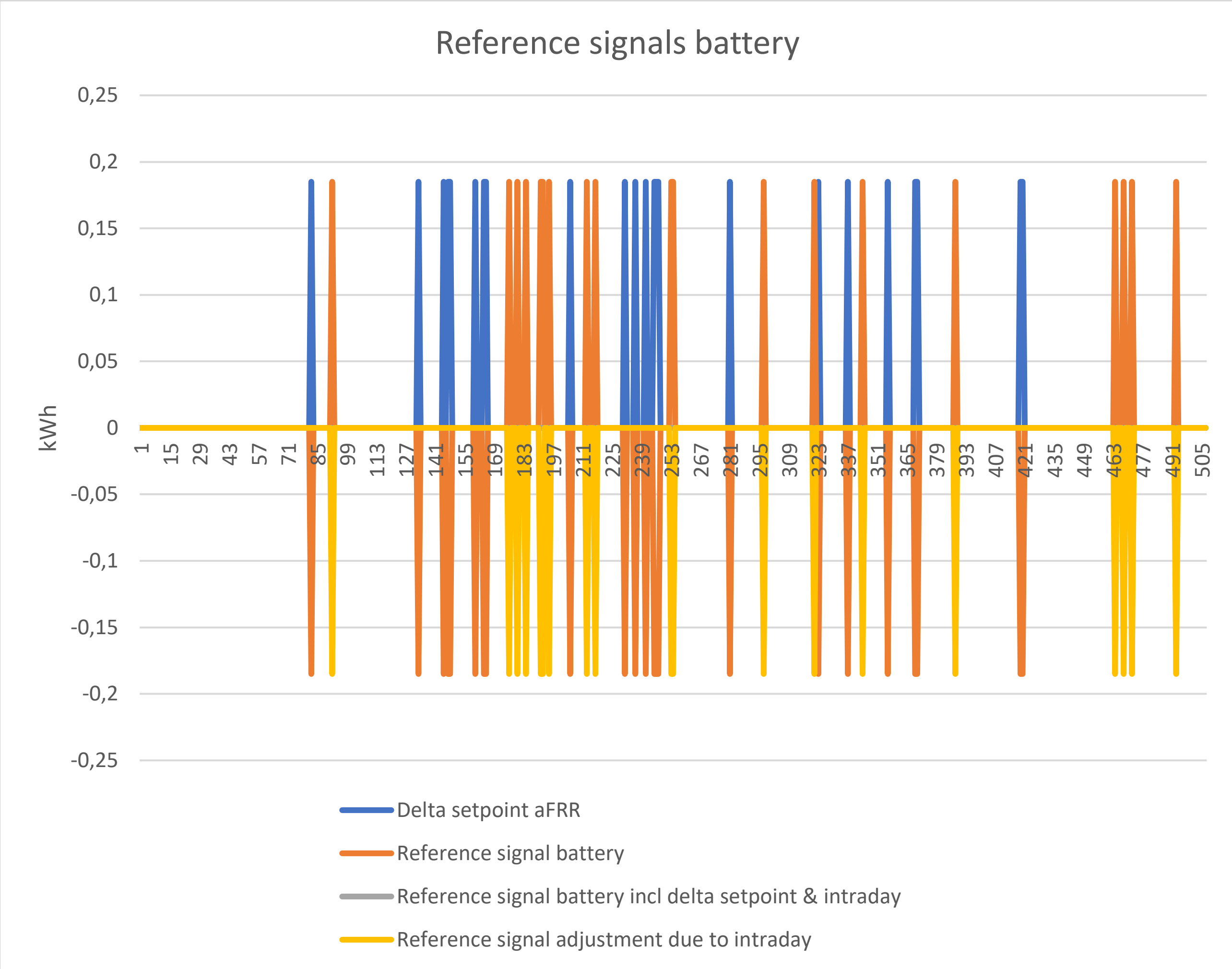


Figure 15 Visualization of wasteful reference signals. Where blue is an activation for aFRR power. The orange line, the reference signal is based on battery storage capacity. Yellow the reference signal adjustment through an intraday deal and the grey line is the corrected reference signal on which TenneT validates whether obligations have been met.

7.1.3 Intraday trading

The battery can only charge at times when an intraday deal had been made. On the intraday market volume can be bought from 3 p.m. until five minutes before delivery. This means that there are different times when intraday volume can be bought. This model uses historical intraday prices 75 minutes before delivery. 75 minutes was chosen because this data was accessible, data from other time intervals was incomplete and/or a lot harder to obtain. This means that this model calculates with an intraday price when it is bought 75 minutes before delivery. In other words, 75 minutes back in time must be determined to buy intraday volume. The technical limitation in this is that intraday volume should only be bought when the battery can also start charging and is not already full. This is calculated with the following formula:

$$Capacity\ bat_{t-5} + \sum_{t-4}^{t-1} Intraday\ volume < Capacity\ bat \qquad (7.3)$$

The capacity of the battery 5 ISP's back in time plus the purchased amounts of intraday volume must be smaller than the storage capacity of the battery. If it is not smaller, it means that the battery is already full at delivery (five quarters of an hour further) and thus does not need the volume to charge. In addition to the technical constraint, a trading strategy can be applied on top of this formula, see also section 7.2

7.1.4 aFRR trading

Bidding on the aFRR energy fee has two restrictions. The security of supply restrictions and the restriction due to purchased intraday volume. An aFRR bid can be changed up to 30min before activation. Therefore, this is the time to decide whether the battery is capable of delivering aFRR. For this reason, the supply security of the battery is achieved by adding the following formula:

$$Capacity\ bat_{t-3} \geq (2 * E_t) + DoD \tag{7.4}$$

In this, Et is the energy that the battery can discharge maximum in one ISP. This formula ensures that two ISP before delivery is considered to ensure that the theoretical capacity is always higher than the Depth of Discharge (DoD) In other words, the capacity of the battery must always be enough to last two more ISP before reaching its DoD. If this battery capacity is no longer high enough, the bid strategy is adjusted with a bid that is very high so that the battery does not need to be activated at that time.

The other technical limitation is that of charging. At times when the battery is about to charge, the battery cannot be called for aFRR delivery. Because intraday volumes are purchased five quarters of an hour before delivery, it is known that the battery cannot provide aFRR at those times and so the energy bids for those times are adjusted so that the battery is not requested to deliver power.

Finally, trading strategies can be applied to the aFRR bids that affect whether or not an energy bid is won.

7.1.5 Cost and revenue

The imbalance price is settled per quarter hour but arises per minute. In other words, the historical imbalance price does not mean that a power was actually activated all the minutes of that quarter-hour. Internal research shows that this ratio is about 74%. In other words, about 74% of the time within 1 quarter hour the imbalance price is higher or equal to the settled price. The formula used to determine costs and revenues for this reason is this:

$$Revenue\ aFRR = P_{bat} * \frac{1}{4} * 0.74 * price\ imbalance_t \tag{7.5}$$

And:

$$Cost\ intraday = P_{bat} * \frac{1}{4} * 0.74 * price\ intraday_t \tag{7.6}$$

Thus, the amount of revenue is equal to what the battery delivers in energy in fifteen minutes multiplied by the imbalance price at that time. The same amount of energy must then be purchased again on the intraday market to recharge the battery.

The battery capacity fee is calculated using the following formula:

$$Capacity\ fee = P_{bat} * p_{isp} * f_{pred} * f_{c-rate} \tag{7.7}$$

Whereby:

P_{bat} Battery power

P_{isp} Specific capacity fee
f_{pred} prediction factor
$f_{c\text{-}rate}$ factor c-rate

Because the capacity price is paid pay-as-bid, it means that an expectation must be made of the price. Because it is generally impossible to carry out a prediction 100% correctly the forecast is multiplied by 60%. Which corresponds to Scholt Energy's historical prediction accuracy for the imbalance and is supported in literature as a realistic forecast factor (Jongsma, van Cappellen, & Vendrik, 2021) (Merten, 2020) (Olk, Merten, Schoeneberger, & Sauer, 2020).

7.2 Trading strategies for intraday and aFRR

The number of activations for aFRR power depends on the energy bids. For this the energy bids have to deal with the technical constraints of security of supply and charging, but the energy bidprice determines if the battery is activated or not. The bidprice are in practice dependent on a trading strategies. To understand the difference and effect between different trading strategies several of these trading strategies are applied. The same also applies to buying intraday volume. Intraday volume can be bought immediately when needed, i.e. when the battery is not fully full, or can be bought at times when the price is more favorable. The different trading strategies used in the model are explained in more detail below. These trading strategies have been discussed with expert within Scholt Energy as realistic trading strategies. However, this does not mean that these strategies are optimal and/or the results can’t be higher in practice.

7.2.1 Monthly averages

The first trading strategy is a trading strategy based on monthly average. Bidding in the aFRR market is done based on monthly average. To estimate when a battery should bid in, it looks at the previous month. From this, the average price of the previous month plus an x percentage is bid. That percentage is what is put on top of the average, for example to increase or decrease the number of cycles. For intraday, the same thing is done. Here the average monthly price of last month is used as the "in bid" value. If the intraday price at that time is lower than last month’s average, and the battery is not completely full, then the intraday volume is bought and the battery starts charging 5 quarters of an hour later (when the purchased volume is delivered). The percentage on the bid price is dynamic. This means that when the battery state of charge is lower, the price for activation becomes higher and the price for charging becomes cheaper. This Is done to represent the real algorithm Scholt Energy used for controlling his batteries whereby the batterie must be available the next day to operate at multiple markets.

7.2.2 Weekly average

The weekly average is a similar strategy to the monthly average. The difference is that now the week before is used as the bid price instead of the month before. Then in the same way the percentage is used to adjust the amount of cycles and to discharge the battery earlier when it is filled up.

7.2.3 Monthly cycles

Monthly cycles determine the price bases on a fixed “ideal” amount of cycles. It looks at the previous month and determines at what price this amount of cycles would be achieved. In other words, at what bid price would the battery have my ideal amount of cycles last month. This price is then bid in as energy compensation for aFRR. Buying intraday is done the same way. At what price can I buy last month's x amount of intraday deals.

7.2.4 Weekly cycles

The weekly cycles work according to the same strategy as the monthly cycles, the only difference is that it does not look at the monthly quantity, but at the week before. In other words, what must the bid price have been the week before to achieve the x number of cycles.

7.3 Results

For generating the results, the model is classified with 3 types of batteries. A battery with a storage capacity is the same size as the power (1c), a battery that has 2x the storage capacity (0.5c) and a battery that has four times the storage capacity (0.25c). All three batteries end up giving about +/- 700 MWh aFRR power. This is to keep the inter-comparison constant. The revenue of the aFRR model is calculated for the year 2021, 2022 and 2023. The 2023 results were obtained by multiplying the first quarter results by four. This is because only the first quarter had sufficient data to run the model. The results of the different bidding strategies for different battery dimensions is shown below:

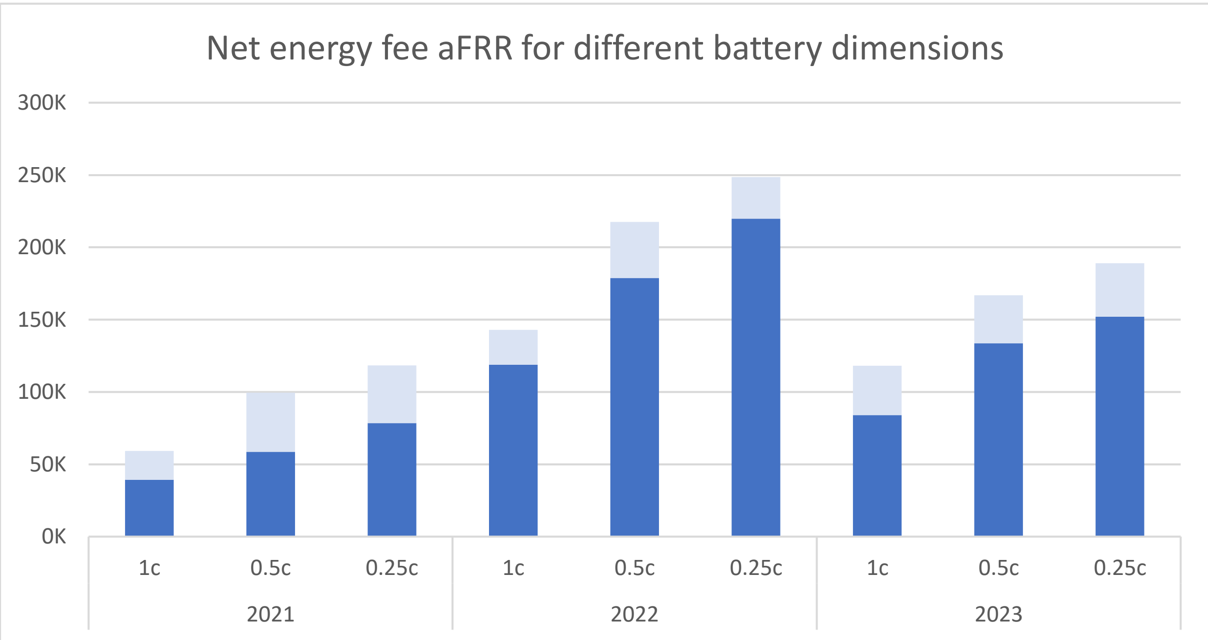


Figure 16 Results of the aFRR revenue model based on the years 2021, 2022 and 2023 whereby the 2023 results are based on Q1 data and extrapolated to a fully year. Results for a battery with as much storage capacity as power (1c), a battery with twice as much storage capacity as power (0.5c) and for a battery with four times as much storage capacity (0.25c).

Figure 16 shows the net energy compensation of the battery following the four trading strategies. Here, dark blue shows the result with the lowest turnover achieved. In light blue, the additional turnover is shown from best strategy. The results are based on a supply of 700 MWh aFRR per year. Based on the results, it has been concluded that the “monthly and weekly average” trading strategy results in the highest revenue, note this is at a suppl of about 700 MWh aFRR .On top of these returns there is a capacity fee. This is the same for all trading strategies because it depends on the battery characteristics and not the trading strategy. This capacity fee, based on the formula 7.7, was in 2021 €154k/MW, in 2022 €550k/MW and 2023 €290k /MW.

Figure 16 shows that net energy revenue for aFRR where highest in 2022, followed by 2023 and finally 2021. De reason for this is the extreme gas prices, see also chapter 3.2.2. It can also be seen that a battery with high storage capacity can generate more revenue than a battery with smaller storage capacity. This is mainly because a battery with higher storage capacity is more flexible in charging and discharging, and thus can choose financially better times to charge and discharge the battery. However, a bigger capacity also means higher investment cost, this will be further elaborated in chapter 8.

8. aFRR on a battery’s business case

In order to determine the effect of the aFRR market on Scholt Energy's business case, a model was developed that can determine the effect of aFRR based on historical achieved data. These results were then applied to Scholt Energy existing business case models to determine the effect of adding aFRR on a battery's business case.

8.1 Model development

The revenue comparison model was developed to provide insight into the effect of aFRR revenues compared to historical achieved revenue of a battery trading on the FCR and imbalance market. FCR in combination with the imbalance is now mainly used by batteries to trade on.

8.1.1 Time and Scope & input

The operation of the model consists of steps of 15 minutes for 1 whole year. By doing so, the results of the aFRR model can easily be used in the new model. In addition, the historical FCR prices and imbalance prices are easy to download per quarter hour. This is of importance because the current control of Scholt Energy's batteries are controlled on these markets. The model uses historical FCR values for the FCR revenue, historical achieved imbalance returns per day for the imbalance revenue and the results obtained from the aFRR model for the aFRR revenue. The data from the aFRR model is from a trading strategy that achieved the highest turnover.

The achieved imbalance revenue is per day, these revenues are prorated for all quarters of a day.

8.1.2 Objective function

The model compares the revenues obtained per day between Scholt Energy's "current" trading strategy of its batteries and the results of the aFRR model. The formula works through an if statement in Excel, comparing the sum of all returns for that day. If the aFRR returns for that day are higher, the battery will trade on the aFRR market and if the value is equal or smaller than the historical achieved value the battery will choose the FCR market and imbalance market.

8.1.3 Model results- gross revenue

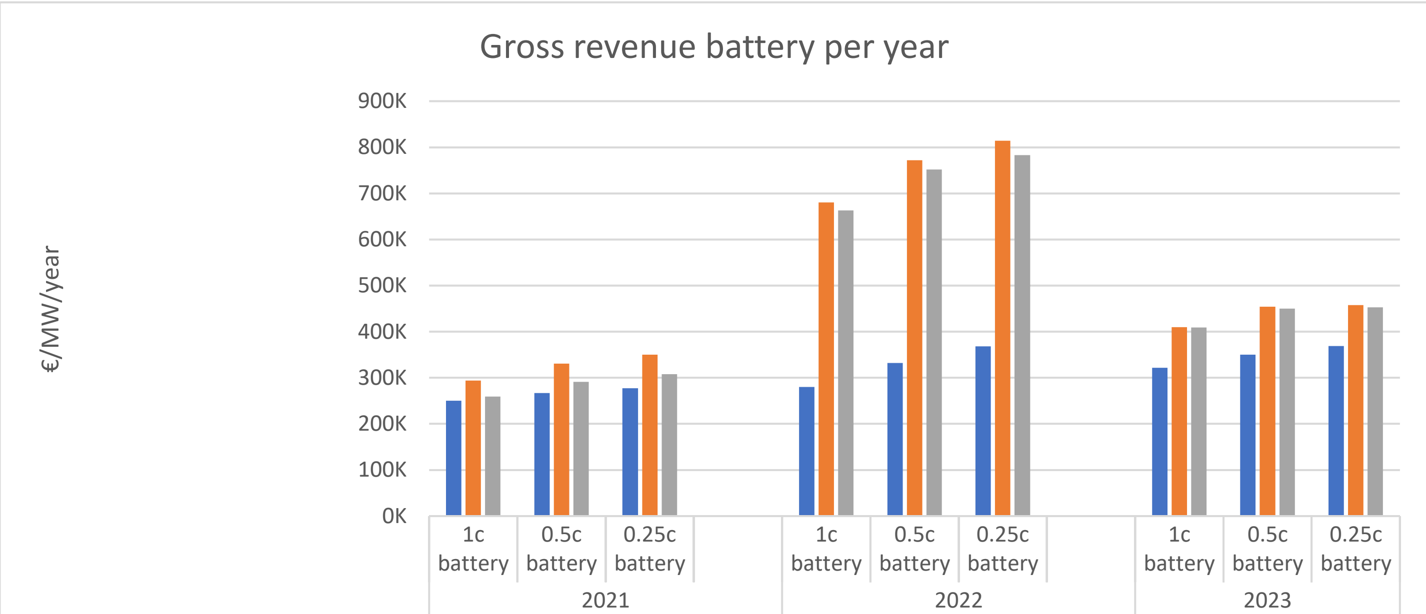
The model compares the highest revenue per day. This involves comparing the battery's historical revenue achieved with the outcome of the aFRR model. In doing so, the model gives two outcomes

1. The perfect foresight achievable turnover of the two markets.
   This is the turnover that would have been achieved if every day the right market was bid into. In reality you have to bid for a balancing market one day in advance, when you win the bid you are obliged to trade on it, it may then be that in hindsight, the other market would yield a higher revenue.
2. The achievable revenue following a realistic trading strategy.
   This is the achievable revenue after it follows a realistic trading strategy that Scholt Energy could use to control the battery.

The revenue achieved is shown for 3 types of batteries namely: a 1c battery, 0.5c battery and a 0.25c battery. The reason is because for these batteries the achieved revenues are known, a smaller c-rate is not known. In addition, towards 2030 mainly 1 and 2 hour batteries (1c and 0.5c) will be realized and some 4 hour batteries (0.25c). (Cappellen, Jongsma, Rooijers, & Vendrik, 2023). Thus, these three types of batteries will mainly be seen in Scholt Energy's portfolio in the coming years.

A trading strategy was used to correct the perfect foresight results to realistic results. For this study, a simplified trading strategy was chosen whereby the market that had generated the most revenue two days ago was bid into. Two days ago is considered because this is the closest day for which you can calculate total daily returns. This cannot yet be done for 1 day in advance since bids must be made as early as 8:00 in the morning for FCR. When this strategy is compared to the maximum revenue achieved, it turns out that about 2/3 of the time the right market is bid in. In other words, the market that was the best choice two days ago is the best choice today 66% of the time.

The current revenue of a battery on the FCR and imbalance compared to the revenue achieved when it also had access to aFRR are shown in figure 17



	2021 1c battery	2021 0.5c battery	2021 0.25c battery	2022 1c battery	2022 0.5c battery	2022 0.25c battery	2023 1c battery	2023 0.5c battery	2023 0.25c battery
FCR + imbalance (current)	250K	267K	277K	280K	332K	368K	322K	350K	369K
Perfect foresight aFRR+FCR+imbalnce	294K	331K	350K	680K	772K	814K	410K	454K	458K
Realistic aFRR+FCR+imbalance	259K	291K	308K	663K	752K	783K	409K	450K	453K

Figure 17 Comparison of gross revenue results for different years of a battery that acts on the FCR and imbalance market compared to a battery that can also trade on the aFRR market. Shown for a situation of perfect foresight and following a realistic trading strategy

Looking at the results of figure 17, it can be seen that in 2021, yields were lowest. Adding the aFRR market with perfect foresight results in an increase of about forty to eighty thousand euros. Realistically, this increase would be a lot lower, namely an increase of 10 to 30 thousand euros per year. In 2022, we see that battery revenues more than double if the battery had also had access to the aFRR market. The increase is mainly due to the extremely high gas prices of 2022. The perfect foresight scenario relative to a realistic trading strategy gives a reduction in revenues of around 20-30k. In 2023, revenues incl. aFRR are a lot higher than if the battery were to trade only on the FCR and imbalance ,around +90k. Note that these are extrapolated results based on Q1 2023 outcomes. The difference between the perfect foresight and realistic 2023 results are very small, around one thousand to five thousand. This is because in the first quarter of 2023, the aFRR market was more attractive than the FCR& imbalance market almost all days of the quarter. The reason is that in the first quarter of 2023, the capacity fee of aFRR was still relatively high, similar to the gas price.

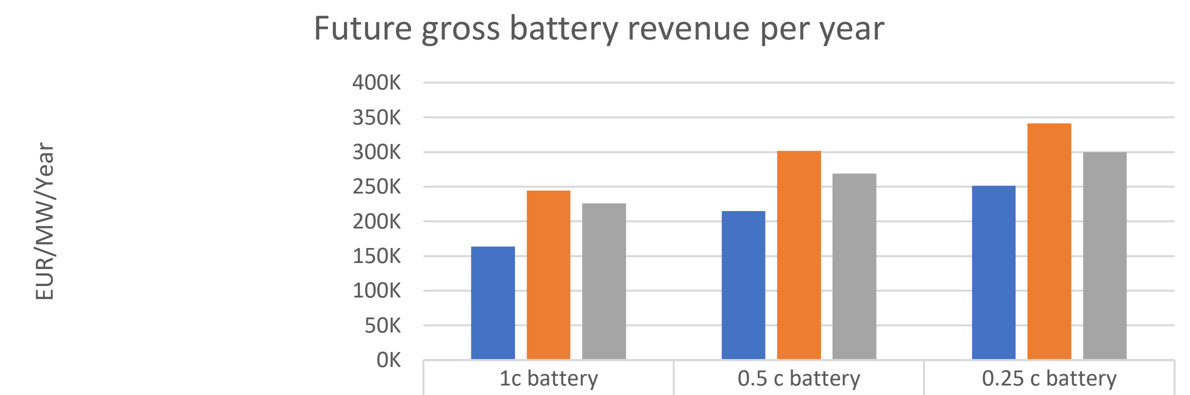
8.1.4 Future outlook

the future expectations for the various components of the electricity market were explained in chapter 3. On the basis of these expectations, the impact of the aFRR market on different battery types of Scholt Energy has again been calculated.

The following assumptions were used for the expected yield of the future outlook:

- FCR fee of average €10/MWh
  The FCR market decreased by 54% compared to 2022 so that the average FCR market is equal to the German FCR market with an average price of €10/MWh.
- aFRR revenue 2021.
  The aFRR revenues are similar to those for the year 2021.
  Because 2022 was a very extreme year, this year cannot be used for reference of future revenues. In addition, 2021 is considered an average year for future aFRR revenue.
- Imbalance revenue of 2022.
  The 2022 imbalance yield is, Scholt Energy expects, a more realistic indication of future imbalance yields due to the 2021 strategy being outdated. The prices of the imbalance are relatively high, but is compensated due to constant improvements of the algorithm in future years.
- Intraday cost of 2021
  Intraday costs should be the same as aFRR year to maintain a realistic picture of net aFRR energy returns.

The results of the future scenario are shown in figure 18. Figure 18 shows what the gross revenue achieved would be from a battery deployed in the aFRR market, with perfect foresight and more realistic sales. From the results, it can be concluded that the turnover of batteries in the future has the potential to increase 80k-90k EUR/MW year when it also participated on the aFRR market. Realistically this increase will be around 50k-60k EUR/MW.



	1c battery	0.5 c battery	0.25 c battery
FCR + imbalance (current)	164K	215K	252K
Perfect foresight aFRR+FCR+imbalnce	245K	302K	341K
Realistic aFRR+FCR+imbalance	226K	269K	300K

■ FCR + imbalance (current) ■ Perfect foresight aFRR+FCR+imbalnce ■ Realistic aFRR+FCR+imbalance

Figure 18 Comparison of gross revenue results for a future market scenario of a battery that acts on the FCR and imbalance market compared to a battery that can also trade on the aFRR market. Shown for a situation of perfect foresight and following a realistic trading strategy.

The percentage distribution of the battery deployment in a future scenario is 50/50. In other words, revenues are active about half the time in the aFRR market and the other half in the FCR imbalance.

8.2 Business case results

The investment cost of a battery is usually expressed as cost per kWh (De groene rekenkamer, 2017). A battery with twice the storage capacity is therefore also (approximately) twice as expensive (Jongsma, van Cappellen, & Vendrik, 2021). So the different returns of battery dimensions (1c, 0.5c, 0.25c) have to be put in perspective with the appropriate investment and annual cost of the whole system. This was done by using Scholt Energy's existing business case models. As Scholt Energy works closely with various relevant parties (battery suppliers, insurers, etc.) for various battery projects, this can be seen as very recent (battery) pricing. In these business case models, the gross revenue of figure 17 and 18 is used. Here, the realistic yields for aFRR and FCR and imbalance are used and it is compared with the revenue from only the FCR and imbalance. From these inputs, the model then calculates the full business case, with the results of the various payback periods visible in Figure 19.

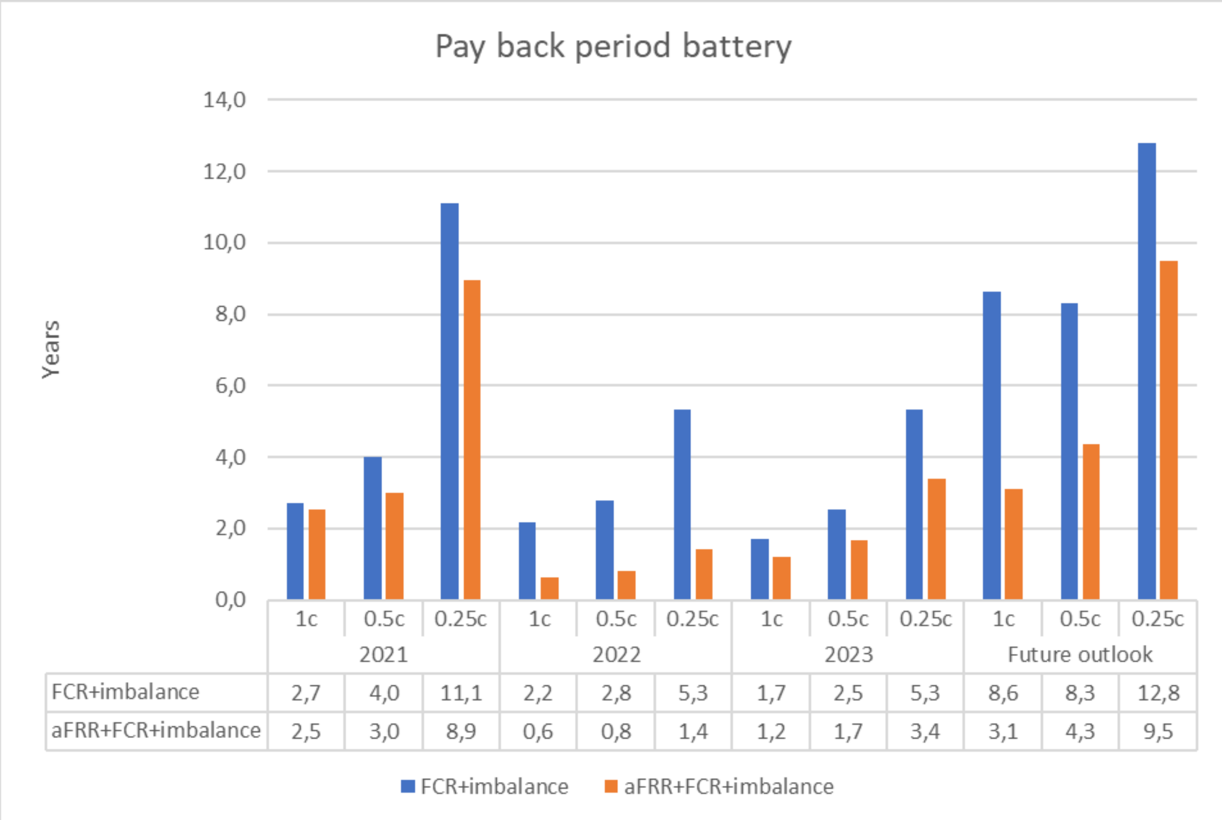


Figure 19 Comparison of differences in payback periods between batteries that can and cannot trade on the aFRR market, based on revenue achieved in different years + a future forecast of revenue.

For all years and battery dimensions, including aFRR, the payback period is lower. This is explainable because the realistic yields including aFRR are higher than only FCR and imbalance, see also figure 19 and 20. The battery payback time is lowest for a 1c battery based on all years, including the future scenario. The difference between the payback time with and without aFRR is the largest in the future scenario. For the future scenario, the payback period decreases from 9 -13 years to 3-10 years. A reduction in payback time means investments become more attractive, and more batteries projects will be developed. For this reason the aFRR market is recommended to include in the trading strategy of BESS. Besides the fact that adding the aFRR market, makes the battery more robust to market developments, it also ensures that the battery gives a higher fee yield for Scholt Energy. Since Scholt Energy receives a fee dependent on the revenue, it is financially attractive for both the investor/owner of the battery and Scholt Energy to achieve the highest possible revenue. For this reason, trading on the aFRR market is recommended. This not only gives a financial advantage to a Scholt Energy and the battery investor, but also reduces the cost of balancing energy in general and thus increases the financial viability of renewable energy projects such as wind and solar.

8.2.1 Sensitivity analysis

Future outlook results are based on expectations. These results therefore face a degree of uncertainty. To better estimate how the results respond to changes, a sensitivity analysis can be performed. Such an analysis involves examining how much the outcomes change with a (percentage) change in the input value. The uncertainty here is mainly in the expected market returns of the different markets in the future, for this reason, for the uncertainty analysis, the three market returns of the battery are adjusted percentage-wise. The sensitivity is tested at + and - 30%, in 10% increments. The reason is because these are realistic deviations from high and low scenarios of the electricity market in the future (Enpuls, 2020) (Afman, Hers, & Scholten, 2017). In doing so, this provides sufficient insight into the effect of the changes on the results. The results are shown in figure 20-22 and show the number of years payback time lower. An example of an outcome from the sensitivity analysis could be: The years the payback time decrease when the battery can also trade on the aFRR market, in a future situation where the FCR generates 10% more revenue (compared to the future situation in 8.1.4). The sensitivity analysis for the three different battery dimensions is shown in figure 23-25, de data on which the figures are based, is shown in table 3-5.

Table 3 Data table sensitivity analysis for the future outlook. Whereby the payback period of a battery is calculated (in years), with and without participation on the aFRR market for different market adjustments. Results for a battery with as much storage capacity as power (1c battery)

Market adjustment	**70%**		**80%**		**90%**		**100%**		**110%**		**120%**		**130%**	
Payback period (years)	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR
FCR	13,2	3,4	11,6	3,3	10,4	3,2	8,6	3,1	7,1	3,0	6,0	2,8	5,2	2,7
Imbalance	12,5	3,3	11,2	3,3	10,3	3,2	8,6	3,1	7,3	3,0	6,2	2,9	5,5	2,8
aFRR	8,6	5,2	8,6	4,2	8,6	3,6	8,6	3,1	8,6	2,7	8,6	2,3	8,6	2,1

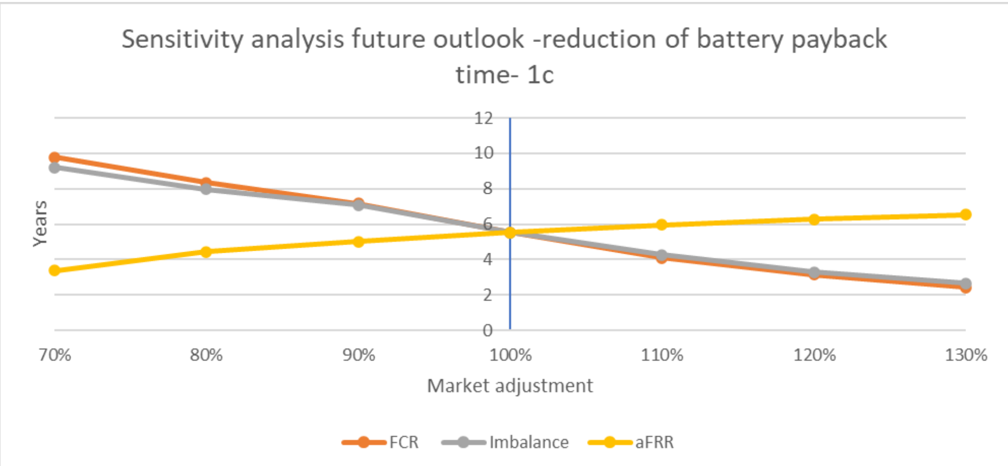


Figure 20 Sensitivity analysis on the decrease of payback period in years, adjusting future returns by percentage in 10% increments. Results for a battery with as much storage capacity as power (1c battery)

Table 4 Data table sensitivity analysis for the future outlook. Whereby the payback period of a battery is calculated (in years), with and without participation on the aFRR market for different market adjustments. Results for a battery with twice as much storage capacity as power (0.5c)

Market adjustment	**70%**		**80%**		**90%**		**100%**		**110%**		**120%**		**130%**	
Payback period (years)	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR
FCR	11,4	4,8	10,6	4,6	9,7	4,5	8,3	4,3	7,2	4,2	6,4	4,0	5,8	3,8
Imbalance	12,8	5,0	11,3	4,7	10,2	4,5	8,3	4,3	6,8	4,1	5,8	3,9	5,0	3,7
aFRR	8,3	6,5	8,3	5,8	8,3	5,0	8,3	4,3	8,3	3,7	8,3	3,2	8,3	2,9

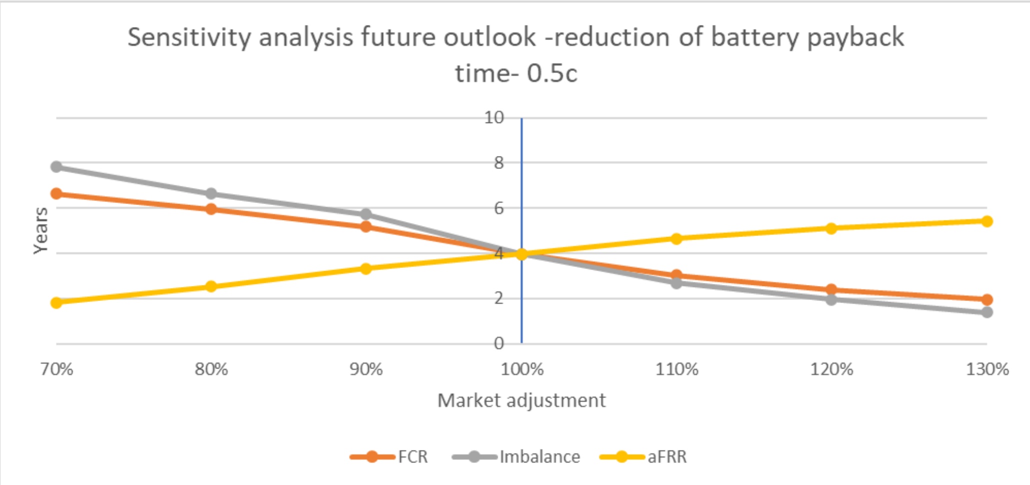


Figure 21 Sensitivity analysis on the decrease of payback period in years, adjusting future returns by percentage in 10% increments. Results for a battery with twice as much storage capacity as power (0.5c battery)

Table 5 Data table sensitivity analysis for the future outlook. Whereby the payback period of a battery is calculated (in years), with and without participation on the aFRR market for different market adjustments. Results for a battery with four times as much storage as power (0.25c).

Market adjustment	**70%**		**80%**		**90%**		**100%**		**110%**		**120%**		**130%**	
Payback period (years)	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR	Excl. aFRR	Incl. aFRR
FCR	15,4	10,4	14,3	10,1	13,5	9,7	12,8	9,5	12,2	9,2	11,5	8,7	11,0	8,0
Imbalance	18,7	10,8	16,1	10,5	14,3	10,1	12,8	9,5	11,6	8,9	10,7	7,9	9,7	7,2
aFRR	12,8	12,2	12,8	11,3	12,8	10,6	12,8	9,5	12,8	7,8	12,8	6,6	12,8	5,6

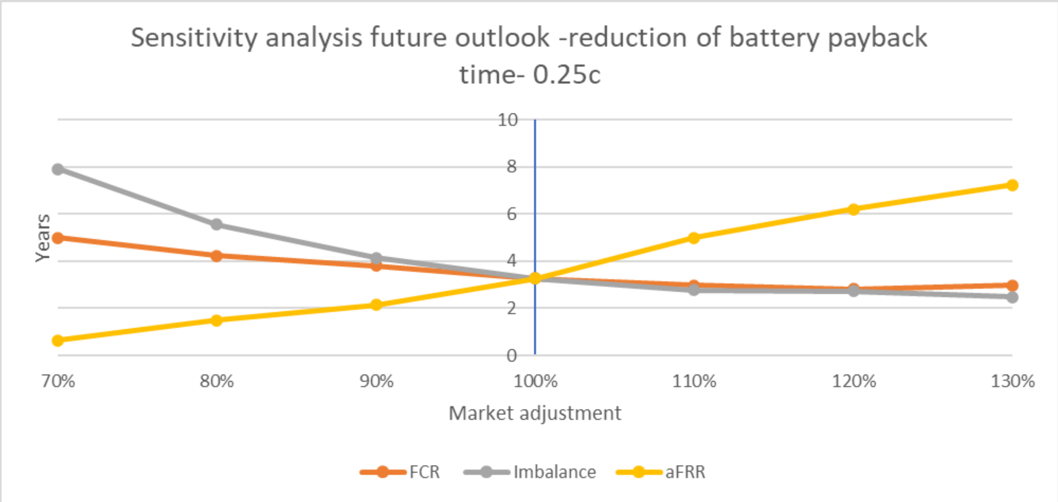


Figure 22 Sensitivity analysis on the decrease of payback period in years, adjusting future returns by percentage in 10% increments. Results for a battery with four times as much storage capacity as power (0.25c battery)

To perform this analysis, the market revenue is adjusted by the corresponding percentage increase or decrease. The other markets remain constant. From the results in Table 3-5 and Figure20-22, it can be seen that if the aFRR market is 30% lower than currently expected, the payback period of batteries in the future reduces by six months to three years. Note that the payback period achieved now may be longer than the battery life. Even if FCR or imbalance generate 30% more revenue than expected, adding the aFRR market will still ensure a reduction in payback time, around 2 years for all three battery dimensions.

Conversely, we see a greater added value of the aFRR market on battery payback. Namely, when FCR or imbalance revenues are lower than currently expected, the reduction in payback time increases. The same goes for when the aFRR market generates more revenues than currently expected, the payback period also decreases more.

In short, with the execution of the sensitivity analysis, it can be established that adding the aFRR market for batteries reduces the battery payback time in a future scenario, however, the amount of years that the batteries actually reduce on its payback time is highly dependent on the actual market development.

9. Discussion

The chapter below serves to reflect on the results of the study. Here, the limitations of the study are shown and a recommendation for follow-up research is given.

The analysis of the impact of aFRR on the business case of large-scale battery storage is mostly based on the results of the revenue model aFRR described in chapter 6. The used model was developed in Excel. As there is a limitation of computing power in Excel when simulating data, it was chosen to use assumptions. For example, the assumption was used that when an energy offer is activated, it should provide energy, 74% of the time in that ISP. In reality, however, activation varies every 15 minutes, so aFRR may be activated all minutes, or only some, which affects the energy fee. In addition, the decision was also taken to reduce aFRR's capacity fee to 60% of revenue. The reason for this is to compensate for the fact that the current capacity fee is paid out using the "pay-as-bid" method which means that an estimate of the fee has to be made. In reality, this means that the published values of aFRR capacity fee are not equal to the actual fee received. Studies and internal knowledge show that with forecasting these values, about 60% of this fee is a realistic starting point. In practise, these values may be higher or lower, affecting the results of this study.

Another limitation is that the results of this study are based on historical years from 2021 to 2023. In these years, batteries have not penetrated the aFRR market. This makes it impossible to validate the battery's associated fees on aFRR with actual results achieved by a battery acting on it. In addition, there are limited scientific articles that can be used to validate the results achieved by a battery on the Dutch aFRR market in those years.

This research is limited to 4 trading strategies that an BSP can use for trading on the aFRR market. These trading strategies were formed through discussions with experts and represent realistic strategies that an BSP such as Scholt Energy can use. However, the focus of these trading strategies was that they are realistic and applicable, these strategies were not optimised for yield due to time constraints of this research. It could be very interesting to further investigate what is the optimal trading strategy for a battery in the aFRR market for the optimal lifetime yields. An optimised trading strategy is particularly interesting for a BSP that benefits from higher returns from its assets in the balancing markets.

The same applies to the trading strategy applicable for choosing the right market. For this study, a trading strategy was chosen that adopts the best market as it was two days in the past. This trading strategy is very simple and causes a decrease in the turnover gained from a battery. For this reason, it is interesting to do a follow-up study on the most optimal strategy that chooses the right market at the right time.

Another interesting follow-up study is research on the added value of batteries on grid stability in the Netherlands. This current research is limited to existing literature on the application of a battery deployment for grid stability. A possible follow-up study could delve further into the different functions of batteries for the purpose of grid stability. This could investigate the extent to which batteries can best be used to stabilize the grid in the best possible manner, now and in the (near) future.

Finally, an interesting follow-up study is to investigate the effect of aFRR combined with intraday trading for a 2c battery or larger. Now, the effect has only been studied for a 1c, 0.5c and 0.25c battery. The reason for this is because, in practice, these are also the batteries controlled by Scholt Energy. Thereby, in the literature, this was also the most common battery dimension for now and in the future. It would be interesting to also investigate the effect of adding the aFRR market on higher battery dimensions than were investigated in this study because the best results were obtained at the highest battery dimension and it is therefore interesting whether this trend continues to occur at higher c values.

10. Conclusion

The aim of this study was to answer the following research question: " What is the effect on a battery's business case by bidding the full power into the aFRR balancing market where contractual obligations are met through trading on the intraday market?"

To better understand the importance of the aFRR product and the participation of batteries in this market, the overall effect of batteries joining the real-time balancing of the Dutch power grid was first investigated. From this, it can be concluded that batteries can contribute to real-time balancing in two ways, through active and passive balancing. Active means that participation is preselected through bidding, with the TSO providing the connection and activation. Passive balancing means a voluntary contribution to grid imbalance, stimulated by the live publication of imbalance prices. Battery entry reduces imbalance costs for both forms of balancing, resulting in a more attractive financial perspective for renewable electricity projects. One form of balancing is not better than another, but they possess different deployment benefits. Active balancing is a more power-efficient way of balancing, while passive balancing is a more cost-efficient way. When deployed in the aFRR market, batteries provide active balancing power. This therefore results in lower imbalance costs than when batteries do not enter this market and is a power efficient way of real-time balancing.

To participate in the aFRR market, regulations drawn up by TenneT must be met. Chapter five describes the legal framework established by TenneT for bidding a battery into the aFRR capacity fee. Here it can be concluded that a battery, or a pool of batteries, is described as limited energy reservoirs and can act as an individual or as a pool on the aFRR market. To still receive a full-capacity payment, the battery must be able to supply energy for the entire contract duration. In practice, this means that batteries must apply charge management where a transaction on intraday underlies the prevention of system imbalance. Furthermore, the intraday deal also means that the battery is unable to deliver aFRR at that time, and the BSP should take this into account in its bidding strategy. To verify that a battery follows these rules, a communication signal must be sent to TenneT and the battery when volume is purchased on intraday. The communication stream required for this control is explained in chapter 6.

From this, it can be concluded that within the current organizational structure, it would be technically possible for Scholt Energy to apply charge management on the intraday market. Here, all signals that Scholt Energy sends on the intraday market should be passed on as BRP to the battery controller and then adjusted at TenneT. Although this structure would be organizationally possible, TenneT CBS for aFRR is currently working on an expansion. This expanded platform can connect BRP and BSP parties so that communication is sent directly to the parties involved, which reduces the chance of errors and provides transparency for TenneT's verification process. It therefore makes more sense for Scholt Energy to join the aFRR market when this expanded CBS is fully developed.

To investigate the effect that the aFRR had on the business case, two models were developed: (1) the aFRR revenue model and (2) the revenue comparison model. In the revenue model, the income of four trading strategies that Scholt Energy could adopt to act on the aFRR market with its battery power has been calculated. The revenue of these four trading strategies has been calculated based on historical data for 2021, 2022, and 2023. Here, 2023 first-quarter data has been extrapolated to a full year due to data availability. From the aFRR revenue model, it can be concluded that revenues for aFRR were highest in 2022, followed by 2023, and lastly 2021.The reason is the strong correlation between the aFRR price and the gas price. Next to that, the yields of a 0.25c battery are the highest, followed by that of 0.5c battery and last is a 1c battery. The reason can be found in the degree of flexibility, where a battery with higher storage capacity can choose to load and unload a "better" time than a battery with less storage capacity. The results of the revenue model only calculate the income of a battery on the aFRR but does not give information about revenue relative to markets where the battery is already participating on. The revenue comparison model does make this comparison. Here, the daily revenue of the aFRR market is compared with the historical revenue achieved on the FCR and imbalance market. This is also described in chapter 8 as the perfect foresight returns. These returns are lower in reality; to correct for this, this study used a simple trading strategy to choose the right market. From analyzing these results, it can be concluded that the realistic yields including aFRR in 2021 added around 10-30k euros per year per MW, going from 250-270k EUR/MW to 260-300k EUR/MW. In 2022, this difference was significantly larger, adding around 380-420k euros per year per MW, going from 280–370k EUR/MW to 660–780k EUR/MW. To which it must be added that this was an extreme year due to extremely high gas prices. In 2023, therefore, we already see another decrease compared to 2022 to around 80-100k additional revenue euros per MW per year when accessing the aFRR, going from 320–370k EUR/MW to 410-450k EUR/MW.

This study also looked at the effect of aFRR on the business case in a future situation. Here again, the effect of aFRR is calculated. From this, it can be concluded that if the future expectation of the markets, as currently expected in literature and experts, becomes true, a battery with aFRR earns about 40-60k euros per year per MW more than a battery that trades only on FCR and imbalance, going from 160-250k EUR/MW with only FCR and imbalance to 225-300k EUR/MW when also participating on the aFRR.

Finally, this study looked at the effect of incremental revenue on the overall battery business case. This was done by using the existing business case models used by Scholt Energy. From this, it can be concluded that a battery dimension of 1c is the most financially attractive form with the smallest payback period in all four years (2021, 2022, 2023 and future scenario), followed by a 0.5c battery and lastly a 0.25c battery. Adding the aFRR market compared to just the FCR and imbalance market, causes the battery, based on historical years, to shrink by about one to four years. Here, the payback time decreases on average one year in 2021, whereas without aFRR the payback period was three, four and 11 years, the payback period with aFRR is two, three and nine years. For 2022, the decrease is on average three years, decreasing the payback period from two to five years, to one to two years. In 2023, the decrease is average 2 years, whereas without aFRR the payback period was two to five years, the payback period with aFRR is one to three years. Based on the years 2021, 2022 and 2023, the effect is the largest for a 0.25c battery. In the future scenario, the effect of entering the aFRR market is the largest; here we see the payback period decreasing from 8-13 years to 3-10 years. As there is a degree of uncertainty in predicting future market returns, a sensitivity analysis has been carried out. From this, it can be concluded that the aFRR market ensures a lower payback period even if revenues from the aFRR are disappointing, but there is a high degree of sensitivity in the number of years the payback period decreases, depending on market developments.

In short, this study concludes that it is regulatory possible to offer the full power of a battery for the aFRR market; this can only be done when there is an intraday market transaction underlying the charging, and at the same time, through a bidding strategy, it is ensured that the battery is not activated at that time. This can be controlled internally through Scholt Energy's existing organizational structure, but it is more likely to participated on the aFRR with batteries once the expanded CBS for aFRR is developed that links the data streams of intraday directly. After Scholt Energy has full access to the aFRR market, this results in a decrease in the payback period to about 4 years based on historical data. For future expected market prices, this could even increase to a five-year shorter payback time compared to the markets it currently operates at. For this reason, trading on the aFRR market is recommended. This not only gives a financial advantage to a Scholt Energy and the battery investor, but also reduces the cost of balancing energy in general and thus increases the financial viability of renewable energy projects such as wind and solar.

Bibliography

Afman, M., Hers, S., & Scholten, T. (2017). *Energy and electricity price scenario's 2020-2023-2030.* Delft: CE Delft.

Alberizzi, A., Zani, A., & Barba, P. D. (2022). *Analysis of the intraday market: statistical analysis of German single intraday coupling.* Rome: 2022 AEIT International Annual Conference (AEIT).

Cappellen, L. v., Jongsma, C., Rooijers, F., & Vendrik, J. (2023). *Beleid voor grootschalige batterijsystemen en afname congestie.* Delft: CE Delft.

CBS. (2022). *Hernieuwbare energie in Nederland 2021*. Retrieved from cbs.nl: https://www.cbs.nl/nl-nl/publicatie/2022/39/hernieuwbare-energie-in-nederland-2021#:~:text=Het%20aandeel%20hernieuwbare%20energie%20in,0%20en%2013%2C4%20procent.

Datta, U., Kalam, A., & Shi, J. (2021). *A review of key functionalities of battery energy storage system in renewable energy integrated power systems.* Energy storage 3.

De groene rekenkamer. (2017). *(Grootschalige) energieopslag door middel van accu's betaalbaar?* Retrieved from groene-rekenkamer.nl: https://groene-rekenkamer.nl/6273/grootschalige-energieopslag-middel-accus-betaalbaar/#:~:text=Aanzienlijk%20meer%20dan%20de%20kosten,GWu%20lijkt%20niet%20erg%20waarschijnlijk.

Demir, S. (2023). *Statistical Arbitrage Trading on Electricity.* Eindhoven: Eindhoven University of Technology.

DNE. (2022). *Smart storage trendrapport.* Dutch New Energy Research.

DNV. (2021). *BATTERY ENERGY STORAGE SYSTEMS IN THE NETHERLANDS.* Arnhem: DNV.

Eicke, A., Ruhnau, O., & Hirth, L. (2021). *Electricity balancing as a market equilibrium: An instrument-based estimation of supply and demand for imbalance energy.* Berlin: Neon Neue Energieökonomik GmbH.

Energids. (2023). *Wat zijn een black-out en een afschakelplan*. Retrieved from energids.be: https://www.energids.be/nl/vraag-antwoord/wat-zijn-een-black-out-en-een-afschakelplan/439/

Enpuls. (2020). *Maatschappelijke kosten-batenanalyse naar toekomstige inpassing van drie alternatieven voor opwek van zonne-energie.* s-Hertogenbosch: Berenschot & Kalavasta.

ENTSOE. (2023). *Prices of Activated Balancing Energy Legacy*. Retrieved from transparency.entsoe.eu: https://transparency.entsoe.eu/balancing/r2/pricesOfActivatedBalancingEnergy/show

Equigy. (2023). *THE CBP PRODUCT*. Retrieved from equigy.com.

Gitis, A., Leuthold, M., & Sauer, D. U. (2015). *Electrochemical Energy Storage for Renewable Sources and Grid Balancing.* Ulm: Elsevier.

Hartman, S. (2022). *ANALYSIS OF THE FEASIBILITY OF BATTERY ENERGY STORAGE AS THE SOLUTION FOR ELECTRICITY GRID CONGESTION.* Delft: Delft University of Technology.

Hu, J., Harmsen, R., Crijns-Graus, W., Worrell, E., & van den Broek, M. (2018). *Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design.* Utrecht: Utrecht Univeristy.

Jongsma, C., van Cappellen, L., & Vendrik, L. (2021). *Omslagpunt grootschalige batterijopslag.* Delft: CE Delft.

Just, S. (2011). Appropriate contract durations in the German markets for on-line reserve capacity. *Journal of Regulatory Economics* (pp. 194-220). Berlin: Springer Nature.

Lund, D. P. (2015). *Review of energy system flexibility measures to enable high levels of variable renewable electricity.* Renewable and Sustainable Energy Reviews.

Merten, M. (2020). *Participation of Battery Storage Systems in the Automatic Frequency Restoration Reserve Market based on Machine Learning.* Aachen: ISEA.

Nemo committee. (2023). *Single Intraday Coupling (SIDC)*. Retrieved from nemo-committee.eu: https://www.nemo-committee.eu/sidc

Next Kraftwerke. (2023). *Balanceringsenergie*. Retrieved from next-kraftwerke.nl: https://www.next-kraftwerke.nl/producten/balanceringsenergie#:~:text=In%202021%20liggen%20de%20vergoedingen,Deze%20meet%20continu%20de%20netfrequentie.

Nordpool. (2023). *About us*. (Nordpoolgroup) Retrieved from nordpoolgroup.com.

Olk, C., Merten, M., Schoeneberger, I., & Sauer, D. U. (2020). *Bidding strategy for battery storage systems in the secondary control reserve.* Achen: Elsevier.

Olk, C., Sauer, D. U., & Merten, M. (2019). *Journal of Energy Storage.* Lleida: Elsevier.

Prakash, K., Ali, M., Nazrul, I. D., Chand, A., Kumar, N. M., Dong, D., & Pota, H. (2022). *A review of battery energy storage systems for ancillary services in distribution grids: Current status, challenges and future directions.* Baseem Khan: Advanced Clean energy technologies.

Rijksoverheid. (2022). *Duurzame energie*. Retrieved from rijksoverheid.nl: https://www.rijksoverheid.nl/onderwerpen/duurzame-energie#:~:text=In%202019%20kwam%208%2C7,vanwege%20het%20tegengaan%20van%20klimaatverandering.

Schittekatte, T. (2022). *Distributed energy resources and electricity balancing: vision for future organisation.* San Domenico di Fiesole: European University Institute.

Slooff, T. J. (2019). *Competitiveness of Battery Energy Storage in the Future Belgian Capacity Market.* Delft: Delft University of Technology.

TenneT 1. (2023). *Balanceringsmarkten*. Retrieved from TenneT.eu: https://www.tennet.eu/nl/balanceringsmarkten

TenneT 2. (2022). *Handboek aFRR voor BSP's.* Arnhem: TenneT TSO B.V.

TenneT 3. (2022). *Handboek FCR voor BSPs.* Arnehm: TenneT TSO B.V.

TenneT 4. (2023). *Handboek/productinformatie Noodvermogen voor BSPs.* Arnehm: TenneT TSO B.V.

TenneT 5. (2022). *Handleiding bieden.* Arnhem: TenneT TSO B.V.

TenneT 6. (2023). *Ondersteunende diensten (Nederland)*. Retrieved from tennet.eu: https://www.tennet.eu/nl/de-elektriciteitsmarkt/ondersteunende-diensten-nederland

TenneT 7. (2023). *Soorten elektriciteitsmarkten*. Retrieved from tennet.eu.nl: https://www.tennet.eu/nl/soorten-elektriciteitsmarkten

Terpstra, N. (2020). *Day-Ahead and Imbalance Price Forecasting on the Ductch Electricity market: A comparisson between time series and Artificial Neural Networks Models.* Eindhoven: Eindhoven university of technology.

Veen, R. A., & Hakvoort, R. A. (2016). The electricity balancing market: Exploring the design challenge. *Utilites Policy* (pp. 186-194). Delft: Delft University of Technology.

Zande, L. v., Saguan, M., Meeus, L., Clachant, J.-M., & Belmans, R. (2009). *Lacking balancing market harmonisation in Europe: room for trader profits at the expense of economic efficiency?* Leuven: Katholieke Universiteit Leuven.

Zwang, J. W. (2022). *Handboek verdienmodellen batterij.* Woudenberg: Stratergy.