Comparative study of the techno-economic performance of various energy storage solutions for fast-acting grid balancing applications

Lappeenranta–Lahti University of Technology LUT

Master’s thesis

2023

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Examiners: Professor Pertti Kauranen

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ABSTRACT

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This thesis focuses on conducting a comparative study to analyze the techno-economic performance of various energy storage solutions for fast-acting grid balancing applications, specifically in frequency control markets. The goal of this research is to provide insights into the suitability of different energy storage technologies for specific frequency control markets, namely FCR-D down-regulation, FCR-D up-regulation, FCR-N, and FFR. By evaluating key parameters such as charge/discharge power, Capex, Opex, and NPV, the study aims to inform stakeholders and market participants about the most appropriate energy storage options for each market. The findings will help guide decision-making processes, optimize energy storage investments, and contribute to the enhancement of grid stability in dynamic electricity markets.

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Lastly, I dedicate this thesis to **Urmia Lake**. It has long been a significant ecological and cultural landmark. However, its current state of decline poses a grave threat not only to the lake itself but also to the surrounding region and its inhabitants. **It needs an urgent international coalition to survive.**

SYMBOLS AND ABBREVIATIONS

Δf	Frequency Deviation	[Hz]
ΔP	Lost Power	[MW]
Δt	Fault Time Period	[s]
E_k	Kinetic Energy	[GWs]

Abbreviations

AC	Alternating Current
aFFR	Automatic Frequency Restoration Reserve
BESS	Battery Energy Storage Systems
BRP	Balance Responsible Party
BSP	Balances Service Provider
Capex	Capital Expenditures
CET	Central European Time
DC	Direct Current
DoD	Depth of Discharge
DR	Demand Response
DSO	Distribution System Operator
ESS	Energy Storage System
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal Operation
FFR	Fast Frequency Reserve
FLH	Full Load Hour

HVAC	High Voltage Alternative Current
HVDC	High Voltage Direct Current
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
LIB	Lithium-ion battery
FRR	Manual Frequency Restoration Reserve
Opex	Operation Expenditures
P2G	Power to Gas
RES	Renewable Energy Sources
rte	round trip efficiency
TSO	Transmission System Operators
VAT	Value-Added Tax
VRE	Variable Renewable Energy

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1 Introduction

Frequency regulation is an essential aspect of maintaining the stability and reliability of electric power systems. The electricity grid operates on a delicate balance between power generation and demand, with various factors influencing the frequency at which electricity is delivered. In most countries, the standard frequency is 50 or 60 Hertz (Hz), depending on the region.

To understand why frequency regulation is needed, we must consider the principles of power generation and consumption. Power plants, whether they are fuelled by fossil fuels, nuclear energy, or renewable sources, are designed to generate electricity at a specific frequency. This frequency is maintained as long as the supply and demand of electricity remain in equilibrium. However, the demand for electricity is not constant. It fluctuates throughout the day due to factors such as industrial activity, commercial operations, and residential usage patterns. Sudden changes in demand can disrupt the balance between supply and demand, leading to frequency deviations. When the demand for electricity exceeds the available supply, the frequency tends to decrease. On the other hand, if the supply exceeds demand, the frequency tends to increase. These frequency deviations can have adverse effects on the power system and the equipment connected to it.

The need for frequency regulation is expected to increase for several reasons. First, there is a growing demand for electricity due to population growth, urbanization, and the proliferation of electronic devices. This increased demand places a greater strain on power systems and makes it more challenging to maintain frequency stability. Second, the integration of renewable energy sources, such as solar and wind, has introduced additional complexities. Unlike conventional power plants, renewable sources are inherently intermittent, as their output depends on weather conditions. Fluctuations in renewable energy generation can cause frequency deviations, especially when the share of renewable energy in the grid is high. Third, the electrification of transportation and the rise of electric vehicles (EVs) are expected to have a significant impact on the power grid. The charging of EVs can introduce sudden and substantial changes in electricity demand, which, if not properly managed, can disrupt frequency stability. Lastly, the decommissioning of conventional power plants, particularly those using fossil fuels, and their replacement with intermittent renewable sources may reduce the inertia of the power system. Inertia refers to the ability of large rotating masses in conventional power plants to stabilize the grid's frequency. With less inertia, it becomes more challenging to respond quickly to frequency deviations.

Considering these factors, the need for effective frequency regulation mechanisms, such as advanced grid control systems, energy storage technologies, and demand response programs, is expected to increase. These measures help to balance the supply and demand of electricity, mitigate frequency deviations, and ensure the reliability of power systems in the face of evolving energy landscapes.

To address the challenges in the frequency regulation market, there is a strong motivation to investigate and adopt new technologies such as batteries. These technologies offer promising solutions for enhancing grid stability, flexibility, and overall system efficiency.

One of the key motivations for exploring battery technologies in frequency regulation is their ability to provide fast and accurate response times. Batteries can rapidly inject or withdraw power from the grid, allowing for swift adjustments to fluctuations in frequency. This responsiveness is crucial for maintaining grid stability and ensuring reliable operation, especially with the intermittent renewable energy sources.

Additionally, investigating new technologies like batteries for frequency regulation offers opportunities to improve system efficiency and reduce operational costs. Batteries can provide valuable grid services beyond frequency regulation, such as voltage support and peak shaving, further enhancing grid reliability and performance. The scalability and modular nature of battery systems also allow for flexible deployment, enabling grid operators to optimize resource allocation and potentially defer costly infrastructure upgrades. Furthermore, advancements in battery technology and decreasing costs make them an increasingly attractive option for frequency regulation. Ongoing research and development efforts focus on improving battery performance, durability, and cost-effectiveness, opening up new possibilities for their integration into the energy system.

● *Nordic electricity market*

Nordpool is one of the largest power markets in Europe and operates spot markets for electricity trading in the Nordic and Baltic regions. It was established in 1996 and is owned by the transmission system operators of the participating countries. The Nordpool spot markets provide a platform for buyers and sellers to trade electricity on a day-ahead and intraday basis. The Nordpool spot markets operate in several countries, including Norway, Sweden, Finland, Denmark, Estonia, Latvia, and Lithuania. These markets enable market participants, such as generators, suppliers, and traders, to buy and sell electricity contracts for specific delivery periods. The prices are determined through a competitive bidding process, where market participants submit their offers to sell or buy electricity. The Nordpool spot markets contribute to the efficient utilization of resources and facilitate price discovery based on supply and demand dynamics. They promote competition, transparency, and liquidity in electricity markets, allowing market participants to manage their positions and hedge against price volatility [1][2].

As for the distribution of different generation technologies in the Nordpool area, the region has a diverse mix of generation sources. The Nordic countries, in particular, have made significant progress in adopting renewable energy sources and reducing dependency to fossil fuels. The distribution of generation technologies varies across countries due to their specific energy resources and policies. Here is a general overview:

-Hydropower: The Nordic region is rich in water resources, and hydropower is a dominant generation technology. Norway and Sweden, in particular, have a substantial share of hydropower capacity, which provides a reliable and flexible source of electricity.

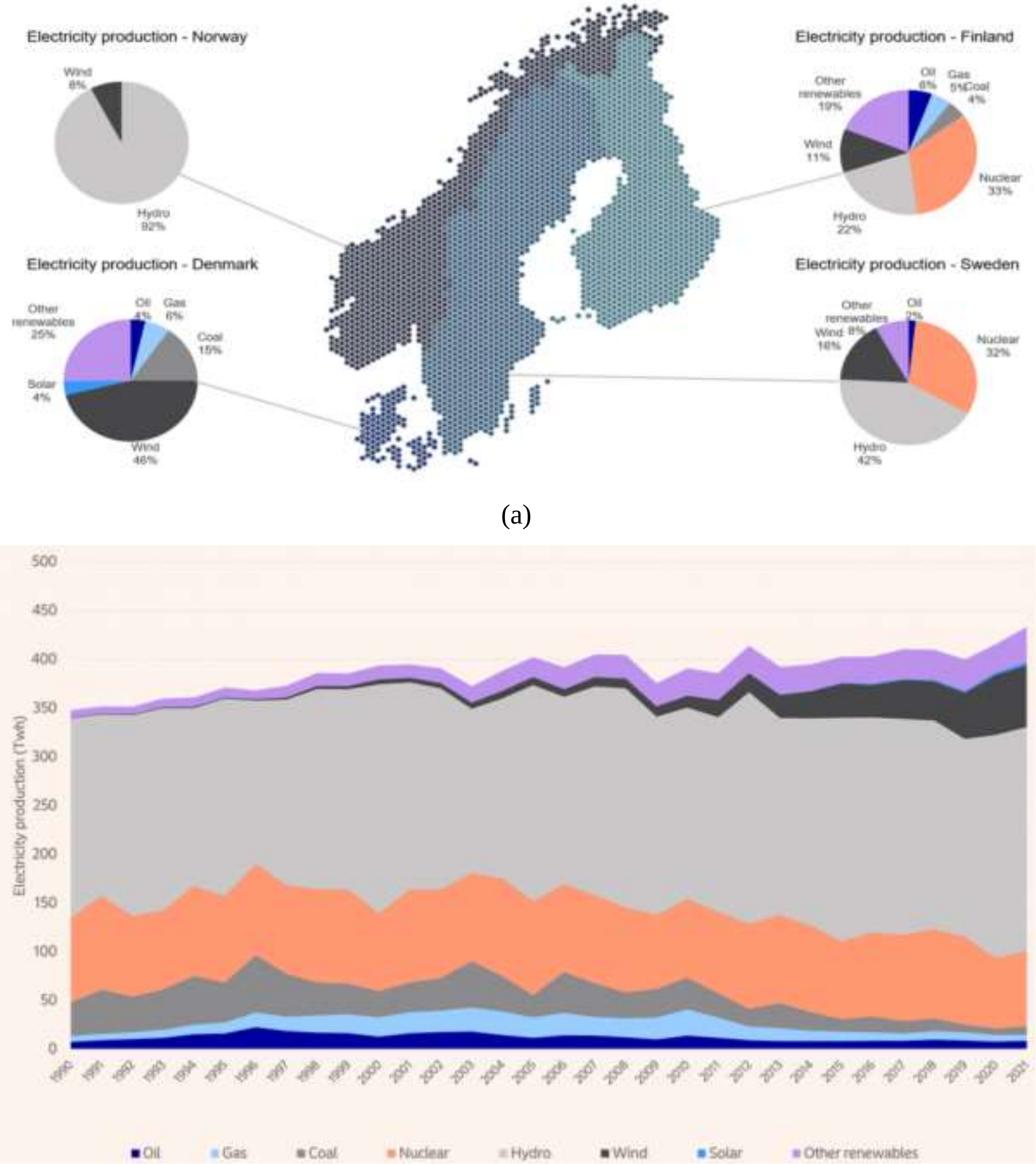
-Wind Power: Wind power has seen substantial growth in the Nordpool area, with significant investments in onshore and offshore wind farms. Sweden, Denmark, and Finland have been actively developing wind energy projects, contributing to the region's renewable energy goals.

-Nuclear Power: Nuclear power plays a significant role in the energy mix of Sweden and Finland. Both countries have nuclear power plants that contribute to their electricity generation capacity and provide a baseload source of power.

-Thermal Power: While the focus is shifting towards renewable energy, thermal power plants, particularly those fuelled by natural gas, still have a presence in the Nordpool area. These plants provide flexibility and support during peak demand periods and when intermittent renewable sources are not sufficient.

-Biomass: Biomass is utilized as a renewable energy source in the Nordpool area, with some power plants using biomass for co-firing or dedicated biomass plants. Biomass can include organic waste, forest residues, and energy crops.

It's important to note that the distribution of generation technologies may vary between countries within the Nordpool area. Each country has its own energy policies, resource availability, and development priorities, which influence the specific mix of generation technologies they employ. Figure 1(a) indicates the Nordic electricity generation by energy source and country and (b) shows the electricity generation mix in the Nordic area in 2021.



(a)

(b)

Figure 1 Nordic electricity generation by energy source and country (a), electricity generation mix Nordic(b), 2021 [3].

In addition to the Nordpool spot markets, the Nordpool area also has frequency regulation markets that play a crucial role in maintaining grid stability. These markets are independent of each other for instance Finland has its own frequency market under the surveillance of Fingrid.

Frequency regulation markets enable the participation of various market players, including power producers, consumers, and specialized service providers, to provide frequency response services to the power system. Frequency regulation is essential to balance the supply and demand of electricity in real-time and maintain the grid frequency within the acceptable range. These markets allow participants to offer their resources or demand response capabilities to help regulate the grid frequency.

In the Nordpool area, frequency regulation markets typically operate through bilateral contracts or through market platforms where participants can submit their offers and bids for frequency regulation services. The market prices are determined based on the supply and demand dynamics of these services. [4]

The resources used for frequency regulation can include various technologies and strategies, such as:

Conventional Power Plants: Thermal power plants, including gas-fired and coal-fired plants, can provide frequency regulation services by adjusting their output to match the grid's needs.

Hydropower: Hydropower plants with fast response capabilities can quickly increase or decrease their generation to help regulate the frequency.

Energy Storage: Battery storage systems or other energy storage technologies can provide rapid response and inject or absorb electricity as needed to stabilize the grid frequency.

Demand Response: Demand response programs allow consumers to adjust their electricity consumption in response to grid signals. They can curtail or shift their electricity usage during high-frequency deviations, contributing to frequency regulation.

● *Frequency regulation market*

Frequency regulation is essential for maintaining the balance of electricity supply and demand and ensuring grid stability. The frequency regulation markets in Finland provide a mechanism for market participants to contribute to grid stability and earn revenues for their services. These markets are designed to incentivize the provision of frequency response resources, encourage the efficient use of available assets, and ensure the reliability of the power system. Figure 2 indicates the standard deviation of the frequency for every month in 2021. It is clear from mentioned controlling technologies there is still a need to control the frequency throughout the year. This shows a dynamic characteristic of the frequency market.

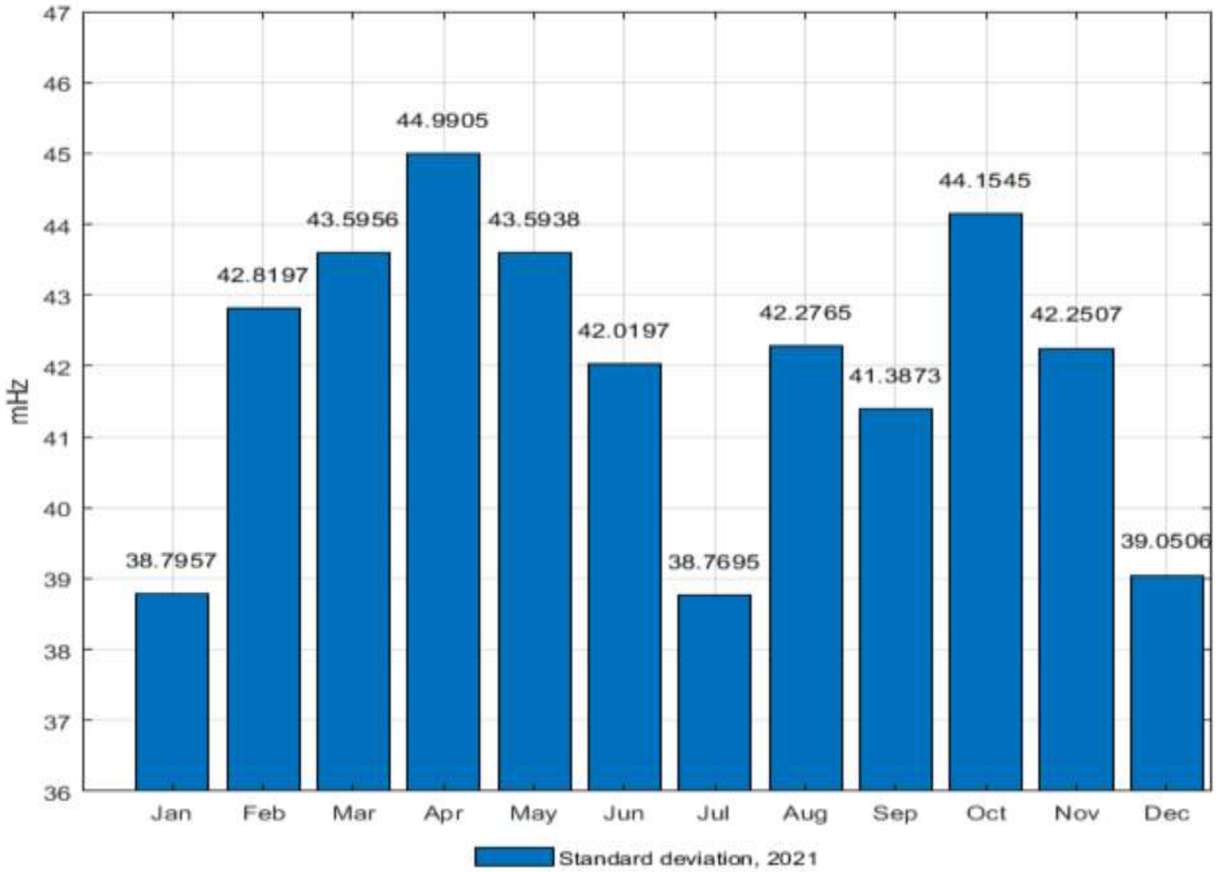


Figure 2 Standard deviation of the frequency in Finland for every month in 2021 [5].

In this context, Fingrid [6], as the national transmission system operator in Finland, plays a key role. Fingrid is responsible for monitoring and controlling the frequency of the network, which traditionally relies on hydropower plants and demand-side measures.

However, with the emergence of affordable electricity storage systems, the role of storage technologies in frequency regulation is becoming increasingly significant. These systems, such as batteries, offer a more rapid and flexible response during emergency situations. In cases of significant frequency deviations that could potentially destabilize the grid, storage systems can react swiftly and contribute to stabilizing the frequency. The power electronic devices integrated into these systems provide the necessary flexibility for effective frequency regulation.

Nevertheless, challenges exist in terms of capacity requirements. Storage systems have limited stored energy density, and technical requirements necessitate higher capacities than the participating capacity in the market. This means that investments in larger storage systems are needed, not only to meet the actual capacity needs of the network but also to comply with the standards and regulations of the corresponding markets.

● *Objectives and structure of the study*

In this study, the objective is to investigate the impact of emerging electricity storage systems and battery technologies, with a particular focus on Technology provided by Geyser Batteries [7] on the frequency regulation in Fingrid. Geyser Batteries recently developed fast-charging technology with a low carbon footprint and have been selected as the subject of analysis in this thesis. The aim is to compare its revenue potential with existing technologies such as supercapacitors and Lithium-ion batteries (LIBs), particularly in the context of the frequency regulation markets.

The study will delve into various aspects of Geyser Batteries, including their technical capabilities, economic feasibility, and operational efficiency in the frequency markets. It will examine factors such as revenue generation, cycling performance, and compatibility with grid requirements. By analyzing and comparing Geyser Batteries with existing technologies, the study aims to provide insights into their competitive advantage and potential impact on the frequency regulation market.

The research methodology will involve a combination of theoretical analysis, modeling, and empirical data collection. Through simulations and case studies, the study will evaluate the revenue potential and operational performance of Geyser Batteries in comparison to supercapacitors and LIBs.

By addressing the objectives outlined in this study, an understanding of the impact of Geyser Batteries and other emerging storage systems on the frequency market will be achieved. The findings will help the existing knowledge in the field and give insights to policymakers, energy market operators, and industry stakeholders. Ultimately, the research aims to facilitate informed decision-making and foster the integration of sustainable and efficient energy storage technologies in the frequency regulation sector.

Chapter 2 focuses on examining the frequency regulation market in Finland. It delves into the different products offered in the market, the technical requirements for participation, and the payment mechanisms. By understanding the structure and dynamics of the frequency regulation market, insights can be gained regarding the market's operations and the role of its products in grid stability.

Chapter 3 investigates the historical market volumes, prices, and trends in the frequency regulation market of Finland. By analyzing past data, patterns, and fluctuations in market volumes and prices, an understanding of the market's behavior and dynamics can be established. This chapter will provide insights into the historical performance and trends of the frequency regulation market in Finland.

Chapter 4 explores the various energy storage technologies relevant to frequency regulation. It focuses on three specific technologies: Li-ion batteries, supercapacitors, and Geyser Batteries. This chapter investigates the technical characteristics, capabilities, and potential applications of each technology, considering their suitability for frequency regulation and grid stability requirements.

Chapter 5 conducts an economic analysis of the energy storage technologies considered in Chapter 4. The analysis includes the calculation of Net Present Value (NPV) and an evaluation of the Capital Expenditures (Capex), and Operational Expenditures (Opex) associated with each technology. This economic assessment provides insights into the financial viability and cost-effectiveness of implementing energy storage solutions for frequency regulation in Finland.

Chapter 6 presents the results obtained from the investigations conducted in previous chapters and provides a comprehensive analysis of the data collected, giving insights into the performance, effectiveness, and potential implications of energy storage technologies.

Chapter 7 concludes the research project by summarizing the key findings, highlighting the significance of the research, and providing actionable recommendations. The chapter will present a holistic understanding of the frequency regulation market in Finland and the potential role of energy storage technologies in enhancing grid stability.

2 Frequency regulation market in Finland

The Nordic Transmission System Operators (TSOs), which include Fingrid in Finland, Svenska Kraftnät in Sweden, Statnett in Norway, and Energinet in Denmark, collaborate to regulate the Finnish and Nordic frequency market. They work together to manage the transmission of electricity between their countries and maintain a stable frequency in the electricity grid. This collaboration is crucial to ensure the reliability and safety of the electricity grid since the production and consumption of electricity can vary significantly and rapidly.

The achievement of good power quality and stability within a power system is a critical concern for TSOs, who must take action to limit frequency deviations. This is because larger deviations can lead to power-generating units being disconnected from the grid and push the system to instability. In the Nordic power system, the nominal frequency is set to 50 Hz, but in practice, the actual frequency varies around this value based on the balance between generation and consumption. When electricity generation surpasses consumption, the frequency rises, and when consumption exceeds generation, the frequency decreases. However, the kinetic energy or inertia of the system persists against frequency change. The Nordic power system is primarily composed of synchronous generators. The kinetic energy in the system comes from the rotational masses that are synchronously connected, such as generators and turbines. Recently, by the high penetration of renewable energies with inverters, the kinetic energy of the network is fluctuating more and puts the network at a high risk of frequency deviation.

Three main factors influence the power system frequency in general. First, power imbalance as the power difference between generation and consumption is the main reason for the frequency deviation. An impressive imbalance comes from disconnecting a large power generation unit or a huge load like industrial consumption. At the same time, the stochastic changes in generation and consumption cause smaller imbalances. The most severe single incident is referred to as the reference incident which has the highest impact on the frequency of the network. Second, as mentioned before more kinetic energy in the power system will cause a higher resistance to change in the frequency. As the frequency of a power system begins to change, the masses present in the synchronously connected machines within the system initiate the process of either absorbing or delivering electric power from the rotational energy. And finally, to ensure that the power system remains balanced, a reserve of power is maintained from power generating units, energy storage units, and consumptions. These reserves are utilized to regulate power exchange within the grid to maintain the balance in the system.

From a broader perspective, frequency control can be divided into two key processes: frequency containment and frequency restoration. The purpose of frequency containment reserves is to address imbalances and maintain system stability by responding to measured frequency deviations. These reserves play a crucial role in stabilizing the overall frequency of the system. In contrast, frequency restoration reserves are specifically designed to restore the frequency to its nominal value of 50 Hz. Once the frequency has been restored, the frequency containment reserves are released and reset to their original state, ensuring they are ready to be activated again if necessary.

- ***Different products and response times***

Within the Nordic power system, frequency control reserves are divided into three distinct subgroups as follows:

Fast Frequency Reserve (FFR): These reserves provide a rapid power response following their activation. FFR reserves are typically used in situations where there is a low level of kinetic energy within the power system and a high risk of imbalance. The FFR reserves are designed to provide a very fast stepwise power activation as soon as the frequency crosses the activation threshold. Factors such as higher volumes of renewable energy sources, the phasing out of nuclear units, and increased imports through HVDC connections can all reduce the level of inertia in the power system.

Frequency containment reserve (FCR): The primary objective of FCR is to stabilize and maintain the frequency of the power system in the event of imbalances. FCR reserves are distinguished by their swift and automatic power activation, which corresponds proportionally to frequency deviations within predefined intervals. Two types of FCR reserves exist: FCR for normal operation (FCR-N) and FCR for disturbances (FCR-D). FCR-N is employed to stabilize fluctuations that arise from regular power system operations, managing the balance between production and consumption. FCR-D, on the other hand, is used to stabilize large imbalances that may arise within the system.

Frequency restoration reserve (FRR): The primary function of FRR is to restore the frequency of the power system back to 50 Hz following a deviation, which in turn releases the activated FCR reserves, thereby restoring FCR capacity. Unlike FCR reserves, FRR reserves are not as fast, and their activation is not as immediate. FRR reserves are divided into two parts: automatic FRR (mFRR) and manual FRR (mFRR). The aFRR is designed to respond automatically to deviations in the frequency, while the mFRR can be activated manually by the system operator if the automatic FRR reserves are insufficient to restore the frequency to its nominal value. Figure 3 indicates the FCR and FFR market activation in frequency intervals. Both FCR-N and FCR-D are activated linearly.

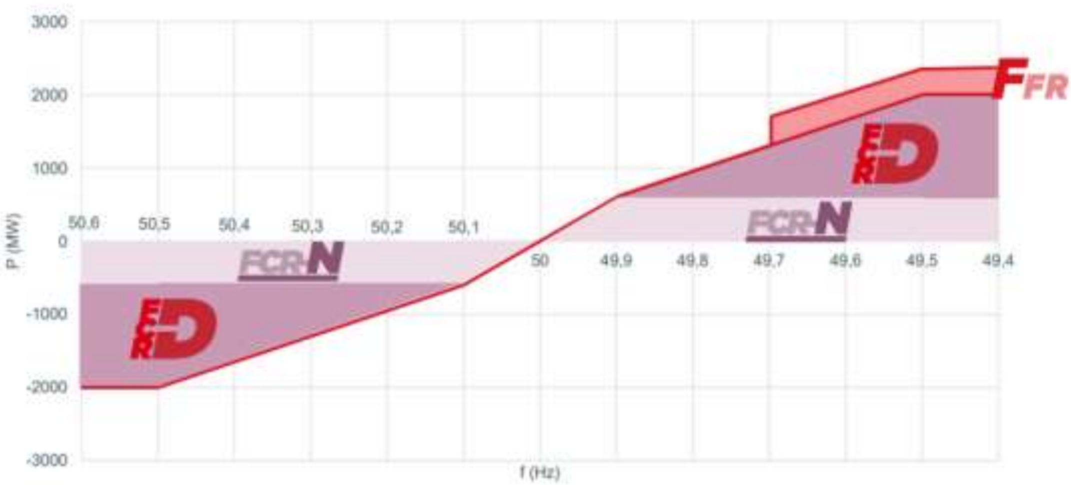


Figure 3 The FCR and FFR market activation in the frequency intervals [1].

Reserve volumes based on the reference incident for different balance markets are given in Table 1. The reserves used to maintain power system balance are categorized into various types, each serving a different purpose.

Table 1 Required reserve volumes based on the reference incident in the Nordic and Fingrid in the different markets.

Reserve Markets	Nordic	Fingrid share	Fingrid requirement
FCR-N	600 MW	19.88%	119 MW
FCR-D up-regulation	Up to 1450 MW	19.88%	Up to 288 MW
FCR-D down-regulation	Up to 1400 MW	19.88%	Up to 278 MW

These categories encompass a spectrum of frequency control reserves, ranging from highly responsive reserves that are automatically activated to slower reserves that require manual intervention for balancing purposes. Figure 4 illustrates a scenario of a frequency disturbance in the Nordic power system, showcasing the activations of various frequency control reserves. As shown in the Figure, a disturbance occurs at time t=0, resulting in a frequency deviation from the nominal value of 50 Hz. The FFR and FCR-D reserve is activated immediately after the disturbance with some seconds difference, and the FRR reserves are activated almost 30 seconds thereafter. As the frequency is restored to its nominal value of 50 Hz, the FCR reserves are deactivated, and the FRR reserves remain activated until the system has returned to a stable state. Figure 4 does not show the activation of FCR-N since a larger disturbance is illustrated[1].

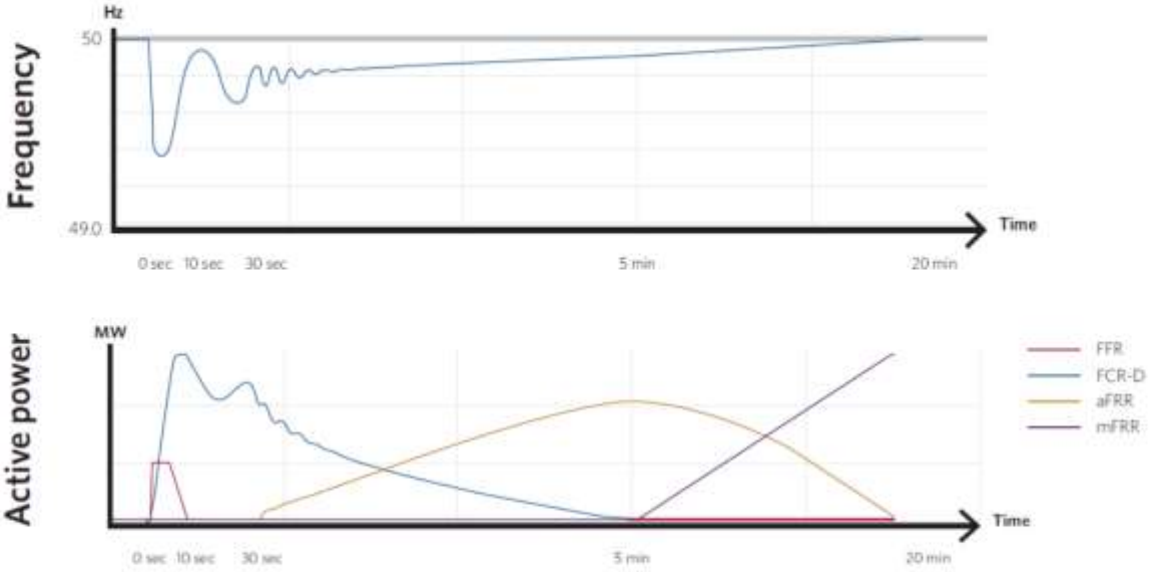


Figure 4 Different frequency control reserves' impact in the grid with a disturbance [2].

In the case of research background in these markets, Huvilinna, in his thesis [4], explored the potential of using a battery energy storage system (BESS) in ancillary service markets by Fingrid. The advantages of a BESS include immediate active power generation and accurate control, while its weaknesses include limited energy capacity, high initial investment, and limited battery lifetime. The study found that a BESS is suitable for the FCR market, but its economic viability depends on the hourly auctioned FCR-N market. The study also suggests that market regulation needs to be altered to optimize the use of a BESS. The use of BESS on the demand side has numerous benefits, including reserve market participation, emergency power, reactive power compensation, peak shaving, and load shifting. BESS is a suitable resource for a symmetrical FCR-N market due to its quick response time, bidirectional nature, and linear control. In addition to that, BESS can play a role in other frequency markets like FCR-D and FFR. However, BESS has unique characteristics and control requirements compared to demand-side loads. BESS is made up of battery cells, a power converter, transformers, and a controller.

Paavilainen [8] investigated whether demand response (DR) can be utilized as a cost-effective solution to address short-term reliability challenges by studying aggregated DR in a virtual power plant context. Specifically, it assesses the practicality of integrating relay-controlled HVAC loads into the linear FCR-N market. This is achieved through the aggregation of diverse demand-side loads. The research delves into the fundamental concepts of DR and virtual power plants, identifies crucial DR assets, and evaluates DR's potential in Finland. The case study findings reveal that combining various demand-side loads can offer a level of frequency regulation that individual resources cannot provide. Nevertheless, the absence of standardized practices and the considerable expenses involved in achieving flexibility pose challenges to fully unlocking the potential of DR services. This is particularly relevant as many of the demand-side loads utilized in DR initiatives were not initially designed with flexibility in mind. The study concludes that commercial HVAC loads, EVs, and energy storage systems are significant sources of flexibility in the future.

The integration of a 2 MW and 1 MWh LIB energy storage system, known as "Batcave," into Finnish electricity reserve markets with the assistance of hydropower was investigated in [9]. Simulation results indicated that while the battery system operated effectively for the majority of the time, hydro backup reserves were required during idling periods. NPV calculations suggested that maximizing the battery's utilization for quick cash flow is more profitable than sparing its use, and utilizing batteries in conjunction with hydropower systems, supported by subsidies, proves to be practical and beneficial for enhancing the technical and economic operation of battery storage systems in the Finnish electricity reserve markets.

Zakeri [10] explored the flexibility of energy systems in integrating variable renewable energy (VRE) sources and emphasized the importance of matching energy supply and demand. It utilized quantitative energy system modelling to assess flexibility, compare solutions, and evaluate their profitability. The study highlighted the need to improve flexibility in the Finnish energy system, identifying large-scale heat pumps and heat storage as promising options. Additionally, it recognized that the profitability of electrical energy storage depends on market compensations and externalities. The findings contributed to informing energy policies for achieving VRE integration targets and enhancing flexibility within energy systems.

2.1 FCR

As Figure 3 indicates, FCR-N is continuously activated in the grid in the frequency interval of 49.9 – 50.1 Hz, and as soon as an error occurs and causes the frequency to outlies the interval 49.9 – 50.1 Hz, FCR-D is activated and limits the frequency deviation from the nominal value. Although the technical requirements and purposes of both yearly and hourly markets are similar in the grid, there are some differences between them. The yearly market involves the procurement of reserve capacity for FCR on a long-term basis. This allows Fingrid to plan and secure the necessary reserves in advance. In the hourly market, market participants offer their reserve capacity to provide frequency containment reserves on an hourly basis. Fingrid, procures these reserves to ensure that the grid frequency is maintained within acceptable limits. The yearly bidding competitions occur in the fall, and it is not allowed to enter a yearly agreement for reserve maintenance during a contractual period. However, reserve providers can enter the hourly market by making a separate agreement with Fingrid, even in the middle of the year, without the need for a yearly agreement. Likewise, the bids from the providers who have participated in the annual reserve plans should be submitted by 6 pm (EET) on the previous day, while bids by the hourly market providers for the next 24-hour period must be submitted by 6.30 pm (EET), with the procured amounts announced at 22:45 (EET). The providers who are eligible to participate in the yearly market must maintain the reserve they sell to the yearly market within their free capacity for the next day. Additionally, they may submit daily bids for their reserve capacity. In other words, providers with yearly agreements can only participate in the hourly market if they have met the reserve amount specified in their yearly agreement [2].

- ***Technical requirements to participate in the FCR market***

The FCR reserves play a crucial role in maintaining the frequency of the power system. While individual FCR providers may not have a substantial influence on the entire grid frequency, it is crucial that the collective behavior of all FCR providers contributes to a stable feedback loop. Each FCR provider should play a role in stabilizing the system, ensuring that if the entire FCR volume was supplied by entities identical to a particular provider, the system would maintain stability with a specific margin of stability. To assess the stability requirement, sine tests are conducted, involving the combination of a nominal 50 Hz frequency signal with a sinusoidal test signal of varying periods. The objective is to ensure that the resulting power output follows a sinusoidal pattern and that the frequency response remains linear. The performance and stability criteria are established under the assumption that both the system and reserves can be analyzed using linear theory. This evaluation enables the determination of whether the FCR providers meet the necessary stability standards in their frequency response and overall performance.

The frequency domain needs are applicable when the reserve exhibits a linear response to a frequency disturbance. In the Finnish electricity system, a Balancing Service Provider (BSP) has the flexibility to measure the system frequency from a selected location. It is essential that the frequency measurement accuracy is a minimum of 10 mHz. This level of precision ensures that the BSP can effectively monitor and assess the frequency deviations in real-time, allowing for timely and accurate control actions to maintain grid stability.

In order to participate in the FCR-N or FCR-D markets, reserve resources are required to meet specific technical requirements and undergo prequalification tests. The detailed process for prequalification of a Reserve Unit can be found in Appendix 1. The responsibility for conducting the prequalification tests lies with the BSP, which ensures that the reserve resource meets the necessary criteria. Fingrid, as the system operator, is responsible for verifying the information and measurement results provided by the BSP and communicating the outcome of the prequalification process to the BSP. This collaborative effort ensures that reserve resources are properly evaluated and qualified to contribute to the FCR-N or FCR-D markets [11].

The activation of FCR-N and FCR-D reserves relies on automatic local control, with Fingrid not directly sending control signals. For a Reserve Unit to participate in reserve maintenance, it must be equipped with a controller that adjusts the power output based on frequency measurements. Table 2 provides a concise overview of the technical requirements that need to be met by the Reserve Unit. These requirements ensure that the Reserve Unit can effectively respond to frequency deviations and contribute to the stability and reliability of the power system.

Table 2 The frequency and response time conditions in the FCR market [11].

Market	Minimum size	Full activation time
FCR-N	0.1 MW	in 3 min after frequency outside 49.9 – 50.1 Hz
FCR-D up-regulation	1 MW	50% within 5s 100% within 30s gradual change between 49.5 – 49.9 Hz
FCR-D down-regulation	1 MW	50% within 5s 100% within 30s gradual change between 50.5 – 50.1 Hz

● ***Payments for standby power, and energy***

The income generated from FCR-D primarily consists of two types of payments: availability payments and activation payments. Availability payments are compensation given to FCR-D providers for being ready to offer the service whenever required, irrespective of whether they are actually utilized. On the other hand, performance payments are made when the FCR-D provider is called upon to respond and successfully deliver the required service. In case the provider not to be able to deliver the necessary capacity it will receive a sanction calculated by Formula (1) [12].

$$\begin{aligned}\text{Sanction}\ (€) = \text{reserve capacity not delivered}(\text{MW}) \times 3 \\ \times \text{FCR yearly market price}\left({}^{€}\!/_{\text{MW}}\right)\end{aligned} \tag{1}$$

It is important to highlight that the electricity grid in Finland is interconnected with the Nordic power system, allowing FCR-D providers in Finland to participate in the wider Nordic FCR market. This integration enables FCR-D providers in Finland to offer their services to other countries within the Nordic region and generate revenue beyond the domestic market. By participating in the Nordic FCR market, Finnish providers have the opportunity to contribute to grid stability and earn additional income by supplying FCR-D services to neighboring countries.

Yearly market: In the yearly market, the price for reserve power capacity remains constant throughout the year. All participants in the market are compensated equally for maintaining their reserve power capacity. The auction for the yearly market takes place once a year, typically in the autumn of the preceding year. This provides participants with a long-term commitment and stability in terms of pricing and compensation for their reserve power capacity.

Hourly Market: The hourly market serves as a means for additional procurement when the bids from the annual market are insufficient to meet the demand. Bids submitted to the hourly market are processed based on price orders. Fingrid, the system operator, confirms the transactions for the following day on the previous evening, with the results being published at 22:45 (EET). This timing is also applicable for publishing the procured volume from the yearly bids.

In the hourly market, the pricing method employed is marginal pricing, which means that the price is determined separately for each hour. This allows for a dynamic pricing mechanism where the price reflects the supply and demand conditions specific to each hour. By utilizing marginal pricing, the market can efficiently allocate the available reserve power capacity based on the prevailing conditions at different times of the day.

In addition to the mentioned markets, Fingrid can procure some capacity from the neighboring countries. The procured amount is also published at the same time. Positive numbers mean the import of capacity to Finland and negative numbers mean the export of capacity from Finland.

Traded energy: In addition to the hourly and yearly markets that are based on the stand-by capacity and will be paid based on the procurement, the providers also will receive income for their traded energy based on the prices in the mFRR market. Since the prices in this market can be negative or positive, the providers would receive incomes or expenditures from energy trading, though in the majority, the prices are positive.

2.1.1 FCR-D

The primary objective of FCR-D is to manage and stabilize the grid frequency during disturbances. This reserve category comprises two separate products: up-regulation and down-regulation. The up-regulation product is designed to address under-frequency disturbances caused by factors such as loss of production or HVDC import from another synchronized area. On the other hand, the down-regulation product is aimed at managing over-frequency disturbances resulting from events like loss of consumption or HVDC export to another synchronized area.

The activation of FCR-D reserves depends on the frequency deviation. The up-regulation product is activated when the frequency falls within the range of 49.5 – 49.9 Hz, while the down-regulation product is activated within the range of 50.1 – 50.5 Hz. The activation of FCR-D reserves is linear within these frequency bands, meaning that the reserve power is proportionally adjusted based on the severity of the frequency deviation.

There are specific requirements for the activation speed of FCR-D reserves. At least 50% of the reserve capacity must be activated within 5 seconds of the disturbance, ensuring a rapid response to frequency deviations. The remaining 50% of the reserve capacity should be activated within 30 seconds, providing a complete utilization of the available reserve power. These activation timeframes are crucial for maintaining the stability and integrity of the grid during disturbances, allowing for prompt frequency containment and restoration. Table 2 provides a summary of the technical requirements and activation parameters associated with FCR-D reserves, ensuring efficient and reliable frequency control during disturbances.

The FCR-D is divided into two products:

- FCR-D up: up-regulation product (power plants boost generation, loads decrease consumption, the battery is discharged)
- FCR-D down: down-regulation product (power plants reduce generation, loads enhance consumption, the battery is charged)

FCR-D up and FCR-D down have their own markets. The activation of reserve capacity for the FCR-D up is triggered when the system frequency drops below 49.9 Hz. If the frequency falls to 49.5 Hz or lower, then the entire reserve capacity must be activated. However, if the frequency is between 49.5 and 49.9 Hz, then according to Figure 3, the amount of activated capacity must be proportional to the deviation in frequency. Likewise, the activation of reserve capacity for the FCR-D down is triggered when the system frequency rises above 50.1 Hz. If the frequency reaches 50.5 Hz or higher, then the entire reserve capacity must be activated.

Required power capacities for a Reserve Unit in both up and down regulations are the same as the participation capacity in the market. This capacity must endure in the grid for 20 minutes. The unit needs to have the ability to activate the reserve capacity completely within 15 minutes after the previous activation [13].

2.1.2 FCR-N

In Finland, the FCR-N revenue is a payment mechanism designed to compensate providers for their ability to uphold frequency stability in the regular operation of the electricity grid. FCR-N suppliers are obligated to adjust their power generation to align with the grid frequency and sustain it at 50 Hz within an ongoing market. Compared to FCR-D, which compensates suppliers for reacting to grid disruptions, FCR-N suppliers are compensated for ensuring the stability of the grid frequency during normal operational conditions. These services are often provided by adaptable resources such as energy storage systems, demand response, and renewable energy generators. FCR-N revenue in Finland is determined by availability and performance payments, like FCR-D. FCR-N providers get paid for being available to provide the service when needed, and they also get paid when they adjust their production and maintain frequency stability successfully based on the energy that they inject into or absorb from the grid. The required power capacity for a Reserve Unit is 1.34 times of the obligatory participation capacity in the market. This capacity must be able to endure for 30 minutes in the grid in both directions [13].

For an energy storage facility participating in FCR-N (Frequency Control Reserve - Normal), the power flow to or from the grid is controlled based on the grid frequency in accordance with reserve operation requirements. This control mechanism applies to the power and energy capacity of the energy storage facility that has been specifically reserved for FCR-N purposes. However, when the power and energy capacity of the energy storage facility is not reserved for FCR-N, there are no limitations on its usage. When an energy storage facility approaches its maximum or minimum charge level, it temporarily suspends the activation of reserve capacity until there is a change in the frequency deviation direction and the corresponding activation requirement. This means that the facility will not provide or absorb power for reserve purposes until the grid frequency deviation changes direction, ensuring that the reserve resources are utilized efficiently and effectively. The activation and control of reserve capacity in an energy storage facility participating in FCR-N are closely tied to the frequency response of the grid. By adjusting the power flow based on frequency deviations, the energy storage facility contributes to maintaining a stable grid frequency within the prescribed range, thereby supporting the overall reliability and stability of the power system [11].

The activated FCR-N volume is published on an hourly basis, one hour after the respective hour has passed. For example, the value for the hour from 07:00 to 08:00 is published at 9 o'clock. The activated FCR-N volume is expressed in MWh and is determined based on the frequency measurements in the Nordic synchronous system. The published value represents the net energy that has been activated as part of the FCR-N reserve. A positive value indicates that the average frequency during the hour was below 50.0 Hz, and the reserve was activated as up-regulation to support the grid. Conversely, a negative value indicates that the average frequency during the hour was above 50.0 Hz, and the reserve was activated as down-regulation to help stabilize the frequency.

The publication of the activated FCR-N volume provides valuable information about the balancing actions taken to maintain grid frequency within the desired range. It allows market participants and stakeholders to monitor and assess the performance and effectiveness of the FCR-N reserve in responding to frequency deviations and supporting the stability of the power system.

Figure 5, based on Fingrid open-source data [14], indicates that a storage system in the FCR-N market would get its maximum and minimum allowed charged levels several times in a year. The figure approves that the grid’s frequency was over 50 Hz, which shows the grid’s tendency was to donate energy to a storage system. Figure 6 also shows a storage system’s traded energy considering standing by status when it receives the maximum/minimum allowed levels while the grid is over-frequency/under-frequency. The figure shows the energy level of the storage system for the hours between 1000 and 2000 of 2022 as a sample period. In both cases, the capacity of the storage system has been considered as 1 MW.

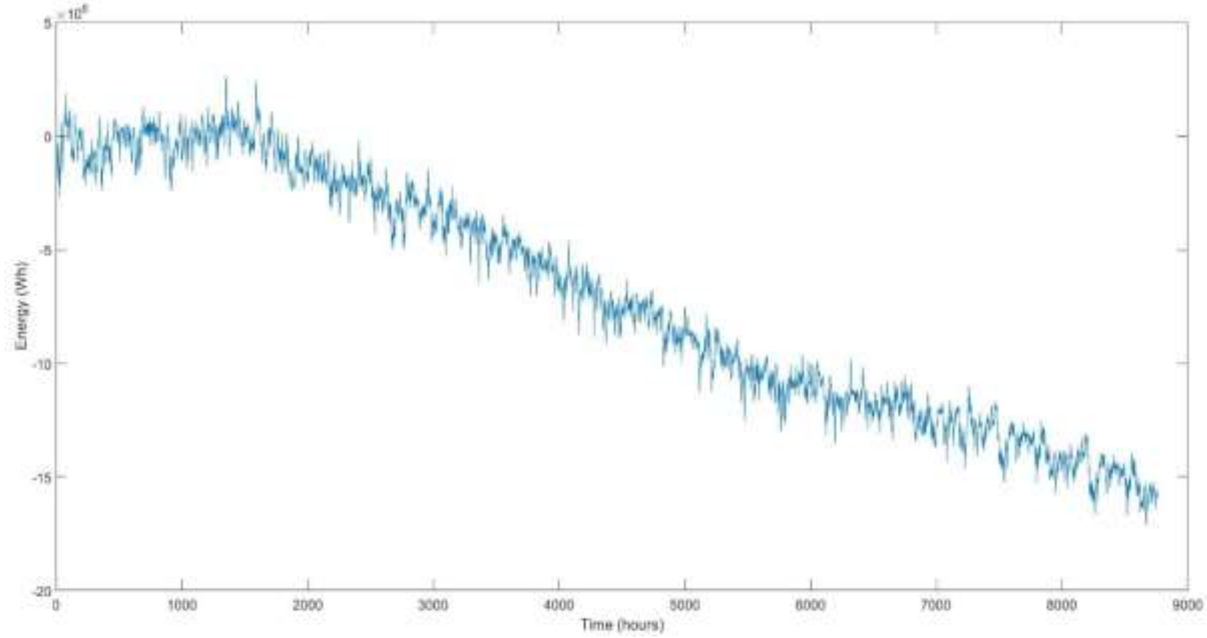


Figure 5 The actual energy needed for the FCR-N market in 2022 to inject into the grid in order to keep the frequency at 49.9 – 50.1 Hz (based on the data in [14]).

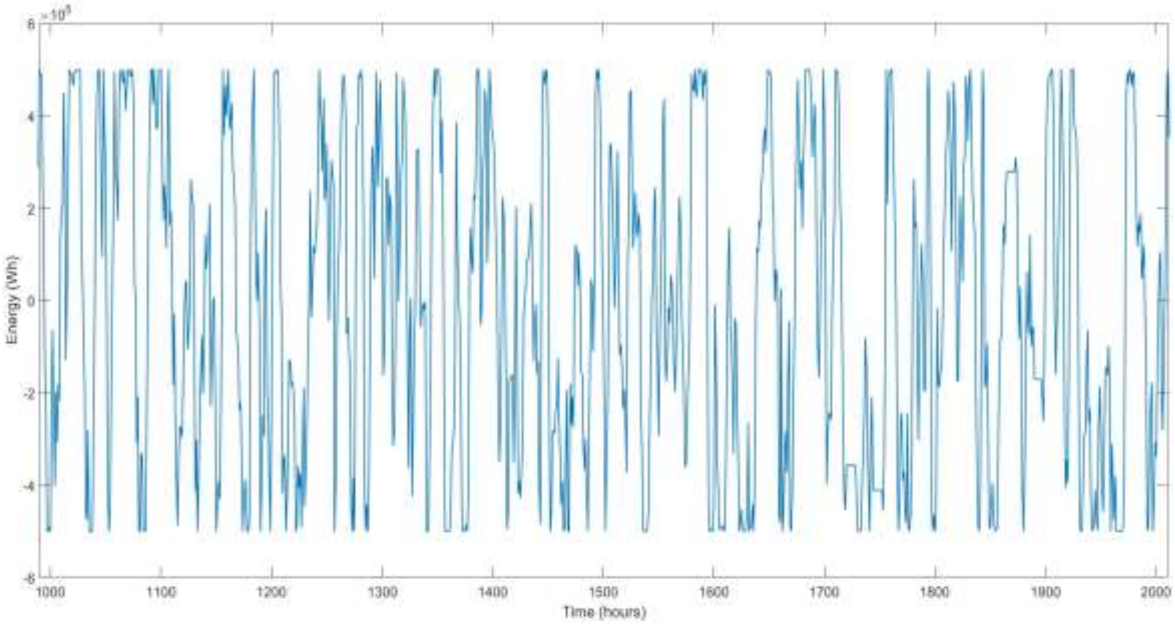


Figure 6 The traded energy of a storage system considering standing by status when it receives the maximum/minimum allowed levels.

2.2 FFR

The FFR acts as a safeguard against a drop in the frequency of the power system below 49.0 Hz, which can occur due to the failure of a single electricity production unit or an (HVDC) link [15]. The FFR is considered specifically to address situations where the power system experiences low inertia. The level of inertia in a power system is closely linked to the rate of change of frequency. If there is insufficient inertia, the frequency may drop too quickly, and the system may reach the point of load shedding before the reserves can respond adequately.

- ***Technical requirements***

In order to participate in the FFR market, reserve units must meet the technical requirements set for the reserve. To demonstrate compliance with these requirements, prequalification tests must be carried out before market participation. Appendix 5 contains information on the prequalification testing sequences and methods for the provision of the FFR units.

To ensure the availability and effectiveness of the FFR-D, the activation of an FFR unit is dependent on automatic local control. In order to participate in the maintenance of the reserve, Reserve Units are required to have a controller that can adjust power output based on frequency measurements. The purpose of the control mechanism is to align the power output of the FFR unit with the measured frequency, enabling it to respond to deviations and disturbances in a timely manner. By adjusting the power output based on the frequency measurement, the FFR unit can actively contribute to the stabilization of the power system frequency. Having a controller that responds to frequency measurements ensures that the reserve is ready for activation when a disturbance occurs. It helps maintain the stability and reliability of the power system by effectively managing frequency deviations and preventing any adverse impacts that may arise from frequency fluctuations.

By employing automatic local control and utilizing frequency measurements, the FFR units play a crucial role in supporting grid stability and ensuring the secure operation of the power system during disturbances. There are two choices for the minimum duration of support provided by the FFR, which depend on how quickly the Reserve Unit can be deactivated or return to a state when reserve capacity is not being used. Activation refers to the process of turning on reserve power in full when the frequency drops below a threshold. The BSP has the flexibility to choose the activation options listed in Table 3.

Table 3 Alternative activation modes for FFR providers.

Activation Frequency (Hz)	Max. Activation time (sec)
49.7	1.3
49.6	1.0
49.5	0.7

● ***Payments for standby, power, and energy***

The procurement of FFR is driven by the inertia of the power system, which means that it is not required for every hour, and the volume to be procured can vary. Fingrid provides a forecast for FFR procurement one week in advance, enabling market participants to plan their bidding strategies. The procurement of FFR takes place through a national hourly market. Participants submit their bids for the hours of the next day on the previous evening. Fingrid determines the price of the reserve capacity for each hour based on the principle of marginal pricing. This means that the price is set according to the most expensive accepted bid among the participants. This process is predictable, as Fingrid forecasts its FFR need considering factors such as wind and sunlight intensity, temperature, grid topology, and other variables that impact network inertia. Consequently, the eligible providers participate in the bidding and based on their price, are procured.

To participate in the FFR market, there are certain requirements for the bid submission. It must contain information such as the type of bid (production, consumption, or aggregated), capacity in MW (with a minimum of 1 MW and a maximum of 10 MW), availability price in €/MW, and the hour in the EET time zone. The bids must be accurate to 0.1 MW and a BSP can submit several bids if needed.

Fingrid checks the bids by price and gives precedence to the minimum price bid (€/MW) for each delivery period. A necessary quantity of bids will be utilized in order of price. Bids with the same prices are used in the order of their submission. Each bid is processed separately. Fingrid confirms transactions for the following day by 22:00 (EET).

Fingrid is required to pay a Capacity Fee to the BSP for its role in maintaining the FFR. However, if the BSP fails to deliver the capacity as promised, they must pay Fingrid the full price of the hour on the FFR Market.

Furthermore, Appendix 6 contains critical information on a sample contract and presents a complete contract for FFR. Appendix 7 lists all companies eligible to participate in the reserve market in Finland, with only six companies meeting the qualification requirements to take part in the FFR market.

2.3 FFR + FCR-D up-regulation

The BSP has the option to submit a combination bid that includes both FCR-D up-regulation and FFR capacities. This allows for flexible bidding of reserve capacity that suits for both products. The activation thresholds and frequency ranges for these reserves are outlined in Figures 1 and 2.

The capacity included in the combination bid can be utilized for either FFR or FCR-D up, depending on the system's needs. Furthermore, reserve capacity that is already participating in the yearly market of FCR-D up can also be offered to the FFR market, providing additional flexibility for market participants.

When trading a combination bid of FFR and FCR-D up on the market, FFR takes priority and is traded first. If the combined bid is utilized on the FFR market, it will not be used on the FCR-D up hourly market. However, if the combination bid is not used in the FFR market, it can be transferred to the FCR-D up hourly market for potential activation.

In the case of a combination bid used on the FFR market, Fingrid will remove the portion of the capacity used from the BSP's reserve plan, ensuring that the reserve capacity is appropriately accounted for and managed.

This approach allows for efficient utilization of reserve capacity by considering the specific needs of both FFR and FCR-D Up markets while providing flexibility for market participants to optimize their bidding strategies and ensure effective utilization of their reserve resources. To clarify, one Reserve Unit can support both the FCR-D up-regulation and the FFR at the same time. But the Reserve Unit's capacity can be utilized only for one reserve market at a time. For instance, if part of the capacity is used for FFR, then less capacity is available for FCR-D.

To meet the technical requirements of the FCR-D, the reserve capacity must activate within a certain time frame, demonstrated in Table 2, when the frequency drops. A portion of the prequalified reserve capacity that activates in a gradually increasing manner can also be used for the FFR. Appendix 3 outlines the capacity calculation for a reserve unit that provides both

FFR and FCR-D up, but some differences in capacity may arise due to time and power limitations [16].

To submit a combination bid for FFR and FCR-D, the BSP must provide the following information in addition to the requirements for an FFR bid:

- The type of combination bid: FFR + FCR-D hourly market or FFR + FCR-D annual reserve Plan
- The FCR-D control method: linear, piecewise linear, or a relay-connected reserve activating in a single step
- Separate prices of availability for FFR and FCR-D (€/MW,h) must be specified.

3 Historical market volumes, prices, and trends

3.1 FCR

Figure 6 indicates the FCR market prices and the volumes from recent years. The volume represents the highest capacity available for reserve provision in the annual market. Figure 7 indicates the price trends over the years in the FCR market from 2011 to 2023. There is a decline in the prices from 2017 upward except for 2023. It would be the influence of Russia's invasion of Ukraine which caused energy problems in the Europe area in 2022. The FCR-N volumes show a relatively consistent trend over the years, ranging from 55 MW to 105.8 MW. FCR-N prices exhibit some fluctuations but generally stay within the range of 12.24 €/MW to 19.10 €/MW. FCR-D up volumes vary between 244.3 MW and 458.3 MW. However, despite a significant increase in provided capacity in the FCR-N down market, the yearly price is the same for 2022 and 2023.

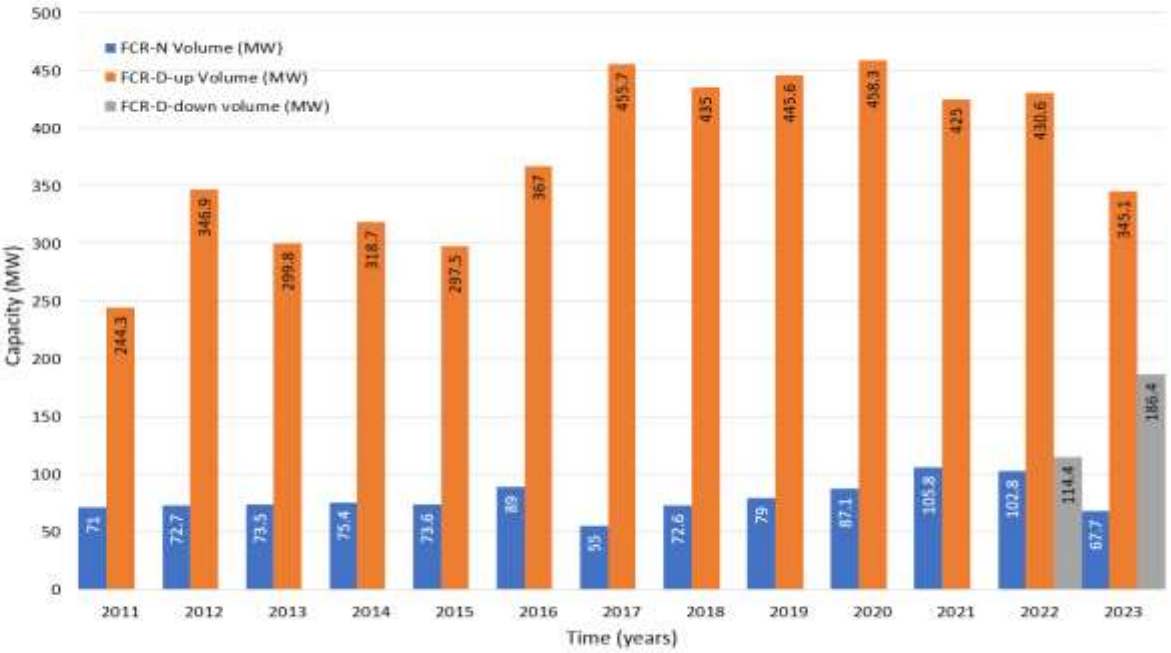


Figure 6 The volumes provided for the FCR yearly market from 2011 to 2023 [17].

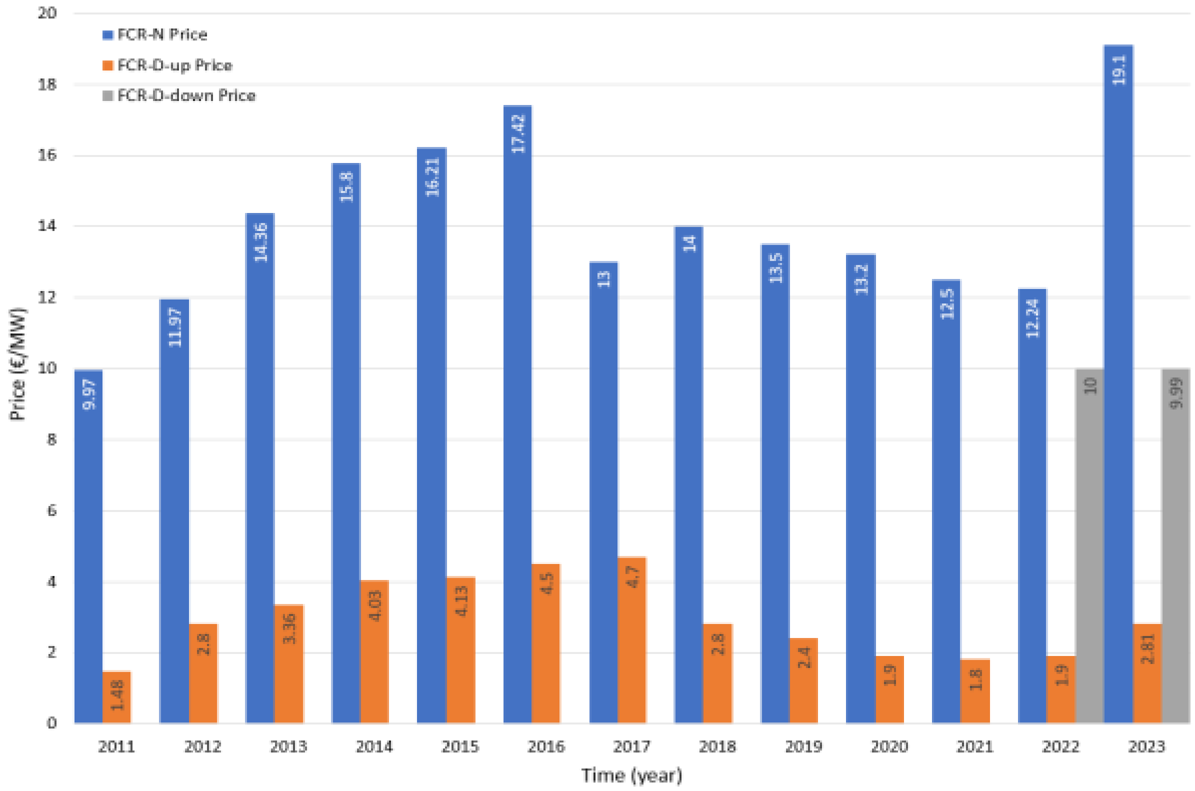


Figure 7 FCR market annual prices over the years 2011 to 2023 [17].

3.1.1 FCR-D

Figure 8 shows the yearly offered and procured percentages for the FCR-D market for the year 2021. A rather low tendency of the electricity storage sector to participate in the FCR-D market is clear in the charts. But in the hourly market, the share of the procured energy from the electricity storage sector is twice the share of the offered energy in that sector. Figure 9 also indicates dramatic growth in electricity storage participation in the hourly market for the year 2022. These also describe the acceptance of electricity storage in the FCR-D market that mostly could be related to the price competitiveness of the storage which can be sold before the other resources.

(a) (b) (c)

Figure 8 FCR-D market in 2021 based on the type of division for a) the yearly market plans (%), b) offered for the hourly market (%), and c) procured from the hourly market (%) [18].

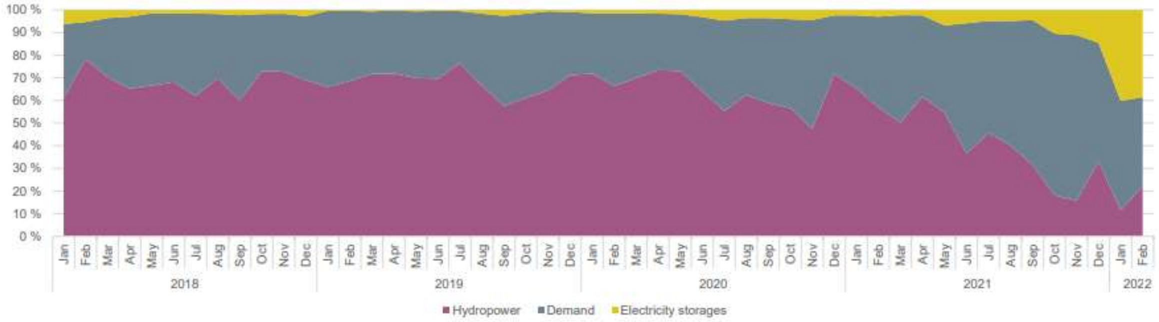
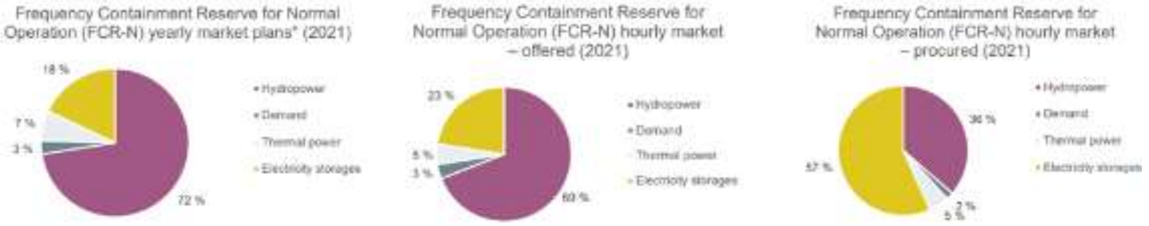


Figure 9 FCR-D in the hourly market based on the provider’s type percentage [18].

According to the technical requirements for FCR-D, reserve providers must have the ability to activate the reserve at full capacity throughout the entire delivery period. However, for units with limited activation capacity, such as battery storage systems or EVs, there is a specific dimensioning requirement. These units must be designed and sized in a way that enables them to sustain continuous full activation for a minimum duration of 20 minutes. This requirement ensures that reserve providers can effectively contribute to maintaining grid stability during disturbances by providing sustained reserve power when needed. Units with limited activation capacity, such as battery storage systems or EVs, are expected to be able to deliver their maximum reserve capacity for an extended period to support grid frequency stabilization.

3.1.2 FCR-N

Figure 10 shows the yearly offered and procured percentages for the FCR-N market for the year 2021. Based on Figure 10 (a), 72% of the yearly market is under the dominance of hydropower and 18% of this market includes electricity storage. However, in the hourly market, 23% of the offered power comes from electricity storage and 69% comes from hydropower, while in procurement, 57% of the whole hourly market is procured from the electricity storage section and only 36% of which is procured from hydropower section. This shows the acceptance of electricity storage in the FCR-N market that could mostly be related to the price competitiveness of the storage, which can be sold before the other resources.



(a) (b) (c)

Figure 10 FCR-N market in 2021 based on the type of division for a) the yearly market plans (%), b) offered for the hourly market (%), and c) procured from the hourly market (%) [18].

3.2 FFR

As it is indicated in Figure 11, the lowest levels of kinetic energy are observed during summer nights when wind production is high and electricity consumption is low. The power system is fundamentally designed to operate with a principle that ensures even in the event of a single electricity production unit or an HVDC link failure, the frequency does not fall below 49.0 Hz. The magnitude of frequency change following a disturbance is influenced by various factors, such as the power change that caused the disturbance, the system's inertia, and the speed at which reserves are activated. The amount of FFR needed varies based on the level of inertia in the power system and the magnitude of the disturbance. Table 4 provides details on the disturbance events that occurred in the Fingrid area in 2021 and their impact on the frequency and inertia of the entire network [5].

In May 2020, the FFR was introduced in the Nordic electricity market. For the year 2022, Fingrid had a 106.5 MW FFR. Figure 12 depicts the percentage of storage and demand side participation shares in Fingrid via a pie chart.

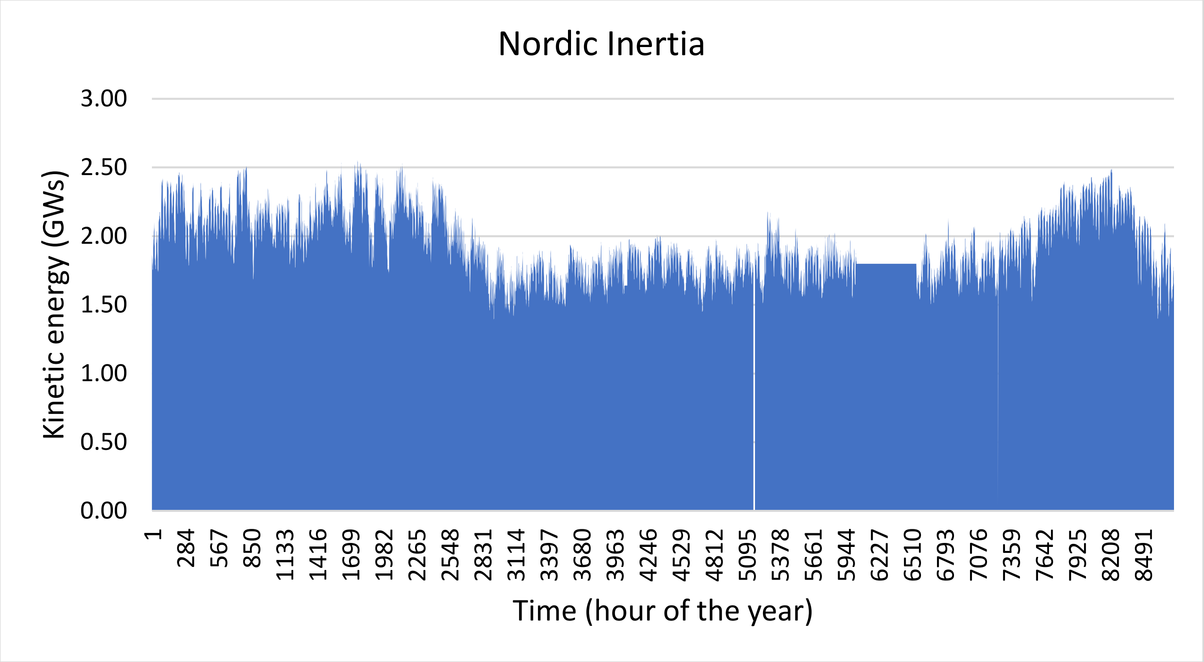


Figure 11 Nordic Inertia over 2022, The lowest levels of kinetic energy are observed during summer nights when wind production is high [19].

Table 4 Disturbance events in 2021 and the impacts on the frequency, power, and kinetic energy of the network [5].

Date	Δf (Hz)	ΔP (MW)	Δt (s)	E_k (GWs)	Reason
07-Feb-2021 08:55:13	-0.368	1399	8.6	210	HVDC
07-Jun-2021 16:24:01	-0.300	539	9.0	174	Other
19-Jun-2021 11:16:19	-0.325	809	10.7	182	Nuclear
30-Jun-2021 18:41:12	-0.376	683	8.2	188	HVDC
04-Jul-2021 09:13:45	-0.416	1250	7.1	174	Other
04-Jul-2021 14:49:31	-0.298	850	9.6	173	Other
17-Jul-2021 16:13:39	-0.311	639	6.2	135	HVDC
02-Sep-2021 13:04:14	-0.444	1234	6.2	165	HVDC
16-Oct-2021 22:27:22	-0.322	695	8.3	184	HVDC
29-Dec-2021 19:14:21	-0.333	1168	7.4	240	Nuclear

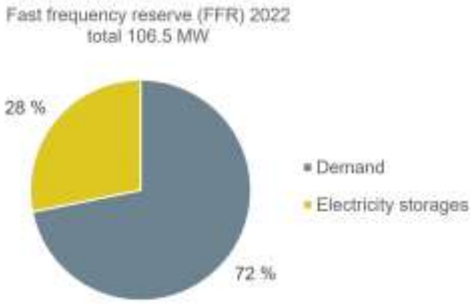


Figure 12 Electricity storage and Demand response shares in FFR capacity in Finland [18].

Figure 13 indicates five different curves in a single graph for the time interval between 25.5.2022 00:00 and 27.5.2022 23:59. Actually, from 25.5.2022 23:00 to 27.5.2022 8:00 is the longest period for having FFR units procured within the whole of 2022 and January 2023. Each FFR unit must be able to sense the frequency drop and then based on the conditions introduced in Table 2, Appendix 2, connect to the grid to help limit the frequency deviation. In 2021 the cases that the grid needed to have the FFR units are listed in Table 5. However, the procurement is done many times during a year. In other words, procurement is done to increase the security of the system against probable faults in the system, which can be more harmful when the inertia of the system is rather low. And the activation happens only in error times in the grid.

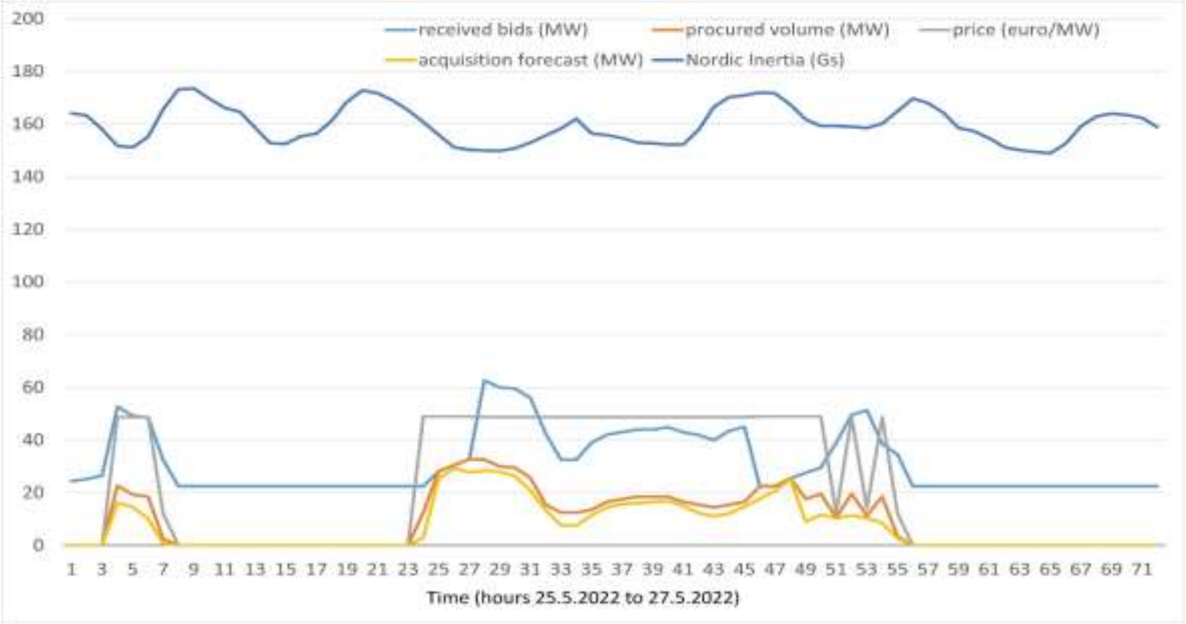


Figure 13 Received bids (MW), Procured volume (MW), Price (€/MW), Acquisition forecast (MW), and Network inertia (GWs) for the period 25.5.2022 to 27.5.2022 [20].

The FFR market has a good potential for income for the providers. Having a unit satisfied by tough standards for FFR like starting in 0.7 seconds or reactivation time of 15 minutes and some other conditions introduced elaborately in Appendix 2, has caused only some limited companies to be qualified for this market. Figure 14 shows the bidding price levels for this market from 1.1.2022 to 31.1.2023. There are just three major pricing levels for only six qualified companies listed in Appendix 7.

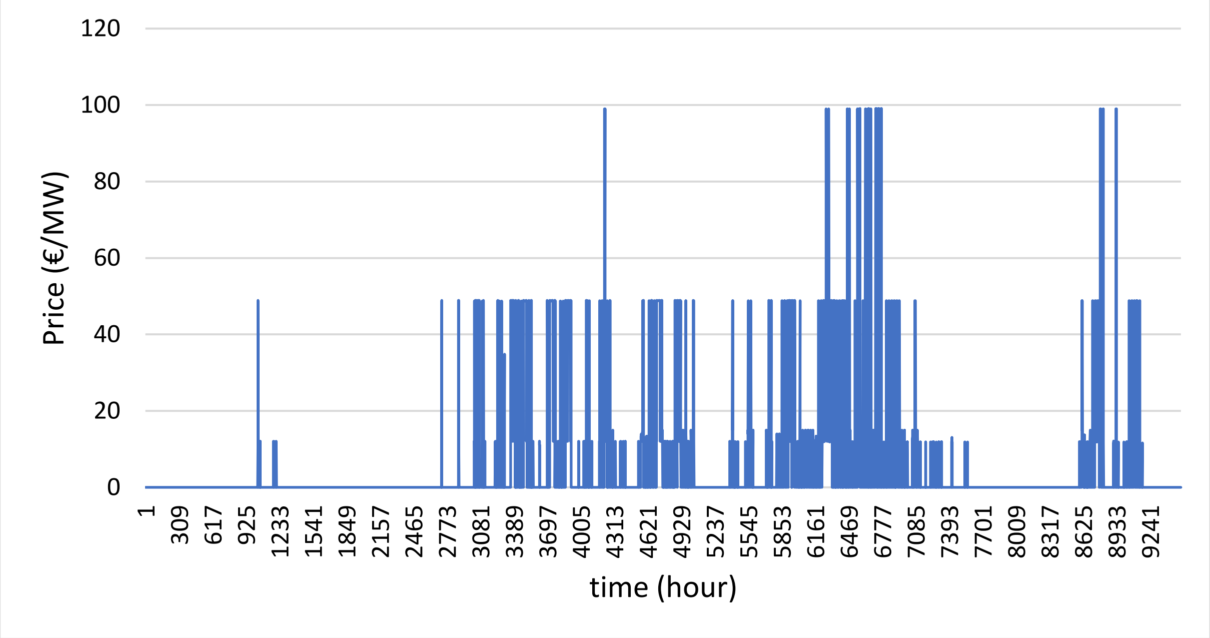


Figure 14 FFR procured prices for 2022 and January of 2023 [21].

4 Relevant energy storage technologies

4.1 Review of electricity storage technologies

Energy storage systems can be classified into various types based on their power capacity and the duration for which they are required to store energy. These storage systems include seasonal, weekly, daily, or hourly storage systems. Each type of storage system has unique requirements and is designed to cater to specific demands. Various energy storage technologies are accessible, encompassing electrochemical, electrical, mechanical, thermal, and chemical storage systems. Electrochemical storage systems include conventional batteries and flow batteries, which are used for stationary applications like grid-level energy storage. Electrical storage systems, such as supercapacitors, are used to provide short-term energy storage solutions. Mechanical storage systems, such as flywheels for short-term, compressed air storages, and pumped hydro storages for both short and medium-term, are used for energy storage. Finally, chemical storage systems, such as hydrogen and synthetic fuels, are used for large-scale energy storage and can be used for a variety of applications, including transportation. Understanding the different types of energy storage technologies and their applications is essential for building a sustainable and reliable energy system. [22][23][24]

The advantages and disadvantages of thermal energy storage, flow batteries, Lithium-ion batteries, Sodium-Sulfur batteries, compressed air energy storage, and pumped hydro storage as viable options for large-scale energy storage are examined in [25]. Metal air batteries are found to have high theoretical energy density. Limited cycle life, slow discharge rate, and even safety concerns are just some reasons to hinder the massive usage of metal-air batteries. Paper [25] also provides a mathematical model for thermal energy storage as a battery and suggests that a comprehensive techno-economic evaluation of energy storage technologies is needed for developing an energy storage technology roadmap. Blanco et al. at [26] discussed various options for managing variability and power surplus in renewable energy systems. Power to Gas (P2G) is seen as an option to deal with power surplus rather than a technology to satisfy current gas demand sustainably. They also discuss the need for efficiency in storage technology, explore various options for energy storage, and highlight areas that remain to be explored in P2G. Even though the production of some energy storage technologies has increased, making them more affordable, many of these technologies are still costly because they are new, require expensive raw materials, and have limited large-scale production. Moreover, there is no one ideal energy storage technology at present that can satisfy all the requirements for optimal grid integration [27].

Cycle life refers to the number of times a battery can be charged and discharged under specific conditions before it reaches the end of its life, usually at 70 - 80% of its initial capacity. However, there is no universally accepted standard for measuring BESS performance. For instance, [28] suggests a cycle life of 3000 cycles at 80% Depth of Discharge (DoD) for LIBs, while [29] reports a cycle life of 1,500 to 4,500 cycles. In contrast, [22] and [23] show a life cycle ranging from 1,000 to 10,000 cycles. Given this variation, it is crucial to carefully design the control strategy for an LIB.

● *BESS cost structure*

A breakdown of the cost structure for an energy storage system, including key components and associated expenses is given in Table 5,

Table 5 Breakdown of the cost structure for an energy storage system [30], [31].

Cost area	**Description**
Cells	The cost of battery cells constitutes a significant portion of the overall system cost. This includes the purchase of Li-ion cells or other types of battery chemistries required for the energy storage system.
Modules	Battery modules are assembled groups of cells that provide the desired voltage and capacity. The cost of modules includes the manufacturing or procurement of module components, assembly, and testing.
Battery Management System (BMS)	The BMS monitors and controls the operation of the energy storage system, ensuring optimal performance, safety, and longevity of the batteries. It includes hardware and software components and incurs costs for development, integration, and testing.
Power Electronics	This component includes inverters, converters, and other power conditioning equipment necessary to interface the energy storage system with the electrical grid or the application it serves. Power electronics costs depend on the power rating, efficiency, and specific requirements of the system.
Housing / Enclosure	The housing or enclosure provides protection and environmental control for the energy storage system. The cost can vary based on the size, materials used, and any additional features such as thermal management or safety measures.

Land Use	The cost of land or site acquisition is relevant for large-scale energy storage systems that require dedicated space for installation. This cost can change significantly depending on the location, accessibility, and local regulations.
Installation and Labour	Expenses associated with the installation of the energy storage system, including labor costs for assembly, wiring, and integration with the electrical system.
Balance of System (BoS)	The BoS costs include various components such as cabling, electrical connections, safety systems, monitoring equipment, and any required infrastructure to ensure the reliable and safe operation of the energy storage system.
Controls and Monitoring	Costs associated to the implementation of control systems, monitoring software, and communication interfaces for remote monitoring, operation, and maintenance of the energy storage system.
Permitting and Regulatory Compliance	Expenses associated with obtaining permits, certifications, and complying with relevant regulations and standards for the installation and operation of the energy storage system

4.2 Lithium-ion batteries

The most popular battery technology for high energy density and efficiency is currently Lithium based batteries. LIBs are the most promising and well-established technology. They have several advantages, such as small size, low weight, and less than 1% self-discharge rate per month. LIBs offer high energy density, with storage efficiency reaching 90% or more. Nevertheless, LIBs do have certain limitations, including high manufacturing costs attributed to special packaging and the requirement for internal protection circuits. Additionally, their lifetime is affected by deep discharges and the surrounding temperature [24][28]. LIB continue to be the primary candidate for energy storage systems on a large scale in the future. While LIBs may not be a cost-effective solution for seasonal storage, recent advancements in their development have resulted in increased power ratings, improved efficiency, longer lifetimes, and decreased costs [24]. To optimize the performance and lifespan of a frequency regulation system based on LIB, two crucial control attributes must be considered: State-of-Charge (SoC) and Depth-of-Discharge (DoD). In reserve markets, BESS charges or discharges based on the grid frequency. In scenarios where the battery is already fully charged and the frequency exceeds the nominal level, it is unable to receive additional charge to assist the grid. Likewise, if the battery is completely discharged and the frequency falls below the nominal level, it cannot discharge further. In such situations, the battery remains inactive until there is a change in the frequency direction. The SoC is to indicate the battery's charge level, and in order to preserve the battery's lifespan, upper and lower limits for the SoC need to be established [32]. In order to avoid the idle state of the batteries, the other strategy can be considered. If the charge and discharge speed of the battery is high, it can sell or buy its needed energy in a short time and come back to participate in the frequency market.

LIB consists of electrode materials, a separator, an electrolyte, and current collectors. The choice of electrode materials, such as lithium cobalt oxide, lithium nickel manganese cobalt oxide, lithium iron phosphate (as cathode), and graphite and silicon (as anode), significantly impacts the battery's electrochemical properties and performance. The charging and discharging processes involve the movement of lithium ions between the electrodes through the electrolyte, with the energy density, specific energy, power density, and specific power determining the battery's energy storage capacity and power capacity. Factors like cycle life and calendar life affect the longevity and usage patterns of LIB.

The cost of LIBs remains a matter of importance. Raw materials, such as lithium, cobalt, nickel, and graphite, play a pivotal role in the cost structure. Improvements in material efficiency, recycling practices, and the development of sustainable supply chains are instrumental in reducing costs. Electrode manufacturing, cell assembly, quality control, and testing also contribute to the overall production costs. Efficient manufacturing processes, including economies of scale, advanced coating techniques, and automation, contribute to cost optimization and increased production capacity. Ongoing research and technological advancements aim to enhance manufacturing efficiency and drive down costs, making LIBs more economically viable.

The market demand for LIBs continues to grow rapidly. EVs represent a significant driver, with increasing adoption due to favorable government policies, declining battery costs, and improved charging infrastructure. Renewable energy integration and grid-scale energy storage applications also contribute to the rising demand for LIBs. Figure 15 shows the LIB demand growth projections by the end of the decade. As the market expands, economies of scale, innovations in battery chemistry, and increased production capacities are expected to further reduce costs, making LIBs more accessible across industries.

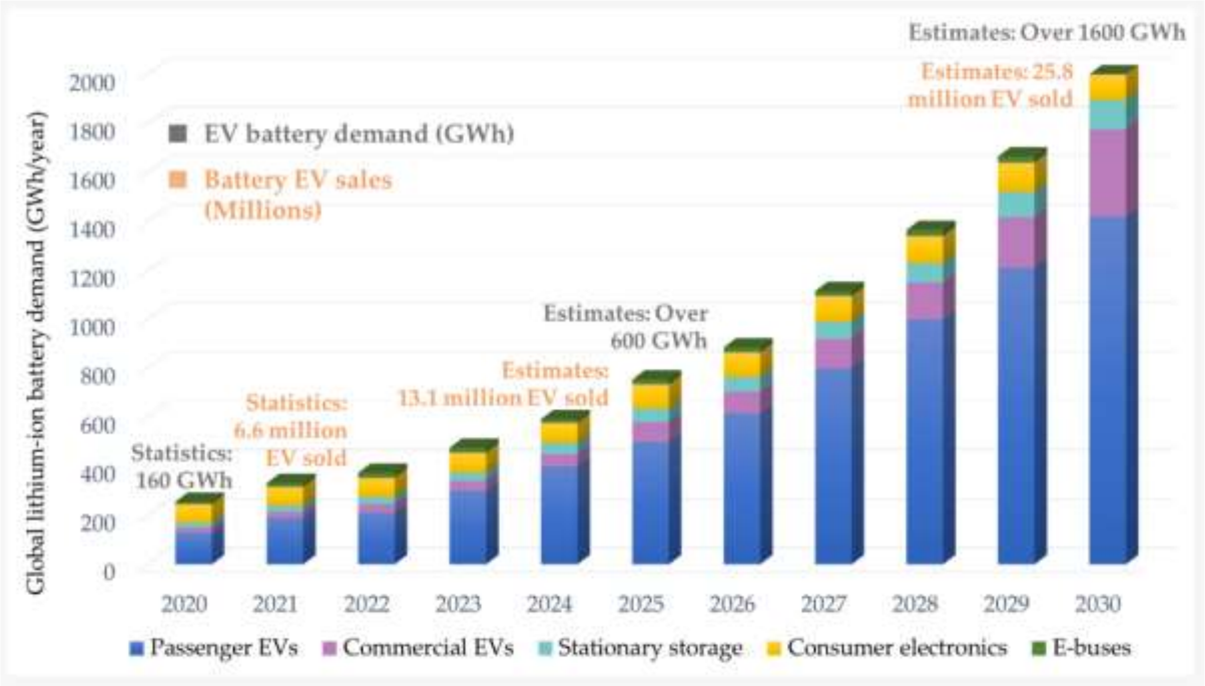


Figure 15 Global LIB demand by sector [33].

In the mass production of LIBs, environmental considerations also must be taken into account. The extraction and processing of raw materials, such as lithium and cobalt, can have environmental impacts. Proper recycling infrastructure and sustainable practices are essential to minimize the environmental footprint of LIBs. Researchers are exploring alternative materials and recycling technologies to enhance sustainability and reduce dependency on scarce resources.

Some common pros and cons related to LIBs are listed in Table 6. It's important to note that the pros and cons can be changed regarding the specific application, battery design, and advancements in the field. Additionally, ongoing research and development efforts are continually addressing some of the limitations associated with LIBs.

Table 6 Pros and Cons of LIBs [34].

Pros.	**High Energy Density:** LIBs offer a remarkable energy density, allowing them to store a significant amount of energy in a compact and lightweight form. This feature makes them ideal for applications like portable electronic devices and EVs where weight and space considerations are crucial.
	Long Cycle Life: In comparison to other rechargeable battery technologies, LIBs generally exhibit a longer cycle life. They are capable of enduring a greater number of charge and discharge cycles before experiencing noticeable capacity deterioration.
	Fast Charging: LIBs can be charged at a faster rate compared to other battery types. Rapid charging capabilities are particularly beneficial for applications that require quick recharging, such as EVs.
	High Power Density: LIBs can deliver high power outputs, allowing for efficient performance in applications that require bursts of power or high energy demands.
	Low Self-Discharge: LIBs demonstrate a lower self-discharge rate when compared to other battery chemistries. This means that they can retain their charge for extended periods without significant loss, reducing the frequency at which they need to be recharged.
Cons.	**Cost:** LIBs can be relatively expensive to manufacture compared to other battery technologies. The cost is influenced by factors like raw materials, manufacturing processes, and economies of scale. However, costs have been declining over time due to advancements in production techniques and increased demand.
	Limited Lifetime: While LIBs have a longer cycle life compared to many other battery types, they do have a finite lifespan. Over time, their capacity gradually decreases, requiring replacement after a certain number of years or cycles.
	Safety Concerns: Although LIBs are generally safe, there have been incidents of overheating, fires, or even explosions. These safety concerns are often attributed to factors such as manufacturing defects, external damage, or improper usage. Proper handling, storage, and adherence to safety guidelines are essential for mitigating risks.
	Resource Intensive: The production of LIBs requires the extraction and processing of raw materials, including lithium, cobalt, nickel, and graphite. The mining and processing of these resources can have environmental and social impacts if not managed responsibly. However, efforts are being made to improve sustainability and develop recycling infrastructure.
	Limited Shelf Life: LIBs can experience capacity loss over time, even when not in use. This self-discharge can affect their ability to hold a charge if left unused for extended periods. Proper storage techniques, including maintaining optimal temperatures, can help mitigate this issue.

The selected LIB for this study is ‘LG CHEM RESU10H’, the datasheet of which can be found in Appendix 8. Table 7 also represents some important key properties of the battery which have been used in this study.

Table 7 Key properties of the LG CHEM RESU10H.

Item	Value
Total Energy Capacity	9.8 kWh
Usable Energy Capacity	9.3 kWh
Max. Charge/Discharge current	11.9 A
Max. Charge/Discharge power	5 kW
Peak Power (only discharging)	7 kW for 10 sec.

4.3 Supercapacitors

Supercapacitors, also known as ultracapacitors or electrochemical capacitors, have emerged as promising energy storage devices with unique characteristics. Supercapacitors hold potential as versatile energy storage devices, offering fast charging, high power density, and exceptional cycling stability. Continuous advancements in materials, manufacturing processes, and cost-reduction strategies are driving their adoption across a wide range of applications. This section aims to explore the technical and economic aspects of supercapacitors, shedding light on their working principles, performance attributes, manufacturing processes, cost factors, and market trends.

Supercapacitors fill the gap between batteries and conventional capacitors. They store electrical energy through the mechanism of electrostatic double-layer capacitance. They consist of two electrodes, typically made of high-surface-area materials like activated carbon, separated by an electrolyte or an ion-permeable membrane [35].

Process innovation and automation contribute to improving the manufacturing efficiency and scalability of supercapacitors [36]. Supercapacitors excel in certain performance aspects. They have ultra-fast charge and discharge capabilities, enabling them to capture and release energy rapidly. This attribute makes them suitable for applications that require high-power bursts, such as regenerative braking in EVs. As mentioned before, Supercapacitors also exhibit a high number of charge-discharge cycles, often reaching over one million cycles, ensuring longevity and reliability [37].

Supercapacitors currently face cost challenges compared to other energy storage technologies. The cost is primarily influenced by the choice of electrode materials, electrolyte components, and manufacturing processes. High-performance materials and low-cost manufacturing techniques are being researched and developed to reduce production costs. Economies of scale, improved energy and material efficiency, and enhanced recycling methods are expected to drive down costs in the future [38].

The market for supercapacitors is witnessing significant growth, driven by various factors. Supercapacitors find applications in various industries, including transportation (hybrid vehicles, electric buses), renewable energy (grid stabilization, smoothing of intermittent sources), and electronics (backup power). The demand for high-power and fast-charging capabilities, coupled with the need for energy-efficient and sustainable solutions, is fuelling the adoption of supercapacitors. As technology advances and costs decrease, supercapacitors are expected to play an increasingly prominent role in the energy storage landscape. [39]

While supercapacitors' energy density may not match that of batteries, their specific power and ability to handle frequent charge-discharge cycles make them advantageous in specific applications. Hybrid energy storage systems combining supercapacitors and batteries are being explored to capitalize on the complementary strengths of both technologies. This hybrid approach aims to optimize energy management, enhance efficiency, and extend the overall system lifespan [40][41].

The supercapacitor selected for this study is the 'Skeleton Skelcap supercapacitor with the product code 6710038'. Table 8 includes the data for this supercapacitor. The comprehensive data about the supercapacitor is given in Appendix 9. The Share of the DC storage block from the total cost in this table is based on Geyser Batteries' internal resources.

Table 8 Key characteristics of the supercapacitor SkelCap code 6710038.

Item	Value
Rated capacitance	3200 F
Rated voltage V_R	2.85 V
Max continuous current	167 A
Lifetime	10 years
Cycles	1,000,000
Share of DC storage block from the total cost	50%
Energy Capacity	3.6 Wh

4.4 Geyser Batteries

Geyser Batteries is a cleantech start-up that specializes in creating and manufacturing an innovative line of secure and eco-friendly power batteries. These advanced batteries employ a unique water-based electrochemistry, setting them apart in the industry. The patented technology is anticipated to enhance the stability of renewable power grids by delivering fast-storage batteries with low cost per charge, minimal CO2 emissions, maximum safety, and easy recyclability. The materials used are conflict-free, devoid of critical raw materials, and readily available locally.

Utilizing widely available chemical materials and water as a solvent for electrolytes, the batteries eliminate the risk of fire or explosion. The implementation of aqueous electrolytes also contributes to a more energy-efficient manufacturing process. These factors make Geyser Batteries a promising and sustainable solution.

Geyser Batteries have been engineered to surpass the performance of some of the finest high-power energy storage solutions presently available. Leveraging decades of research, development, and technological progress, these batteries integrate the energy storage capacity of batteries with the resilience and exceptional high-power performance of supercapacitors, all within a single electrochemical system.

Geyser's power batteries are at the forefront of electrochemical energy storage, pushing the boundaries in terms of the number of charge-discharge cycles and operational temperature range.

The innovative bipolar design employed in Geyser Batteries ensures the largest possible cross-section for internal current, resulting in uniform current density on electrodes. This distinctive feature leads to low and consistent heat generation, allowing for easy heat control. As a result, customers can expect a long-lasting and reliable battery life with minimal maintenance required. Figure 16 depicts the exploded schematic of a Geyser battery.

Table 9 provides key specifications for the Geyser Battery. These values are based on my approximations from the discussions with Geyser Batteries company. These are only assumptions, and the company was aware of these assumptions and their applications in the calculations, however these can be just an approximation from the real numbers in a prototype.

Figures 17 and 18 show the charge and discharge voltage and current curves for fast and big cycles modes respectively. Figure 19 also indicates the charge and discharge power curve for the big cycle mode.

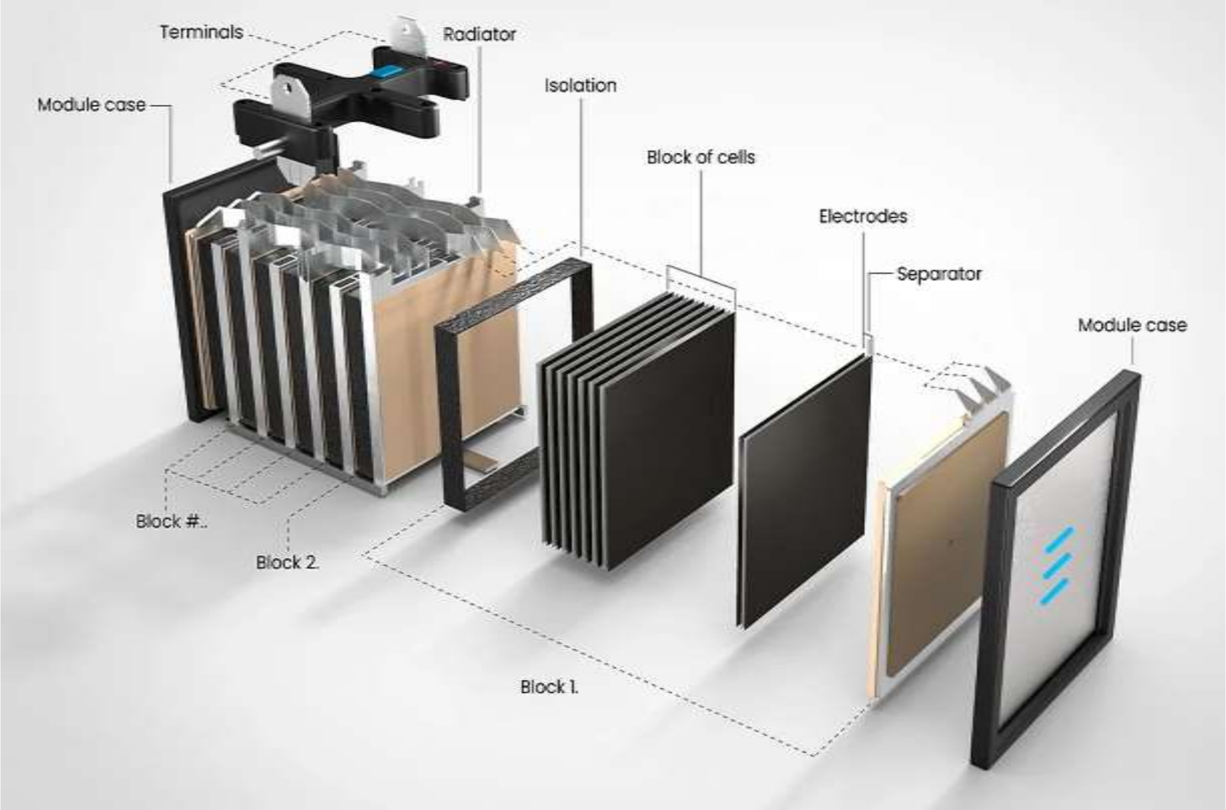


Figure 16 The exploded schematic of a Geyser battery [7].

Table 9 Key characteristics of Geyser Batteries.

Item	Value
Rated voltage	12.8 V
Max energy	4 Wh
Max charge/discharge power	500 W
Max charge/discharge power (<20 s)	800 W
Cycles	1000,000
Efficiency	0.98
Share of DC storage cost from the total BESS cost	55%
Lifetime	20 years

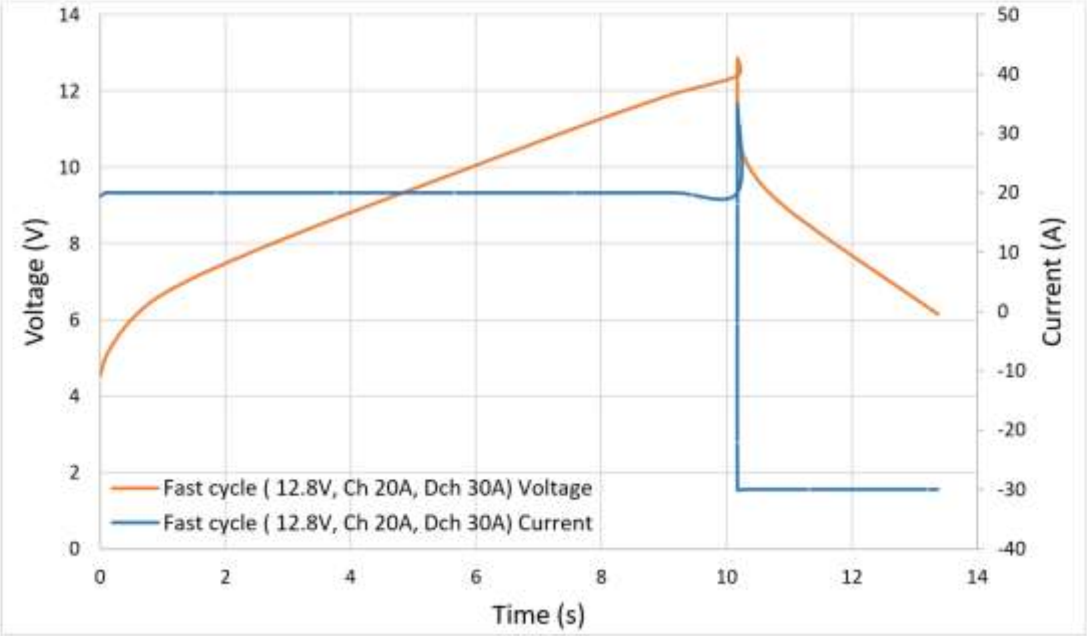


Figure 17 Geyser Batteries fast cycle charge and discharge curve.

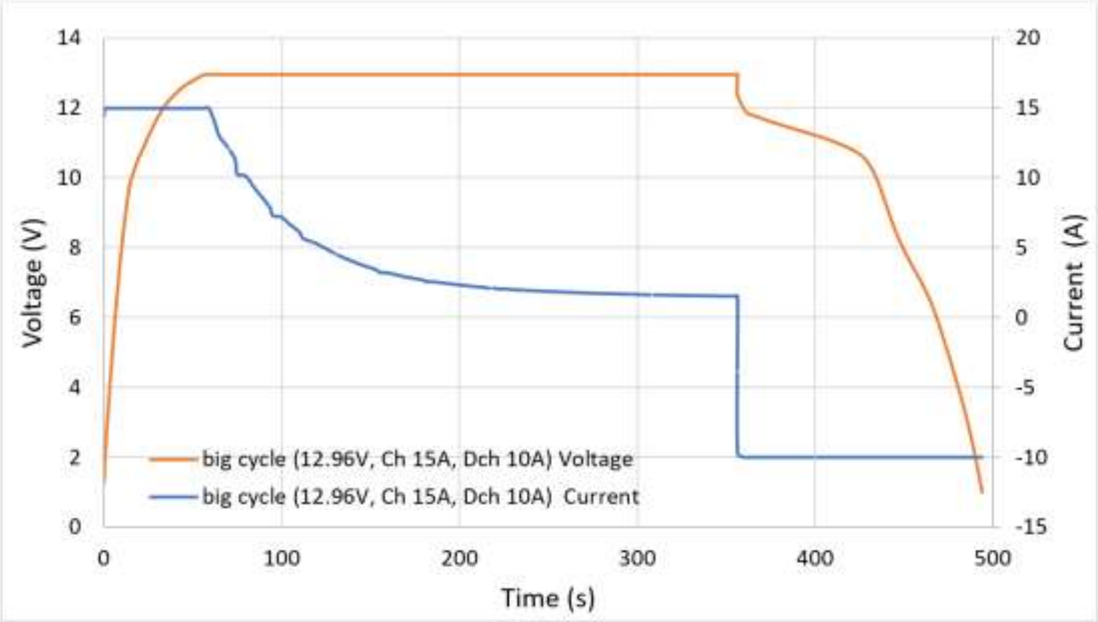


Figure 18 Geyser Batteries big cycle charge and discharge curves.

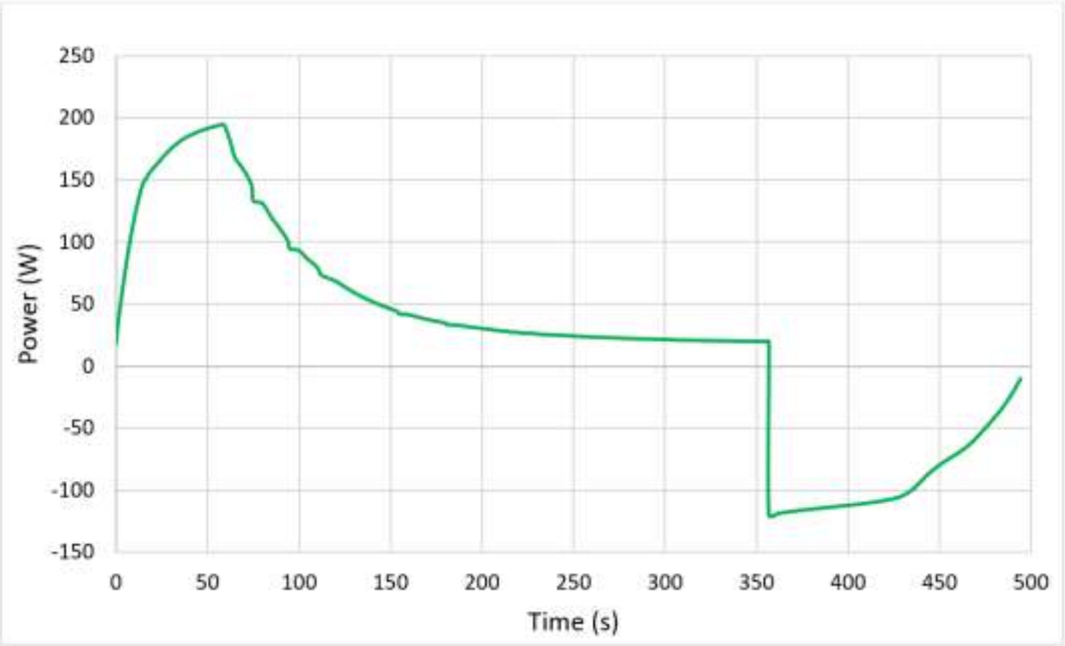


Figure 19 Charge and discharge power in big cycle mode.

- ***ESS Sizing***

Equation (2) is used for calculating the required number of storage units in a BESS in the FCR-D market with the recovery and activation times.

$$N = \begin{cases} \dfrac{t_1 . P_e}{t_2 . P_u} & t_2 . P_u \leq E_u \\ \dfrac{t_1 . P_e}{E_u} & \text{else} \end{cases} \tag{2}$$

N,	Number of required storage units
P_e,	Power capacity of participant entity in the frequency market
P_u,	Power capacity of a single storage unit
t_1,	Time the unit must be able to endure in the grid
t_2,	Recovery time
E_u,	Energy capacity of a single storage unit

Equation (3) is also for calculating the number of storage units in the markets with only the endurance time in the grid like FCR-N and the markets with very short endurance time in comparison with recovery time resembling FFR. Since in equipment with high power-to-energy ratio, a short time is needed to recharge the discharged energy, this formula is also used to calculate the number of equipment like supercapacitors and Geyser Batteries in all market participations.

$$N = \begin{cases} \frac{P_e}{P_u} & t_1 . P_u \le E_u \\ \frac{t_1 . P_e}{E_u} & \text{else} \end{cases} \tag{3}$$

For batteries, in most applications, DoD is considered 80%. Also, it is assumed that the battery set is charged up to the SoC of 80%. Therefore, 60% of the total capacity of a battery set can participate in the applications. Consequently, the following information is considered for the variables in Equations (2) and (3).

$E_u = 0.6E_B$ E_B, usable energy of the battery

$P_u = P_B$ P_B, the power capacity of the battery

For supercapacitors, the following information is considered for the variables in Equation (3).

$$E_u = E_{useful} \tag{4}$$

$$P_u = \frac{E_{useful}}{t_1} \tag{5}$$

In Equation (5) also t_1 is the time the unit must be able to endure in the grid. E_{useful} and P_{useful} are calculated in the following sequence. From the datasheet, Appendix 9, for a constant current and capacitance the stored energy is,

$$E = \frac{CV^2}{2 \times 3600} \text{ [Wh]} \tag{6}$$

Since the best performance voltage range is between V and ${}^{V}\!/_{2}$, the useful energy would be,

$$E_{useful} = E(V_R) - E\left(\frac{V_R}{2}\right) = \frac{3}{4}E(V_R) = \frac{3}{4}E_{max} \tag{7}$$

Likewise, usable energy can be assumed as 100% in Geyser Batteries as they can be discharged to 0% SOC and upper limit SOC of 80, 90 or 100% do not affect lifetime for the Geyser Batteries, the following information is considered for the variables in Equation (3).

$\mathrm{E_u = E_B}$	$\mathrm{E_B}$, usable energy of a battery cell block
$\mathrm{P_u = P_B}$	$\mathrm{P_B}$, the power capacity of a battery cell block which participates in the frequency regulation

5 Economic analyses

5.1 Net present value calculation

NPV provides insights into the costs of the FFR and FCR markets. By comparing the costs and potential revenues of participating in each market, BSPs can determine which market offers the most favourable returns and allocate their power capacity and energy accordingly. Understanding which market to participate in is critical for BSPs looking to optimize their revenue streams.

- ***NPV***

NPV is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. The profitability of a projected investment or project is evaluated using NPV in investment planning.

The NPV is determined by evaluating the current value of anticipated future cash flows using an appropriate discount rate. It serves as a financial indicator to evaluate the profitability of a project. In essence, projects with a positive NPV are considered financially viable and worth pursuing, while projects with a negative NPV are typically not recommended. Formula (8) represents the equation used to calculate the NPV [42].

$$\mathrm{NPV} = -\mathrm{Capex} + \sum_{t=1}^{n} \frac{\mathrm{R_t} - \mathrm{Opex}}{(1+\mathrm{i})^{\mathrm{t}}} \tag{8}$$

Capex,	Initial capital required
$\mathrm{R_t}$,	Net cash inflow during period t. In the frequency market case, it can be considered annually
Opex,	Total current costs during the period t
i,	Discount rate

In general, a high positive value for NPV is desirable and a zero NPV means the project will give back only the expenditures without any profit. Likewise, a negative NPV shows that the project's revenue will not afford the costs.

In most cases like frequency markets, because of the high volatility in the power and energy prices, revenue prediction for the upcoming years is a matter of difficulty. However, since in this thesis, the goal is to compare different technologies, even a non-accurate assumption will have the same impact on all results. Therefore, the results would still be reliable for finding the most profitable market for a technology.

- ***Capex***

Capex, in the context of an energy storage system, refers to the capital expenditure associated with the planning, construction, and installation of the storage infrastructure. It encompasses the costs related to the physical components of the system, including the purchase and installation of batteries, inverters, control systems, electrical infrastructure, and any necessary site preparations. Capex also includes the expenses incurred during the engineering and design phase, permits and regulatory compliance, project management, and other associated costs.
Calculating Capex for an energy storage system involves estimating the total investment required for the project, considering factors such as equipment costs, labour expenses, engineering fees, construction materials, and any additional indirect costs. It is essential to accurately assess these expenditures to determine the feasibility and financial viability of the storage project. Table 10 is a list of Capex in detail for an electrical energy storage system.

Table 10 Capex components for an electrical energy storage system [30].

Balance of System category	Balance of System
Electrical Infrastructure and Interconnection	Internal and control connections
	Power Electronics
	Wiring and Conduits
	DC cabling
	Inverter
	Switchgear
	Transformers
	Energy Management System
	Monitors, Controls and Communications
Generation equipment and Infrastructure	Constructions
	Storage Packs
	Storage component containers
	Storage Management System
	Thermal Management System
	Fire Suppression System
	Racking
	Foundation for equipment
Installation	Distributable labor and materials
	Engineering
	Sturt up and commissioning
Owner’s cost	Development costs
	Environmental studies and permitting
	Insurance costs
	Legal fees
	Preliminary feasibility and Engineering studies

- ***Opex***

Opex, in the context of an energy storage system, refers to the operational expenditures associated specifically with the ongoing maintenance, management, and performance of the system. It encompasses the costs incurred to ensure the efficient operation and optimal functioning of the energy storage system throughout its lifespan.

For an energy storage system, Opex includes expenses such as regular inspections, system monitoring, maintenance activities, system repairs, component replacements, charging energy, and any necessary upgrades or modifications. These costs are essential for maximizing the system's performance, minimizing downtime, and ensuring its reliability and safety. Opex may also include costs related to system integration with the electrical grid, grid management services, compliance with regulatory requirements, insurance, and any necessary training or staffing. These ongoing expenses are necessary to maintain the system's functionality, comply with industry standards, and meet operational and safety requirements.

Estimating and managing Opex is crucial for effective project planning, budgeting, and financial analysis of an energy storage system. It allows project owners and operators to evaluate the long-term operational costs, assess the system's economic viability, and determine the overall cost-effectiveness of the project. Opex is estimated at 2.5% of the capital costs every year [30]. Table 11 includes a list of Opex factors for an electrical energy storage system.

Table 11 List of Opex Components for an electrical energy storage system.

Fixed costs	Administrative fees
	Administrative labor
	Insurance
	Legal fees
	Taxes
	Site Security
Maintenance	General maintenance
Replacement costs	Removing and renovating costs

- ***Capex and Opex values in different technologies***

Based on the data from [43], the price for the battery cells and modules is almost 35.66% of the total needed capital to install a LIB-based ESS. This percentage has been claimed as 50.2 in [30]. Amin in [31] also introduces four different percentages of 29, 53, 55, and 63 for the cost of LIB out of the total ESS cost. Consequently, the fair percentage would be the average amount of all given numbers for this study which would be 40%. The information about Capex and Opex for different technologies is given in Table 12. Price per energy unit of a single storage part comes from dividing Cost of one storage unit by the Energy Capacity of one storage unit. In case of LG CHEM RESU10H the Price per energy unit of a single storage part is considered as 172 €/kWh [43]. Regarding Capex of ESS, LIBs has the lowest value (0.43 €/Wh) and SkelCap supercapacitor has significantly higher value (19.5 €/Wh). Geyser Batteries

ESS Capex value falls in between the previous two with a Capex of 1.13 €/Wh of energy capacity

Table 12 Key properties of LG CHEM RESU10H, SkelCap, and Geyser Batteries.

	LG CHEM RESU10H	**SkelCap code 6710038**	**Geyser Batteries**
Price per energy unit of a single storage unit	0.172 €/Wh	9.7 €/Wh	0.63 €/Wh
Energy Capacity of one storage unit	9800 Wh	3.6 Wh	4 Wh
The average cost share of the DC storage block from the total ESS cost	40%	50%	55%
Cost of one storage unit	1685 €	35 €	2.5 €
Cost of installation for one unit	4212 €	70 €	4.5 €
Capex of ESS	0.43 €/Wh	19.5 €/Wh	1.13 €/Wh
Opex percentage of Capex	0.7 %/year	0.7 %/year	0.7 %/year
Opex ESS	0.003 €/Wh/year	0.136 €/Wh/year	0.008 €/Wh/year

5.2 FCR-D

In order to calculate the revenue from the FCR-D market with a 1 MW unit, there can be considered two different resources. One is the revenue from the annual market plan, and the other is the revenue from the hourly market. Let’s assume that 0.2 MW out of this 1 MW is for the annual market plan and the remaining 0.8 MW has been procured in the hourly market. The division comes from the BSP’s policies. One reason for being motivated in the annual market participation might be the constant price for the capacity. Since dynamic markets have high volatility, annual markets’ deterministic prices can balance this volatility to some extent. However, because the income of the yearly market is rather low in comparison with the hourly market, its share has been considered only 20 percent of the total capacity. These are the revenue sources for the capacities. In addition to that, BSP pays or receives some compensation for the energy consumption or generation of electricity. The price for this energy is calculated based on the mFRR up and mFRR down-regulation prices. The FCR-D provider must measure the frequency of the network in real-time, and activate the unit based on it. For the analysis, the 10 Hz frequency samples are available in Fingrid’s open data [14], in which the frequency samples for the years 2021 and 2022 were extracted and in order to reduce the calculation burden the average frequency for a second are used in this study. The calculation method is based on the flowcharts in Figure 20 for the FCR-D up-regulation market and Figure 21 for the FCR-D down-regulation market. In these flowcharts, some assumptions and simplifications, such as instant activation and no loss of profit due to empty or full battery, have not been taken into account. But the only case that has been considered is round trip efficiency (rte). The rte consists of battery DC/DC, AC/DC and transformer losses. It may vary among different technologies, however, as it only affects on the revenue from the traded energy and because this revenue is considerably low in comparison with the revenue from the yearly and hourly markets, small differences will only cause slight changes in the results. As the main factor from the grid’s point of view is maintaining the obligatory power capacity (1 MW), in the down-regulation, the entire unit (including internal losses) acts as a consumption load, there is no need to consider the impact of the rte in the FCR-D down-regulation. But in the up-regulation the unit shall act as a power source that in addition to support the obligatory power capacity for the grid, it must be able to compensate for its internal losses. Thus, the installed capacity would be affected by rte. In this study rte is assumed to be 0.9, an average from the values discussed in [44] for both the LIB and the supercapacitors which are in the similar range of 0.85-0.95. For the Geyser Batteries also the rte is considered as 0.9. In the up-regulation market, the impact of the rte caused the needed capacity increase by approximately 11% (1 MW/0.9).

5.3 FCR-N

In order to calculate the revenue from the FCR-N market with a 1 MW obligatory power capacity, as mentioned in section 2.1.2, the needed installed capacity must be 1.34 MW. For this market, there can be considered two different resources like for FCR-D. One is the revenue from the annual market plan, and the other is the revenue from the hourly market. Here also it is assumed that 20% of this 1.34 MW is for the annual market plan and the remaining 80% has been procured in the hourly market. These are the revenue sources for the capacities. In addition to that, BSP pays or receives some money for the energy consumption or generation of electricity. The cost for this energy is calculated based on the mFRR up and mFRR down-regulation price. For the frequency for one second, the average value of 10 Hz frequency samples [14] is taken into account. The calculation of revenue from the FCR-N market is based on the flowchart provided in Figure 22. Because the impact of the rte is in the range of the 34%

surplus capacity mentioned in the standards, it is not considered in the revenue calculation except for up-regulation status. In the up-regulation the unit must also compensate for the internal losses of the ESS in addition to the energy injection to the grid. The up-regulation price consistently being higher or equal to the down-regulation price implies that the ESS can potentially receive compensation through the energy fee, regardless of its efficiency and degradation cost. This suggests that the revenue generated from participating in up-regulation activities can offset any potential efficiency losses or degradation costs associated with the ESS [45].

5.4 FFR

Equation (9) is used to calculate the weighted hourly average price values for a year (8760 hours),

$$\mathrm{whap} = \frac{\sum_{i=1}^{8760} \mathrm{PrV_i} \times \mathrm{P_i}}{\sum_{i=1}^{8760} \mathrm{PrV_i}} \tag{9}$$

where whap is the Weighted hourly average price, PrV is the procured volume in the FFR market and P is the price for the i_{th} hour.

For instance, based on this equation, the weighted average price for 2021 in [46] can be calculated using the data provided in [47] and [48].

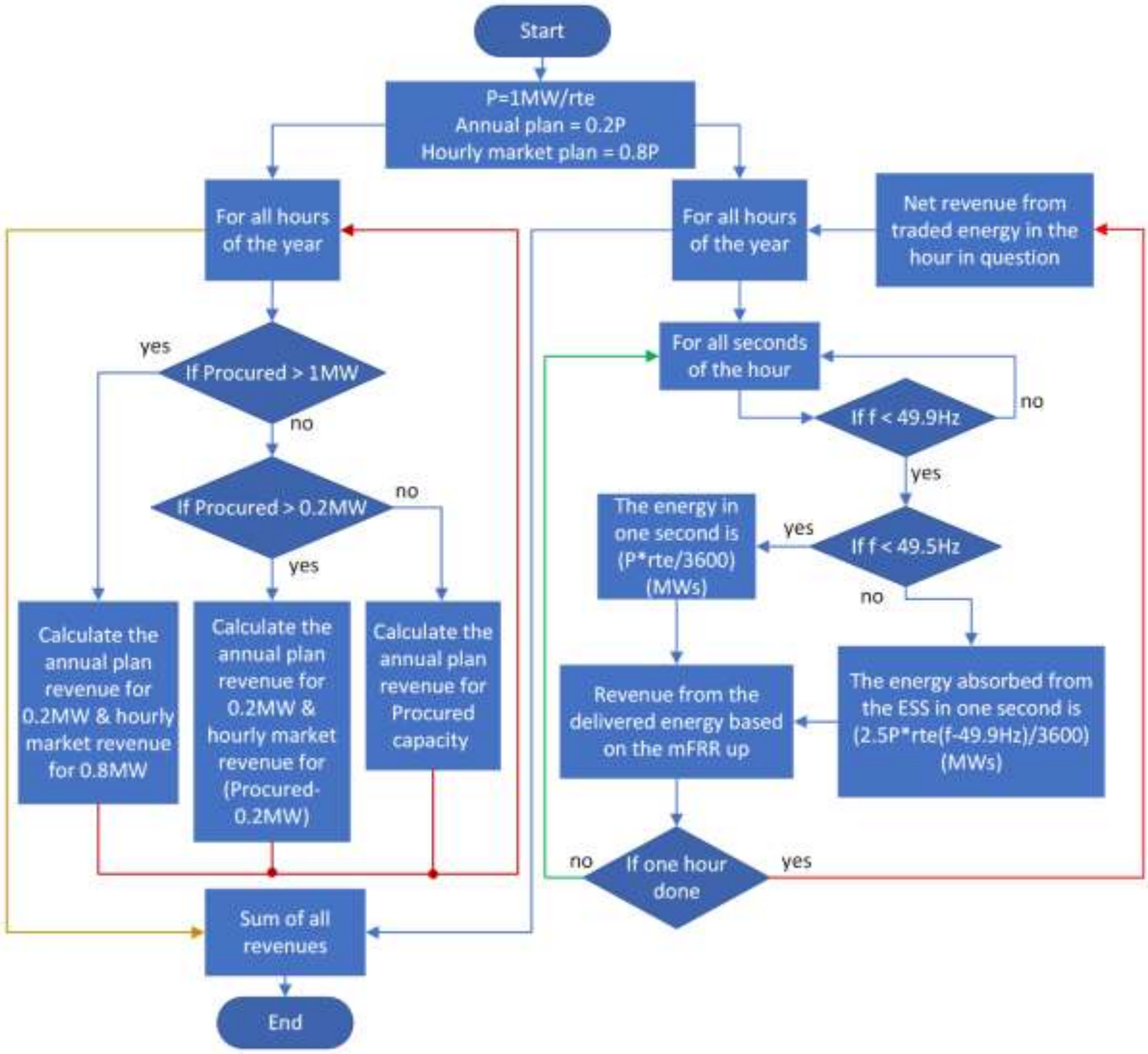


Figure 20 Revenue model flowchart for 1 MW capacity in the FCR-D up market.

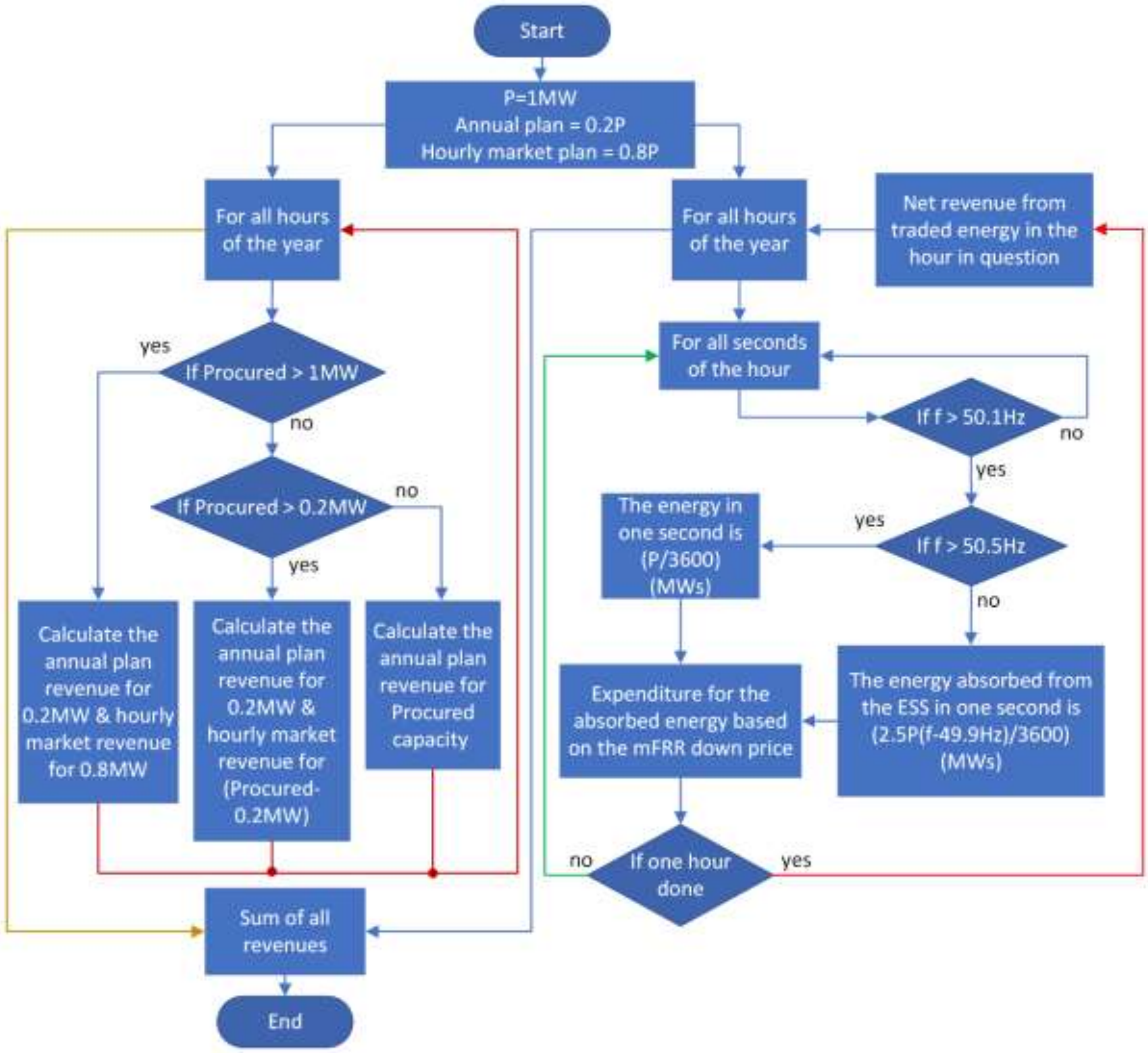


Figure 21 Revenue model flowchart for 1 MW capacity in the FCR-D down market.

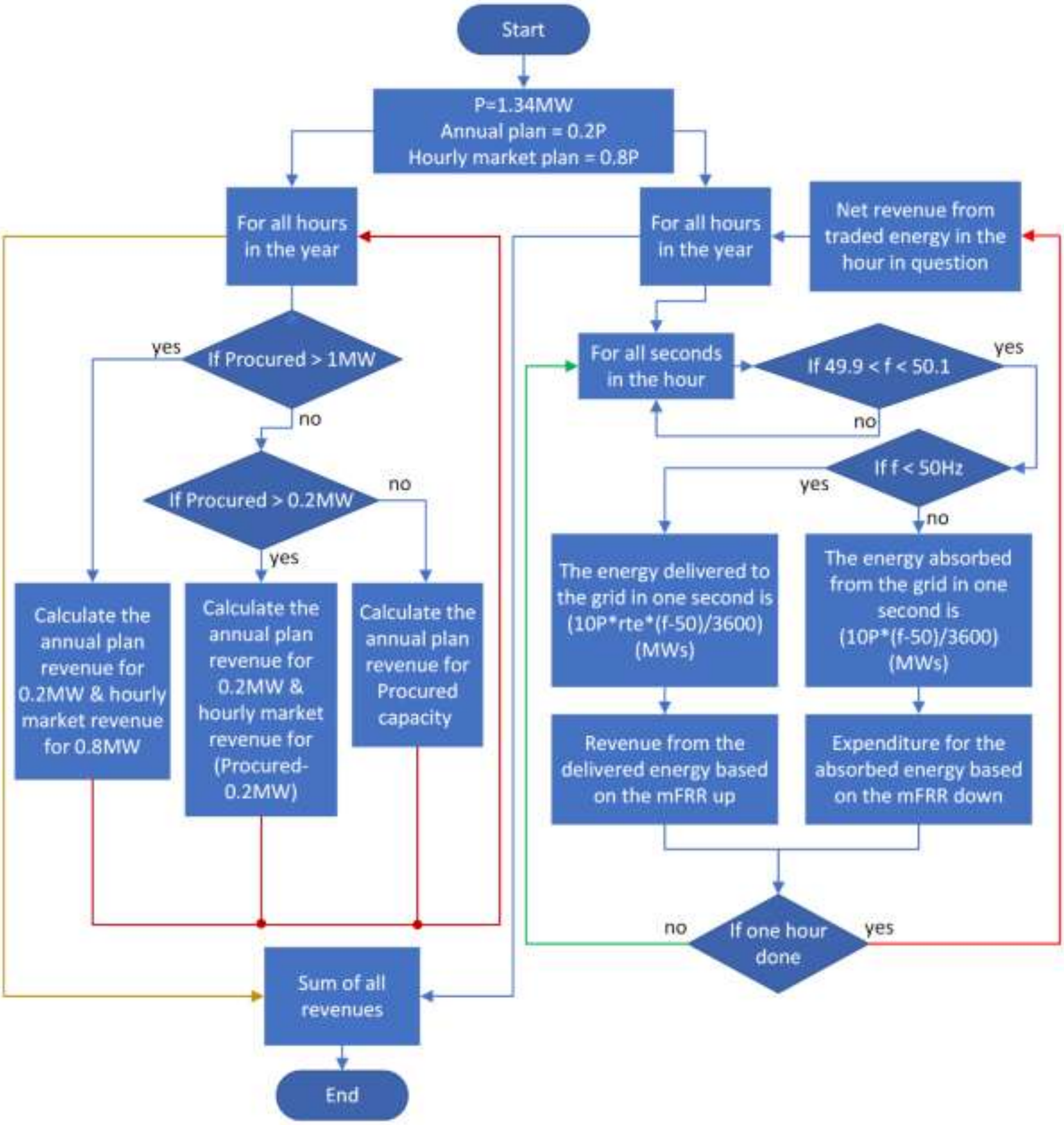


Figure 22 Revenue model flowchart for 1 MW capacity in the FCR-N market.

6 Results

6.1 FCR-D

Table 13 includes statistical information on the total and partial income from the FCR-D up-regulation market for three consequent years of 2020 to 2022 and Table 14 has the same data for the FCR-D down-regulation only for 2022 since the data for FCR-D down-regulation is only available for 2022.

Table 13 Data about a 1 MW unit participating in the FCR-D up-regulation market in 2020, 2021, and 2022.

	Unit	**FCR-D up**		
		2020	2021	2022
The planned capacity for the annual market	MW	0.2	0.2	0.2
Planned capacity to participate in hourly market	MW	0.8	0.8	0.8
Annual total delivered energy to the grid	MWh/year	6.52	6.63	3.17
Yearly market prices	€/MW	1.9	1.8	1.9
Delivered energy income	€	123	216	471
Income from FCR-D upregulating market with 0.2 MW participating in the annual market	€	2,943	2,963	3,150
Income from FCR-D upregulating market with 0.8 MW participating in the hourly market	€	46,234	46,631	90,433
Income from FCR-D upregulating market with 1 MW capacity participation (0.2 MW annual & 0.8 MW hourly markets)	€	49,300	49,810	94,054
Income from FCR-D upregulating market with 1 MW participating only in the annual market	€	14,798	15,014	16,177
Income from FCR-D upregulating market with 1 MW participating only in the hourly market	€	57,920	58,507	113,521

In Table 13, the total delivered energy to the grid fluctuates over the years, with a decrease from 6.52 MWh/year in 2020 to 3.17 MWh/year in 2022. Despite the decrease in delivered energy, the income from the FCR-D upregulating market increases. Regarding the incomes from annual and hourly markets, to have a fair comparison, it is important to consider 1 MW participation capacity in each market. With these conditions, the ratios for annual market and hourly market incomes would be 25%, 25%, and 14% for the years 2020 to 2022 respectively. This shows in these three consequent years the income potential is high in hourly market participation.

Table 14 Data about a 1 MW unit participating in the FCR-D down-regulation market in 2022.

	Unit	**FCR-D down**
The planned capacity for the annual market	MW	0.2
Planned capacity to participate in hourly market	MW	0.8
Annual absorbed energy	MWh/year	-4.02
Yearly market price	€/MW	10
Absorbed energy expenditure	€	-436
Income in FCR-D down-regulation with 0.2 MW participating in the annual market	€	14,840
Income in FCR-D down-regulation with 0.8 MW participating in the hourly market	€	171,500
Income from FCR-D downregulating market with 1 MW capacity participation (0.2 MW annual & 0.8 MW hourly markets)	€	185,904
Income from FCR-D downregulating market with 1 MW participating only in the annual market	€	73,534
Income from FCR-D downregulating market with 1 MW participating only in the hourly market	€	213,964

Focusing on the FCR-D down-regulation market in Table 14, the unit absorbs energy from the grid (-4.02 MWh/year) in this case. The annual market price is 10 €/MW, resulting in an income of 14,840 € for 0.2 MW participation in the annual market and a higher income of 171,500 € for 0.8 MW participation in the hourly market. The total annual income with 1 MW capacity participation in the FCR-D down-regulation market is 185,904 €. Here also, regarding the incomes from annual and hourly markets, in order to compare the incomes in an equal condition, it is important to consider 1 MW participation capacity in each market. Therefore, the ratio for annual market and hourly market incomes is roughly 34% in 2022. This shows the income potential is high in FCR-D down-regulation hourly market participation.

Required LG CHEM RESU10H

LIB is power limited in FCR-D. From the flowchart in Figure 20, the power capacity of the BESS for FCR-D up-regulation is 1.11 MW considering the impact of the rte. However, this would be 1 MW for FCR-D down-regulation since the rte does not affect the power capacity, Figure 21. In these markets, 15 minutes of recovery time and 20 minutes for the ability to endure in the grid are needed based on the standards. And also, because the power capacity of a single battery is 5 kW and E_u is 5.58 kWh (60% of 9.3 kWh) according to Equation (2) 267 battery cells for FCR-D down-regulation and 296 battery cells for FCR-D up-regulation are needed.

Required Skelcap

Supercapacitors are energy limited in FCR-D. As mentioned above the ESS's power capacity for FCR-D up-regulation is 1.11 MW considering the impact of the rte and 1 MW for FCR-D down-regulation since the rte does not affect the power capacity, Figures 20 and 21. In this market, based on the 3.6 Wh maximum energy given in the datasheet, Appendix 9, according to Equation (5) the useful energy would be 2.7 Wh. This energy must endure 20 minutes in the grid; therefore, the power of a single supercapacitor is 8.1 W. Consequently, according to Equation (3), 137,175 and 123,457 supercapacitors are needed for FCR-D up-regulation and down-regulation markets respectively.

Required Geyser Batteries

Geyser Batteries also are energy limited in FCR-D. In this market, based on the 4 Wh maximum energy given in Table 9, considering the ability of being fully charged and discharged, E_u is 4 Wh as well. Since this energy would be traded in 20 minutes the power of a single cell block can be 12 W. Consequently, according to Equation (3) and the fact that the ESS's power capacity for FCR-D up-regulation is 1.11 MW shown in Figures 20, and for FCR-D down-regulation is 1 MW depicted in Figures 21, 92,593 and 83,334 Geyser Batteries are needed for FCR-D up-regulation and down-regulation markets respectively.

Table 15 shows the NPV and required data to calculate of which for a unit with different technologies in the FCR-D down-regulation markets for the year 2022. As well as Table 16 includes the required number of DC storage units and Capex and Opex amounts for each technology and the associated NPV values for the three consequent years of 2020 to 2022.

Table 15 NPV and required data to calculate it for all three technologies in the FCR-D down-regulation market in 2022.

	Unit	LG CHEM	SkelCap	Geyser Batteries
Numbers of DC storage units	-	267	123,457	83,334
Capex	€	1,124,600	8,642,000	375,000
Opex	€/year	7,872	60,490	2,625
Discount rate	%	7.5	7.5	7.5
Lifetime	year	20	10	20
FCR-D down market revenue 2022	€/year	185,904	185,904	185,904
NPV in 2022	€/MW	690,340	-7,781,200	1,493,400

Table 16 NPV and required data to calculate it for all three technologies in the FCR-D up-regulation market from 2020 to 2022.

	Unit	LG CHEM	SkelCap	Geyser Batteries
Numbers of DC storage units	-	296	137,175	92,593
Capex	€	1,246,000	9,602,000	417,000
Opex	€/year	8,730	67,220	2,917
Discount rate	%	7.5	7.5	7.5
Lifetime	year	20	10	20
FCR-D up market revenue 2020	€/year	49,300	49,300	49,300
NPV in 2020	€/MW	-833,130	-9,725,200	56,186
FCR-D up market revenue 2021	€/year	49,810	49,810	49,810
NPV in 2021	€/MW	-827,930	-9,721,700	61,385
FCR-D up market revenue 2022	€/year	94,054	94,054	94,054
NPV in 2022	€/MW	-376,890	-9,418,000	512,430

For the FCR-D down-regulation market as presented in Table 15, LGCHEM needs 1,124,600 €, SkelCap demands 8,642,000 €, and Geyser Batteries has a Capex of 375,000 €. The lower Capex for Geyser Batteries could positively influence its NPV compared to the higher Capex for SkelCap. The Opex represents the annual operating expenses for each technology. LGCHEM has an Opex of 7,872 €/year, SkelCap has 60,490 €/year, and Geyser Batteries has 2,625 €/year. The lower Opex for Geyser Batteries may also contribute to its favorable NPV compared to the higher Opex for SkelCap. Focusing on NPV values, LGCHEM demonstrates a positive NPV of 690,340 €/MW, indicating it is an economically viable and attractive option for investors. In contrast, SkelCap displays a significantly negative NPV of -7,781,200 €/MW, suggesting unfavorable returns on investment. However, Geyser Batteries shows a positive

NPV of 1,493,400 €/MW, making it a feasible and promising option for the FCR-D down-regulation market.

Consequently, for FCR-D down-regulation market, LGCHEM and Geyser Batteries exhibit positive NPV values, indicating their economic feasibility and attractiveness for the FCR-D down-regulation market in 2022. However, SkelCap's negative NPV suggests potential financial risks and the need for further evaluation before considering its implementation in this market.

For the FCR-D up-regulation market as shown in Table 16, the required number for LG CHEM is 296 batteries, SkelCap 137,175 supercapacitors, and Geyser Batteries 92,593 batteries. LG CHEM has a Capex of 1,246,000 €, SkelCap has a higher Capex of 9,602,000 €, while Geyser Batteries have the lowest Capex of 417,000 €. The lower Capex for Geyser Batteries contributes to its higher NPV values compared to the other two technologies in all years. On the other hand, also, LG CHEM's Opex is 8,730 €/year, SkelCap has 67,220 €/year, and Geyser Batteries has the lowest Opex of 2,917 €/year. Again, the lower Opex for Geyser Batteries might positively impact its NPV compared to the higher Opex for SkelCap.

Considering NPV values, it is observable that LG CHEM and SkelCap consistently show negative NPV values for all three years while for Geyser Batteries the values are positive. This indicates that SkelCap and LG CHEM or in general supercapacitors and LIBs may encounter financial challenges and potential risks in the FCR-D up-regulation market. Furthermore, the FCR-D up-regulation market revenue is consistent across all three technologies, remaining at 49,300 €/year in 2020, 49,810 €/year in 2021, and increasing to 94,054 €/year in 2022.

As a result, the analysis highlights the significance of Capex, Opex, and the number of batteries in evaluating the economic performance of energy storage technologies in the FCR-D up-regulation market. Geyser Batteries seem to be the most promising option with positive NPV values in 2022, while SkelCap and LG CHEM struggle with negative NPV values throughout all three years.

6.2 FCR-N

Table 17 includes information on the total and partial income from the FCR-N market. All the calculations for the FCR-N market have been done based on the flowchart in Figure 22 which is for revenue calculations for the FCR-N market. The yearly market prices range from 12.24 €/MW in 2022 to 13.20 €/MW in 2020. The total delivered energy to the grid fluctuates over the years, while the absorbed energy from the grid is negative, indicating energy being taken from the reserve unit. The income from delivered energy increases, resulting in net annual revenue from traded energy of 17,950 € in 2020, 22,064 € in 2021, and 55,610 € in 2022. The total annual income from the FCR-N market varies depending on the participation capacity. The total annual revenues are 186,884 €, 142,207 €, and 327,141 € for the years from 2021 to 2023 respectively. In terms of the incomes from annual and hourly markets, to have a fair comparison, 1 MW participation capacity is considered in each market. With these conditions, the ratios for annual market and hourly market incomes would be 42%, 89%, and 65% for the years 2020 to 2022 respectively. This shows a considerable volatility in these three consequent years and also indicates the income potential is still high in hourly market participation.

Table 17 The information about a 1 MW unit participating in the FCR-N market in 2020, 2021, and 2022.

	Unit	**FCR-N**		
		2020	**2021**	**2022**
Yearly market prices	€/MW	13.20	12.50	12.24
Annual total delivered energy to the grid	MWh/year	1418.4	1513.2	1,486.5
Annual total absorbed energy from the grid	MWh/year	-1418.3	-1512.8	-1,486.8
The yearly income from the delivered energy	€	51,295	117,970	250,590
The yearly payment for the absorbed energy	€	-33,345	-95,906	-194,980
Net annual revenue from the traded energy	€	17,950	22,064	55,610
Income in FCR-N with 0.2 MW participating in the annual market	€	22,724	21,554	20,501
Income in FCR-N with 0.8 MW participating in the hourly market	€	146,210	98,589	251,030
Income from FCR-N market with 1 MW capacity participation (0.2 MW in annual & 0.8 MW in hourly markets)	€	186,884	142,207	327,141
Income from FCR-N market with 1 MW participating only in annual market	€	131,370	129,614	175,607
Income from FCR-N market with 1 MW participating only in hourly market	€	200,720	145,304	414,460

Required LG CHEM RESU10H

LIB is power limited in FCR-N. In this market, considering 30 minutes for the ability to endure in the grid based on the standards and the 5 kW power capacity of a single battery. On the other hand, according to Figure 22, the required power capacity for the reserve unit is 1.34 MW in order to participate with 1 MW obligatory power in the market. Therefore, based on Equation (3) 268 battery cells are needed.

Required Supercapacitors

Supercapacitors are energy limited in FCR-N. Here also, because the charge and discharge characteristics of supercapacitors are the same since the time period for endurance is 30 minutes, the power capacity for a supercapacitor would be different than the endurance time was 20 minutes in FCR-D markets. According to Equation (7), the useful energy is 2.7 Wh. Therefore, the power of a single supercapacitor is 5.4 W. Consequently, according to Equation (3), 248,149 supercapacitors are needed.

Required Geyser Batteries

Geyser Batteries are energy limited in FCR-N. In this market also, based on the 4 Wh maximum energy given in Table 9, E_u would be also 4 Wh. Since this energy must be traded in 30 minutes the power of a single cell block can be 8 W. Consequently, because of a 1.34 MW required power capacity for the reserve unit, according to Equation (3), 167,500 cell blocks are needed. The Capex, Opex, and NPV values are presented in Table 18. This table specifically focuses on a unit equipped with 1 MW power capacity in different technologies in the FCR-N market for the years 2020 to 2022.

Table 18 NPV and required data to calculate it for all three technologies in the FCR-N market from 2020 to 2022.

	Unit	**LG CHEM**	**SkelCap**	**Geyser Batteries**
Numbers of DC storage units	-	268	248,149	167,500
Capex	€	1,128,800	17,370,000	753,750
Opex	€/year	7,900	121,590	5,276
Discount rate	%	7.5	7.5	7.5
Lifetime	year	20	10	20
FCR-N market revenue 2020	€/year	186,884	186,884	186,884
NPV in 2020	€/MW	695,820	-16,922,000	1,097,600
FCR-N market revenue 2021	€/year	142,207	142,207	142,207
NPV in 2021	€/MW	240,360	-17,229,000	642,190
FCR-N market revenue 2022	€/year	327,141	327,141	327,141
NPV in 2022	€/MW	2,125,700	-15,960,000	2,527,500

According to Table 18, LG CHEM has a Capex of 1,128,800 €, SkelCap has a considerably higher Capex of 17,370,000 €, while Geyser Batteries have a relatively lower Capex of 753,750 €. The significant difference in Capex values indicates varying levels of investment required for each technology, which may impact their overall financial performance. Likewise, LG CHEM's Opex is 7,900 €/year, SkelCap has a significantly higher Opex of 121,590 €/year, and Geyser Batteries has the lowest Opex of 5,276 €/year. The variation in Opex values also may influence the overall cost-efficiency and profitability of each technology.

Taking the NPV values into account, it is vivid that LG CHEM and Geyser Batteries exhibit positive NPV values over the three years, while SkelCap consistently displays negative NPV values. This suggests that LG CHEM and Geyser Batteries have the potential to generate returns on investment in the FCR-N market, whereas SkelCap may face financial challenges.

6.3 FFR

Considering Equation (9), the annual revenue in this market comes from the summation of hourly procured capacity by Fingrid. This amount would be 58,878 € in 2022 with a weighted average price of 39.2 €/MW. This value was 64,196 € in 2021, with a weighted average price of 45.4 €/MW in Table 19. Despite 88 hours increase in the procurements in 2022 in comparison with 2021, the revenue fell about 8.3%. Table 19 shows the numbers calculated for a unit with 1 MW capacity.

Table 19 FFR market’s weighted hourly average price, number of hours that procurement was done, total revenue for 2021 and 2022 for a unit with 1 MW capacity.

Year	Weighted hourly average price (€/MW)	Procured hours in a year	Total FFR market revenue (€)
2021	45.4	1414	64,196
2022	39.2	1502	58,878

Required LG CHEM RESU10H

LIB is power limited in the FFR market. There are two optional participating modes in this market. In order to participate with 1 MW capacity in 30-second mode, the nominal power capacity is 5 kW. Thus, according to Equation (3), 200 battery cells are needed. If the 20%

over-delivery also be taken into account, the battery numbers would be 240. But to participate with 1 MW capacity in 5-second mode, the nominal power capacity is 7 kW, with this power capacity in 5 seconds, the batteries have enough energy for the required deactivation period mentioned in Appendix 2. Therefore, according to Equation (3), 143 battery cells are needed. Besides, if the 20% over-delivery also be considered, the battery numbers would be 179.

Required Supercapacitors

Supercapacitors are energy limited in the FFR market also. According to Equation (7), the useable energy is 2.7 Wh. In order to participate with 1 MW capacity in 30-second mode, based on Equation (5), and considering 20% over-delivery the power capacity would be 270 W. Because in the 30-second mode, there is no need for a deactivation period, according to Equation (3), 3704 Skelcap supercapacitors are needed for FFR market participation in the 30-second mode.

In the 5-second mode, the usable energy must be delivered during 5 seconds of support time with 20% overdelivery and the deactivation time with a declining rate of $0.2P_u$/second which by considering the 20% overdelivery will take 6 seconds, Appendix 2. Thus, the power capacity would be 1080 W. Based on Equation (3) 926 Skelcap supercapacitors are needed for FFR market participation in the 5-second mode. Therefore, considering both modes' required supercapacitors, 926 is the most appropriate option to participate in the FFR market.

Required Geyser Batteries

Geyser Batteries are energy limited in FFR also. As mentioned before E_u is 4 Wh. In order to participate with 1 MW capacity in 30-second mode, the required power capacity to deliver 4 Wh of a single battery to the grid is 480 W which is lower than the maximum allowed discharge power in Table 9. Because in the 30-second mode, there is no need for a deactivation period, according to Equation (3), and considering 20% over-delivery, 2500 cell blocks are needed for the FFR market to participate in the 30-second mode.

In the 5-second mode, the energy must be delivered during 5 seconds of support time. The deactivation time with a declining rate of $0.2P_u$/second with considering the 20% over-delivery will take 6 seconds, Appendix 2. Thus, the power capacity needed for a cell block would be 2250 W. However, this amount is larger than the maximum power mentioned for the power capacity for applications under 20 seconds. Therefore, the maximum power is set to 800 W. Based on Equation (3) 1250 Geyser battery cell blocks are needed for FFR market participation in the 5-second mode. Therefore, considering both modes, the required Geyser Batteries are 1250.

Table 20 NPV and required data to calculate it for all three technologies in the FFR market for 2021 and 2022.

	Unit	**LG CHEM**	**SkelCap**	**Geyser Batteries**
Numbers of DC storage units	-	179	926	1250
Capex	€	754,000	64,820	5,625
Opex	€/year	5280	454	40
Discount rate	%	7.5	7.5	7.5
Lifetime	year	20	10	20
FFR market revenue 2021	€/year	64,196	64,196	64,196
NPV in 2021	€/MW	-153,310	372,710	648,420
FFR market revenue 2022	€/year	58,878	58,878	58,878
NPV in 2022	€/MW	-207,520	336,210	594,200

The NPV values and related data for three different energy storage technologies operating in the FFR market during 2021 and 2022 are given in Table 20. Regarding initial investment, LG CHEM has a Capex of 754,000 €, SkelCap requires 64,820 €, and Geyser Batteries have the lowest Capex at 5,625 €. The differences in Capex reveal varying levels of financial commitment for each technology. Opex annually for LG CHEM amount to 5,280 €, while SkelCap has an Opex of 454 € and Geyser Batteries only 40 €.

In terms of comparing the NPV values, Geyser Batteries have the highest NPV in 2021 and 2022, signifying strong investment potential. SkelCap also demonstrates a positive NPV, though lower than Geyser Batteries. In contrast, LG CHEM shows negative NPV values for both years, indicating potential financial difficulties. The results highlight the importance of Capex, Opex, and the number of storage units in evaluating the economic viability of energy storage technologies in the FFR market.

6.4 Sensitivity analysis

● *Sensitivity analysis of the revenue and the participation share in the annual market plan in 2022*

The sensitivity analysis examines the revenue changes or sensitivity against variations in the BSP's decision regarding annual plan participation and the allocation of capacity to the hourly market for the FCR-D up-regulation, FCR-D down-regulation, and FCR-N markets in 2022. The data represents the total revenue as a percentage of the revenue potential from full participation in the hourly market, with different annual plan percentages out of the total capacity for each market.

For the FCR-D up-regulation, the revenue gradually decreases as the annual plan percentage increases. At 10% annual plan participation, the revenue reaches 91% of the maximum, and it reduces to 14% at 100% annual plan participation as is shown in Figure 23 with a blue streak. This sensitivity analysis demonstrates that higher annual plan participation leads to a reduction in revenue, indicating that full participation in the hourly market is more lucrative compared to the annual plan.

Similarly, for FCR-D Down-regulation, the revenue declines as the annual plan percentage increases. At 10% annual plan participation, the revenue represents 93% of the maximum, and it decreases to 34% at 100% annual plan participation as is depicted in Figure 23, the orange streak. This analysis reinforces the observation that higher annual plan participation results in a decrease in revenue, emphasizing the advantage of full participation in the hourly market over the annual plan.

Moving on to FCR-N, the revenue gradually decreases as the annual plan percentage increases. At 10% annual plan participation, the revenue represents 94% of the maximum, and it reaches 42% when the annual plan participation is at 100% which is shown in Figure 23, the grey streak. This sensitivity analysis underscores the trend observed in the other markets, highlighting the benefits of full participation in the hourly market over the annual plan.

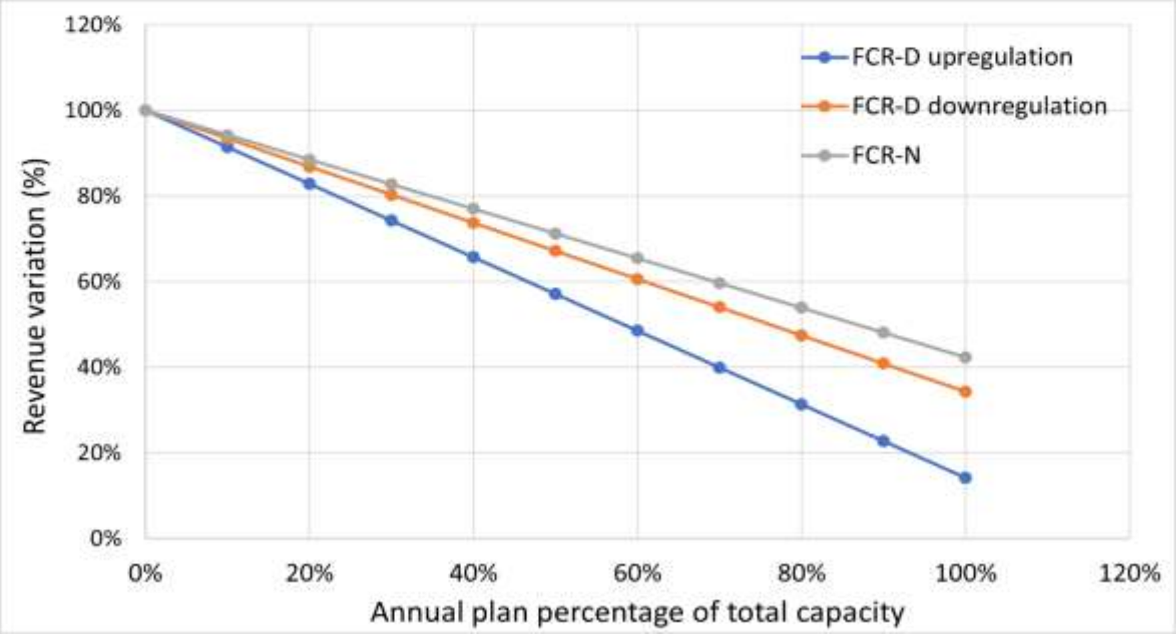


Figure 23 Sensitivity analysis of revenue with the variation in annual plan percentage of total capacity in FCR markets.

The sensitivity analysis of the revenue data reveals notable differences among the three markets. The FCR-D up-regulation market exhibits higher sensitivity to changes in annual plan participation, with even a small increase in the annual plan percentage leading to a significant reduction in revenue potential. In contrast, the FCR-D down-regulation market shows slightly lower sensitivity, and the FCR-N market demonstrates a relatively lower sensitivity compared to the FCR-D up-regulation. These differences indicate that the revenue potential and the optimal strategy for maximizing revenue differ among these markets.

Regarding the annual plan participation share in the markets, the sensitivity analysis emphasizes that increasing annual plan participation results in a gradual decrease in revenue for the FCR-D up-regulation, FCR-D down-regulation, and FCR-N markets. The FCR-D up-regulation market is the most sensitive, followed by the FCR-D down-regulation and FCR-N markets. These findings underscore the importance of carefully evaluating the sensitivity and considering market dynamics when making decisions regarding annual plan participation and hourly market engagement to maximize revenue potential in these markets.

- ***Sensitivity analysis for Geyser Batteries with Capex, Opex, and Discount rate in different markets***

This section analyses the sensitivity of NPV in four different markets FCR-D up-regulation, FCR-D down-regulation, FCR-N, and FFR. The focus is on Geyser Batteries and their sensitivity to variations in three parameters: discount rate, Capex, and Opex. The graphs in Figures 24 to 27 depict the changes in NPV when these parameters are altered within a range of ±30%. It is important to note that the analysis is specific to Geyser Batteries, and the values provided reflect deviations from the data presented in Tables 15, 16, 18, and 20 for the market 2022.

Figure 24 shows the sensitivity analysis of NPV in the FCR-D up-regulation market. In this market, a -30% change in the discount rate leads to a substantial +36% increase in NPV, while a +30% change in the discount rate causes a significant -27% decrease in NPV. Similarly, a -30% change in Capex results in a +24% change in NPV, whereas a +30% change in Capex leads to a -24% change in NPV. Moreover, a -30% change in Opex causes a minor +2% change in NPV, and a +30% change in Opex causes a corresponding -2% change in NPV. Notably, NPV responds nonlinearly to changes in the discount rate, indicating the critical role of this parameter in influencing the financial viability of Geyser Batteries.

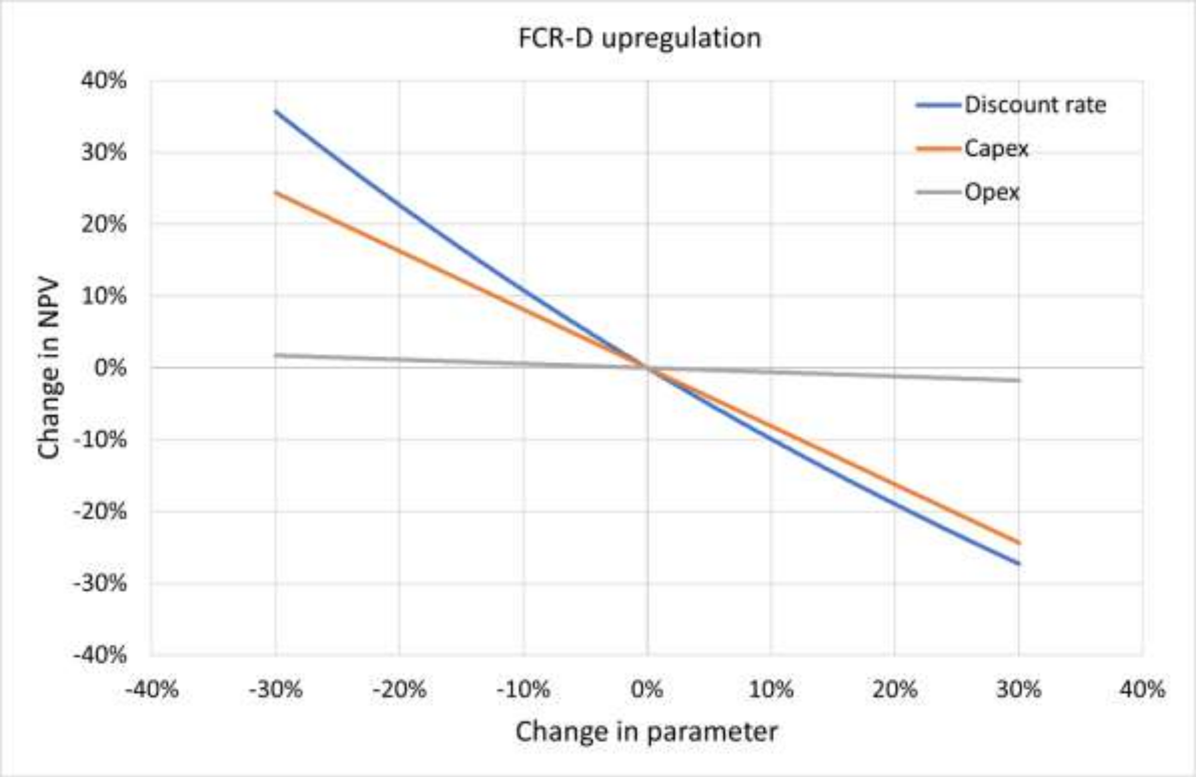


Figure 24 Sensitivity analyses for Geyser Batteries in the FCR-D up-regulation market in the market 2022.

Moving on to the FCR-D down-regulation market, the sensitivity analysis demonstrates distinct patterns in Figure 25. This market exhibits similar patterns, where a -30% change in the discount rate causes a +24% increase in NPV, and a +30% change in the discount rate results in a -19% decrease in NPV. Changes in Capex show a +8% change in NPV for a -30% variation and a -8% change for a +30% variation. Furthermore, Opex demonstrates a +1% change in NPV for a -30% variation and a -1% change for a +30% variation. The consistent linear behavior of NPV concerning Capex and Opex highlights their relatively stable impact on the FCR-D down-regulation market.

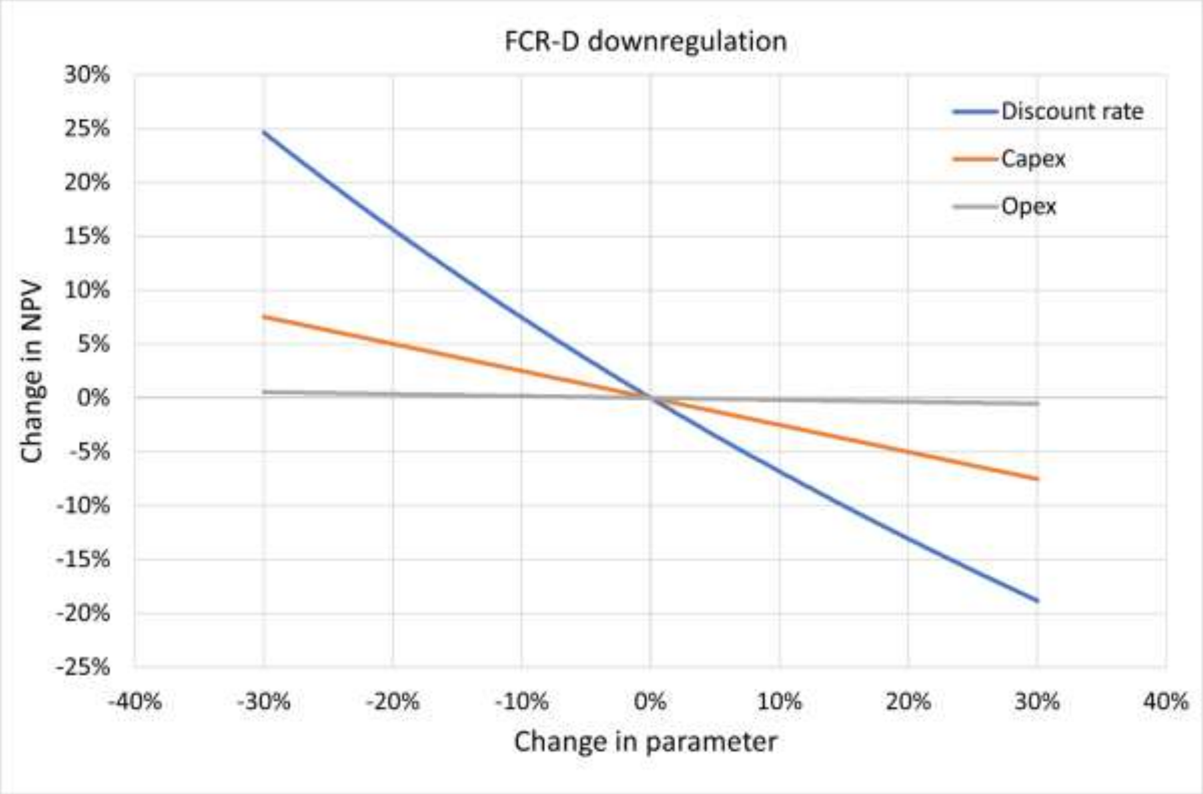


Figure 25 Sensitivity analyses for Geyser Batteries in the FCR-D down-regulation market in the market 2022.

In Figure 26, in the sensitivity analyses of the FCR-N market, similar trends in NPV as in the previous markets are obvious. A -30% change in the discount rate corresponds to a +25% increase in NPV, while a +30% change in the discount rate results in a -20% decrease in NPV. Changes in Capex lead to a +9% change in NPV for a -30% variation and a -9% change for a +30% variation. Opex shows a +1% change in NPV for a -30% variation and a -1% change for a +30% variation. Once again, NPV demonstrates linear changes for Capex and Opex and nonlinear changes for the discount rate.

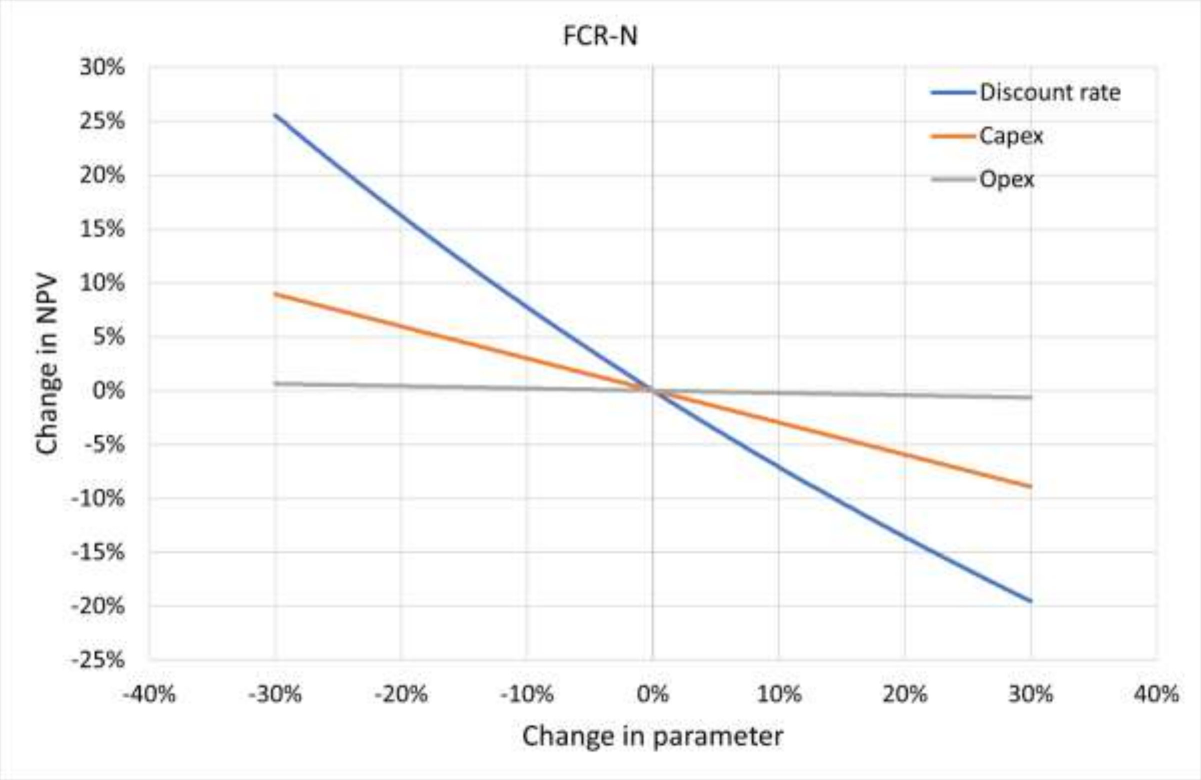


Figure 26 Sensitivity analyses for Geyser Batteries in the FCR-N market in the market 2022.

Lastly, in the FFR market sensitivity analyses in Figure 27, NPV behaves differently compared to the previous markets. A -30% change in the discount rate results in a +20% increase in NPV, while a +30% change in the discount rate causes a -15% decrease in NPV. Interestingly, changes in Capex and Opex lead to minimal effects on NPV in the FFR market, with both parameters showing negligible changes close to 0%.

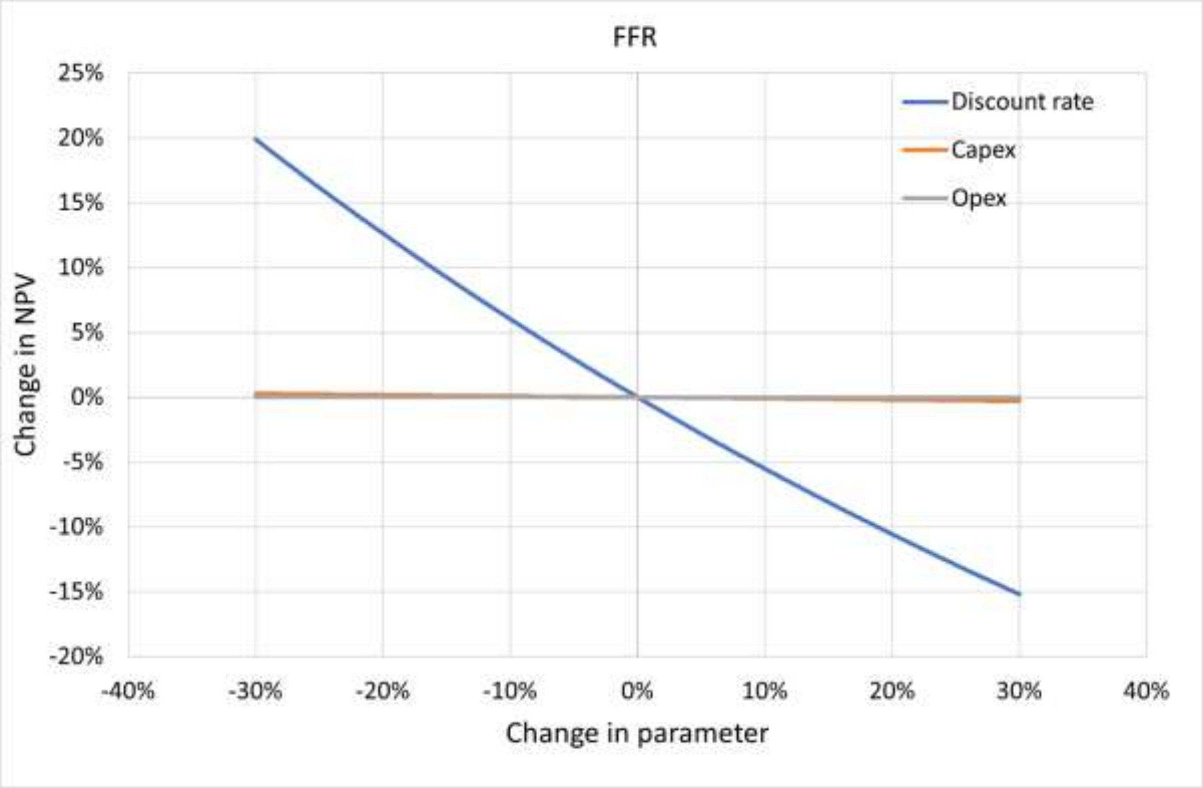


Figure 27 Sensitivity analyses for Geyser Batteries in the FFR market in the market 2022.

The comparative analysis of the graphs highlights the distinct behavior of NPV against different parameters in each market. Notably, the FCR-D up-regulation market demonstrates the highest sensitivity to changes in the discount rate, while the FFR market is relatively less affected by such changes. The linear changes in NPV for Capex and Opex across all markets emphasize the importance of careful cost considerations and investment efficiency.

In conclusion, the sensitivity analysis provides valuable insights into the financial dynamics of Geyser Batteries in various markets. Understanding the distinct responses of NPV to changes in discount rate, Capex, and Opex is crucial for making informed investment decisions and optimizing profitability in the evolving energy landscape.
By examining the changes in NPV resulting from adjustments in the discount rate, Capex, and Opex, meaningful conclusions can be drawn about the sensitivity and performance of Geyser Batteries in different market scenarios. The discount rate has a nonlinear impact on NPV across all markets. Decreasing the discount rate demonstrated a positive sensitivity, leading to notable increases in NPV for all markets. Conversely, increasing the discount rate exhibited a negative sensitivity, resulting in decreased NPV. This highlights the importance of carefully considering

the discount rate when evaluating the financial viability of Geyser Batteries in various market contexts.

Furthermore, variations in Capex showed consistent linear effects on NPV across the markets. Decreasing Capex led to significant positive sensitivities, resulting in substantial increases in NPV for FCR-D up-regulation, FCR-D down-regulation, and FCR-N markets. However, for the FFR market, the impact of Capex on NPV was relatively minimal. Conversely, increasing Capex generated negative sensitivities, leading to considerable decreases in NPV across all markets. This emphasizes the significance of cost considerations and investment efficiency when assessing the profitability of Geyser Batteries.

On the other hand, changes in Opex had a relatively lower impact on NPV compared to the discount rate and Capex. Both decreases and increases in Opex resulted in minor sensitivities, with the effects on NPV remaining relatively stable across all markets except for the FFR market where its impact is negligible. While Opex variations did not exhibit strong influences on NPV, careful management and optimization of operational expenses remain crucial for maintaining profitability in the Geyser battery market.

Overall, the sensitivity analysis demonstrates that Geyser Batteries are subject to varying sensitivities and market dynamics depending on the specific market and parameter being considered. This underscores the importance of conducting thorough financial analyses and considering market-specific factors when making investment decisions related to Geyser Batteries. By understanding the sensitivity of NPV to changes in the discount rate, Capex, and Opex, stakeholders can make informed choices and implement strategies that maximize profitability and market competitiveness in the evolving energy landscape.

7 Summary and Conclusions

The NPV values for different technologies in all markets are presented in Table 21. The red and green colors show the non-profitability and profitability in the markets respectively and the intensity of the colors shows the priority degree in every market. For instance, in the FCR-N market, the first priority would be Geyser Batteries and thereafter LG CHEM, and in the FCR-D up-regulation, the only profitable technology is Geyser Batteries. However, the Skeleton supercapacitor has the most disadvantage of all.

Table 21 The non-profitability and profitability of the different technologies in the different markets based on the NPV values (€/MW).

	LG CHEM battery	**Skeleton supercapacitor**	**Geyser battery**
FCR-D down-regulation 2022	690,340	-7,781,200	1,493,400
FCR-D up-regulation 2020	-833,130	-9,725,200	56,186
FCR-D up-regulation 2021	-827,930	-9,721,700	61,385
FCR-D up-regulation 2022	-376,890	-9,418,000	512,430
FCR-N 2020	695,820	-16,922,000	1,097,600
FCR-N 2021	240,360	-17,229,000	642,190
FCR-N 2022	2,125,700	-15,960,000	2,527,500
FFR 2021	-153,310	372,710	648,420
FFR 2022	-207,520	336,210	594,200

This research emphasizes the importance of considering financial parameters, technological capabilities, and market requirements in the selection and investment decision-making processes for energy storage technologies in frequency control applications. By aligning the technology choice with the specific market characteristics, stakeholders can make informed decisions to enhance grid stability and optimize energy storage investments.

A comprehensive analysis of energy storage technologies for frequency control in power systems was provided across four distinct markets: FCR-D down-regulation, FCR-D up-regulation, FCR-N, and FFR. The study seeks to determine the most appropriate energy storage technology for each market by analyzing critical parameters such as Capex, Opex, NPV, and charge/discharge power.

The analysis of the revenue in different markets provided valuable insights. In the FCR-D up-regulation market, despite a decrease in delivered energy over the years, the income increases. Notably, higher participation in the hourly market leads to a significant rise in income. In the FCR-D down-regulation market, energy is absorbed from the grid, resulting in income from both annual and hourly market participation. The FCR-N market showed fluctuating delivered energy and increasing income from traded energy. The FFR market generated the lowest revenue among the analyzed markets.

In terms of investment opportunities, the FCR-D down-regulation market offers potential profitability for LG CHEM batteries and Geyser Batteries, as indicated by their positive NPVs. However, investing in Skeleton supercapacitors in this market may not generate favorable financial returns. In the FCR-D up-regulation market, only Geyser Batteries showed positive NPVs for the examined years of 2020 to 2022, and the other two technologies indicated potential financial challenges, though supercapacitors showed major non-profitability. In contrast, the FCR-N market presented a favorable investment scenario for LG CHEM batteries and Geyser Batteries, with positive NPVs indicating potential positive net returns. On the other hand, investing in Skeleton supercapacitors in the FCR-N market may not be financially viable.

For the FFR market, investing in Skeleton supercapacitors holds the potential for favorable financial returns, while investing in LG CHEM batteries may not be advantageous. Geyser Batteries also showed potential for positive net returns with a considerably higher NPV in comparison with SkelCap supercapacitors.

In this study, the annual Opex was considered 0.7% of Capex. However, taking the unique conditions of the frequency regulation markets such as long stand-by time to be activated or being in charged or discharged mode for a long time between two activations (in the FCR-D up and down-regulations and FFR markets), as well as using only fractional of the energy capacity of ESS in FCR-N market, may have a rather considerable impact on the Opex values, though this impact is not expected to have a decisive effect on the entire results. In addition, having an equal Opex percentage for all technology caused large differences in the Opex values in the markets which comes from the large Capex values. These differences also might be affected by the changes in the Opex percentage of Capex values.

Furthermore, as the main objective of the study has been to compare the selected technologies and the degradation of the Geyser Batteries under practical use cases is not known, degradation has been only accounted for by the different useful life of the technologies. It is obvious that the components should be slightly oversized to account for the degradation effects.

Overall, the revenue analysis highlighted the varying financial performance of each market. It is crucial to carefully evaluate the investment potential of different energy storage options in each market based on their NPVs to make informed decisions.

The sensitivity analysis revealed important findings for Geyser Batteries in different markets. The discount rate had a nonlinear effect on NPV, with decreasing rates resulting in increased NPV and vice versa. Capex variations show consistent linear effects, where decreasing Capex led to higher NPV and increasing Capex caused decreases. Opex changes had a relatively minor impact on NPV.

- ***Future research needs***

Future research should focus on investigating the potential of combining multiple energy storage technologies to meet the requirements of different frequency control markets. This analysis could explore the synergistic effects and cost-effectiveness of integrating LIBs, supercapacitors, and Geyser Batteries, among others. Furthermore, studying the frequency regulating markets of specific countries, such as Germany and Britain, would provide valuable insights into the market dynamics, regulatory frameworks, and technology preferences. Understanding the nuances of different frequency markets and their unique characteristics would help optimize energy storage strategies and investments on a regional or national level.

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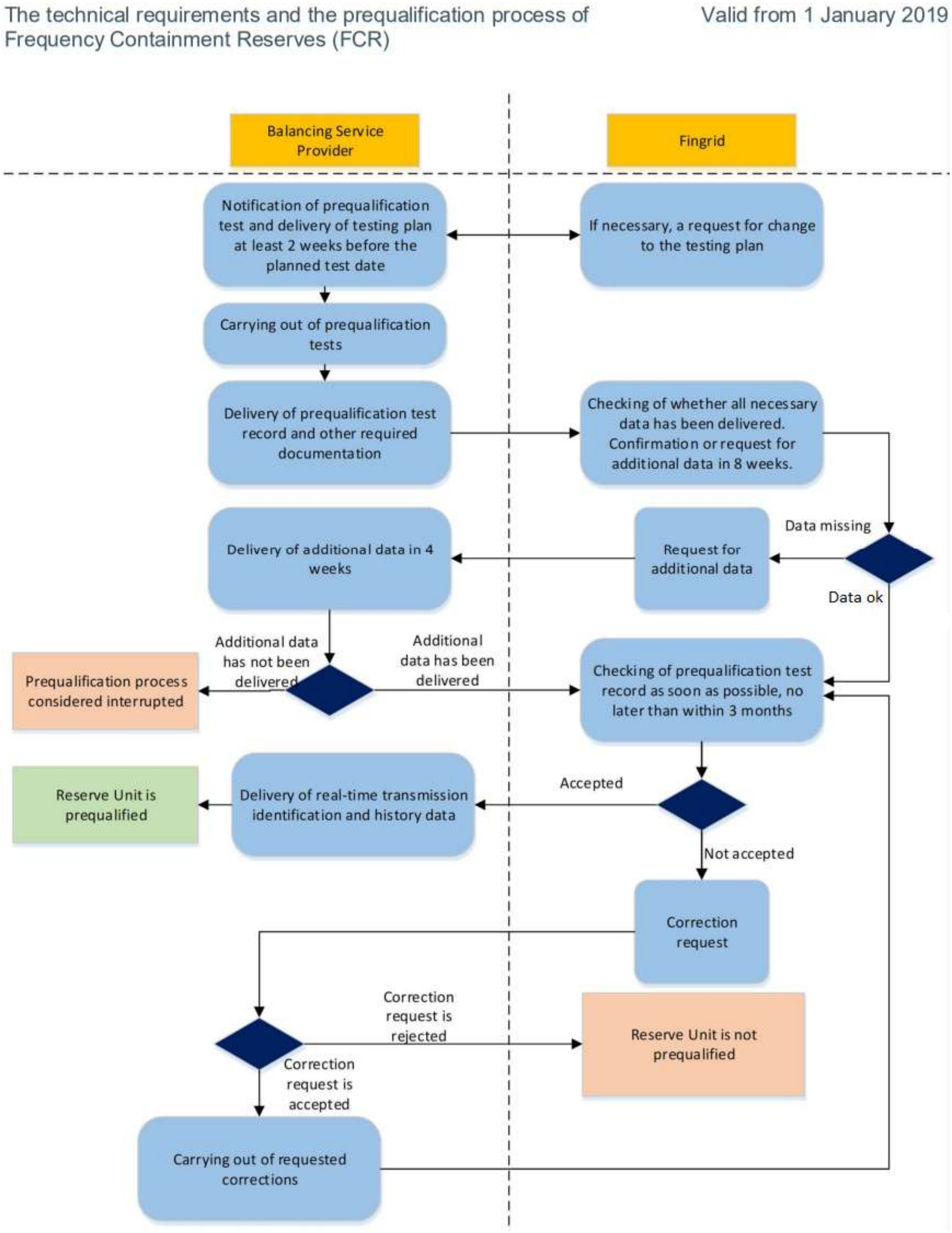
Appendix 1. FCR prequalification sequences and states [11]



Appendix 2. The requirements for FFR market participants [49][13]

Irrespective of the frequency, the reserve is required to remain operational for a specified minimum duration. During activation, the Reserve Unit must maintain a power level that is equal to or higher than the initial power level. Once the minimum duration is met, deactivation can occur, regardless of the frequency. As indicated in Figure 1, if the power deactivation rate remains below 20% of the FFR capacity per second, the minimum activation duration is set at 5 seconds. However, if the deactivation rate exceeds this threshold, the minimum activation duration increases to 30 seconds, as shown in Table 3. Moreover, it is essential that a Reserve Unit can be reactivated within 15 minutes of the last activation.

Recovery and reactivation

To initiate recovery and reactivation, specific requirements must be met by the reserve unit. Recovery involves drawing power from the grid, which could entail actions like replenishing the SoC of an energy storage device or restoring a converter-connected generator to its nominal rotational speed. However, during recovery, the amount of power drawn should not exceed 25% of the Reserve Unit's FFR capacity.

In the case of a Reserve Unit with a minimum support duration of 30 seconds, as depicted in Figure 2, it can commence the recovery process immediately after the minimum support duration has passed. On the other hand, a Reserve Unit with a minimum support duration of 5 seconds, Figure 3, can initiate recovery 15 seconds after the minimum support duration has elapsed.

It is crucial that a Reserve Unit is capable of reactivation after a maximum of 15 minutes have elapsed since its last activation. This means that the length of one activation cycle should not exceed 15 minutes, ensuring timely and responsive reactivation capabilities for maintaining grid stability.

Table 2 Selective activation modes for FFR providers.

Activation frequency (Hz)	Max. Activation time (sec)
49.7	1.3
49.6	1.0
49.5	0.7

Table 3 Minimum support duration of the FFR.

Minimum support duration (sec)	Maximum speed of deactivation
30	Not limited
5	Up to 20% of the reserve capacity per second

Table 4 Events list caused to frequency drop under 49.7 in 2022.

	Event date	Event time	Received bids
1	02.01.2022	01-02	Yes
2	06.01.2022	22-23	Yes
3	29.01.2022	17-18	No
4	24.04.2022	10-11	Yes
5	10.06.2022	04-05	Yes
6	14.06.2022	15-16	Yes
7	19.07.2022	14-15	Yes
8	29.08.2022	11-12	Yes
9	24.09.2022	21-22	Yes
10	10.10.2022	09-10	Yes
11	12.10.2022	11-12	Yes
12	09.11.2022	11-12	Yes

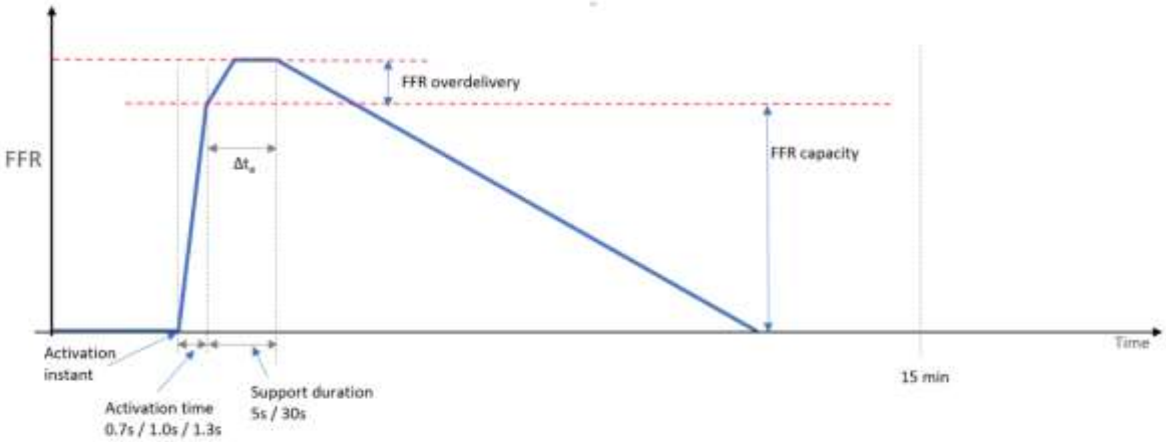


Figure 1 A general graph for an FFR unit including activation time, support duration, and deactivation time.

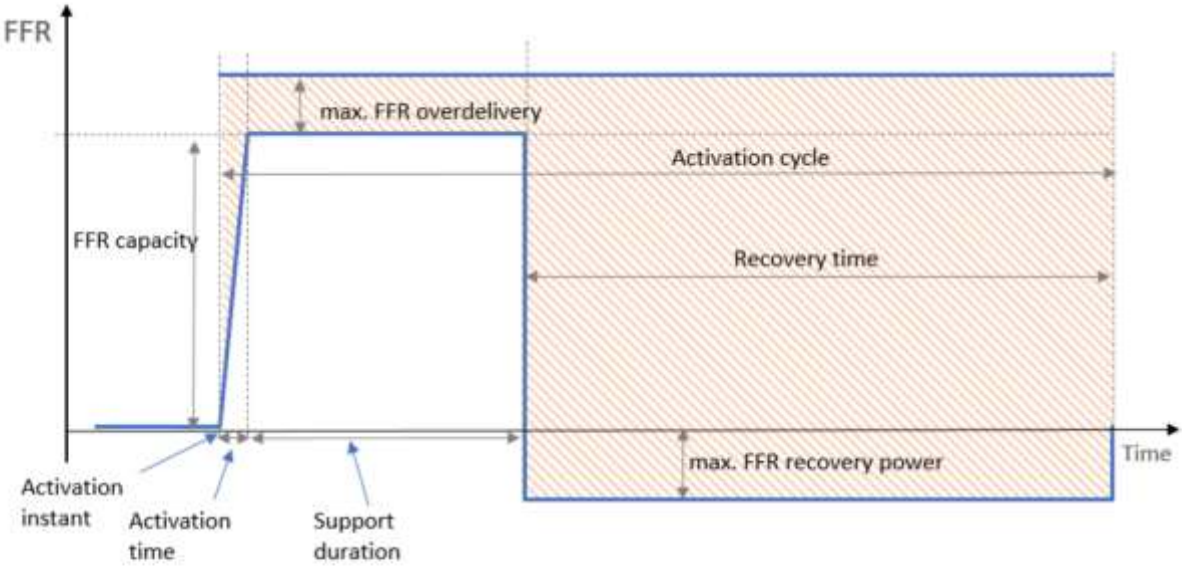


Figure 2 Recovery curve for 30-second support duration units.

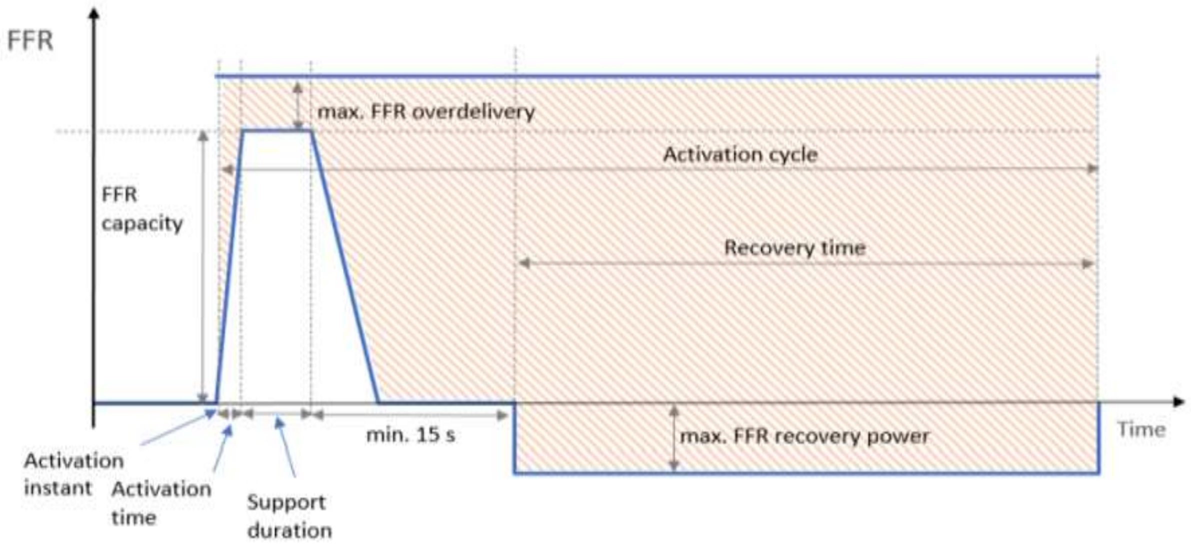


Figure 3 Recovery curve for 5-second support duration units.

Appendix 3. Maintaining the FCR-D up and the FFR with the same Reserve Unit [13]

Figure 1 illustrates the approach for calculating reserve capacity, specifically focusing on the power output of the Reserve Unit concerning frequency variations from 49.9 Hz to 49.5 Hz in incremental steps. The red section of the curve in the graph represents the accepted capacity for FFR ($\mathrm{C_{FFR}}$), which is determined according to the following procedure:

$$\mathrm{C_{FFR}} = \Delta \mathrm{P_{1s}} = 2\mathrm{MW}$$

In order to calculate the capacity of the FCR-D, the measured power capacity at 5 and 30-second modes is reduced by the volume of the FFR,

$$\mathrm{C_{FCR-D}} = \min \{2 \times (\Delta \mathrm{P_{5s}} - \mathrm{C_{FFR}}), (\Delta \mathrm{P_{30s}} - \mathrm{C_{FFR}})\} = 8\mathrm{MW}$$

The following power capacities can be sold by the unit in question:

a) 2MW of FFR and 8MW of FCR-D, or

b) 0MW of FFR and 12MW of FCR-D

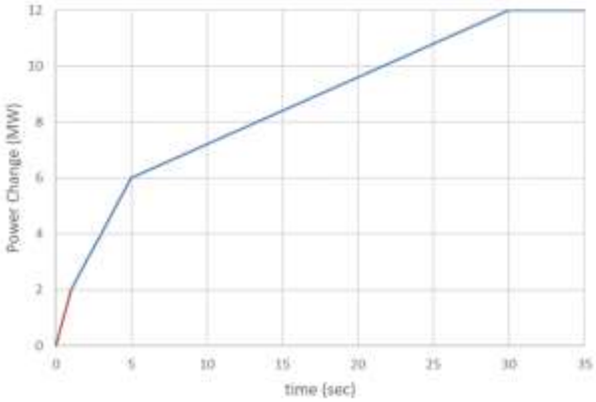


Figure 1 FFR and FCR-D for the same Reserve Unit.

Appendix 4. Prequalification testing sequences and methods of the FFR provision [49][13]

The BSP holds the responsibility of ensuring that every Reserve Unit involved in maintaining the FFR adheres to the technical requirements outlined in the document. To validate the compliance of these units, prequalification tests are carried out under regular operating conditions. These tests thoroughly assess the functionality of all designated control settings for the Reserve Unit.

To be eligible to participate in the FFR market, providers must successfully pass these prequalification tests, which serve as a demonstration of their adherence to the specified technical requirements. This rigorous evaluation process ensures that only qualified and technically capable Reserve Units are allowed to contribute to the FFR and support the stability and reliability of the grid system.

The document [50] describes the testing procedures required to qualify entities offering FFR services in the Nordic power system. It comprises four main sections: a summary of the prequalification planning process, recommended to start well in advance; preparations before conducting the tests; the testing phase itself; and post-testing tasks, which involve handling the test results and preparing for the formal application. Table 1 presents essential criteria for FFR provision, including the minimum measurement required for the entity.

Table 1 Requirements for measurements.

Measured quantity	Category	Rated power	Accuracy	Resolution	Sampling rate
Active power	1	< 2 MW	±5%	0.01 MW	10 Hz
	2	2 – 10 MW	±1%		
	3	> 10 MW	±0.5%		
Grid frequency			±10 mHz	10 mHz	10 Hz
Applied frequency			± 10 mHz	10 mHz	10 Hz

Prequalification test

Test methods

There are two viable approaches for conducting the prequalification of the Fast Frequency Reserve. The more favorable option involves employing an external synthetic test signal. For further details on the second test method, please consult reference. [50]

Test program

In order to assess the capacity of all participating entities, a prequalification test is essential. This test entails executing a frequency ramp or step response sequence as outlined in Figures 2 and 3. To determine the appropriate frequency threshold for FFR activation, one must consider the options specified in the technical requirements for FFR. The ramp or step response should commence from a starting frequency within the range of 49.9 to 50.1 Hz. Before applying the test signal, it is imperative to record measurement data for a minimum duration of 2 minutes, and the logging process must persist until the providing entity is deactivated and ready for a new activation.

Step response test

To carry out step response tests, it is necessary to execute two distinct steps as visually represented in Figure 2. To activate the resource for FFR, a step response sequence is performed with the first step taken to a level just above the activation threshold, followed by the second step taken just below the threshold required for activation. The FFR activation must be triggered within a frequency range of ±0.05 Hz relative to the chosen frequency threshold for activation. This means that after the first step, FFR activation should not take place while following the second step, FFR activation should occur.

Ramp response test

When performing a ramp response test following the guidelines in Figure 3, the ramp's speed is not critical, but it should not exceed -0.2 Hz/s in order to capture the frequency level during activation. Similar to the step response test, FFR activation should take place within a frequency range of ±0.05 Hz from the frequency threshold for activation.

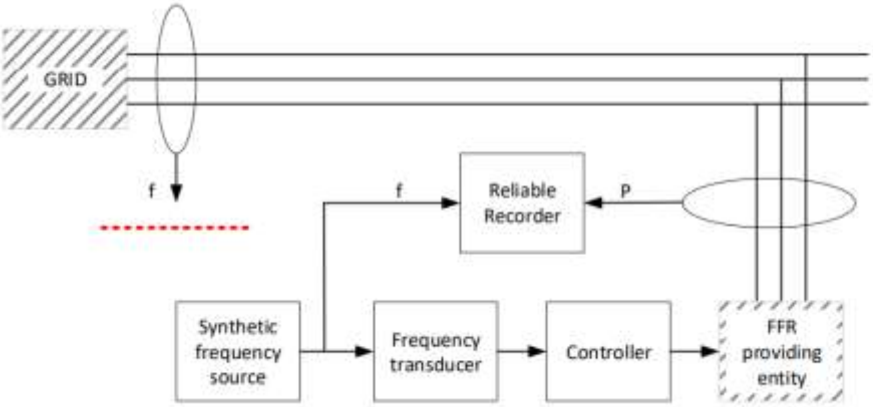


Figure 1 Test with an external synthetic frequency signal.

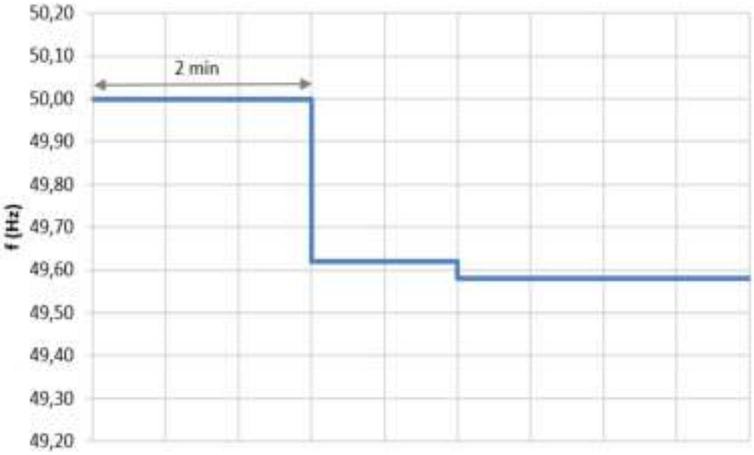


Figure 2 A step response sequence for FFR activation at a level of 49.6 Hz.

Figure 3 FFR ramp response test.

Appendix 5. Calculation of capacity and compliance in an FFR unit [49]

Figure 1 indicates the capacity, over-delivery, activation time, and support duration for an FFR entity.

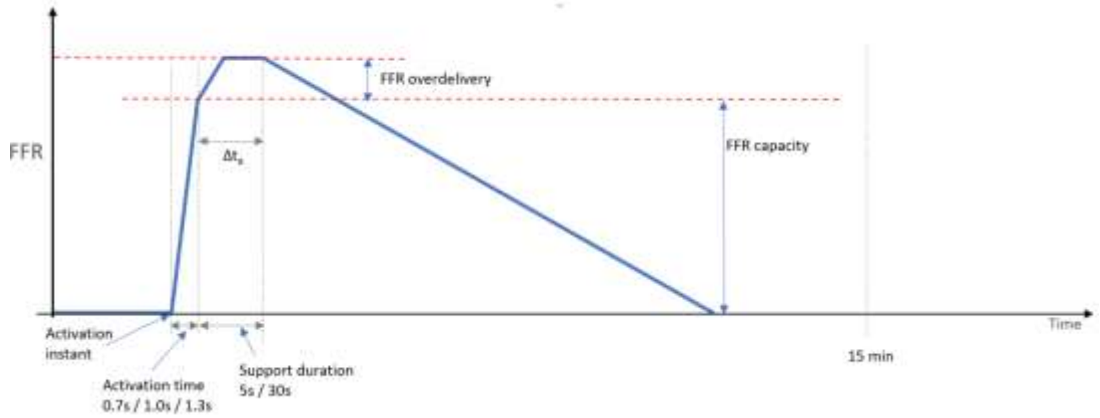


Figure 1 Identification curve for an FFR unit, the capacity, over-delivery, activation time, and support duration.

Calculation of prequalified capacity

The capacity of a prequalified FFR unit refers to the minimum amount of FFR it can provide within a defined time interval Δt_a, as depicted in Figure 1. Mathematically, this capacity can be expressed as follows:

$$C_{pre-qual} = \min\left(\mathrm{abs}\left(P(t) - P(0)\right)\right) \text{ (MW)}$$

Where,

$C_{pre-qual}$	prequalified FFR capacity (MW)
$P(t)$	The exchanged power between the grid and the Reserve Unit (MW)
$P(0)$	The baseline for power capacity
t	Time, where $t \in \{t_{Full\ Act}, t_{Full\ Act} + t_{Min\ Dur}\}$
$t_{Full\ Act}$	maximum activation time (0.7, 1.0, or 1.3s)
$t_{Min\ Dur}$	minimum duration time (5.0 or 30s)

Calculation of overdelivery of prequalified FFR

As per the document, the maximum permissible excess supply of FFR capacity is restricted to 20% of the prequalified FFR capacity, as illustrated in Figure 1. To determine the excess FFR supply, one must find the difference between the maximum delivered FFR capacity within the time interval Δt_a and the prequalified FFR capacity, and then express this difference as a percentage of the prequalified FFR capacity. The mathematical formula for this calculation is provided below:

$$\mathrm{FFR_{OD}} = \frac{\max\left(\mathrm{abs}\left(P(t) - P(0) - C_{\mathrm{pre-qual}}\right)\right)}{C_{\mathrm{pre-qual}}} \times 100\%$$

Where,

$\mathrm{FFR_{OD}}$	over- of FFR [%]
$C_{\mathrm{pre-qual}}$	prequalified FFR capacity [MW]
$P(t)$	exchanged power between the grid and the Reserve Unit [MW]
$P(0)$	The baseline for power capacity
t	Time, where $t \in \{t_{\mathrm{Full\ Act}}, t_{\mathrm{cycle}}\}$
$t_{\mathrm{Full\ Act}}$	maximum activation time (0.70, 1.00, or 1.30 s)
t_{cycle}	Time to complete a whole FFR activation cycle, including activation, deactivation, and recovery.

Appendix 6. Sample contract for FFR market

The sample contract between the two parties entails several crucial provisions, outlined below:

- Control Properties and Prequalification Tests: The contract ensures that the control properties of the reserve capacity are verified through prequalification tests and listed in an electronic data system known as RESTORE.

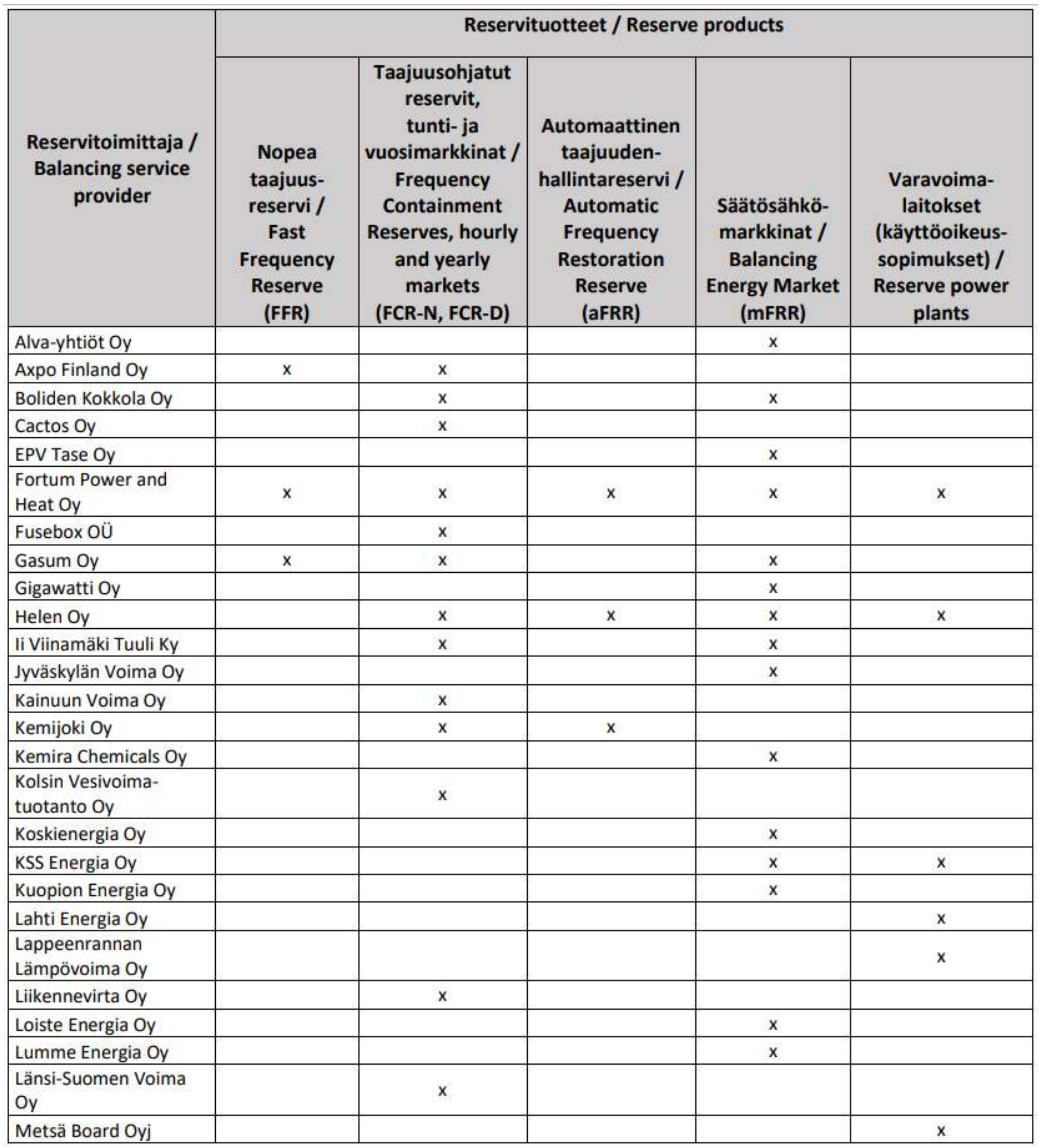
- Value-Added Tax (VAT) Payment: In addition to the specified fees, Fingrid, one of the contracting parties, is obligated to pay the applicable VAT at any given time.

- Force Majeure Clause: In cases of force majeure, both contracting parties have the right to restrict or completely interrupt the maintenance of reserves. Force majeure refers to events beyond the control of a party, unknown to both parties at the time of the agreement's conclusion, and not preventable or avoidable through reasonable measures. Such events may render the maintenance of reserves impossible, significantly complicated, or otherwise unreasonable. Examples of force majeure events include war, internal unrest in a country, sabotage, explosions, fires, prolonged faults at power plants, extreme weather conditions, general disruptions in traffic, strikes, stoppages of key employee groups, lock-outs ordered by employer organizations, measures by authorities, or other reasons with significant and unusual consequences.

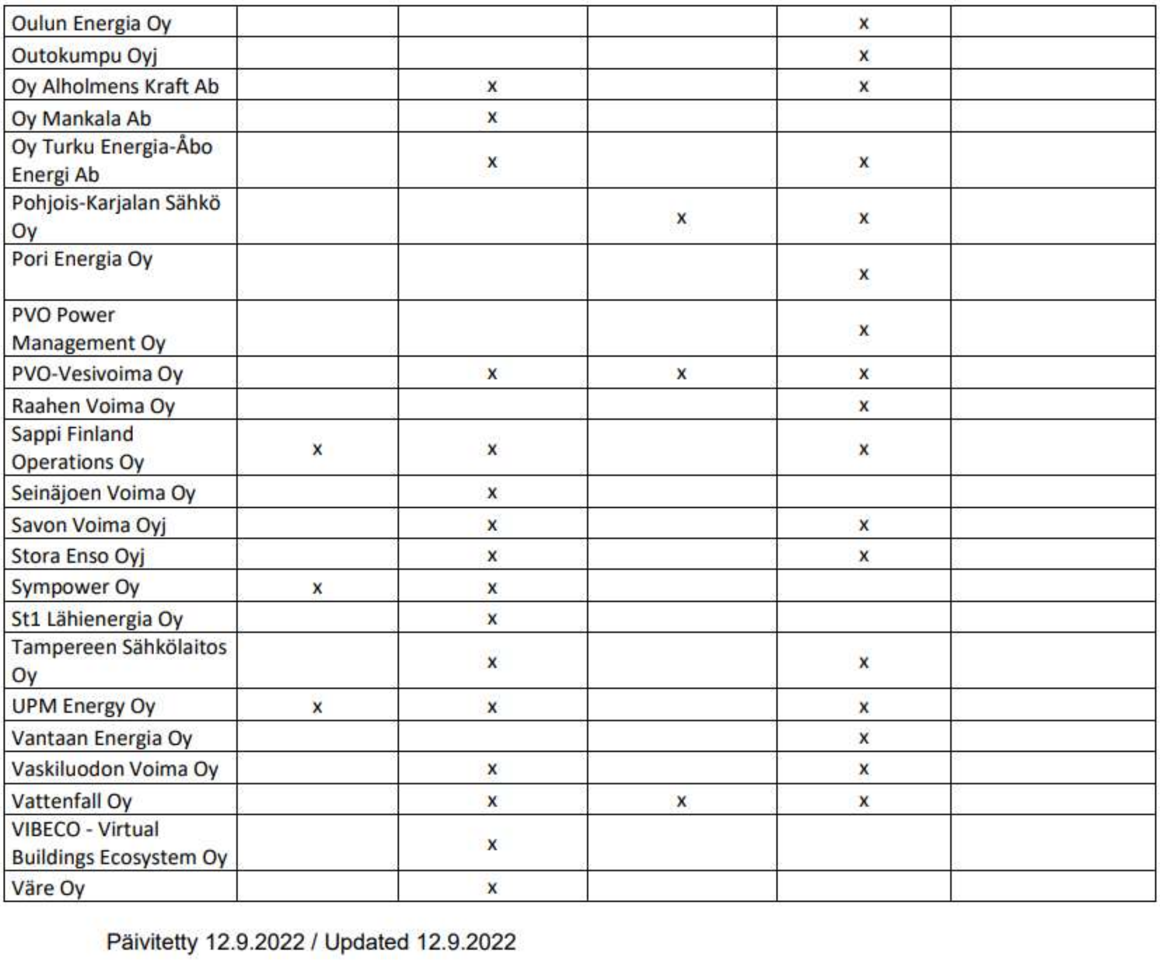
- Confidential Information Handling: Both parties are prohibited from disclosing confidential information related to the agreement to third parties without written consent from the other party. However, Fingrid may disclose confidential information to a third party for research studies commissioned by them, specifically concerning the functioning or development of the reserve market. In such cases, Fingrid is required to sign a non-disclosure agreement with the third party, wherein the third party agrees not to share party-specific information during or after the research study. The other contracting party must be informed beforehand regarding the disclosure of information for the mentioned research purposes.

These are some important points of a complete contract. The reference [15] includes a sample contract with more clauses and considerations.

Appendix 7. Balancing service providers and reserve products in Fingrid [50]



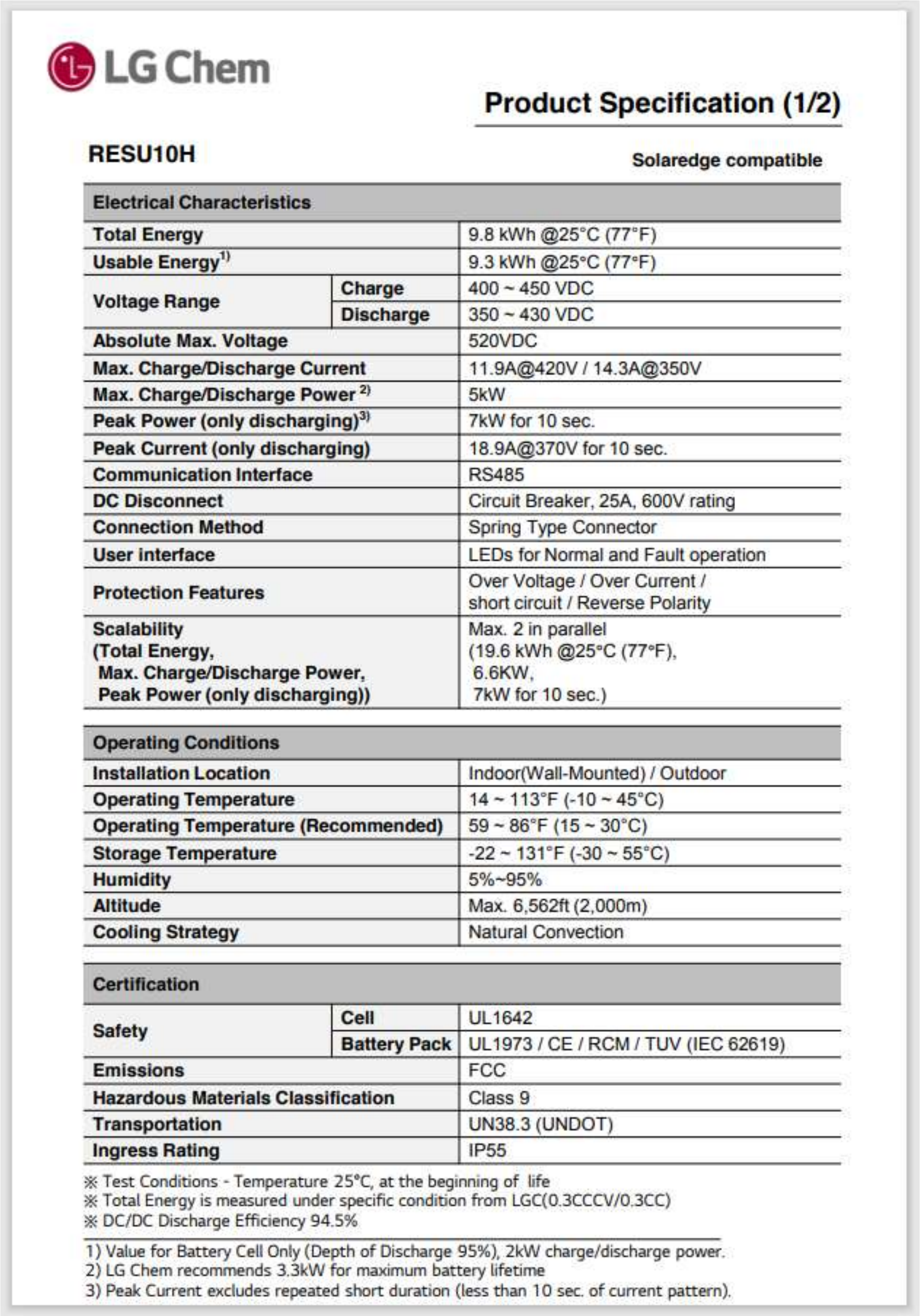
Reservitoimittaja / Balancing service provider	Reservituotteet / Reserve products				
	Nopea taajuus-reservi / Fast Frequency Reserve (FFR)	Taajuusohjatut reservit, tunti- ja vuosimarkkinat / Frequency Containment Reserves, hourly and yearly markets (FCR-N, FCR-D)	Automaattinen taajuuden-hallintareservi / Automatic Frequency Restoration Reserve (aFRR)	Säätösähkö-markkinat / Balancing Energy Market (mFRR)	Varavoima-laitokset (käyttöoikeus-sopimukset) / Reserve power plants
Alva-yhtiöt Oy				x	
Axpo Finland Oy	x	x			
Boliden Kokkola Oy		x		x	
Cactos Oy		x			
EPV Tase Oy				x	
Fortum Power and Heat Oy	x	x	x	x	x
Fusebox OÜ		x			
Gasum Oy	x	x		x	
Gigawatti Oy				x	
Helen Oy		x	x	x	x
Ii Viinamäki Tuuli Ky		x		x	
Jyväskylän Voima Oy				x	
Kainuun Voima Oy		x			
Kemijoki Oy		x	x		
Kemira Chemicals Oy				x	
Kolsin Vesivoima-tuotanto Oy		x			
Koskienergia Oy				x	
KSS Energia Oy				x	x
Kuopion Energia Oy				x	
Lahti Energia Oy					x
Lappeenrannan Lämpövoima Oy					x
Liikennevirta Oy		x			
Loiste Energia Oy				x	
Lumme Energia Oy				x	
Länsi-Suomen Voima Oy		x			
Metsä Board Oyj					x



Oulun Energia Oy				x	
Outokumpu Oyj				x	
Oy Alholmens Kraft Ab		x		x	
Oy Mankala Ab		x			
Oy Turku Energia-Åbo Energi Ab		x		x	
Pohjois-Karjalan Sähkö Oy			x	x	
Pori Energia Oy				x	
PVO Power Management Oy				x	
PVO-Vesivoima Oy		x	x	x	
Raahen Voima Oy				x	
Sappi Finland Operations Oy	x	x		x	
Seinäjoen Voima Oy		x			
Savon Voima Oyj		x		x	
Stora Enso Oyj		x		x	
Sympower Oy	x	x			
St1 Lähienergia Oy		x			
Tampereen Sähkölaitos Oy		x		x	
UPM Energy Oy	x	x		x	
Vantaan Energia Oy				x	
Vaskiluodon Voima Oy		x		x	
Vattenfall Oy		x	x	x	
VIBECO - Virtual Buildings Ecosystem Oy		x			
Väre Oy		x			

Päivitetty 12.9.2022 / Updated 12.9.2022

Appendix 8. Characteristics of LG battery [51]



LG Chem

Product Specification (1/2)

RESU10H

Solaredge compatible

Electrical Characteristics		
Total Energy		9.8 kWh @25°C (77°F)
Usable Energy1)		9.3 kWh @25°C (77°F)
Voltage Range	**Charge**	400 ~ 450 VDC
	Discharge	350 ~ 430 VDC
Absolute Max. Voltage		520VDC
Max. Charge/Discharge Current		11.9A@420V / 14.3A@350V
Max. Charge/Discharge Power 2)		5kW
Peak Power (only discharging)3)		7kW for 10 sec.
Peak Current (only discharging)		18.9A@370V for 10 sec.
Communication Interface		RS485
DC Disconnect		Circuit Breaker, 25A, 600V rating
Connection Method		Spring Type Connector
User interface		LEDs for Normal and Fault operation
Protection Features		Over Voltage / Over Current / short circuit / Reverse Polarity
Scalability (Total Energy, Max. Charge/Discharge Power, Peak Power (only discharging))		Max. 2 in parallel (19.6 kWh @25°C (77°F), 6.6KW, 7kW for 10 sec.)

Operating Conditions	
Installation Location	Indoor(Wall-Mounted) / Outdoor
Operating Temperature	14 ~ 113°F (-10 ~ 45°C)
Operating Temperature (Recommended)	59 ~ 86°F (15 ~ 30°C)
Storage Temperature	-22 ~ 131°F (-30 ~ 55°C)
Humidity	5%~95%
Altitude	Max. 6,562ft (2,000m)
Cooling Strategy	Natural Convection

Certification		
Safety	**Cell**	UL1642
	Battery Pack	UL1973 / CE / RCM / TUV (IEC 62619)
Emissions		FCC
Hazardous Materials Classification		Class 9
Transportation		UN38.3 (UNDOT)
Ingress Rating		IP55

※ Test Conditions - Temperature 25°C, at the beginning of life
※ Total Energy is measured under specific condition from LGC(0.3CCCV/0.3CC)
※ DC/DC Discharge Efficiency 94.5%

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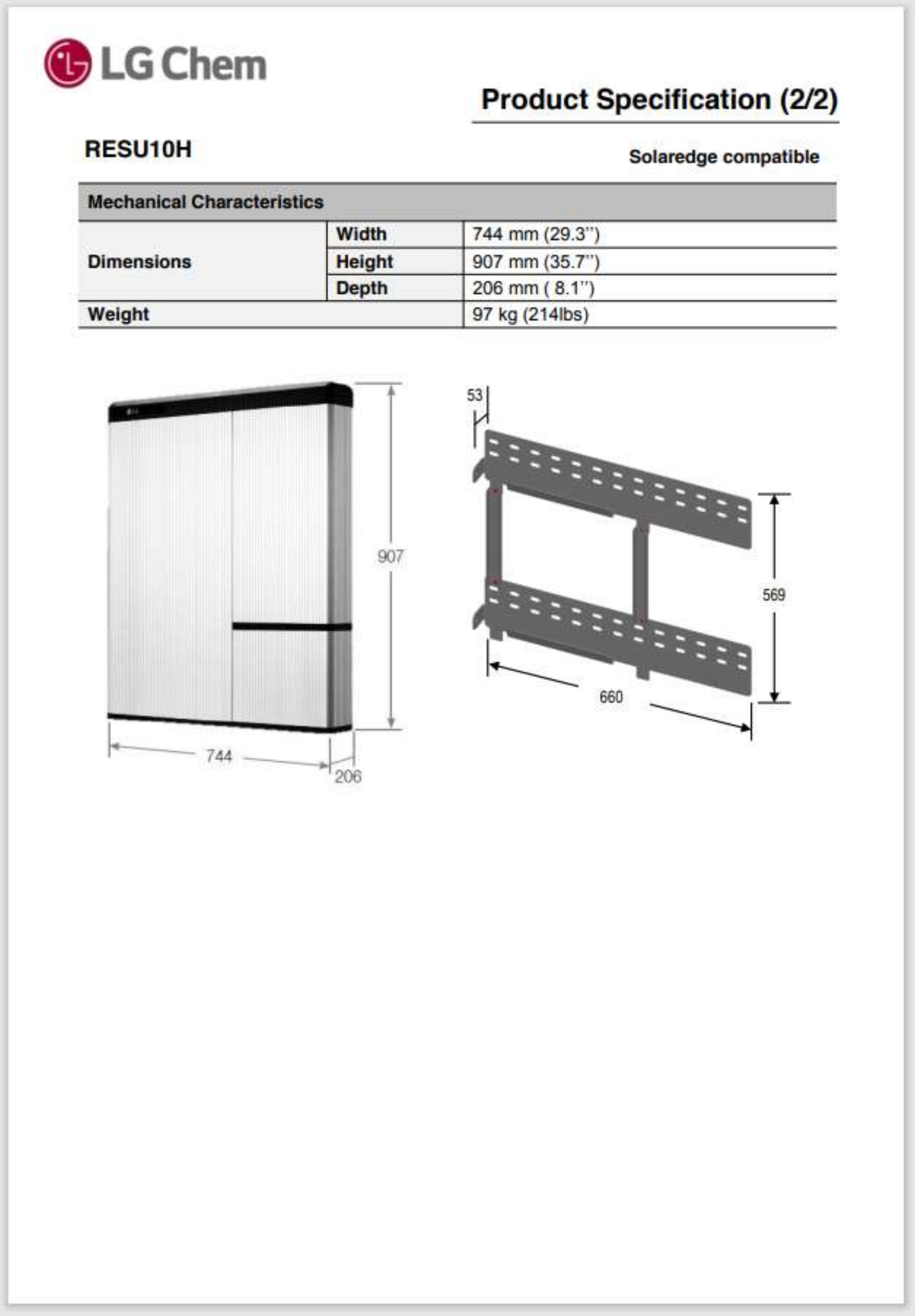
1) Value for Battery Cell Only (Depth of Discharge 95%), 2kW charge/discharge power.
2) LG Chem recommends 3.3kW for maximum battery lifetime
3) Peak Current excludes repeated short duration (less than 10 sec. of current pattern).



LG Chem

Product Specification (2/2)

RESU10H

Solaredge compatible

Mechanical Characteristics		
Dimensions	**Width**	744 mm (29.3'')
	Height	907 mm (35.7'')
	Depth	206 mm (8.1'')
Weight		97 kg (214lbs)

Appendix 9. Characteristic of Skeleton supercapacitor [52]

DATA SHEET

SkelCap
supercapacitor

- Capacitance 3200 F
- Extreme power density
- Durable and safe aluminum casings
- Weldable terminals*
- High cycle life >1,000,000 cycles
- High temperature tolerance (operating and storage)
- German quality
- RoHS compliant
- UL certified

General	Value	Unit
Rated voltage V_R	2.85	V
Surge voltage V_s	3.0	V
Rated capacitance	3200	F
Specific energy	6.8	Wh/kg
Product code	6710038	
DC 10ms ESR rated	0.14	mΩ
DC 1s ESR rated	0.18	mΩ
Maximum peak current, for 1 second [1, 9]	2.89	kA
Leakage current (At 2.85 V, 25 °C and 72 hours, max)	11.0	mA

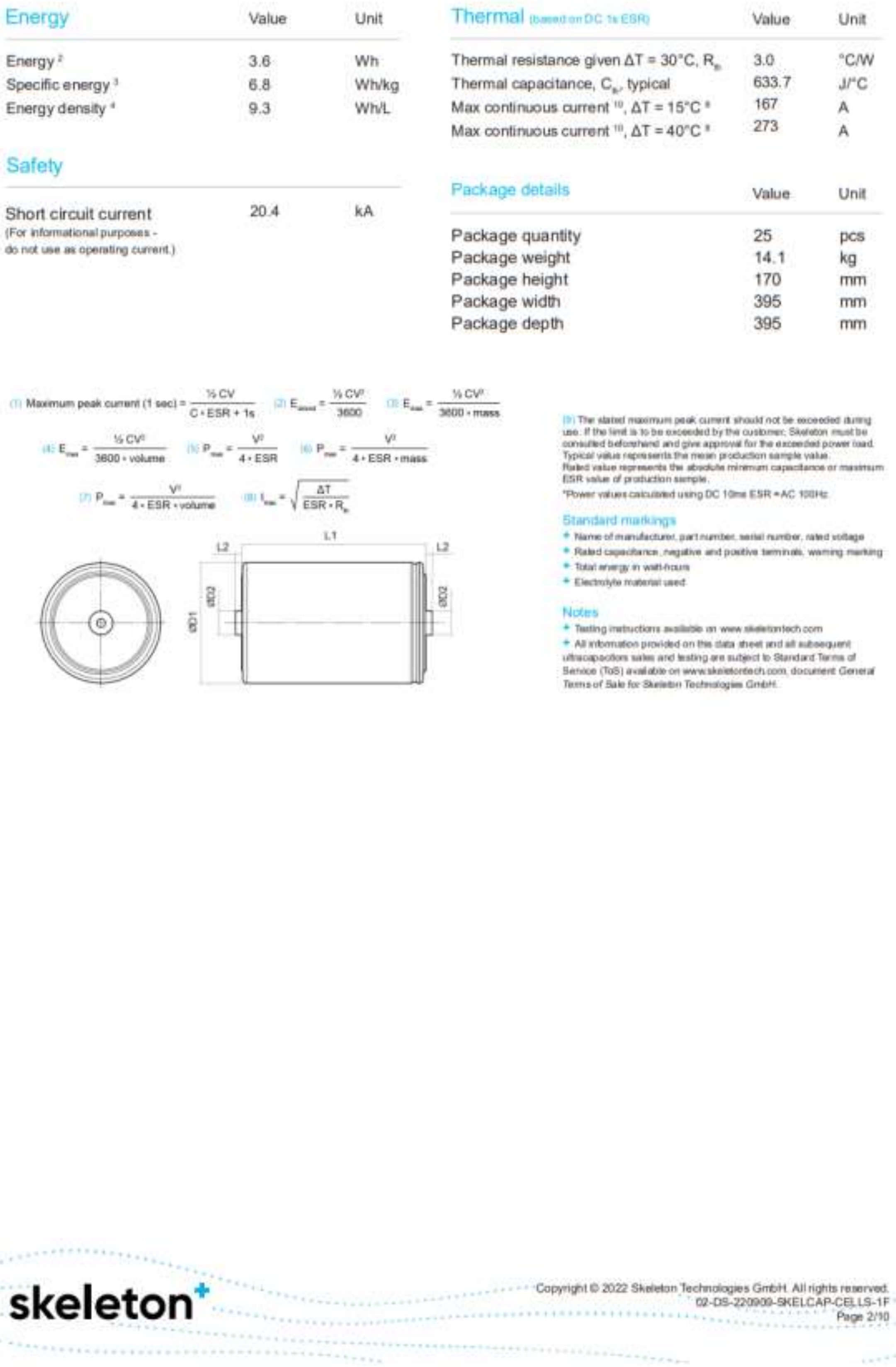
Standards and certifications	
Vibration Specification	ISO 16750-3, Table 12
Certifications	RoHS, UL 810A

Physical parameters		
Mass, typical (± 3-6 g, from small to large size)	0.53	kg
Volume	0.390	L
Diameter (± 0.2 mm, including label), D1	60.2	mm
Length (± 0.3 mm), L1	138	mm
Terminal diameter, D2	12	mm
Terminal length, L2	3.2	mm

Power	Value	Unit
Nominal power, calculated from 10ms ESR (for comparison)		
Specific power, matched impedance [6]	27	kW/kg
Power density, matched impedance [7]	37	kW/L
Nominal power, calculated from 1s ESR (for engineering)		
Power, matched impedance [5]	11.3	kW
Specific power, matched impedance [6]	21	kW/kg
Power density, matched impedance [7]	29	kW/L

Temperature and Life		
Operating temperature range		
Minimum	-40	°C
Maximum	+65	°C
Storage temperature range (uncharged)		
Minimum	-40	°C
Maximum	+50	°C
Life		
Lifetime @ V_R and +65 °C Capacitance decrease 20% against rated value; 1s ESR increase 100% against rated value	1500	Hours
Storage life @ RT, uncharged	10	Years
Cyclelife @ RT, between V_R and $V_R/2$	1,000,000	Cycles

skeleton⁺



Energy

Energy	Value	Unit
Energy[2]	3.6	Wh
Specific energy[3]	6.8	Wh/kg
Energy density[4]	9.3	Wh/L

Safety

Safety		
Short circuit current (For informational purposes - do not use as operating current.)	20.4	kA

Thermal (based on DC 1s ESR)

Thermal (based on DC 1s ESR)	Value	Unit
Thermal resistance given ΔT = 30°C, R_{th}	3.0	°C/W
Thermal capacitance, C_{th}, typical	633.7	J/°C
Max continuous current[10], ΔT = 15°C[8]	167	A
Max continuous current[10], ΔT = 40°C[8]	273	A

Package details

Package details	Value	Unit
Package quantity	25	pcs
Package weight	14.1	kg
Package height	170	mm
Package width	395	mm
Package depth	395	mm

(1) Maximum peak current (1 sec) = $\frac{\frac{1}{2} CV}{C \cdot ESR + 1s}$ (2) $E_{stored} = \frac{\frac{1}{2} CV^2}{3600}$ (3) $E_{max} = \frac{\frac{1}{2} CV^2}{3600 \cdot mass}$

(4) $E_{max} = \frac{\frac{1}{2} CV^2}{3600 \cdot volume}$ (5) $P_{max} = \frac{V^2}{4 \cdot ESR}$ (6) $P_{max} = \frac{V^2}{4 \cdot ESR \cdot mass}$

(7) $P_{max} = \frac{V^2}{4 \cdot ESR \cdot volume}$ (8) $I_{max} = \sqrt{\frac{\Delta T}{ESR \cdot R_{th}}}$

(9) The stated maximum peak current should not be exceeded during use. If the limit is to be exceeded by the customer, Skeleton must be consulted beforehand and give approval for the exceeded power load. Typical value represents the mean production sample value. Rated value represents the absolute minimum capacitance or maximum ESR value of production sample.

*Power values calculated using DC 10ms ESR ≈ AC 100Hz

Standard markings

- Name of manufacturer, part number, serial number, rated voltage
- Rated capacitance, negative and positive terminals, warning marking
- Total energy in watt-hours
- Electrolyte material used

Notes

- Testing instructions available on www.skeletontech.com
- All information provided on this data sheet and all subsequent ultracapacitors sales and testing are subject to Standard Terms of Service (ToS) available on www.skeletontech.com, document General Terms of Sale for Skeleton Technologies GmbH.

skeleton