



Estimating potential revenue generation by energy storage systems providing multiple services to the Nordic electricity markets (Finland) through the QuESt Valuation Application

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Keywords: Nordic electricity markets, QuEST by Sandia, Day-ahead market, Ancillary services market, Energy Storage Systems (ESS), Revenue from ESS

This thesis evaluates the potential revenue generated by energy storage systems (ESS) in the Nordic electricity markets, particularly for the Finland region, using the open-source QuEST Valuation Application developed by Sandia National Laboratories. The study addresses a research gap by providing a comprehensive economic analysis of ESS profitability across various market segments, such as day-ahead, intraday, and regulation markets. The report used a unique optimization model with historical data to calculate the potential revenue from energy arbitrage and frequency regulation.

The findings will impact the way revenue calculations are viewed and the integration of ESS for grid stability, efficiency, and economic development. The breakdown also delves into various energy storage technologies and the Nordic power market, highlighting the crucial role of ESS in supporting renewable energy integration and achieving sustainability goals and growth.

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SYMBOLS AND ABBREVIATIONS

\bar{S}	Energy capacity	[MWh]
\bar{Q}	Energy charge/discharge rating	[MWh]
S_0	Initial state of charge	[MWh]
η	Efficiency	[%]
t	Hour	[h]
R	Interest/discount rate	[€]
C_{mcd}	Marginal cost of discharge	[€/KW – yr]
P	Nominal power rating	[MWh]

Abbreviations

ESS	Energy storage systems
TSO	Transmission system operator
aFRR	Automatic frequency restoration reserve
mFRR	Manual frequency restoration reserve
ISO	Independent system operator
RTO	Regional transmission organization
LMP	Locational marginal pricing
NREL	National renewable energy laboratory
PNNL	Pacific northwest national laboratory
DOE	Department of energy
CAISO	California independent system operator
PJM	Pennsylvania-new jersey-maryland interconnection

MISO	Midcontinent independent system operators
NYISO	New york independent system operator
ISO-NE	Independent system operator new england
SPP	Southwest power pool
VRLA	Valve-regulated lead-acid
HRPSoC	High-rate partial state of charge
LFP	Lithium iron phosphate
PHES	Pumped hydroelectric energy storage
DER-CAM	Distributed energy resources-customer adoption model
HOMER	Hybrid optimization of multiple electric renewables
SAM	System advisor model
REopt	Lite renewable energy integration & optimization
BSET	Battery storage evaluation tool
ESCT	Energy storage cost tool
OSESMO	Open-source energy storage model
QUEST	Quantitative energy storage tool

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Acknowledgements

Symbols and abbreviations

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1 Introduction

Due to the growing use of renewable energy sources, defined by their intermittent and variable nature, the development of effective energy storage systems (ESS) has become necessary to stabilize the grid and provide a reliable electricity supply. Renewable energy sources in power grids are crucial for achieving sustainable energy systems. From the perspective of this necessity, evaluating energy storage is essential. It allows us to compare and distinguish the efficiency with which various storage technologies improve the stability and dependability of the grid.

According to Field, energy storage systems will be vital components in renewable energy's instability, even in the current comprehensive European power grid [1]. In the European Union plan, ESS is one of the most important and critical technologies for achieving the 2050 target [2]. However, the boundary is the sophistication analysis of the price-cost of the energy storage system [3].

Electricity is a commodity, such as copper, oil, and grain. However, the electricity market has unique physical characteristics that differ it from other existing markets:

- Time: It's quite impossible to store a huge amount of electricity economically, which leads to gradual fluctuations in its value.
- Location: Electricity flow, especially renewable energy, is very challenging to control, and the transmission needs to be kept safe to preclude blackouts. This kind of difficulty affects locations a lot.
- Flexibility: Electricity demand needs to balance with electricity generation to prevent unexpected blackouts. Demand and renewable energy availability can fluctuate as some power stations experience slow output and failures. Therefore, the ability to adjust generation and consumption quickly is crucial.

These characteristics result in multiple electricity markets (energy, transmission capacity, flexibility) that operate in real-time until the delivery is finished [4]. While EU electricity markets are deregulated, other regions may have different regulatory models [5]. The Figure

1, that follows provides a high-level overview of the power markets that are currently in operation inside the European Union.

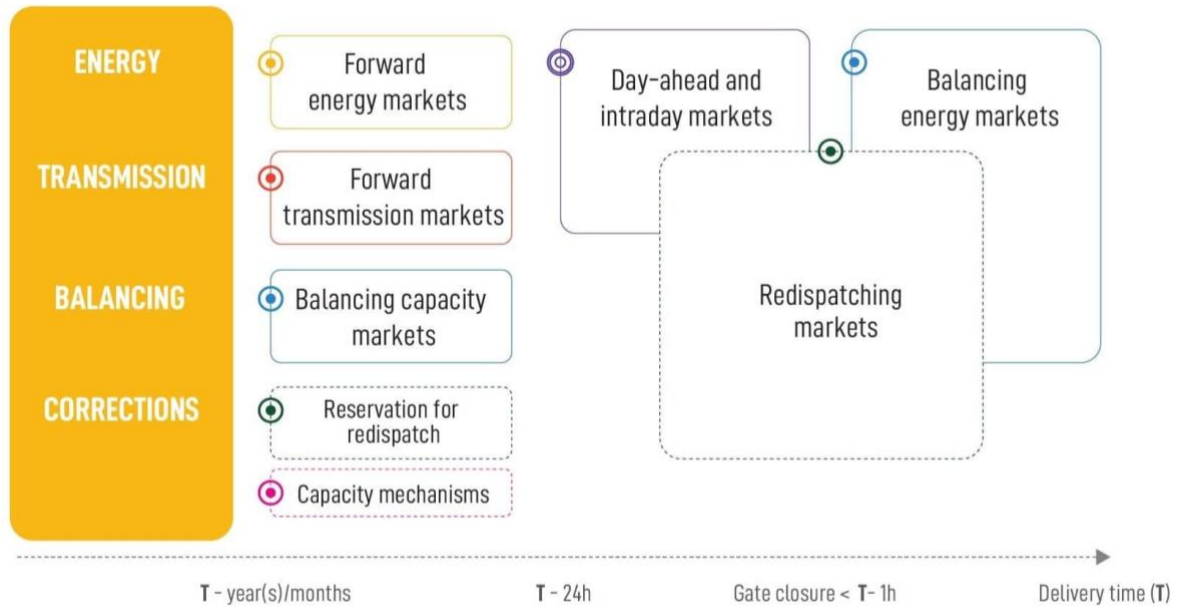


Figure 1 The typical sequence of existing electricity markets in the EU [5].

The day-ahead Price coupling initiative was announced in 2014–2015 [6] by the Nordic power market in conjunction with other European power exchange nations. Finland, Norway, Sweden, and Denmark are part of this collaboration. This initiative connects the power markets of the European Union with different pricing patterns and structures. Furthermore, this policy benefits the collaborator and opens new routes for gain through the ESS for energy arbitrage.

1.1 Aims and motivation

This thesis aims to deliver an implementable framework for maximizing the valuation of energy storage systems (ESS) from Finland's perspective (Part of the Nordic power market). The goal is to utilize the QUEST valuation software [7] and convey it to the Finnish environment through arbitrage and frequency regulation.

This study's motivation is to evaluate the economic performance of energy storage systems (ESS) in the Nordic Region using optimization models, which is crucial in this modern era. A valuation optimizer looks at many different factors in discrete-time, energy-based unben

programs to find the best way to run the ESS process. It focuses on energy trading and frequency regulation to make the most money possible. These models evaluate different market-related parameters, such as electricity prices, regulation capacity prices, and performance metrics.

Multiple types of energy storage capable-valuation tools are available, where they serve different purposes and have different characteristics.

- DER-CAM (The distributed energy resources-customer adoption model): Developed by Lawrence Berkeley National Laboratory (LBNL), it is an optimization tool for sizing DERs within microgrids. It uses mixed integer linear programming to select optimal DER combinations [8], focusing on reducing problem complexity using limited data [9].
- HOMER (The hybrid optimization of multiple electric renewables): Originally from the National Renewable Energy Laboratory (NREL), it is now commercially used for microgrid design [8]. It uses rules-based dispatch to optimize behind the meter of DER mixes [10].
- SAM (The system advisor model): Also Developed by NREL, it focuses on estimating the cost of energy from solar-plus-storage systems using rules-based dispatch without optimizing storage size [8]. It can handle energy arbitrage or demand reduction but not co-optimized services [11].
- REopt Lite (Renewable energy integration & optimization): Developed by NREL, optimizes the size and dispatch strategy for wind, solar, and battery storage in grid-connected scenarios, considering critical load requirements during outages. It uses a mixed integer linear program with a perfect foresight approach [10].
- BSET (The battery storage evaluation tool): From Pacific Northwest National Laboratory (PNNL) models provide various services like energy time shift, frequency regulation, and outage coverage. It calculates optimal dispatch and benefits based on input parameters and includes an optimal sizing tool for battery storage [12].
- ESCT (The energy storage cost tool): Developed by Navigant for the US DOE, ESCT models various large-scale storage technologies. It calculates values using average energy prices, limiting the number of stacked services and not representing optimum cases due to simplified assumptions [13].
- OSESMO (Open-source energy storage model): OSESMO is an open-source tool based on MATLAB or Python for dispatch optimization of storage systems paired with PV. It

is focused on California's Self-Generation Incentive Program but is applicable elsewhere. It optimizes carbon emissions outcomes and energy bill savings [14].

- **QUEST (Quantitative energy storage tool):** Developed by Sandia National Laboratories, it is an open-source dispatch optimization model with perfect foresight. It can download ISO data and tariffs, perform sensitivity analyses, and handle use cases like energy bill reduction and wholesale market participation [7].

This study is based on the QUEST (Quantitative Energy Storage Tool), specifically the valuation part of the QUEST. Here are the details of the valuation optimizer.

QUEST- by Sandia National Laboratories

QuEST is a Python-based application suite for energy storage modeling and analysis. This tool is free and open source, and its goal is to make Sandia energy storage analytics research tools accessible. It is a software application suite for energy storage evaluation. QuEST develops to analyze the benefits provided by energy storage to the grid and utility customers. This research is backed by the U.S. Department of Energy Office of Electricity Energy Storage program under the guidance of Dr. Imre Gyuk. Now, the important thing is to make it an industry where projects become commercially viable, and this is done by reducing cost and increasing value. It's not only the amount of energy the kilowatt hours or kilowatts are essential, but the quality of the energy that comes in, and that's what energy storage provides. It provides real value in introducing renewable energy [7].

- **QuEST valuation**

Valuation is part of Quest's mainstream line; it has several modes of analysis to detail and simplifies the process. With the appropriate historical market data of a specific electricity market area's payment structure and energy storage, the Quest Valuation application format will allow us to determine the maximum revenue possible through energy arbitrage or offering ancillary services in an electrical market.

Wizard, on the other hand, is part of Valuation analysis. It will provide an organized understanding of assessing and summarizing the anticipated revenue of a specific market area (in this research, only the Finland region from the Nordic power market) and energy storage devices. The other option is Batch runs mode, which offers extra adaptability and can be personalized for more detailed analysis. The last option in the Valuation is a built-in

results viewer for quick access to results, which helps to get the exported data much more quickly. The base software for the U.S. market supports all kinds of ISO/RTO databases [7].

1.2 Literature review

Comprehensive research has been ongoing on energy storage and market integration, which are the two main supports in the modern electricity market. They provide energy arbitrage, frequency regulation, and grid stability. The two possible studies were completed by [15] and [16], where the authors emphasized the operational strategies for the ESS. [15] Established the day-ahead market for pumped hydroelectric energy storage (PHES) by employing electricity price arbitrage without any profitability calculation. [16] Investigate the economic viability (day-ahead, regulation, and reserve markets) of electricity storage for the power market of West Denmark. The study found no economic viability for EESs for the big storage sizes, except for PHES with allocated availability costs and black-start income. The approach used does not account for functional and substitute prices for ESS.

The literature on the economic feasibility of ESS is primarily systematic. These two papers examine economic viability and market analysis. [17] study is based on the optimal sizing and scheduling of battery energy storage systems (BESS) for three markets: New York West in the United States, Ontario in Canada, and Queensland in Australia. The study employs many datasets for energy arbitrage. Likewise, [18] it Illustrates the profit maximization of EES in various market levels, such as day-ahead, intraday, and regulation markets, highlighting benefits from price arbitrage and ancillary services.

Multiple investigations based on technical and economic challenges have shown that one of the major challenges to deploying ESS is accurately quantifying its economic value. [19] and [20] explored the two different electricity area markets, PJM, and New York. Both papers highlight electricity prices based on small-scale energy storage with historical data sets, proving the intricacies of this kind of system and potential economic profitability.

In [15], [17], and [21], briefed practical application cases that provide the functioning and economic performance of ESS in the real world. For these cases, historical or predictive data from various markets are often used for simulation and ESS operations, demonstrating notable profit fluctuation determined by market-specific factors.

1.3 Research gaps and contributions

The existing literature largely unexplored the comparative feasibility study of energy storage systems (EES) in the Nordic region across different market levels. While numerous studies analyze ESS benefits within specific contexts or markets, a comprehensive assessment of EES performance and profitability across various Nordic electricity markets (such as day-ahead, intraday, and regulation markets) must be reported. This research gap highlights the need for targeted analysis to understand how ESS can be optimized across these different market segments to maximize economic and operational benefits in the Nordic region.

Despite extensive research on energy storage systems, there is a lack of targeted studies assessing the revenue potential of ESS, specifically within the Finnish regions of the Nordic market. This thesis aims to fill this gap by providing a detailed economic analysis and revenue estimation model with the help of QuEST tailored to Finland's market conditions. This study offers a comprehensive evaluation of ESS profitability in Finland using advanced optimization techniques and historical market data. It also explores the combined effects of arbitrage and frequency regulation on revenue generation, an area that has received limited attention in the context of the Nordic market.

1.4 Structure of the thesis

Chapter 2 studies the Energy market and storage system and conducts a background study regarding them in terms of the QuEST application.

Chapter 3 studies the optimization model. The two types of optimization models represented here are the arbitrage and regulation models. This section also presents a new model for the Nordic Market (Finland). The storage system model has also been discussed for the projected model.

Chapter 4 is all about the measurement value from the projected formula and the comparison with the real-world data.

2 Energy market and energy storage system (ESS)

This chapter examines energy market structure and efficiency, including spot, futures, and equilibrium markets. It scrutinizes the sale, pricing, and regulation of electricity and the roles of various stakeholders such as producers, users, and operators. In addition, it analyzes energy storage systems (ESS), discusses technologies such as batteries, their advantages, operational principles, and challenges, and also highlights the importance of ESS in grid stability, emphasizing the integration of stability and renewable energy.

2.1 Energy market

An energy market is a system through which electricity is traded, priced, and regulated. This includes markets, including the general market, where electricity is bought and sold for immediate delivery, and futures markets, where contracts are made for future delivery. An equilibrium market also has an energy market to ensure real-time synchronization between supply and demand. Participants in the energy market include producers, consumers, and regulators, all of whom work together to provide a stable and efficient energy flow.

Below, the Finnish market and USA energy markets are discussed for background on the QuEST application.

2.1.1 Finland energy market

In the Nordic nations (Finland, Norway, Sweden, and Denmark), physical power is traded in two distinguishable areas: the Nord Pool Spot and the local transmission system operators (TSO) markets. Both of these sites are known as energy marketplaces. Closed tendering is the method of exchanging services, and the market prices are determined by the supply and demand situation. Day-ahead trading, as well as intraday trading on Nord Pool Spot, are available on the market. The local TSO in Finland- Fingrid Oyj, is responsible for holding ancillary service markets. Figure 1 shows the power markets in Finland in detail.

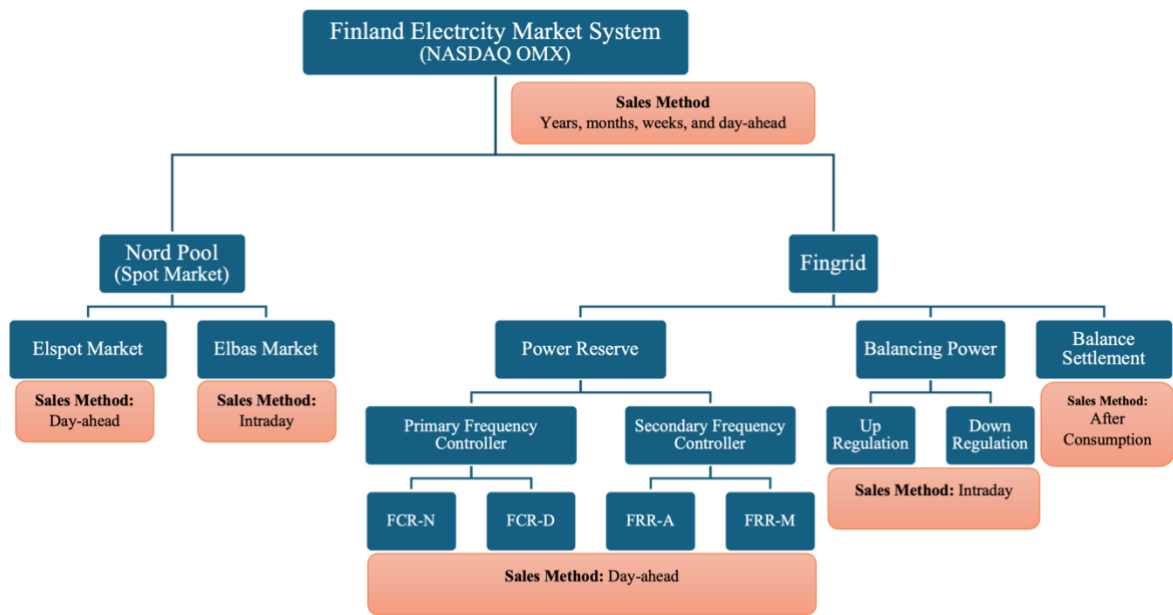


Figure 2 Finland electricity market

The wholesale market sets the price of electric energy, whereas the retail market facilitates transactions between power producers and users. Electricity consumers, including residential and commercial users, can purchase their electricity from a supplier of their preference. The market has been operational for more than two decades. Historically, the biggest power consumers have generated or bought a portion of their electricity from the wholesale electricity market. For instance, homeowners can purchase power directly at a price set in the wholesale market or generate a portion of their electricity using their equipment [22].

The common electricity market and electricity network in Finland serve as valuable tools for individuals who generate their own power. They facilitate the continuous adjustment of electricity demand and supply.

2.1.1.1 Spot market

For the spot market, Nord Pool operates as a market-based in the Nordic nation. It is organized by the Foreningen Samkjøringen, a power trading association founded in 1932 by eastern Norwegian energy firms under Augustin Paus. Nord Pool is jointly owned by Euronext (66%) and TSO Holding (34%). The Nord Pool Spot market area has expanded to

include all Nordic and Baltic states. Currently, Nord Pool Spot is the largest global power market based on the total number of deals conducted, providing trading, clearing, settlement, and related services in day-ahead and intraday markets across 16 European countries [23].

2.1.1.1.1. Elspot market

The day-ahead electricity market is known as the Elspot market. Between 2009 and 2013 [6], the Nordic power market discovered its effectiveness in using Elspot pricing for Finland [24]. This market operates as an open auction; participants can bid and purchase electricity for the next day. Elspot is a very flexible market, and participants can bid for hourly, block, or forthcoming hours before 13:00 (time zone in Finland: GMT+3). The participants receive the accepted bid price the following day at 13:45 [25].

2.1.1.1.2. Elbas market

Elbas operates as an intraday system, making trading simpler and faster with multiple customizations and various functionalities across different markets [6]. It is a physical market that operates on the basis of real-time power trading, whether it is day- or year-round. Elbas allows trading to continue until one hour or even up to 45 minutes in advance. This system primarily aims to balance supply and demand during unpredictable days, but it also has the potential to alter the trading dynamics of the Elspot market [24].

More flexibility and customization are helping Elbas grow, and as the urge to increase renewable energy power grows, Elbas's future becomes more visible [26].

2.1.1.2 Ancillary service markets

Fingrid Oyj, the Finnish Transmission System Operator (TSO), is responsible for maintaining the stability and security of Finland's power system. In a competitive market, Fingrid plays a very important role in providing ancillary services.

- Frequency containment reserves (FCR)
- Frequency restoration reserves (FRR)

- Balancing power markets
- Voltage support
- Black start services

Those services, known as grid balancing services, balance the production and consumption of electricity in the market. The balancing, also known as the frequency of the electricity grid, operates at approximately 50 Hz. Figure 3 illustrates the frequency control process.

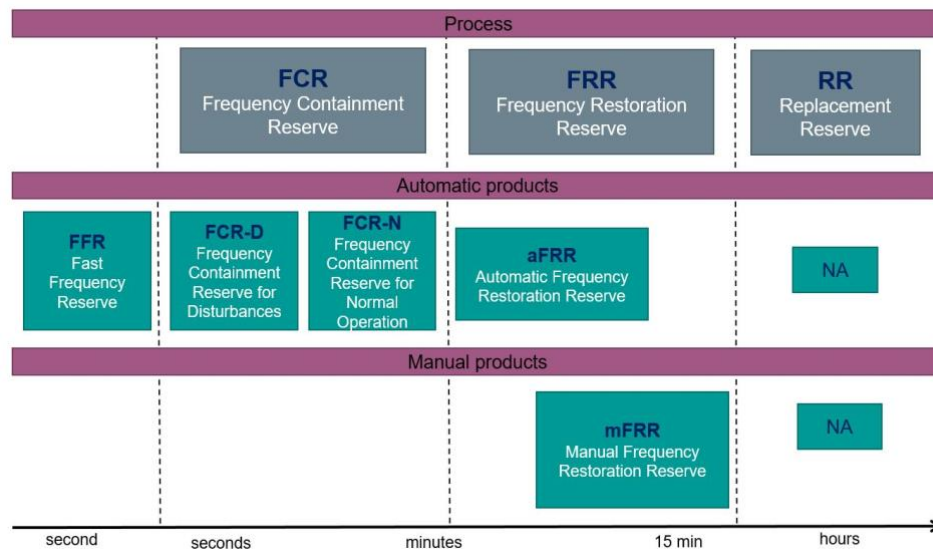


Figure 3 The process of power reserve markets for frequency control [24].

Grid balancing stabilizes the grid fluctuations by managing both supply and demand, resulting in a flawless, stable electricity supply to consumers.

2.1.1.2.1. Frequency containment reserves (FCR)

The Frequency Containment Reserve for Normal Operation (FCR-N) and the Frequency Containment Reserve for Disturbances (FCR-D) are two distinct types of active power reserves. The power system automatically controls and activates these reserves in response to frequency deviations. Specifically, the FCR-N helps maintain frequency levels during normal operation, while the FCR-D addresses frequency deviations caused by power grid disturbances.

2.1.1.2.1.1. FCR for normal operation (FCR-N)

The reserve range frequency is 49.9 Hz to 50.1 Hz, stabilizing normal grid operations. The system must be symmetrically controlled, with the ability to increase or decrease power production or consumption based on its needs. The FCR-N requires a minimum bid size of 0.1 MW and full power activation within 3 minutes, adhering to the power system frequency.

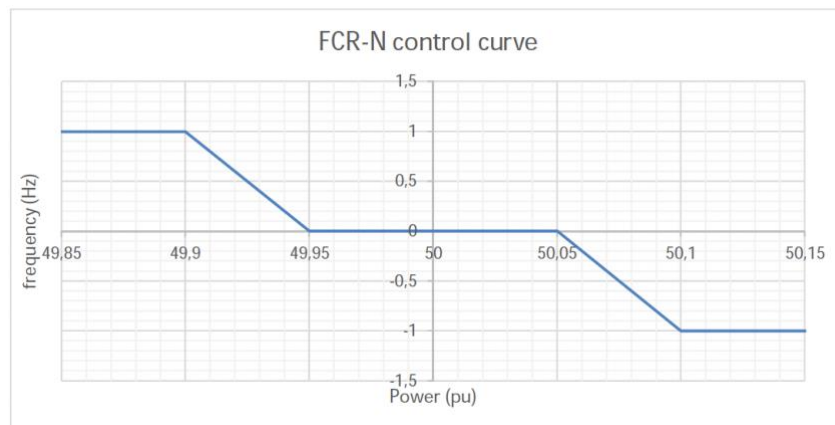


Figure 4 FCR-N control curve [27].

2.1.1.2.1.2. FCR for disturbances (FCR-D)

The design of the power system allows for a significant deviation in frequency from the typical range of 49.5 Hz to 50.5 Hz, which triggers this reserve. The minimum bid size of 1 MW separates it into items subject to either up-regulation or down-regulation. The time required to activate reserves depends on the degree of frequency deviation from its intended value and the specific characteristics of the energy resource supplying the reserves.

Table 1 FCR-D & FCR-N market rules for different resources [24] [27].

Resource	Full Activation Time	Other
Power plant reserves	5s / 50% 30s / 100%, with frequency 49.50 Hz	N/A
Relay-connected loads	Immediately with frequency $30s \leq 49.70$ Hz or $5s \leq 49.50$ Hz	Load can be reconnected to grid, when frequency is at least 49.90 Hz for five mins
Idle reserve power machines	Reserve should be activated when frequency $30s \leq 49.70$ Hz	Machine can be disconnected from grid, when frequency is at least 49.90 Hz for five minutes
FCR-N (Normal Operation)	Approximately 63% within 1 minute; Approximately 95% within 3 minutes	Must be capable of both up- and downregulation to maintain frequency within 49.9 Hz to 50.1 Hz range; Load can be reconnected to grid, when frequency is at least 49.90 Hz for five minutes

2.1.1.2.2. Frequency restoration reserves (FRR)

A malfunction in a single electricity production unit or a high-voltage direct current (HVDC) link often causes power outages. For these purposes, FRR serves as a safeguard for the power system. It restores the grid drop frequency, which is less than 49.0 Hz. The FFR operates when the system experiences low inertia, primarily linked to the frequency change rate within a power system. For instance, the low presence of inertia will cause a frequency drop, and the system will collapse with load shedding due to the lack of reserves.

2.1.1.2.2.1. Automatic frequency restoration reserve (aFRR)

The Nordic TSO presented aFRR (Automatic Frequency Restoration Reserve) in 2013, as it desired to restore the balance of the power system quickly. aFRR can stabilize the power system frequency, which assures the 50 Hz nominal value. It can also activate automatically based on Frequency divergence. The ability to quickly and automatically restore frequency

deviations ensures the smooth operation of the power grid and minimizes the risk of power outages or equipment failure.

The Nordic TSOs have introduced automatic frequency restoration (aFRR), which is critical for maintaining grid stability, especially during unexpected events or sudden changes in power demand or supply. This proactive approach to frequency regulation supports the broader integration of renewable energy sources.

2.1.1.2.2. Manual frequency restoration reserve (mFRR)

One of the Nordic TSO's most valuable components is the mFRR. Unlike aFRR, the TSO manually activates the mFRR and frequently uses it when a sufficient aFRR system is not available. The mFRR is capable of matching supply and demand in both normal and disturbed operations and rebalancing the power system.

The implementation of the Manual Frequency Restoration Reserve (mFRR) to the Nordic power market, impact significantly to the stability and reliability of the regional power system. This initiative stemmed from the need to address the increasing complexities and demands placed on the grid, especially with the growing integration of renewable energy and the associated variability in power generation.

Table 2 Comparison of aFRR and mFRR [24].

Aspect	aFRR	mFRR
Purpose	Stabilize frequency to 50 Hz.	Restore balance between supply and demand during operations and disturbances.
Activation Mechanism	Automatic, based on frequency deviations, signal sent every 10 seconds.	Manual, activated by Fingrid's Main Grid Control Center.
Minimum Capacity	1 MW	Varies based on grid needs.
Full Activation Time	Up to 5 minutes	Depends on bid and grid needs.
Market and Procurement	Hourly market and inter-TSO trades; focuses on high-variation hours.	Part of the balancing energy market, requires a market contract.
Compensation	Marginal pricing for capacity, separate energy fees for actual use.	Financial compensation for up-regulating energy bids.

2.1.1.2.1. Balancing power market

The balancing capacity power market was oriented during the 2016 spring. The reserve distributor of capacity bids in the balancing capacity market is approved; this market gives up financial compensation by regulating energy bids. The balancing capacity market ensures that Fingrid has sufficient Manual Frequency Restoration Reserve to cover the dimensioning fault while maintaining Fingrid's own and leasing reserve power plants. Balancing Power Market mechanisms for up-regulation and down-regulation:

2.1.1.2.1.1. UP-regulation

UP-Regulation is essential for balancing the grid solidity, notably during peak times of high demand or sudden drops in the energy power supply. In the Nordic power market, and more specifically, the Finnish power market, which is run by Fingrid, participants (bidders) can join the up-regulation by increasing their power production or reducing their power consumption. The inherent flexibility of this approach enables us to adapt and respond dynamically, ensuring that the grid maintains a balanced state at all times [24].

2.1.1.2.1.2. Down-regulation

Down-regulation is significant alongside up-regulation for the purpose of balancing the power grid. During the excess power supply or reducing the demand, down-regulation makes its impact. Here, the participants (bidders) can take specific individual actions to maintain the balance. In the down-regulation process, the excess power that results from reduced production or increased consumption is then purchased from Fingrid. This kind of dealing entitles Fingrid to manage and balance the grid in the most effective way. And also ensure the supply corresponds to the demand as closely as possible [24]. It is possible to submit bids for balancing energy for any resources that are capable of executing a change of power of 5 MW in fifteen minutes (or 1 megawatt if electronic activation is being used). In line with the requirements for the balancing energy bid, the bids are delivered to Fingrid no later than 45 minutes before the hour of operation.

2.1.1.2.2. Reserve market operations

Reserve markets are an important component of the wider Nordic electricity market, which includes transmission system operators (TSOs) from Sweden, Norway, and Denmark. These TSOs work closely together to ensure adequate reserve levels, control grid frequency, and support system reliability. Fingrid generates deposits through a combination of long-term annual contracts and short-term hourly trading. Much of the work is done through annual contracts, primarily because of its low cost relative to hourly market price fluctuations.

The efficiency and cost-effectiveness of these supporting infrastructures are critical to the stability of the Finnish electricity system. Fingrid development and ongoing maintenance in these markets ensure that the grid can respond robustly to changes in electricity generation and consumption, thereby preserving the reliability of electricity transmission.

Fingrid's reserve markets are primarily based on an efficient exchange of information between the operating equilibrium and Fingrid through the VAKSI system. This Internet-based application allows providers to bid and receive activations for reserved markets. Other methods, such as EDIEL and ECP messages, are also used for real-time reporting and data transfer.

2.1.2 Background of QuEST application used market (comparison)

In order to guarantee a steady supply of energy over broad regions, Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) work together to strike a balance between the level of power generation and the level of demand in real-time. They collaborate with energy suppliers and utilities to coordinate the management of wholesale energy markets in order to supply power that is both inexpensive and environmentally friendly. Additionally, ISOs and RTOs are at the forefront of developments in revolutionary grid technologies, which are aimed at enhancing the grid's dependability, resilience, and efficiency.

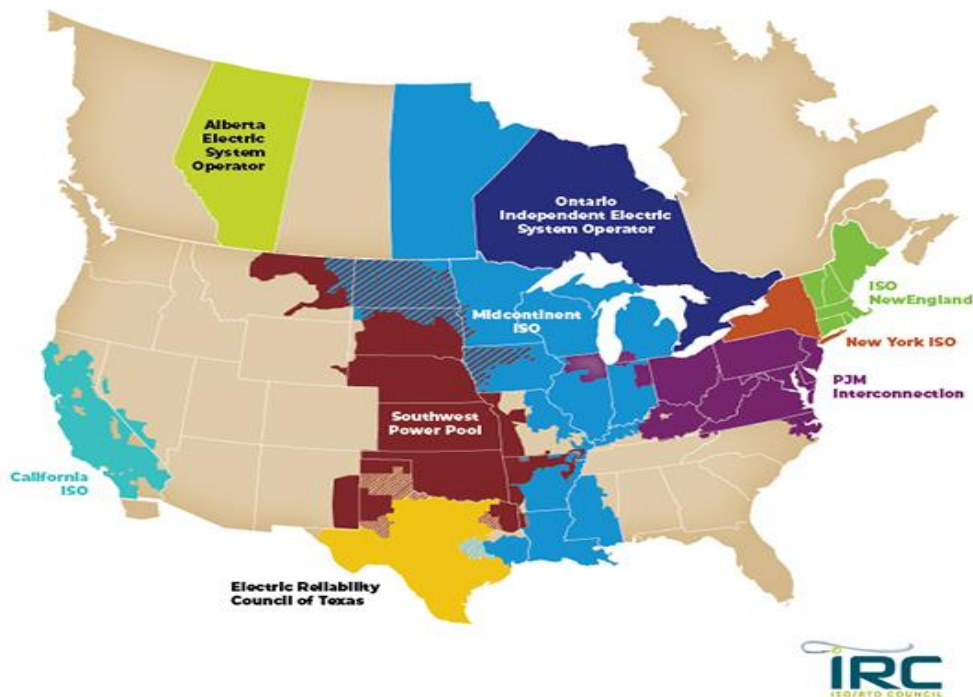


Figure 5 ISO/RTOs maps across the USA market [82].

2.1.2.1 ERCOT (Electric Reliability Council of Texas)

ERCOT ensures reliable electricity distribution for over 26 million people in Texas, USA. ERCOT frequency regulation market doesn't deliver performance in frequency regulation or credits; it only provides the capacity. Regulation up and down has distinct pricing, making it a two-product frequency regulation market [28].

The market operates as a standalone system; its services are operated in real-time or in advance. Its structure fosters competitive bidding and effective price distribution, assuring state energy distribution reliability and cost efficiency [29].

2.1.2.2 PJM (Pennsylvania-New Jersey-Maryland Interconnection)

PJM Interconnection is an RTO (Regional Transmission Organization). It is the core source of wholesale power suppliers for 13 states and the District of Columbia [30]. PJM controls competitive wholesale markets, such as energy markets for the day ahead and capacity markets in real-time, and provides services for these markets. For the PJM market, economic

efficiency and dependability are the main priorities, along with finding a way to control prices. PJM is very cruel to power grid stability [31].

2.1.2.3 MISO (Midcontinent Independent System Operators)

MISO is known for managing the electricity dispatch for 15 states in the USA and Manitoba, Canada. Its operations are mainly day-ahead in real time and also in different auxiliary service markets. MISO uses LMP in a brief Locational Marginal Pricing method to ensure energy efficiency and marginal cost. Other research and studies show that MISO's role is for grid operation, and renewable energy sources are enriching and integrating [32].

2.1.2.4 NYISO (New York Independent System Operator)

The NYISO operates New York State's energy system. It oversees the day-ahead, real-time, and capacity markets, as well as related services. It has the right to trade power on a wholesale basis. For effective congestion control and grid optimization, NYISO uses LBMP, known as location-based marginal pricing. In their research [33] elucidated the operation of NYISO, highlighting its effective market operation and its dedication to supporting renewable energy sources [34].

2.1.2.5 ISO-NE (The Independent System Operator New England)

ISO-NE is accountable for the New England area; it organizes and supervises the wholesale electronic market power for different kinds of functionality and the bulk power system. ISO-NE's markets include the day-ahead and real-time markets with additional capacity and auxiliary markets. For handling effective congestion, it utilizes the locational margin price. ISO-NE ensures economic efficiency and reliability for the upcoming energy market [35] [36].

2.1.2.6 SPP (The Southwest Power Pool)

Similar to other markets, SPP engages in more than just power control; it also focuses on building strong relationships. It operates in 14 states, depending on the wholesale market and the electrical system. SPP handles day-ahead and real-time markets. The market design prioritizes the reliability and cost-effectiveness of electricity transmission by using locational marginal pricing to represent the associated costs accurately [37].

2.1.2.7 CAISO (The California Independent System Operator)

ISO projects high-voltage power lines in California to transmit electricity. It controls both day-ahead and real-time energy markets, as well as auxiliary services required. The CAISO operator reliably maintains one of the most modern and largest power grids. In addition to that, it runs a wholesale market that is transparent and easily accessible to all. The organization works tirelessly day and night to meet consumers' electricity needs, while also increasing the amount of renewable energy to pave the way for a clean, sustainable grid in the future [38].

2.2 Energy Storage

Energy storage is a device that stores (charged) electricity (in a power network form) and discharges it (in an electricity form) when necessary. The electricity pricing depends on the surplus electricity as it is possible to store it for future use or sell it to another user when required. Energy storage technology is incredibly versatile, finding applications in various sectors. It is essential to modern life, from powering portable devices to operating transport vehicles and providing stationary energy resources. Energy storage is a remarkable technology for the environment. Now, the world is trying to shift its dependence from fossil fuels to renewable energy. In addition, it will be much more sustainable for the consumer in terms of costs. The disadvantage of renewable energy is unpredictability, so storing it is crucial. We also need to count on storage capacities as well as losses. Energy storage is essential for keeping up with today's fast-developing green world.

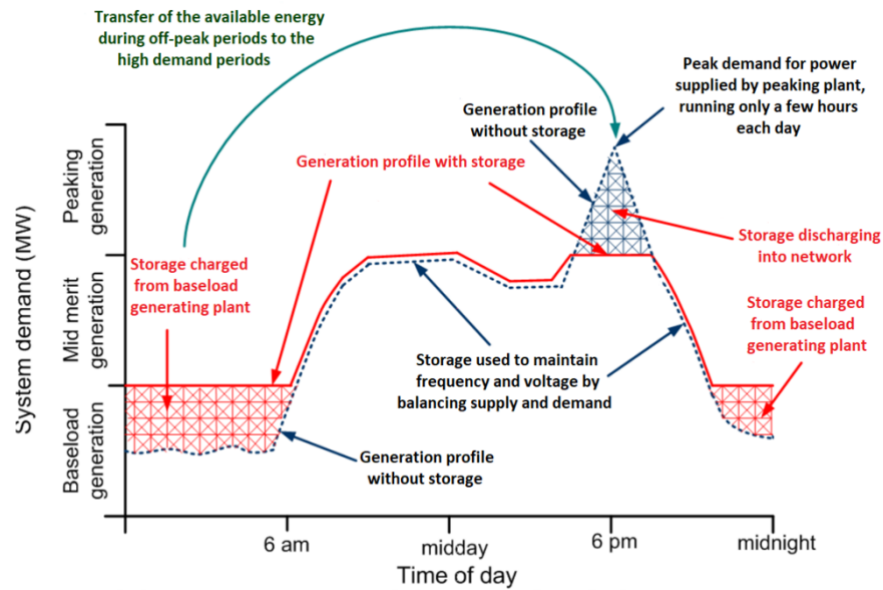


Figure 6 Basic functional idea of the energy storage [78].

2.2.1 Why energy storage necessary

The European Union has set an ambitious target of achieving carbon neutrality by 2050. Therefore, a carbon-free electricity system is vital for the European Union to meet this target. However, as much as it is an essential element, it is important to note that an EFS could not reduce total emissions by 55% from 1990 levels, as presented in the Finnish program [39].

Finland has already exceeded 50% of its total consumption from total energy sources [40]. This success mostly came from the vast availability of hydro and wind power. However, the elevated penetration from renewable sources causes various types of inertia and stable frequency in the grid as it has replaced the base power station. For example, if the percentage of wind energy goes up in the grid and the hydropower goes down, the grid stability becomes vulnerable, and the need for other techniques emerges.

In the past, the enormous hydropower supply in the Nordic nations restricted the market entrance requirements for energy storage. This was when other European countries began to see active involvement from storage assets. However, the introduction of a common Nordic fast-frequency market in 2020 brought about a change in the situation. This market eliminated entry barriers and specifically triggered the participation of fast-responding assets, such as grid-scale energy storage. As a result, energy storage investors and project owners received quick and attractive returns.

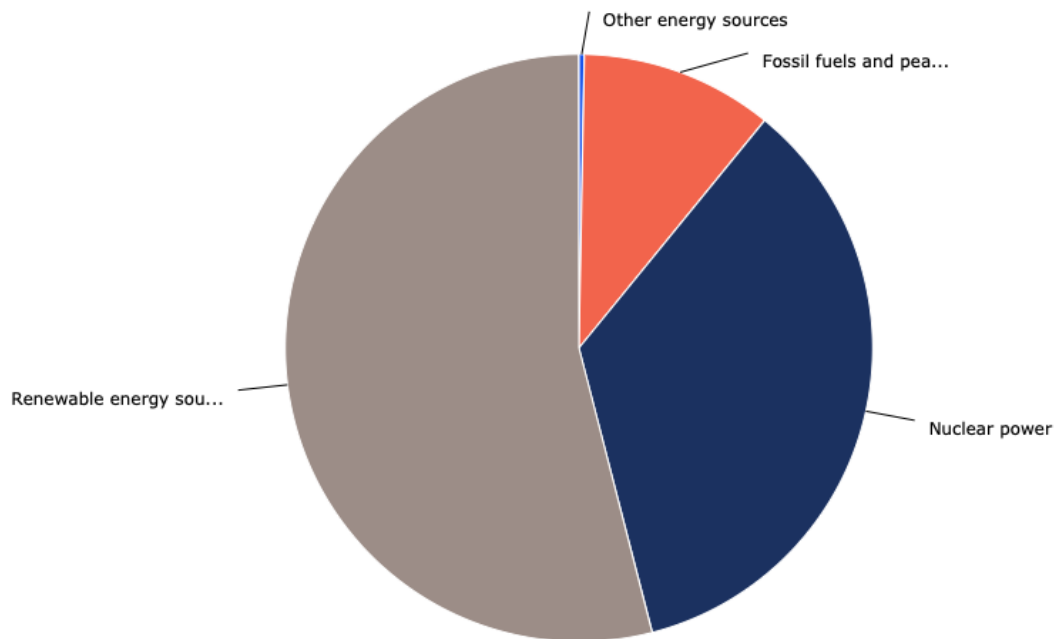


Figure 7 Shares of renewable energy sources in total electricity production by 2022 [40].

Currently, the Nordics have about 200 MW of battery-based energy storage systems in operation. Furthermore, the total capacity of recent announcements and ongoing projects in Sweden and Finland exceeds 450 MW [41].

The significant expansion of wind power installations and the constraints of the current pumped hydro energy storage (PHES) infrastructure in Finland are driving the battery storage industry. The primary focus of battery storage projects in Finland is the ancillary services market, which currently has a capacity of around 400 MW and includes operating batteries with a total capacity of roughly 100 MW [41].

2.2.2 Energy storage technology

In the current market, different types of storage are available for use, which use different kinds of technology, such as chemical, electrochemical, electrical, mechanical, and thermal systems. The continuous growing development of these technologies in the various phases and stages makes this technology's comparative study really hard to track.

Based on the uses of storage systems, there are mainly four types of division that can be seen :

1. Low-power remote transducer and emergency terminal feeding.

2. Remote medium-power use (individual electrical systems, town supply).
3. Peak-leveling network connection application.
4. Power-quality control application.

Small-scale devices employ various energy storage methods, including kinetic energy (flywheel), chemical energy, compressed air, hydrogen (fuel cells), or supercapacitors or superconductors. On the other hand, large-scale systems, categorized as three and four, store energy in different forms such as gravitational (hydraulic systems), thermal (sensible, latent), chemical (accumulators, flow batteries), or compressed air [42].

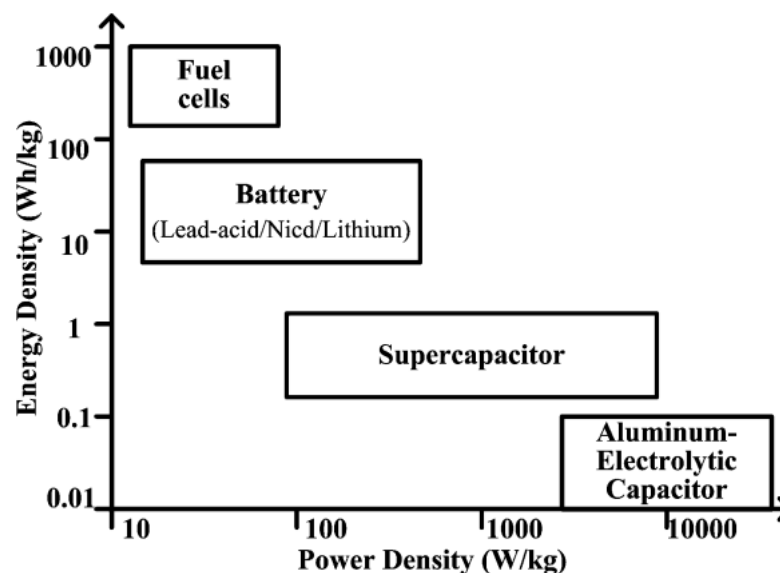


Figure 8 The power density and energy density of different power storage systems in the Ragone plot [43].

The graph above compares the power and energy density of different storage technologies. The graph mentions four types of technology: fuel cells, batteries, supercapacitors, and aluminum-electrolytic capacitors. The method in the Ragone plot demonstrates the balance between how much energy it can store and the rate at which it can transfer power from the system [43].

The Ragone plot for energy storage is a very demanding and resourceful tool for electrical engineering and engineering management because of its resources in selecting energy storage. The plot is very suitable and has valuable information about different kinds of

applications regarding energy storage systems. Also, it balances quick power deliveries with energy storage periods.

2.2.2.1 Li-Ion battery

Lithium-ion batteries are the digital technological revolution in our current mobile world. The market for lithium-ion batteries is seeing a significant surge, mainly due to the rising desire for electric-powered automobiles. Lithium-ion batteries will store and stabilize the intermittent and variable supply of green energy from renewable sources and, most importantly, the gap between energy supply and demand.

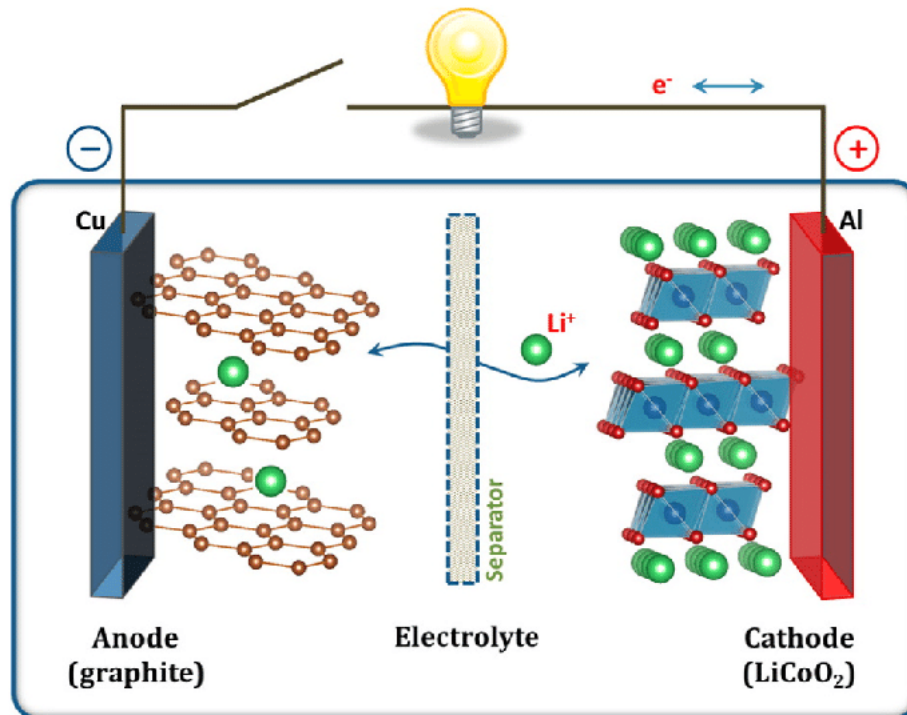


Figure 9 Schematic of a Li-ion battery ($\text{LiCoO}_2/\text{Li}^+$ electrolyte/graphite) [45].

A Li-ion battery is developed by connecting individual Li-ion cells in parallel (to augment current), in series (to amplify voltage), or in mixed arrangements. A module may accommodate many battery cells. Several modules may be integrated into a battery pack. An electrochemical cell has two electrodes, the anode and the cathode, separated by an electrolyte. The electrolyte may exist in either a liquid or solid state. A typical Li-ion cell comprises a cathode (positive electrode) and an anode (negative electrode) connected by an

electrolyte containing lithium ions [44]. The electrodes are separated by a microporous polymer membrane, which permits the transfer of lithium ions while preventing the flow of electrons. Aside from liquid electrolytes, polymer, gel, and ceramic electrolytes have also been investigated for use in Li-ion batteries. Figure 4 depicts the fundamental operational concept of a standard Li-ion battery cell [45].

Li-ion batteries have inherent benefits compared to alternative chemistries, such as having the most minimal reduction potential among all elements and the utmost achievable cell potential. Given the increasing costs of oil and the advancements in exploration and mining technology, which contribute to the growth of global oil reserves and resources, it is very improbable that there will be a scarcity of Li-ion batteries shortly [46]. Nevertheless, the rising costs can impede the development of Li-ion batteries in the renewable energy storage sector [47].

2.2.2.2 Advanced lead-acid battery

Lead-acid batteries are the most widely used rechargeable battery technology due to their affordability and dependable performance. This makes them cost-effective for various applications, such as uninterrupted power supply and power quality regulation.

In the 1960s and 1970s, a groundbreaking discovery was made. A lead-acid battery could be designed to facilitate substantial oxygen recombination, similar to how recombination occurs in sealed nickel-cadmium cells from that period. This led to the creation of initial designs using immobilized, gelled electrolytes in the 1960s and further advancements in the 1970s with the use of an absorbent glass mat separator to hold the electrolyte between the

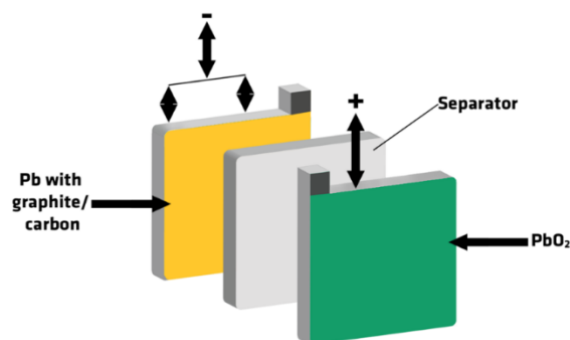


Figure 10 Carbon enhanced lead-acid battery for HRPSoC applications [52].

electrodes. These designs, widely known as GEL VRLA and AGM VRLA [48], respectively [49], marked a significant leap in lead-acid battery technology [50].

However, starting in the late 1980s, introducing excessive carbon into a VRLA (valve-regulated lead-acid) battery has significantly improved its cycle life, exceeding ten times the previous performance [51]. This is especially beneficial for the HRPSoC (high-rate partial state of charge) operation, which is necessary for numerous grid-scale storage applications [52]. Carbon has been investigated as a potential additive to lead-acid battery electrodes through several methods. The hybrid "Ultrabattery" created by CSIRO has been the most notable so far. A carbon-based electrochemical capacitor with an asymmetric structure is integrated with a lead-acid battery to form a single cell, significantly enhancing the operation of the hybrid renewable power system on a chip (HRPSoC) [53](Figure 5). Ultra battery is a hybrid device that combines a conventional lead-acid battery positive plate (PbO_2) with a negative electrode made of a parallel carbon electrode and a lead-acid negative plate [54]. Conventional lead-acid batteries cannot meet the requirements of high-rate, partial-state-of-charge (HRPSoC) operations. Future technical requirements for automotive and energy storage will likely pose challenges for lead-acid batteries [55]. This indicates that they must enhance their power and lifetime performance to meet future requirements and maintain their industry position [56].

2.2.2.3 Flywheel battery

The operation of a flywheel battery is very simple and efficient. It stores energy kinetically with a spinning rotor called a flywheel, which rotates less frictionally and very fast. Whenever there is a power demand, the kinetic energy stored in the flywheel slows down and converts into electrical energy [57].

In this manner, kinetic energy is converted into electrical energy, and the flywheel functions as a mechanical storage device [57]. The mass applied in the flywheel is typically a solid or hollow cylinder [58].

Various motors are used in flywheel storage systems, depending on the manufacturer. However, the Permanent Magnet Synchronous Motor (PMSM) is the most

prevalent type due to its exceptional efficiency and power density. Furthermore, the rotor's shape factor impacts the flywheel's energy density [59].

Flywheels demonstrate their versatility by being primarily used in uninterruptible power supply (UPS) systems. They are also functional as an alternative to batteries by delivering quick load or as a battery supplement, decreasing the number of discharge cycles and improving their longevity.

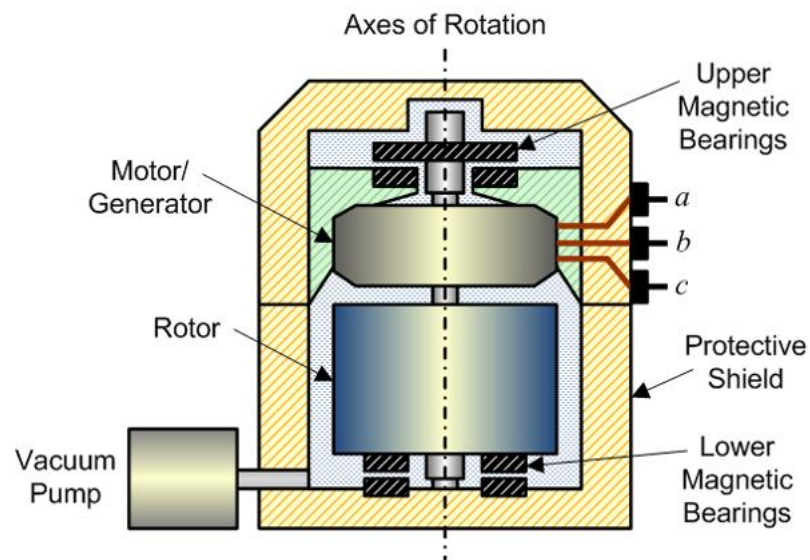


Figure 11 The basic structure of flywheel [79].

Compared with the VRLA battery, flywheels present a more tolerable and efficient storage system, especially for a long-standing performance that is much more impactful to the environment [60].

2.2.2.4 Vanadium redox flow battery

Vanadium redox flow batteries (VRFBs) are typically rechargeable batteries with flow that utilize vanadium ions in different oxidation states to store chemical potential energy. This technology was developed in the 1980s at the University of New South Wales [61]. VRFBs are considered to have one of the most comprehensive patterns among various storage types in the market [62]. However, they also help the battery enhance its capabilities. The two tanks shown in Figure 7 are filled with vanadium-based electrode solutions left and right, and the cell in the middle connects them. The electrodes pass through the cell through the two pumps, which create charging and discharging in the cell [63].

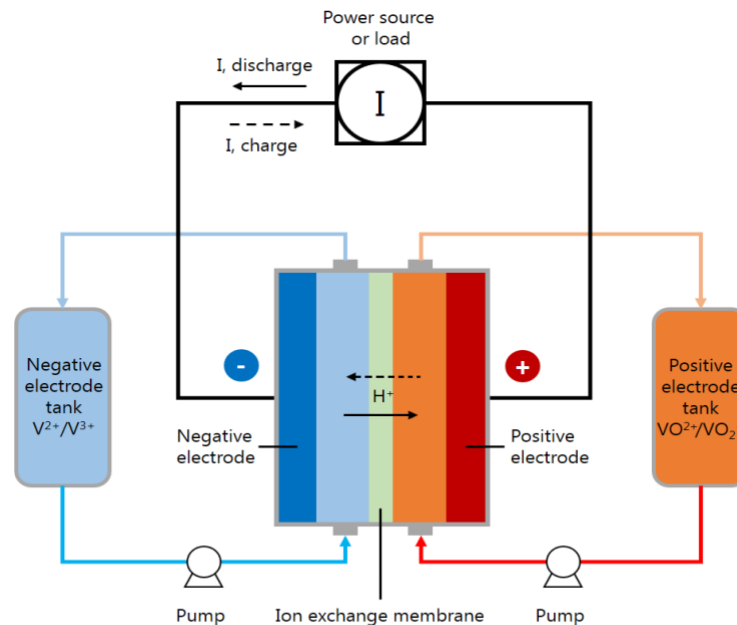


Figure 12 Schematic representation of vanadium flow battery system [80].

Its capacity is quite large compared to others. Because of their scalability, VRFBs can maximize energy, which can be very helpful for leveling renewable energy's instability and enhancing grid stability [62].

The best advantage of VRFB batteries is their life cycle, as they can hold up the power for an exceptional period with minimal damage over thousands of cycles [64]. This is a massive advantage as the world is running for renewable sources, which can be a perfect solution for the future. Also, VRFB's power capacity depends on the electrolytes, not the battery cell, allowing more customization to fulfill the market demands [65].

Soon, VRFBs could match the scale of other storage types [66], but the less energy-dense and higher initial cost are the obstacles to this development [67].

2.2.2.5 Li-Iron phosphate battery

Lithium iron phosphate, also known as LFP(LiFePO₄) [68], is a lithium-ion battery that uses a different material (lithium iron phosphate) in the cathode. John B. Goodenough discovered LFP in late 1996 [69].

LFP batteries are developed with a lithium iron phosphate cathode, a graphite anode, and an electrolyte that moves between the lithium ions. In the charging process, lithium ions move from the anode to the cathode, and the opposite occurs during discharge mode [69].

LFP is a safe and stable battery on the market because of its rigid phosphate structure. Therefore, the oxygen could not mix with the high temperature, which gives the LFP battery very suitable thermal stability and safety. LFP has a longer lifespan [70], exceeding 2000 cycles [71]. Most LFPs are used for EVs, grid energy storage, handling electronics instruments, etc. Compared to lithium-ion batteries, LFPs are cheaper and safer. For those reasons, differentiated EVs makers like Tesla and BYD see LFP as a real option for the future. Also, LFP batteries are great options for stabilizing renewable energy sources like solar and wind [72] [73]. However, LFP has recently been widely adopted, especially in the EV and renewable energy storage system sector. However, energy density and overall energy capacity are not the best in the current market [74].

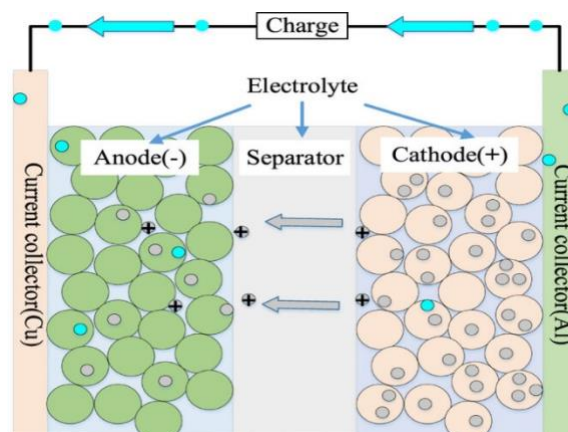


Figure 13 The internal structure of Lithium Iron Phosphate battery [81].

3 Optimization model

Optimization models are energy-based linear programs that operate in discrete time. It is commonly used to monitor energy storage systems (ESS). This model monitors the status (SOC) of the energy storage system (ESS) hourly on a monthly timescale. The SOC is determined by the amount of energy added and released. The objective functions and constraints of this model focus on maximizing profits through arbitrage, defined as the practice of buying low and selling high, and providing frequency control services.

3.1 Energy storage model

A set of parameters represents the fundamental structure of energy storage.

The Power Rating (MW): It represents the maximum power an electrical energy storage device can handle during the charge and discharge phases. The model has just one power rating that applies to both procedures. The discrete-time model's hourly timestep allows for the expression of an energy charge rating in MWh.

The Energy Capacity (MWh): It represents the total energy storage capacity of the device. It is a critical parameter because it determines how long and to what extent the energy storage system can discharge. Since a higher energy capacity translates into the device being able to physically save and discharge more electricity, this qualifies it for applications requiring continuous flows of power over longer, stretched periods.

Round Trip Efficiency (%): This indicates the losses incurred when the system stores input power. Battery-pack-level efficiency tests your storage system, including all energy losses during charging and discharging. Higher round-trip efficiency represents lower energy losses and a more efficient system.

Storage Efficiency (%/h): This indicator indicates each step's capacity and illustrates the rate at which self-discharge or other losses reduce the stored energy per unit of time. Increased storage efficiency implies retaining more energy for future use, reducing the required charges.

Point to be noted, To define the device in order to take into consideration reserves in order to fulfil commitments that were not simulated in this analysis, other parameters can be employed, including the following:

Minimum Reserve Charge (MWh): This is the energy kept in reserve for discharging purposes most of the time to support resilience applications. Generally, it represents a percentage of the overall energy capacity, thereby increasing the minimum state of charge available for market use.

Maximum Reserve Capacity (MWh): Energy forgone to preserve the charge for utility uses [e.g., primary frequency response applications]. Generally, it is defined as a percent of the energy-rated value, limiting the maximum state of charge available for the market.

Min Regulation Reserve Charge (MWh): The minimum energy against the regulation capacity rests to ensure enough power for discharge during genuine system reserve calls. It is usually a fraction (or percent) of the regulation bid, thus raising the smallest state of charge available for market admission.

Maximum Regulation Energy Reserve Charge (MWh): The energy that XGW indicates shall be reserved for use should there not be enough energy available to enable charging to meet actual regulation capacity requirements. Usually, this is a fraction of the regulatory offer, limiting the maximum amount you can charge up for the market.

This optimization model emphasizes the amount of energy absorbed or released at any given time during activities such as mediation or regulation. In terms of mediation, the device maintains a constant output power over time. We assume that the device is capable of following the regulatory signal. When comparing the ramping time, we can disregard the impact of the ramping rate. We will need a model that estimates the ramp rate if it is slow relative to the period.

3.2 Arbitrage Only (Scenario 1)

Arbitrage involves buying electricity when prices are low and selling them when prices rise. This short-term price differential allows ESS to use fluctuating electricity prices to generate revenue. Price fluctuations in the Nordpool market serving the Nordic countries, including Finland, are affected by various factors such as renewable energy, weather, and market demand. ESS can increase earnings through arbitrage through cash-fair receipts and disposal

in high-value areas. Advanced optimization models can predict price trends and optimize the charging and discharging process of the ESS to maximize profitability.

For a storage device that participates in arbitrage only, the decision variables are q_i^d , q_i^r , and s_i .

The recursion relation describing the state of charge s_i for $i > 0$ is given by:

$$s_{i+1} = \eta_s s_i + \eta_c q_i^r - q_i^d \quad (1)$$

with:

$$s_0 = S_0 \quad (2)$$

The constraints on the state of charge s_i , the quantity purchased q_i^r , and the quantity sold q_i^d at each time step i are given by:

$$\begin{aligned} \delta_s^{\min} \bar{S} &\leq s_i \\ s_i &\leq (1 - \delta_s^{\max}) \bar{S} \\ q_i^r + q_i^d &\leq \bar{Q} \\ s_N &= S_0 \end{aligned} \quad (3)$$

for all $i \in \mathcal{T}$. The first two sets of constraints limit the state of charge between its minimum and maximum values as specified at each time step. The next set of constraints limits the total energy charged over the time step (both charging and discharging) to the energy charge limit (derived from the power limit) at each time step. This constraint permits charging and discharging during the same time step but restricts the throughput based on the power rating.

The objective is to maximize the total revenue over the time horizon. We do not include costs associated with, e.g., charging or discharging. If data is available, it may be included in the objective function, changing the objective to profit maximization. Otherwise, the objective function for the arbitrage-only model is:

$$= \sum_{i \in \mathcal{T}} [q_i^d - q_i^r] \lambda_i e^{-Ri} \quad (4)$$

Revenue is solely generated by buying and selling energy. The arbitrage-only model can therefore be summarized as follows:

$$\max_{q^d, q^r, s} J \quad (5)$$

subject to:

$$\begin{aligned} s_{i+1} &= \eta_s s_i + \eta_c q_i^r - q_i^d \\ \delta_s^{\min} \bar{S} &\leq s_i \leq (1 - \delta_s^{\max}) \bar{S} \\ q_i^r + q_i^d &\leq \bar{Q} \\ s_0 &= S_0 \\ s_N &= s_0 \end{aligned} \quad (6)$$

for all $i \in \mathcal{T}$.

Note:

In many areas, the net energy for regulation is settled at a real-time price. This provides an additional arbitrage opportunity between the day-ahead price and the real-time price. These models are primarily concerned with arbitrage and regulation revenue from the day ahead market; therefore, the price λ_i typically represent the day-ahead LMP. While this does not reflect the actual settlement process, it keeps the optimization from incorporating any arbitrage between the day ahead and the real-time market.

3.3 Arbitrage and regulation

Energy storage systems can increase their utilization and profitability through arbitrage and regulation. The system can participate in energy intermediary and regulatory markets, seamlessly transitioning between the two based on market conditions and grid requirements. The Act specifies energy storage systems for ancillary participation service markets, especially for frequency regulation. Frequency control balances supply and demand to

ensure a constant frequency in the network. Depending on the region, we typically maintain the frequency around 50 or 60 Hz.

Frequency regulation is another important service provided by ESS. It maintains the efficiency of the grid to balance supply and demand. Grid operators often pay ESS to provide regulatory services that help maintain this balance. The ESS is capable of providing both regulation up (increasing the output power) and regulation down (decreasing the output power) functions. Compensation for these services can be substantial, especially in markets that demand higher order frequencies. Integrated ESS for frequency regulation in the Nordpool market not only supports a stable grid but also ensures revenue stability.

3.3.1 Arbitrage and regulation (ERCOT) (Reference model)

ERCOT's frequency regulation market does not explicitly provide credits based on frequency regulation performance, only for capacity offered. It offers different prices for regulation up and regulation down, and it is thus considered a two-product frequency regulation market.

For a storage device that participates in both arbitrage and frequency regulation, the decision variables are $q_i^d, q_i^r, q_i^{ru}, q_i^{rd}$, and s_i

The recursion relation describing the state of charge s_i for $i > 0$ is given by:

$$s_{i+1} = \eta_s s_i + \eta_c q_i^r - q_i^d + \eta_c \delta_i^{rd} q_i^{rd} - \delta_i^{ru} q_i^{ru} \quad (7)$$

with:

$$s_0 = S_0 \quad (8)$$

The constraints on the decision variables are given by:

$$\begin{aligned} \delta_{\text{reg}}^{\min} q_i^{ru} + \delta_s^{\min} \bar{S} &\leq s_{i+1} \\ s_{i+1} &\leq (1 - \delta_s^{\max}) \bar{S} - \eta_c \delta_{\text{red}}^{\max} q_i^{rd} \\ q_i^r + q_i^d + q_i^{ru} + q_i^{rd} &\leq \bar{Q} \\ s_N &= S_0 \end{aligned} \quad (9)$$

for all $t \in \mathcal{T}$. The first two sets of constraints limits the state of charge between its minimum and maximum values as specified at each time step. The δ_{reg} factors are safety factors used to reserve energy capacity headroom and/or legroom to avoid penalties due to not meeting regulation obligations; they are defined as fractions of the capacity bid. The next set of constraints limits the total energy charged over the time step (both charging and discharging) to the energy charge limit (derived from the power limit) at each time step. This constraint permits charging and discharging during the same time step but restricts the throughput based on the power rating. Bids for regulation up/down are constrained together with arbitrage-related actions.

The objective function for the model is:

$$J = \sum_{i \in \mathcal{T}} [(q_i^d - q_i^r)\lambda_i + \lambda_i^{c,ru} q_i^{ru} + \lambda_i^{c,rd} q_i^{rd} + (\delta_i^{ru} q_i^{ru} - \delta_i^{rd} q_i^{rd})\lambda_i] e^{-Ri} \quad (10)$$

In addition to the arbitrage revenue stream, electricity prices are accounted for depending on the actual amount of the regulation bid that is called upon. Additionally, the revenue from regulation up/down bids is included. The ERCOT arbitrage and regulation model can therefore be summarized as:

$$\max_{q^d, q^r, q^{qu}, q^{-1}, s} J \quad (11)$$

subject to:

$$\begin{aligned} s_{i+1} &= \eta_s s_i + \eta_c q_i^r - q_i^d + \eta_c \delta_i^{rd} q_i^{rd} - \delta_i^{ru} q_i^{ru} \\ \delta_{\text{reg}}^{\min} q_i^{ru} + \delta_s^{\min} \bar{S} &\leq s_{i+1} \leq (1 - \delta_s^{\max}) \bar{S} - \eta_c \delta_{\text{reg}}^{\max} q_i^{rd} \\ q_i^r + q_i^d + q_i^{ru} + q_i^{rd} &\leq \bar{Q} \\ s_0 &= S_0 \\ s_N &= S_0 \end{aligned} \quad (12)$$

for all $i \in \mathcal{T}$.

Note:

The δ_i^{ru} and δ_i^{rd} terms are assumed to be fixed for all time in the absence of additional information.

3.3.1 Arbitrage and regulation- Crossborder formula (Finland_Nordic, Scenario 2)

Cross-border trading in the energy market involves the exchange of electricity between neighboring countries. Finland has several interconnectors with neighboring countries (Sweden, Norway, Estonia, and Russia) (Russia was discontinued in the past year). These interconnectors are critical infrastructure that enables cross-border electricity flows. This kind of trading is crucial due to the integrated nature of the Nordic shared electricity market. Cross-border trading impacts revenue generation by exploiting price differences, increasing market liquidity, providing energy security, enabling participation in ancillary services, integrating renewable energy, and navigating regulatory frameworks.

The cross-border trading for Finland is mainly related to the integrated framework support from the Nord-Pool electricity market with European regulation and national oversight by Fingrid. Finland's cross-border trading electricity market highly depends on the physical infrastructure - interconnectors, market mechanisms for capacity allocation, and zonal pricing. This infrastructure ensures proper efficiency and power flow to the grid. Also, the price optimization, enhanced energy security, and better integration of renewable energy sources. However, the difficulty of congestion management and regulatory compliance still have a significant impact.

Adapting the model for the ERCOT market to fit the Nord Pool (specifically the Finland segment) market framework involves considering several key differences between these markets. Nord Pool operates with a different set of market dynamics, especially due to its focus on renewable energy and the integration of cross-border energy trading. Here's how the model can be adapted:

The provided modified equation for Nord Pool is:

$$J = \sum_{i \in \mathcal{J}} [(q_{d,i}^d - q_{a,i}^a) + \lambda_{ru}^i q_{ru}^i + \lambda_{rd}^i q_{rd}^i + (\delta_{ru}^i - \delta_{rd}^i) \lambda_i] e^{-Ri} + C_{\text{cross-border}} \quad (13)$$

Where:

- $q_{d,i}^d$: Discharged energy for day-ahead market.
- $q_{a,i}^a$: Arbitrage energy component.

- λ_i : Price of electricity.
- λ_{ru}^i : Price for regulation up.
- λ_{rd}^i : Price for regulation down.
- δ_{ru}^i : Efficiency factor for regulation up.
- δ_{rd}^i : Efficiency factor for regulation down.
- R : Discount rate.
- $C_{\text{cross-border}}$: Cost or revenue associated with cross-border trading.

Subject to the following constraints,

$$\begin{aligned}
 s_{i+1} &= \eta_s s_i + \eta_c q_i^r - q_i^d + \eta_c \delta_i^{\text{rd}} q_i^{\text{rd}} - \delta_i^{\text{ru}} q_i^{\text{ru}} \\
 0 &\leq s_i \leq \bar{S} \\
 q_i^r + q_i^d + q_i^{\text{ru}} + q_i^{\text{rd}} &\leq \bar{Q}
 \end{aligned} \tag{14}$$

for all time periods $i \in \mathcal{T}$.

Revenue Calculation:

The total revenue from energy arbitrage and regulation, with cross-border trading is calculated as:

$$\begin{aligned}
 r_{\text{arb}} &= \sum_{i \in \mathcal{T}} \lambda_i (q_i^d - q_i^r) \\
 r_{\text{reg}} &= \sum_{i \in \mathcal{T}} \lambda_i^{\text{c,ru}} q_i^{\text{ru}} + \lambda_i^{\text{c,rd}} q_i^{\text{rd}} + \lambda_i (\delta_i^{\text{ru}} q_i^{\text{ru}} - \delta_i^{\text{rd}} q_i^{\text{rd}}) \\
 r &= r_{\text{arb}} + r_{\text{reg}} + r_{\text{cross-border}}
 \end{aligned} \tag{15}$$

Where, $r_{\text{cross-border}}$ includes costs or revenues from cross-border trading.

$$r_{\text{cross-border}} = \sum_{i \in \mathcal{T}} (\lambda_{\text{import}} q_{\text{import}} - \lambda_{\text{export}} q_{\text{export}}) - \sum_{\text{costs}} C_{\text{cross-border}} \tag{16}$$

λ_{import} : Price of imported electricity.

- λ_{export} : Price of exported electricity.

- $C_{\text{cross-border}}$: Costs associated with cross-border trading, such as tariffs and transmission fees.

By engaging in cross-border trading, the prices λ_i can reflect more favorable conditions from neighboring markets, increasing r_{arb} .

Cross-border capabilities enhance participation in ancillary services, potentially increasing q_i^{rd} , q_i^{ru} and r_{reg} .

The data required to run this analysis in FI are the day ahead LMP, reg up price, and the reg down price.

Market Prices and Regulation:

- Prices ($\lambda_i, \lambda_{ru,i}, \lambda_{rd,i}$) in Finland's Nord Pool zone affect the trading strategies.
- Efficiency factors ($\delta_{ru,i}, \delta_{rd,i}$) reflect real-world conditions and regulation compliance.

Here, If the energy storage device is not participating in frequency regulation, q_i^{ru} and q_i^{rd} are equal to zero for all $i \in \mathcal{T}$.

State of charge equation:

1. The equation includes terms for energy charged and discharged, as well as the effects of regulation up and down.
2. The efficiencies (η_s and η_c) are considered, which is important for reflecting real-world conditions.

Objective function:

1. The objective function is structured to maximize net revenue, considering both the energy arbitrage (buying low, selling high) and the benefits from participating in regulation up and down markets.
2. The inclusion of cross-border trading costs or revenues is particularly relevant for Nord Pool due to its integrated nature across multiple countries.

3. The exponential discount factor e^{-Ri} accounts for the time value of money.

Regulatory and market considerations:

1. Nord Pool has more extensive regulations regarding renewable energy and carbon emissions, which might necessitate the inclusion of carbon pricing in the revenue calculations.
2. The role of renewable energy sources like wind and solar can lead to more significant fluctuations in electricity prices due to weather-related variability, impacting both the arbitrage opportunities and the value of energy storage for grid stabilization.

Summary of constraints:

1. State of charge limits:

- The state of charge (s_i) within the minimum and maximum storage capacity of the energy storage system:

$$\delta_{\min}S \leq s_i \leq \delta_{\max}S \quad (17)$$

- This ensures the energy storage system does not overcharge or fully deplete.

2. Energy balance:

- The total energy charged and discharged, including regulation, should not exceed the storage capacity in any time step:

$$q_{r,i} + q_{d,i} + q_{rd,i} + q_{ru,i} \leq Q \quad (18)$$

- This ensures the total throughput is within the power rating of the storage system.

Energy Arbitrage and Regulation:

- Energy arbitrage ($q_{a,i}$) involves buying low and selling high within Finland's market context.
- Participation in regulation up and down ($q_{ru,i}, q_{rd,i}$) provides additional revenue streams.

3. Charging and discharging:

- Simultaneous charging and discharging within the same time step are not typically allowed, but if allowed, it should respect the maximum throughput:

$$q_{r,i} + q_{d,i} \leq Q \quad (19)$$

4. Cross-border trading:

- As the system is involved in a cross-border trading, additional constraints might apply depending on the regulations and agreements between regions:

$$q_{cb,i}(\text{cross-border trading}) \leq Q_{cb} \quad (20)$$

Interconnectors and Capacity:

- Finland's interconnectors with Sweden, Estonia, Norway, and Russia determine the cross-border capacity (Q_{cb}).
- These interconnectors' capacities are allocated through market mechanisms like auctions.

5. Non-negativity:

- The amount of energy charged, discharged, and reserved for regulation must be non-negative:

$$q_{r,i} \geq 0, q_{d,i} \geq 0, q_{rd,i} \geq 0, q_{ru,i} \geq 0 \quad (21)$$

6. Regulation constraints:

- The energy reserved for regulation up and down should be within specific limits to ensure availability:

$$q_{ru,i} \leq \delta_{ru}S, q_{rd,i} \leq \delta_{rd}S \quad (22)$$

4 Measurement of valuation (Finland)

The conclusions explain how the implanted formula behaves with the historical data of the Finnish electricity market into the system of QUEST valuation. The optimization method has been used discreetly to simulate and determine the necessary valuation from the implemented formula and selected data.

4.1 Scenario 1- Arbitrage only

Scenario 1, “Arbitrage Results for Energy Storage Systems in Finland,” summarises the results of optimising revenue generation from energy storage systems through arbitrage in the Finland segment of the Nordic electricity markets. The analysis is based on data from January 2021 to December 2021, utilising the QuEST Valuation tool.

Scenario Summary:

- Market Area: FI (Finland)
- Pricing Node: SUOMI
- Dates Analyzed: January 2021 to December 2021
- Revenue Streams: Arbitrage
- Energy Storage Device: Li-ion Battery

Table 3 Selected energy storage device characteristics.

Parameter	Value	Units
Power rating	36.0	MW
Energy Capacity	24.0	MWh
Round-trip efficiency	90.0	%
Self-discharge efficiency	100.0	%/hour

Constraints option:

- Time periods are hourly.
- The discount or interest rate is fixed and equal to 0.
- The energy provided for regulation up and down equals 25% of the quantity offered.

The results and representations are:

- Monthly total revenue in €
- Revenue by source (€)

- Frequency of participation in each available revenue stream
 - Total activity participation (%)
 - Activity participation by source (%)

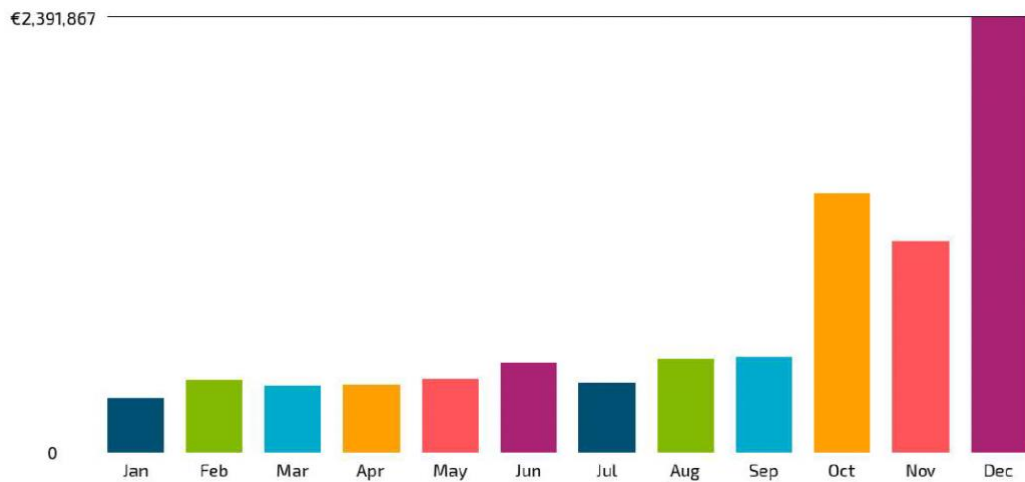


Figure 14 Monthly total revenue in €

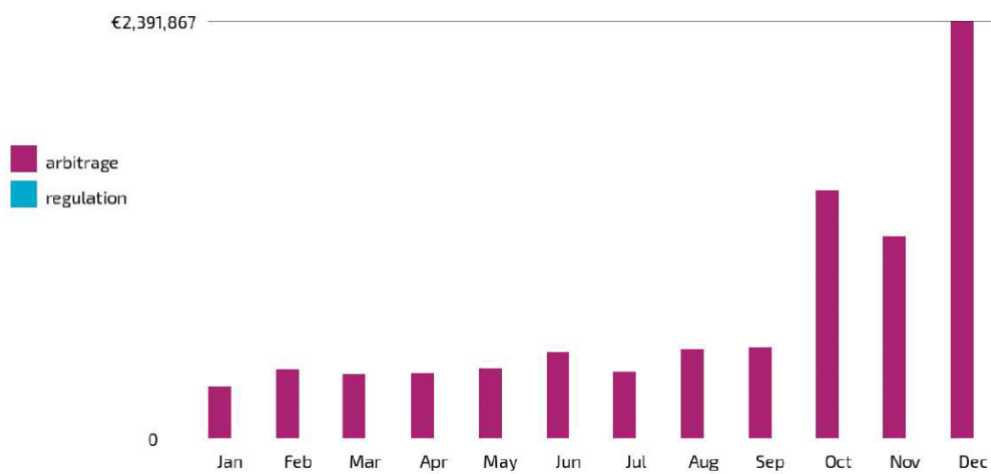


Figure 15 Revenue by source (€)

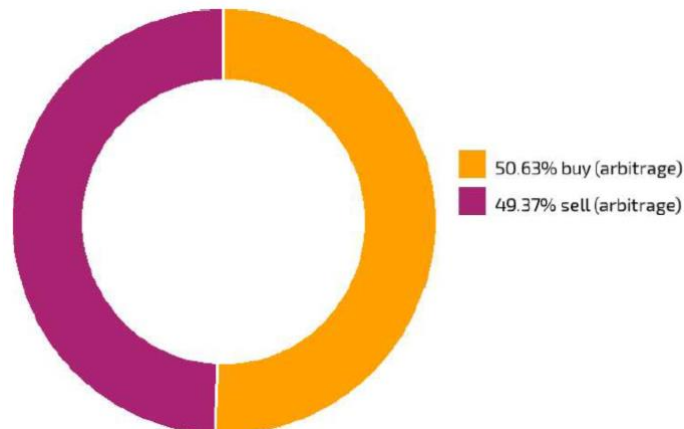


Figure 17 Total activity participation (%)

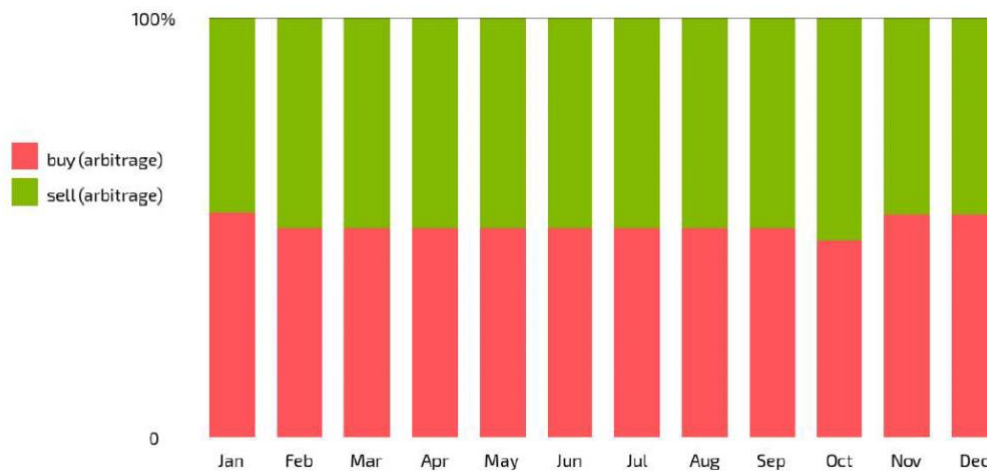


Figure 16 Activity participation by source (%)

4.1.1 Summary of results

- Total revenue generated: €2,391,867

Monthly total revenue:

This illustrates the total revenue generated from the energy storage system (ESS) each month from January to December 2024. The chart reveals significant fluctuation in monthly revenue, with December showing the peak, indicating a peak in market price differentials that the ESS was able to capitalize on. The consistency in other months demonstrates the ESS's capability to generate steady revenue, albeit at lower levels than in December.

Revenue by source:

This result chart shows the total monthly revenue by source, arbitrage activities primarily drove revenue, as the energy storage system did not participate in frequency regulation for this analysis.

Total activity participation:

This pie chart result displays the overall participation of the ESS in buying and selling activities throughout the year. The chart is divided into two segments:

- Buy (arbitrage)
- Sell (arbitrage)

Buy Segment: This segment represents the percentage of time the ESS spent buying electricity (charging) for arbitrage purposes, which accounts for 50.63% of the total activity.

Sell Segment: This part represents the percentage of time the ESS was engaged in selling electricity (discharging) for arbitrage purposes, which accounts for 49.37% of the total activity.

The nearly equal distribution between buying and selling activities indicates a balanced approach to arbitrage. This ensures that the ESS maximizes opportunities to exploit price differentials without favoring one activity over the other.

Activity participation by source:

The bar chart shows the monthly distribution of buying (charging) and selling (discharging) activities as percentages of total activity. The consistent distribution across the months suggests a stable and balanced approach to arbitrage throughout the year. The chart also reinforces the pie chart's depiction of a nearly equal split between buying and selling activities, demonstrating the ESS's effective management in capturing revenue from both sides of the market.

4.1.2 Conclusion

The Quest result demonstrates that energy storage systems can generate significant revenue through arbitrage in the Finland segment of the Nordic electricity markets. The optimization results highlight the potential for revenue maximization by strategically buying and selling

electricity based on market prices. This approach effectively leverages the storage system's capabilities and market opportunities to achieve optimal financial outcomes.

The result analysis also reinforces the depiction of a nearly equal split between buying and selling activities, demonstrating the ESS's effective management in capturing revenue from both sides of the market.

4.1.2.1 Calculation context

Given the power and energy capacity, the storage system can cycle multiple times daily, capturing price differentials. Here's a rough calculation:

1. Average Price Differential:
 - Assume an average price differential of €50/MWh (based on historical Nord Pool data).
2. Daily Revenue Potential:
 - Daily energy cycled: $24 \text{ MWh} \times 36 \text{ MW} = 864 \text{ MWh/day}$
 - Daily revenue: $864 \text{ MWh/day} \times €50/\text{MWh} = €43,200$
3. Annual Revenue Potential:
 - Annual revenue: $€43,200/\text{day} \times 365 \text{ days} = €15,768,000$

However, this is a simplistic view, and actual revenues would be lower due to operational constraints, efficiency losses, and not always hitting the maximum price differential.

4.1.2.2 Reasonable assessment

Based on the simplified potential revenue and considering operational realities, the calculated revenue of €2,391,867 appears to be on the lower side, suggesting conservative estimates or potentially more realistic operational constraints.

The revenue of €2,391,867 is reasonable considering typical constraints and operational conditions in the Finland segment of the Nordic electricity market. It aligns with a conservative estimate compared to the theoretical maximum potential.

4.2 Scenario 2- Arbitrage and regulation

This study evaluates the revenue potential of a Li-ion battery energy storage system (ESS) in Finland's Nordic electricity market through arbitrage and frequency regulation services. Utilizing the QuEST Valuation tool, data from January 2024 to December 2024 was analyzed to optimize revenue generation from these two services. The findings indicate substantial revenue opportunities, underscoring the economic viability of integrating ESS in the Finnish energy market.

With the increasing integration of renewable energy sources, the need for flexible resources like energy storage systems (ESS) to maintain grid stability and optimize market operations has become critical.

This study explores the dual revenue streams from arbitrage and frequency regulation services to assess the financial performance of a Li-ion battery ESS in Finland's electricity market.

Scenario Summary

- Market Area: Finland (FI)
- Pricing Node: SUOMI
- Dates Analyzed: January 2024 to December 2024
- Revenue Streams: Arbitrage and frequency regulation
- Energy Storage Device: Li-ion Battery

Table 4 Energy storage device characteristics

Parameter	Value	Units
Power rating	36.0	MW
Energy Capacity	24.0	MWh
Round-trip efficiency	90.0	%
Self-discharge efficiency	100.0	%/hour

Assumptions

- Time periods are hourly.
- The discount/interest rate is fixed at 0.
- Energy provided for regulation up is 25% of the offered quantity.
- Energy provided for regulation down is 25% of the offered quantity.

4.2.1 Summary of results

- **Total Revenue**

The total revenue generated from the ESS over the analysis period was €2,391,867. This revenue includes contributions from both arbitrage and regulation services, highlighting the ESS's ability to exploit various market opportunities.

- Monthly Total Revenue

Revenue generation exhibited monthly variability, with notable peaks. December emerged as the most profitable month, reflecting significant market price differentials that the ESS capitalized on.

- **Revenue by Source**

- Arbitrage: The primary revenue source, leveraging price differentials between charging and discharging periods.
- Regulation: An additional revenue stream, though its impact was secondary in this analysis.

- **Activity Participation**

- Total Activity: The ESS engaged in 50.63% buying (charging) and 49.37% selling (discharging) activities, maintaining a balanced approach throughout the year.
- Monthly Activity Participation: Consistent engagement in market activities was observed, with a relatively even distribution of buying and selling actions.

- **Visual Representations**

- Monthly Total Revenue in €

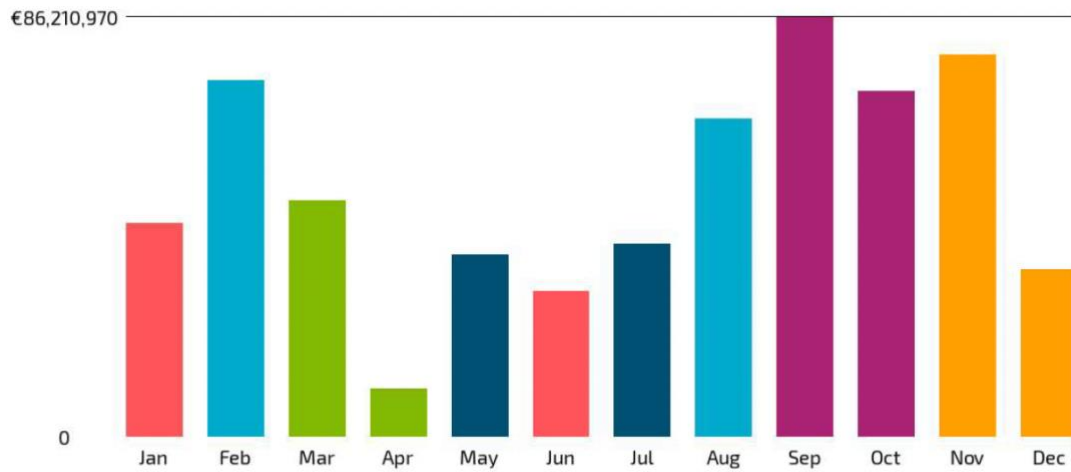


Figure 18 Monthly revenue data of cross-border formula regulation.

- Revenue by Source (€)

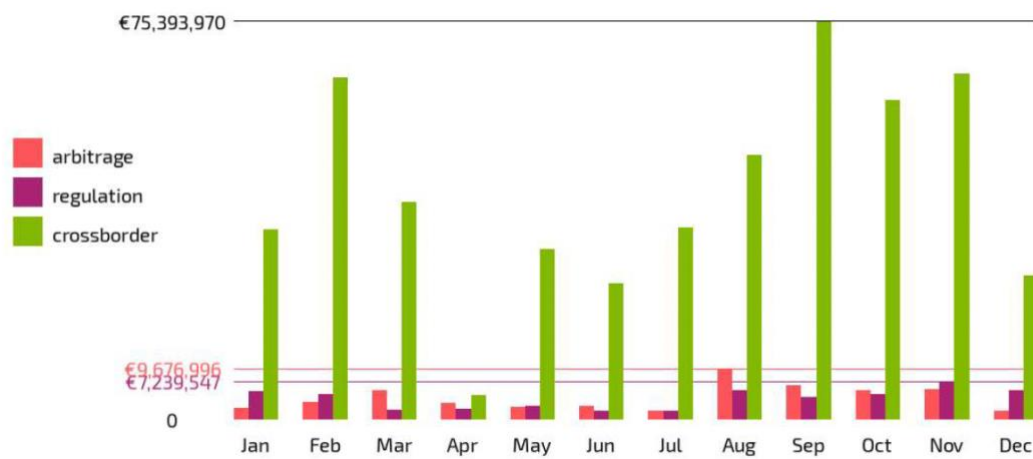


Figure 19 Scenario 2 revenue by sources like arbitration, regulation, and cross-border.

- Total Activity Participation (%)

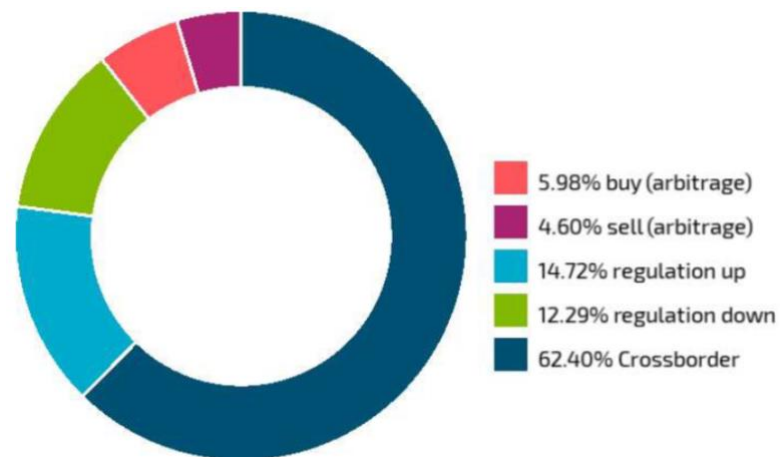


Figure 20 Total activity participation of scenario 2.

- Activity Participation by Source (%)

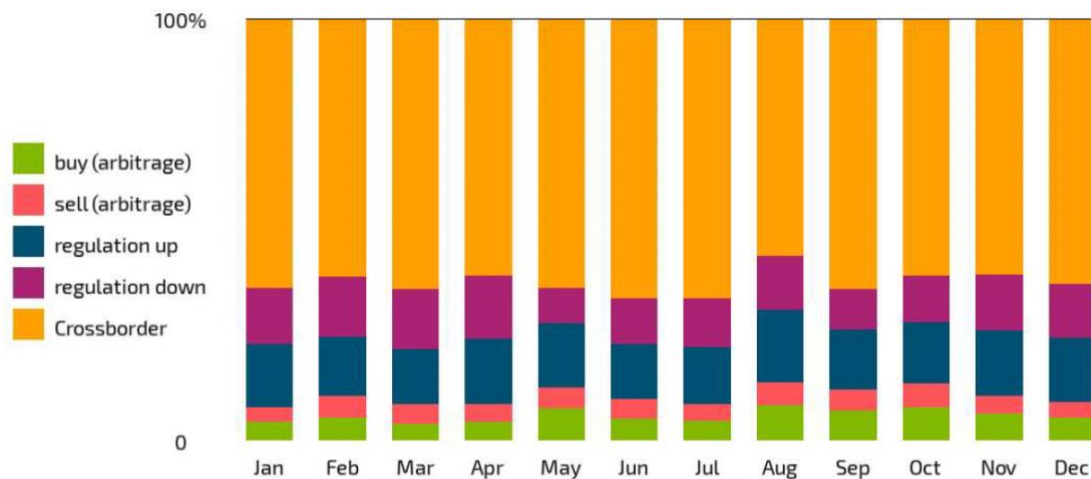


Figure 21 Activity participation results from the source for scenario 2.

4.2.2 Conclusion

This study demonstrates that energy storage systems can significantly enhance revenue through strategic participation in both arbitrage and frequency regulation markets in Finland.

The findings underscore the financial viability and strategic importance of integrating ESS in the Nordic electricity market, providing valuable insights for investors and grid operators. The results affirm the economic benefits of deploying ESS in Finland's Nordic electricity market. The substantial revenue from arbitrage underscores the ESS's potential to leverage market price fluctuations. Although regulation services contributed less in this analysis, they still represent a viable supplementary revenue stream.

5 Conclusion

This study and implementation highlight the significant benefits of energy storage systems participating strategically in both arbitrage and frequency regulation markets in Finland. The findings emphasize the financial viability and strategic importance of integrating ESS in the Nordic electricity market, providing valuable insights for investors and grid operators. The substantial revenue from arbitrage underscores the potential for ESS to capitalize on market price fluctuations. While regulation services contributed less in this analysis, they still offer a viable supplementary revenue stream.

The analysis of arbitrage-only, arbitrage and regulation scenarios confirms the significant revenue potential for energy storage systems in Finland's electricity market.

- **Arbitrage-Only Scenario 1:** Demonstrated substantial revenue generation by exploiting price differentials. This scenario showcased the ESS's ability to maximize financial returns through strategic market participation without the added complexity of regulation services.
- **Arbitrage and Regulation Scenario 2:** Highlighted additional revenue opportunities by providing frequency regulation services. This dual approach leveraged the operational flexibility of the ESS to offer ancillary services, enhancing overall profitability and supporting grid stability.

The economic benefits and strategic importance of deploying ESS in the Nordic electricity market affirm the value of investing in energy storage technologies. These findings support the broader adoption and integration of ESS to improve grid stability, optimize market operations, and achieve optimal financial outcomes.

- **Future development options**

Future development for this application is vast. For instance, unlike manual input, the API can develop the modified "Valuation Optimizer" data collection, allowing real-time data to be uploaded into the interface. All the APIs can be found in the Fingrid—Open data plate, with the proper instructions for all required data. It will increase the ability of the application

as now it is limited to fixed-year data. If API is devolved, the application can do any year revenue calculation, including the running year and the previous year (which year data is available in the Fingrid- open data platform).

In this paper and application, the study was done only for the Finland region from the Nordic Power Market. However, the application is also capable of doing calculations for other regions. So, there are options to add other Nordic Power market regions. This will open a new dimension and option for the user to compare and analyze this market more comprehensively.

These are just a few examples of the developments that can be done for these applications; notably, there are a few other options that can be modified from the original QuEST application (like BTM, Technology Selection, and storage performance). Idea generation can be done for this existing application or independently; it certainly needs to be for the Nordic Power Region Market.

If the application can be fully updated, it will be very useful for the targeted users and other researchers to calculate revenue for any specific region from the Nordic Power Market Area.

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Appendix 1. The Installation Process of the Application

The application file can be found in GitHub, both the original and modified versions;

QuEST by Sandia National Laboratories.: <https://github.com/sandialabs/snl-quest>

Modify the QuEST Valuation version for Finland (Valuation FI):

Evaluate potential revenue generation by energy storage systems providing multiple services for the Nordic electricity markets (Finland) through QuEST Valuation Application.

([https://github.com/ArafathUzzamanMD/potential-revenue-generation-by-ESS-for-the-Finland-electricity-market-by-QuEST-Application.](https://github.com/ArafathUzzamanMD/potential-revenue-generation-by-ESS-for-the-Finland-electricity-market-by-QuEST-Application))

The installation process of the Valuation FI:

All kinds of necessary accessories (like pyomo, Pyutilib, GLPK, prompt) have been updated on this modified executable version so that only the installing process is needed for using this application

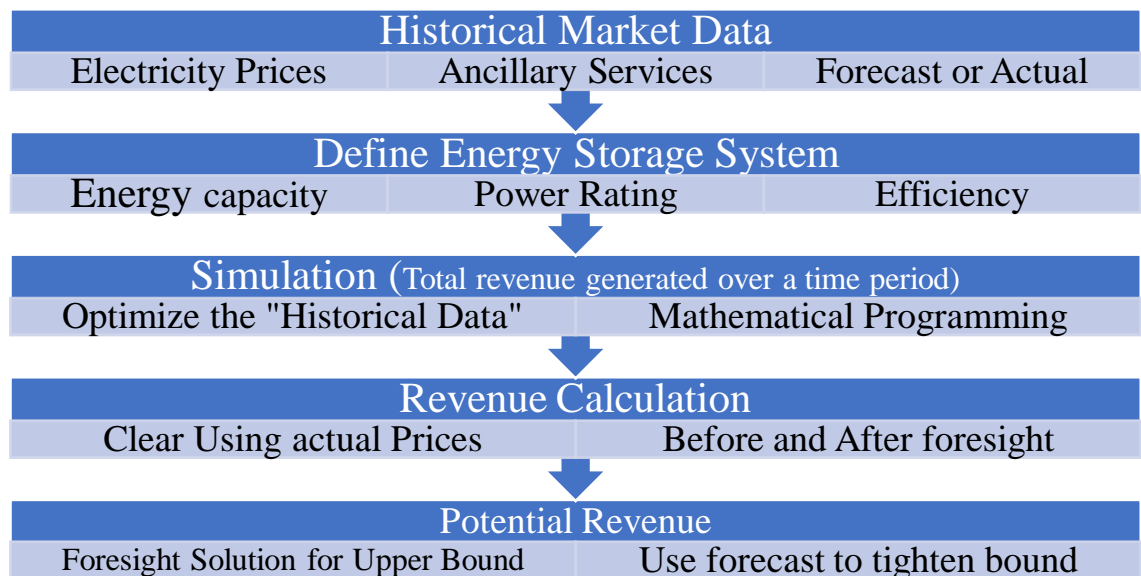
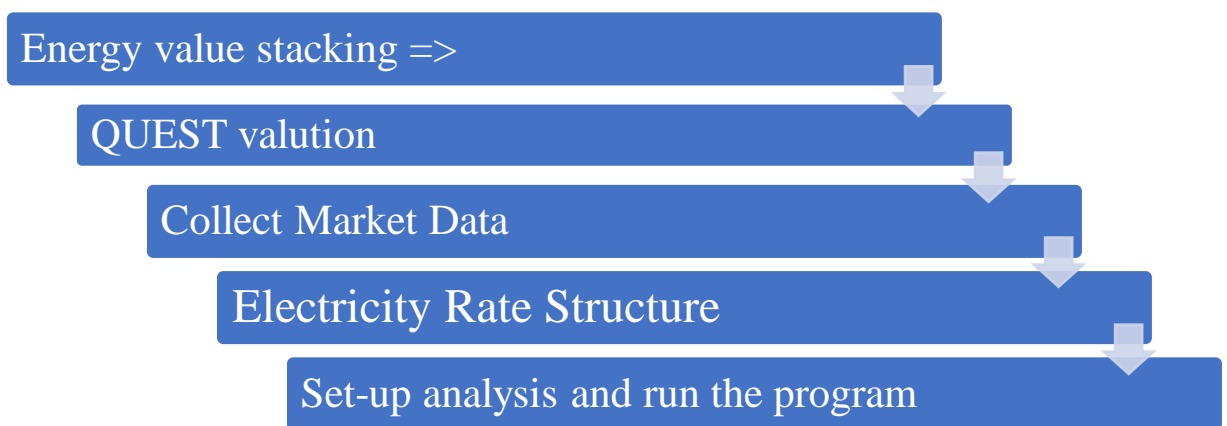
- Download the main file Valuation Fi from the given location.
- After downloading the file, unzip the file with the same name in the location “DESKTOP” on your personal PC. (Note: make sure that the file has the same exact name, ‘Valuation FI’, and is placed on the desktop)
- After that, open Valuation FI and find ‘run.bat’ to run the application. (Note: It will install the Python on its own- if not on the PC and will download all kinds of necessary paths; please be patient for a few minutes)
- Finally, it will automatically complete its installation process and show the application's main platform. If it doesn't show, then click the ‘main’ file from the file section.
- Even after that, if it doesn't open, then need to replace the GLPK file inside the application. Click here to download [GLPK](#)

Appendix 2. The process of the QuEST valuation process

Market data (Value stacking)

As a part of the Nord Pool electricity market, Finland also participates in a broader regional market, which could influence the strategies for value stacking.

The flow of process:



* Note: The simulation is governed by restrictions on the state of charge, as well as limitations on power and energy, in addition to other constraints. Simulation subjected to the state of charge limits power/energy limits other constraints.

Appendix 3. The Data management for the application

The data collection for the application is a very crucial and vital step. All the data collected for this application are free and have permission to use.

- Arbitrage only

For arbitrage, the hourly electricity market price data are taken from the 'Oomi Energia' (Oomi Energia is a local electricity sales company originating from local energy utilities across Finland) website [75].

Reasons: The main reason for taking the data from this Oomi website is the clarity and open data organization. The data is also regulated with the Nord Pool spot market system. It is also available to analyze hourly/day/month/year, and it is also easy to access the historical data from this site.

Difficulty: The data was given in c/kWh format, which needed to be converted into €/MWh.

Link: [Oomi- Spot price of electricity](#)

- Arbitrage and Regulation

Scenario 2:

Data abbreviation:

1. Regulation Up - Frequency containment reserves for disturbances upwards regulation, nordic trade
2. Regulation Down - Frequency containment reserves for disturbances downward regulation, nordic trade
3. Responsive Reserve Service (RRS) - Frequency Containment Reserve for Normal operation, foreign trade
4. Non-Spin Reserve Service (Non-Spin) on Finland market - Balancing Capacity (mFRR), up, hourly market, procured volume?
5. Cross border

Link: <https://data.fingrid.fi/en/datasets> ,

https://transparency.entsoe.eu/transmission/r2/dailyImplicitAllocationsCongestionIncome/show?name=&defaultValue=true&viewType=TABLE&areaType=BORDER_BZN&atch=false&dateTime.dateTime=26.05.2024+00:00|UTC|DAY&CTY|10YFI-1-----

[U|SINGLE=CTY|10YFI-1-----U|SINGLE&border.values=CTY|10YFI-1-----](#)
[U!BZN_BZN|10YFI-1-----U_BZN_BZN|10Y1001A1001A39I&dv-datatable length=10](#)

Additional data :

Intraday Market Prices:

- Hourly prices for buying electricity (charging prices, $E_{b,i}(t)$):
 - Down-regulation price in the Balancing energy market
 - <https://data.fingrid.fi/en/datasets/106>
 - Imbalance price
 - <https://data.fingrid.fi/en/datasets/319>
- Hourly prices for selling electricity (discharging prices, $E_{s,j}(t)$):
 - Up-regulating price in the Balancing energy market
 - <https://data.fingrid.fi/en/datasets/244>
 - The sales price of production imbalance electricity
 - <https://data.fingrid.fi/en/datasets/93>

Balancing Market Prices:

- Prices for up-regulation:
 - Price of the last activated up-regulation bid
 - <https://data.fingrid.fi/en/datasets/22>
 - Automatic Frequency Restoration Reserve, price, up
 - <https://data.fingrid.fi/en/datasets/52>
- Prices for down-regulation:
 - Price of the last activated down-regulation bid
 - <https://data.fingrid.fi/en/datasets/251>
 - Automatic Frequency Restoration Reserve, price, down
 - <https://data.fingrid.fi/en/datasets/51>