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Optimization Model Based Techno-Economic Assessment for Optimal Siting, Sizing and Energy Market Participation of Battery Energy Storage System to Enhance Grid Flexibility

School of Technology and Innovations
Master of Science in Technology
Master's Programme in Smart Energy

Vaasa 2025

UNIVERSITY OF VAASA
School of Technology and Innovations

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Title of the thesis:	Optimization Model Based Techno-Economic Assessment for Optimal Siting, Sizing and Energy Market Participation of Battery Energy Storage System to Enhance Grid Flexibility		
Student Number:	2302031		
Degree:	Master of Science in Technology		
Discipline:	Masters in Smart Energy		
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Year:	2025	**Pages:**	79

ABSTRACT:

This thesis investigates a 20 kV Medium Voltage (MV) radial distribution network located in Porkholm, Finland, as part of the PEAK project in collaboration with the Distribution System Operator, Esse Elektro-Kraft Ab. The Porkholm 20 kV distribution network, which serves a combination of dispersed urban and scattered rural consumers, often faces significant operational challenges, including irregular load profiles and voltage instability. These issues compromise system reliability and efficiency, highlighting the growing need for enhanced network flexibility to accommodate fluctuating demand.

To address these challenges, this study explores the integration of a Battery Energy Storage System (BESS) as a flexible solution that enhances grid stability while maximizing revenue through strategic participation in energy markets. A two-stage optimization framework is developed, incorporating piecewise linearized power flow modelling and Mixed-Integer Linear Programming (MILP), to determine the optimal siting, sizing and energy market participation of BESS. This technical approach is complemented by a comprehensive techno-economic analysis, aiming to balance operational constraints with market based economic performance.

In the first stage, the optimal BESS location is identified by targeting nodes with the highest voltage deviation and minimum BESS size, thereby improving voltage stability and overall network flexibility. Simulation results confirm that strategic placement of BESS significantly enhances voltage profiles and system reliability. The second stage involves determining the optimal BESS size by simulating its participation in both the Day-Ahead Spot Market and the Frequency Containment Reserve for Normal operation (FCR-N) market. In this stage, a strategic market participation approach is developed to allocate BESS capacity effectively between the two markets, aiming to maximize revenue while maintaining grid support functions.

Finally, the economic feasibility of BESS deployment is evaluated using key financial metrics. The Net Present Value (NPV) analysis confirms positive long-term returns, with a payback period of approximately 6 years under a 5% discount rate. The Levelized Cost of Electricity (LCOE) is calculated at 0.2788 euro per kWh over the project’s lifetime. These findings demonstrate that when BESS is optimally sited, correctly sized, and strategically integrated into energy markets, it can deliver both technical benefits and cost-effective energy services to the MV distribution network.

KEYWORDS: Battery Energy Storage System (BESS), Network Flexibility, MILP Optimization, Congestion Mitigation, FCR-N, Spot Market, Techno-economic Analysis.

Contents

Figures

Tables

Abbreviations

aFRR	automatic Frequency Restoration Reserve
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
DER	Distributed Energy Resource
DSO	Distribution System Operator
EV	Electric Vehicle
FCR-N	Frequency Containment Reserve for Normal Operation
FCRN-D	Frequency Containment Reserve for Disturbances
FFR	Fast Frequency Reserve
LCOE	Levelized Cost of Electricity
LV	Low Voltage
mFRR	manual Frequency Restoration Reserve
MILP	Mixed Integer Linear Programming
MV	Medium Voltage Distribution Network
MV	Medium Voltage Distribution Network
NPV	Net Present Value
OLTC	On Load Tap Changer
OPEX	Operational Expenditure
PV	Photovoltaic
RES	Renewable Energy Sources
SOC	State of Charge
SOH	Sate of Health
TOU	Time of Use
TSO	Transmission System Operator
VRE	Variable Renewable Energy

1 Introduction

A stable power system's fundamental requirement is to balance supply and demand across the network (Ten & Hou, 2024). An unmanageable power system creates frequent demand spike which leads to instability, increased operational costs and price spike, all of which negatively impact both on utilities and consumers (Sayed et al., 2024). Balancing can be achieved utilizing different types of Flexible Energy Resource (FER) considering existing network's characteristics across Transmission System Operator (TSO) to consumer level (Uzum et al., 2024). While TSO handles bulk-system balancing, DSO increasingly needs local flexibility to manage distribution level constraints (Patig et al., 2022). However, this thesis focuses on a Finnish Distribution System Operator (DSO) Esse Elektro-Kraft Ab Medium Voltage (MV) radial networks flexibility considering Battery Energy Storage System (BESS). In this context, a two-stage optimization model and an economic model has been developed to allocate optimal siting and sizing of BESS and its participation in different energy market maintaining coordination between TSO -DSO and conducted a comprehensive Techno-Economic analysis. This chapter illustrates a thorough background to the study, clear definition of the problem statement, organising the objective of the thesis and formulation of the research questions. Through this foundational overview, first chapter provides a clear insight of the research and demonstrates the importance of technoeconomic analysis to integrate BESS in MV network.

1.1 Background and Motivation

The development of power system is one of the remarkable engineering and technological achievement in human history. From the early ages, the goal is the same to deliver electricity reliably, safely, and economically. Though the goal is same but the way we try to manage is changed. Today's energy system is undergoing major transformation driven by climate changes, digitalization and green energy transition. In recent years, Variable Renewable Energy (VRE) integration is remarkably increased. By

20th century, VRE generation has been increased around 9000 TWh and in Finland 42.1% of electricity supply is provided with VRE. This transformation brings with new challenges both technically and economically and requires developing new solution and strategies to manage.

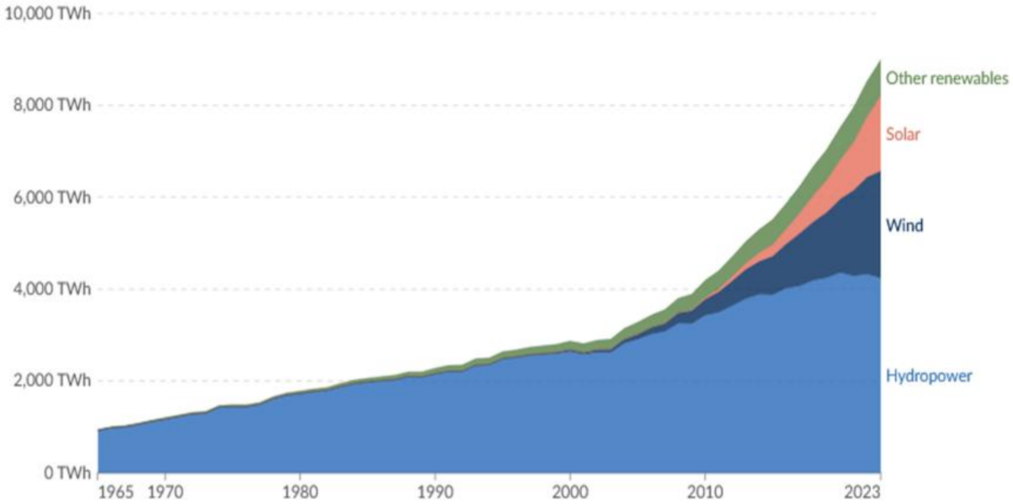


Figure 1. Globally Renewable Energy Integration (Ritchie et al., 2024).

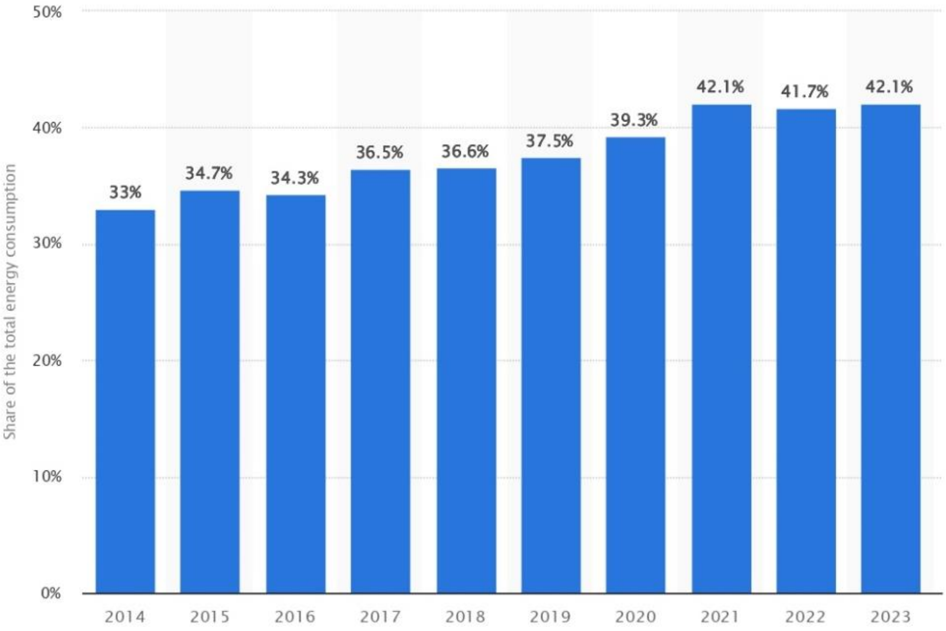


Figure 2. Finland Renewable Energy Generation (Statista, 2025).

1.1.1 Flexibility Needs in MV Network

Earlier MV networks consisted of radial lines designed to only carry power from the primary substation to the loads, leading to a steady variation of voltage along the route and slowly changing load curves unlike transmission corridors which deal with bulk power in both directions. However, nowadays MV network is integrating more DER and facing evolving load patterns, it becomes more technical challenges in maintaining power quality and system wide stability (Muzammal Islam et al., 2024). A Photovoltaic (PV) plant, the day with maximum solar radiation, generates more power pushing feeder to reach over voltages, while heavy peak loads or remote rural consumers rise heavy voltage drops (Gandhi et al., 2020). Traditional voltage control method or equipment like On Load Tap Changer (OLTC) or capacitor banks may struggle to effectively respond to frequently fluctuations with renewable generation which leads to raise voltage limitations (Sarimuthu et al., 2016).

On the other hand, by integrating DER, there are challenges adherence to thermal limits of lines and transformers (Coletta et al., 2020). MV radial networks have capacity ratings, and surges in demand for example electric heating during winter peaks in cold climate or generating more power from DER can cause overloads (J. Hu et al., 2021). Such thermal stress does not only cause to equipment damage but also make DSO to curtail DER output or reinforce lines. Simultaneously, Electric Vehicle (EV) charging or electric heating, can greatly increase peak loads on 20 kV feeders. Similarly, clustering of PV or wind can create network congestion in some parts of the network operating near their transformer limits. Network Congestion and thermal issues generally occur relatively for brief periods mostly in peak hours or high generation intervals; however, DSO must consider infrastructure planning to meet those worst-case situations (Silva et al., 2018).

The active injection of power from various DER sources at the MV level alters fault currents and power flow directions, which is challenging to maintain coordination of protection devices and the stability of the network(Razavi et al., 2019). Besides DER issues, rural distribution system encounters remarkable voltage drops in normal conditions because the consumers are distributed over long intervals in long radial network (Rakhmonov et al., 2020). Overusing electrical heating in winter can lead to currents above their safety limits, and starting large motors also causes short voltage drops which can lead a section of the network to low voltages (Akmal et al., 2014). These technical issues collectively limit the hosting capacity of the distribution network for example the amount of new DER capacity that can be accommodated without violating voltage or thermal limits (Dong et al., 2024). In summary, MV distribution network in Finland and elsewhere is facing complication related to manage voltage regulation difficulties, thermal overload risk and congestion points as the network is evolving to more dynamic configuration. This makes to deploy FER to mitigate these issues in real time.

1.1.2 Enhancing Grid Flexibility with BESS

BESS provides promising support to address and mitigate above challenges and enhance grid stability. BESS can act as a highly flexible controllable resource connected at the MV network and enhances operational supports and infrastructure management. Recent studies underscore that appropriate allocation of BESS placement and sizing improve distribution network performance and reliability. Moreover, by the integration of innovative control strategy, BESS can activate charging during off peak periods for low demand or excess generation and discharging during on peak hour or shortfalls, support peak shaving and load levelling (Elio & Milcarek, 2023). Therefore, it manages thermal stress on feeders and transformers by reducing peak currents and mitigates congestion and costly network upgrades (Prakash et al., 2022).

BESS unit can also provide rapid voltage regulation and improve power quality in the network by injecting or absorbing reactive or active power in response with local grid during voltage rise due to high penetration of solar generation as well as support sagging voltage during heavy load (Ghazavi Dozein et al., 2021). Additionally, BESS can store surplus power from VRE and utilizes when required and increases DER hosting capacity without effecting voltage and thermal limits. In essence with the integration of BESS, the remaining power from utilities during off peak period are managed without violating network constraints (Efkarpidis et al., 2023).

Beyond steady state operation, BESS can highly improve grid reliability and resiliency with the help of its fast-acting capabilities. During the event of upstream outages or fault, Grid Forming Inverter (GFM) based BESS can independently handle the abnormality of the system and can steadily supply power to the network in islanded mode by maintaining network constraints (Babu et al., 2024). Moreover, BESS can be activated as a backup power support when network faces overload resulting from unexpected load growth (Parthasarathy et al., 2022). Normally in this type of situation, DSO dispatches some parts of the network to manage this kind of situations however with the deployment of BESS such kind of issues are smartly managed by supplying extra required power to the network such capabilities improve the System Average Interruption Duration Index/System Average Interruption Frequency Index (SAIDI/SAIFI) reliability indices (Siregar & Sihaloho, 2024). Overall, BESS enables DSO to manage peak demand, improve renewable integration, stabilizes voltage and frequency and lowers the need of network upgrades.

1.1.3 BESS in Energy Markets

While DSO deploys BESS as a primary support for the local grid, the same asset can be utilized in different energy arbitrage and ancillary service markets to support TSO and can earn additional revenues. Effective integration of BESS for such purposes require appropriate coordination between TSO and DSO (Parthasarathy et al., 2021). In Finland, the power system is part of synchronized Nordic grid and Fingrid maintains different types of reserve market for flexibility services. Key ancillary services including FCR-N, FCR-N for disturbances, Fast Frequency Reserve (FFR), Automatic Frequency Restoration Reserve (aFRR) and manual Frequency Restoration Reserve (mFRR). These services are critical in maintaining grid stability which requires quick response from BESS depending on type of services (Chen et al., 2016). BESS is well suited for this these reserve markets for its fast responsive characteristics (Motta et al., 2021). In recent years, BESS earns significant revenue by participating in frequency reserve markets by injecting or absorbing required power with instant activation. Frequency-reserve services have been shown by market studies to be the greatest source of profit for battery storages in Europe. In 2022, a survey in Europe found that using energy arbitrage usually does not lead to remarkable revenue whereas frequency regulation market participation gains significant revenue (Y. Hu et al., 2022).

With proper communication framework, BESS injects or absorbs required power to the grid. In this context, appropriate coordination is required so that BESS should not face any conflict on activating its charging and discharging cycle based on local grid condition and TSO requirements (Celli et al., 2021). Generally, for the ancillary market participation, a particular amount of power from BESS is reserved for providing the services (Y. Hu et al., 2022). According to the contract if BESS fails to provide the reserve services, TSO could issue penalty to DSO (Alazemi et al., 2022). In this thesis the practical assumption is that local network constraints are satisfied first, and the remaining capacity is offered to Fingrid’s reserve markets and the day-ahead spot market, reflecting the minimal coordination necessary for reliable participation.

1.1.4 Techno-Economic Perspectives for DSO

BESS is one of the best choices for DSO to improve network’s flexibility, reliability and ensure resiliency. As it is expensive to implement and maintain, DSO needs to carefully assess whether the investment in BESS is financially worthwhile or not. This is where techno economic analysis becomes important, it combines technical performance such as how much the battery improves voltage or reduces line loading with comprehensive financial analysis like how much money it saves or earns. New studies at feeder level suggest that a BESS with can reduce annual loss on feeders and decrease peak voltage changes (Alrashidi, 2022).

Traditional upgradation in network component such as line and transformer capacity is often approved as long-term investment. However, BESS is a newer type of solution, and the regulators may require solid proof and operational planning to make sure that it is cost effective. To do this, DSO uses financial analysis considering Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, and Levelized Cost of Energy (LOCE) (Peng et al., 2021). These assessment help to differentiate the expenses and future profits of the BESS over its lifetime. NPV calculation results either positive or negative value which means that whether the future cash flows is higher than the investment. If it is positive NPV, the project is considered beneficial. Moreover, the Payback Period calculation tells how many years it will take to recover the initial cost. A case study on Second-Life EV Battery participation in Frequency Containment Reserve services found that bundling revenue from offering frequency reserves with savings achieved at feeder level enables Internal Rate of Return (IRR) values between 8 and 21 percent and shortens project payback periods from 5 to 8 years (Janota et al., 2020). Therefore, a well techno economic analysis gives appropriate decision for a BESS project that the project is both technically useful and financially sound. This thesis demonstrates such assessment to recommend the best size and location in a Finnish 20 kV MV radial network.

1.2 Case Company (A Finnish Rural 20 kV Radial Distribution Network)

The work of this thesis has been conducted as part of the PEAK (Pathways to Energy Autonomy and Knowledge-Based Flexibility) project, coordinated by the University of Vaasa, in collaboration with a Finnish power company Esse Elektro-Kraft Ab. In this study, Esse Elektro-Kraft Ab is considered as the case company (*PEAK Project*, 2025).

Esse Elektro-Kraft Ab provides power distribution services to rural region of Ostrobothnia by receiving power from TSO as well as from their own power generation units from Hydropower, Wind Power and Solar Park. There is total 4 numbers of primary 110/20 KV substation with 18 numbers of 20 KV feeders. However, this thesis focuses on one 20 kV network (Porkholm network) to deploy a BESS by assessing comprehensive technoeconomic analysis utilizing a 2-stage optimization model and an economic analysis model. The length of the network is 55 KM with 39 distribution substations. The consumers in the network are far from each node of the network which increases resistivity with the length results voltage drop and line loss. The objective is to integrate Flexible resource as BESS to address these challenges, enhance flexibility and boost revenue by participating in different energy market.

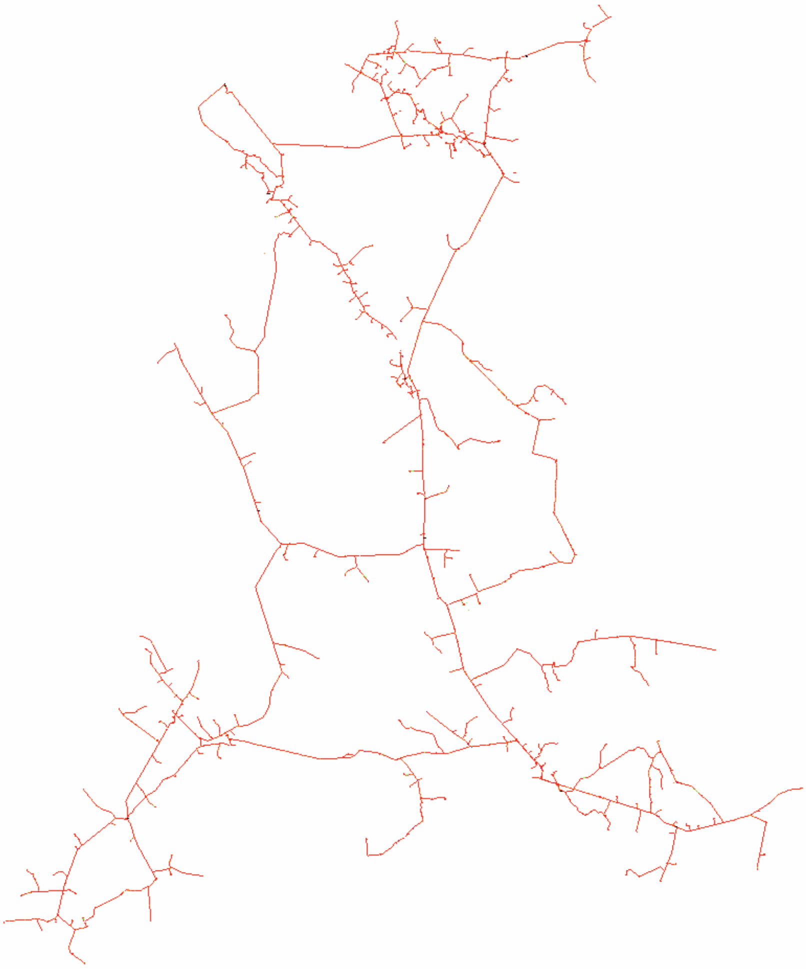


Figure 3. 20 kV Finnish Rural Network.

1.3 Problem Statement and Research Questions

20 kV Porkholm network is increasingly facing technical challenges due to evolving load patterns and rising peak demand. These changes lead to voltage instability, particularly during periods of high demand which comprises power quality and system reliability. Although voltage instability is the primary issue, it can also trigger secondary technical issues such as increased network loss, equipment overloading and reduced lifespan of network components. The DSO aims to make the most of the existing infrastructure by avoiding expensive upgrades to line or transformer capacity. As the network transitions towards dynamic and potential distributed energy resources, there is a growing need of flexible solution to maintain operational stability and meet energy efficiently. To tackle these challenges, the deployment of BESS is considered a suitable flexible solution due to its fast response capabilities and versatility. BESS can effectively manage voltage fluctuations, reduce peak demand, and alleviate network congestion. Its ability to take part in energy and reserve market also supports economic viability. Therefore, a techno-economic approach is essential to ensure its optimal integration into the MV network.

To respond to the issues outlined above, the following research questions have been developed to guide the study:

1. How can BESS be optimally allocated and sized to maximize flexibility and reliability?
2. How can BESS be simultaneously participated in Day ahead spot market and Frequency Containment Reserve for Normal operation (FCR-N) market by maintaining coordination between TSO and DSO?
3. How techno-economic analysis can guide DSO to make appropriate investment decision for the deployment of BESS considering NPV, Payback Period and LCOE?

By addressing above mentioned problem statement along with subsequent research question this study aims to provide comprehensive techno-economic analysis result for the deployment of BESS in Porkholm 20 kV distribution network.

1.4 Research Objectives

This thesis aims to deliver an effective strategy for enhancing flexibility in medium-voltage distribution network facing increasing technical challenges. With a focus on the 20 kV Porkholm network, the study will investigate how BESS can be optimally integrated to manage voltage instability, peak demand, and congestion. A techno-economic perspective will be adopted to ensure both technical feasibility and financial viability. The objectives of the study are articulated below:

Objective 1: Optimal siting and sizing of BESS to improve network stability and resiliency.

This study aims to create an optimization framework that identifies the most suitable location and size for BESS, based on both technical efficiency and economic viability. Firstly, piecewise linearized power flow analysis will be applied to evaluated network performance and identify potential bottlenecks. Based on these insights, the model will identify suitable locations and size of BESS. Finally, BESS placement will be finalized through stability analysis, while its sizing will be based on the system's ability to inject or absorb power under varying network conditions.

Objective 2: Participation of BESS in Day ahead spot market and FCR-N market

After getting the optimal location and minimum sizing, BESS will be participated in day ahead spot market and FCR-N market to determine maximum BESS capacity that can be finalized and maximize the revenue from the energy market participation. In this stage, BESS will participate simultaneously in both markets considering coordination between DSO and TSO. Finally, both market participation will be evaluated to determine which market participation will bring maximum profit for DSO.

Objective 3: Techno-economic analysis for the deployment of BESS in Porkholm Network.

Furthermore, a comprehensive techno-economic analysis will be conducted considering whole year simulation to finalize net present value of BESS investment, cash flow, payback period and LCOE while maintaining technical constraints. This assessment will be carried out to make decision for DSO whether the invest is profitable or how to approach for the investment for the deployment of BESS in Porkholm network.

By addressing above objectives, this study aims to provide structured and data driven approach to integrate BESS in MV network. Through the integration of power flow analysis, multistage optimization, and market participation modelling, the study not only identifies optimal siting and sizing of BESS but also ensures its technical impact and economic viability.

1.5 Scope and Limitation

This thesis focuses on developing an optimization-based techno-economic model for the deployment of BESS into the existing 20 kV Porkholm MV network. The study covers the assessment of network limitations, including thermal capacity, voltage regulation, and the need for system flexibility. This model is designed to find the most suitable BESS placement and capacity while maintaining technical reliability and financial viability. Additionally, the study includes formulating an operational strategy for BESS participation in the Day-Ahead Spot Market and the FCR-N market to enhance network flexibility and support financially viable deployment decisions.

While this study presents a comprehensive approach to optimal BESS integration, it excludes the impacts of variable renewable energy (VRE) and electric vehicle (EV) loads. These factors may require separate analysis to assess their influence on BESS deployment. Moreover, the model includes BESS participation in the FCR-N market with coordination with TSO however a detailed strategic coordination framework needs to be developed to support efficient and aligned market participation.

1.6 Thesis Structure Overview

The thesis follows a structured format to present the research conducted for a comprehensive techno-economic assessment of BESS in MV distribution network utilizing a two-stage optimization model and an economic model. The following sections are a comprehensive overview of each chapter of the thesis.

Chapter 1: Introduction

Chapter one lays the groundwork for the study by outlining its background, highlighting the core issue, defining the research aims, and stating the guiding questions. It also highlights why the study is important. This chapter helps the reader to understand the context and purpose of the study and explains why it is relevant.

Chapter 2: Literature Review

The chapter reviews related literatures on MV network flexibility, optimal placement and sizing of BESS, different types of energy market participation, techno-economic optimization techniques and newer approaches for MV network flexibility and deploying BESS in MV network. It provides a review of the literature and sets the theoretical framework of the research.

Chapter 3: Methodology

This chapter outlines the research methodology used to prepare a two stage piecewise linearized power flow optimization model and one economic analysis model to study MV networks flexibility by strategy for BESS deployment. It describes data preparation process using real network information and electricity market prices, the network analysis approach, the development of optimization model, and the techniques used for comprehensive techno-economic analysis.

Chapter 4: Results and Findings

This chapter is provided with techno-economic analysis results before and after the integration of BESS in the network. Based on 2024 network data, multiple scenarios were developed and simulated to assess the techno-economic feasibility of BESS deployment.

Chapter 5: Discussion and Conclusion

The last chapter provides the summary, and the major contributions of this study to the area of MV network Flexibility utilizing BESS and the recommendation on future research.

2 Literature Review

The chapter covers the current studies on how to optimally allocate the siting and sizing of BESS in MV rural network considering Techno economic analysis. Key issues are covered such as MV network challenges, Flexible resource for network stability, BESS siting and sizing methods, flexibility market participation of BESS and economic analysis concept for the deployment of BESS. The purpose of this review is to build a solid theoretical foundation that informs the modelling approach and supports the integration of BESS as a viable solution for enhancing both technical performance and economic efficiency in distribution system. With this knowledge, it allows us to provide a detail analysis results from technoeconomic point of view for the deployment of BESS in MV rural network.

2.1 MV Network

MV network has traditionally operated as radial circuit designed for unidirectional power flow from substation toward end users resulting in predictable voltage profiles and manageable loading conditions. However, recent trends in electrification and integration of renewable energy have fundamentally altered this operational paradigm, which creates new flexibility needs in MV distribution grid.

2.1.1 Voltage Regulation Challenges

Rural MV networks, such as the 20 kV feeder is particularly vulnerable to voltage deviations, and protection coordination issues due to extensive length, high impedance, and dispersed consumer loads (Saboori et al., 2015). Voltage challenges are prominent, with significant voltage drops occurring during peak hours and substantial voltage rises when distributed Photovoltaic (PV) generation is high (Wang et al., 2019). These voltage challenges, driven by frequent fluctuations in renewable generation, often occur faster than the response capabilities of traditional voltage control device such as On Load Tap

Changer (OLTC), making them less effective under such dynamic conditions (Elrayyah & Singh, 2020, Olatunde et al., 2020).

2.1.2 Thermal Overload and Congestion

Thermal overloads constitute another critical bottleneck, particularly during extreme weather conditions or periods of high renewable generation. Transformer and conductor could reach their nominal rating, driven by short term peak from electric heating and electric vehicle charging (EV). Additionally, network congestion frequently occurred, where renewable generation and variable loads are clustered which led to section of the network operating close to or exceeding their limits (Syranidou et al., 2020). Rural and suburban feeders are especially prone to overload during coincident high-load and high-generation periods. Moreover, limited conductor capacity, coupled with uncoordinated DER output, intensifies congestion risk and restricts available headroom for further renewable integration (Dargaville et al., 2021).

2.2 Overview of Flexibility in Power System

The growing share of VRE and the widespread electrification of transport, heating, and industry have made today's electricity network far more complex. This is especially true for MV distribution grid, where operators must keep voltage and frequency steady even though power flows quickly in both directions. Flexibility at distribution level has now emerged as a major solution to combat challenges emerging from VRE integration and increased electrification.

2.2.1 Flexibility: Concept and Classifications

In power network, flexibility generally refers to the grid's capability to adjust active and reactive power flows in real-time to ensure stable and efficient operation. This capacity becomes significant in MV network with high penetration of renewable energies. ISGAN (2021) discussion paper offered a multi-dimensional definition of flexibility, where flexibility has been described as its capability to reliably manage the variations in both generation and consumption across different system layers. This report distinguished between flexibility from a technical perspective related to physical asset, infrastructure and from the user perspective which emphasizes consumer behaviour and participation.

Based on flexibility services it can be classified into temporal, geographical, and operational types (W. Zhang & Zavala, 2023). The author proposes a computational framework to allocate flexibility resource in a power network and underscored how temporal flexibility for example load shifting and battery storage control is the key to adapt time varying condition, while geographical flexibility such as optimal BESS placement addressed grid congestion at specific nodes. Furthermore, Vagropoulos et al. (2022) highlighted, operational flexibility by proposing TSO-DSO market coordination framework which illustrates how real time reserve activation and reactive power management could be utilized to stabilize MV network during fluctuating load and generation events.

Additionally, Luo et al. (2022) analysed, several demand response models and load adjustment strategies. They validated the effectiveness of temporal flexibility in peak demand reduction and cost minimization for system operator. The findings underscore the growing reliance on consumer level response to ensure real time operational flexibility, particularly the network experiences stress from decentralized resources.

2.2.2 Flexibility under Rising VRE and Demand Electrification

The growing contribution of VRE, such as wind, solar, and electrification of heating, transportation, and industrial sectors lead increasing rate of uncertainty and variability into MV network. This evolution requires enhanced flexibility to maintain power quality and supply continuity. A detailed techno economic analysis has been assessed in Colombian grid under different VRE penetration level by González-Dumar et al. (2024). They introduced flexibility indices and highlighted that higher flexibility reduces VRE generation curtailment, better renewable integration, and ensures stable voltage profiles across distribution feeders.

Apribowo et al. (2024) addressed, this issue and proposed a BESS siting and sizing optimization model to support flexibility in Finnish MV rural network. Their findings evaluated the significance of BESS on network performance under different VRE uncertainty scenarios. A coordinated control of storage has been proposed that significantly reduces voltage swings and alleviates feeder overloads. In another study, Bolfek et al. (2024) focused on voltage triggered flexibility. The author analysed how limited observability MV network, particularly rural network, could benefit from voltage-based activation of flexibility resources like BESS. This study provides a solution to local congestion and fluctuation, especially during massive EV adoption and rising demand of heating electrification.

2.2.3 Technological Pathways to Grid Flexibility

A numerous numbers of literature identify multiple sources of flexibility essential to address the dynamic demands in MV distribution network. Demand side flexibility is one of the prominent sources of flexibility. A spatial temporal model has been proposed by Agbonaye et al. (2021) to map residential and commercial demand flexibility in United Kingdom. Using smart meter data and building energy usage profiles, the author analysed the shiftable load potential across different neighbourhood. The findings underscored that targeted demand side intervention could delay reinforcement needs in constrained MV network by reshaping load patterns, particularly during on peak hours.

Energy storage, particularly BESS, is another vital contributor. Levin et al. (2023) examined the role of BESS in decarbonizing electricity system through multiple storage pathways. The study employed a techno economic model that simulated BESS participation in different energy market and policy scenarios. The analysis showed that the deployment of BESS can improve system wide resilience and manage network variability, especially in MV network with low inertia renewable energy resources.

2.3 BESS in Distribution Network

BESS is the one of the promising flexible resources for MV network. Unlike traditional reinforcement measures, BESS offers dynamic controllability that supports grid reliability, operational supports and increase hosting capacity. BESS's fast responsive capabilities make them valuable especially in rural radial network where voltage stability, congestion and peak load management are critical challenges. This section gives a thorough review of BESS regarding the technical roles, operational benefits to integrate in MV network.

2.3.1 Optimal Siting and Sizing of BESS

BESS are increasingly integrated into MV network to improve network stability and resilience. To deploy BESS in the network, optimal allocation of siting and sizing is essential otherwise maximum flexibility would not be accessible from BESS. Different studies conducted to allocate accurate location and capacity of BESS considering technical constraint of the network and economic viability.

In the reviewed studies, BESS siting and sizing were carried out by simulating their impact on specific distribution networks while considering voltage and loading constraints. One study used a real MV/LV network in Cape Town with high rooftop PV penetration; the authors applied quasi-dynamic simulations and voltage time-series analysis to identify nodes with persistent overvoltage, then sized the BESS based on energy needed to mitigate these violations (Mudimu et al., 2024). Another study applied optimization on the IEEE- 33 and 69 bus system, where voltage deviation, energy losses, and peak shaving are considered as performance metrics, BESS sizes were computed by iteratively adjusting energy and power capacity to meet technical limits under time-varying load and solar data (Wichitkrailat et al., 2024). These analyses ensured that both placement and capacity aligned with system operating conditions and planning goals.

Moreover, recent research applies piecewise linearized power flow optimisation model utilizing Mixed Integer Linear Programming (MILP) methods to fit nonlinear grid constraints into a manageable optimization problem (Khajeh et al., 2023). These models are very appropriate for large radial MV networks, where more precise nonlinear modelling would be complicated in terms of resources. Piecewise linear models simplify the relationship between voltage and current into segments (Jiang et al., 2020). This approach significantly captures voltage and current constraint as per existing network parameters and by using of deterministic solvers it provides most accurate and realistic results (Khajeh et al., 2023).

Choosing an appropriate optimization technique depends on the problem's complexity, the extent of available data, and the precision required in the solution. However, deterministic solvers are widely used for reliability and scalability in practical utility studies (Risi et al., 2022). On the contrary, in situations where the solution space is complex and non-convex or there is lack of information, metaheuristic techniques such as Genetic Algorithm and Particle Swarm Optimization (PSO) have been applied (Papazoglou & Biskas, 2023). Although these techniques give solutions that are close to ideal in a shorter amount of calculation time, they often do not ensure global optimality.

Several works highlight the need for time-series simulation at timescales to accommodate load variability and renewable generation patterns. For instance, Zhang et al. (2024) include hourly demand and price data in a two-stage optimization model at which the first stage finds the BESS placement and size and the second optimizes the operation under market constraints. The structure of this process follows a sequential order that fits with real world planning processes and that allows a clear segregation between strategic and operational decisions.

Some researchers used the combination of economic evaluation and technical optimization to develop multi objective frameworks. At the same time, they are designed to minimize power losses and investment cost with satisfying voltage and line loading constraints (Ahmadi et al., 2021). Others added market participation for example day ahead or ancillary market as an objective function term to put more emphasis on revenue stacking and regulatory compliance (Rancilio et al., 2022). The evolving needs of the power grid, changing market rules, and advancements in computing power have led to a wide range of modeling strategies for BESS siting and sizing presented in recent studies. It has been confirmed that optimal BESS placement should not only consider network topology, loading and constraint violation based on utility values, but also optimise economic trade-off and market dynamics.

2.3.2 Voltage Control

BESS offers range of technical benefits which enhance the stability of network. One of the benefits is voltage stability especially for the network with high penetration renewable energies. The fast-acting capabilities of BESS absorb or inject required reactive power to the network to stabilize the voltage during the time of sudden load increase or decrease. BESS significantly manage voltage deviations in rural 20 kV radial network in coordination with OLTC from primary substation transformer and capacitor bank units by controlling reactive power in the network (Kotsalos et al., 2020). In such schemes BESS handles fast voltage deviations. On the other hand, an OLTC is also used to manage voltage by adjusting its taps when demand rises, it increases the voltage to maintain stable levels. This feature is known as Line Drop Compensation (LDC). If PV shift their output rapidly due to clouding, the current in the transformer can also vary quickly. Sudden changes in OLTC operations can make the regulator adjust its position a lot. Making these changes in the OLTC several times can lower its overall reliability and reduce its age (Elrayyah & Singh, 2020).

2.3.3 Congestion Relief and Peak Shaving

Beyond voltage regulation, congestion relief is another critical and most commonly in MV network where BESS is effective. Optimal placement of BESS at critical nodes in MV feeders can manage thermal limits by supporting local consumption during on peak hour or absorbing excess renewable energy during off peak hours. Laaksonen et al. (2025) demonstrated the interaction of DER and BESS in MV network and found that congestion ranges in feeders were significantly reduced when BESS was coordinated with DER dispatch. The study showed that BESS with sensitive droop control can tackle problems with power oscillations at the connection point between HV and MV grids. Additionally, deploying BESS at mid-feeder made it possible to reduce voltage swings in local areas and clear upstream congestion during extreme frequency situations (Laaksonen et al., 2025). Liu et al. (2023) suggested a method that combines the work of both BESS and EV to reduce peak load efficiently. A multi objective optimization model was considered to help minimize power losses, peak demand and energy costs by means of a Modified Opposition-based Ranking-Based Human Psychology Optimizer (MORBHPSO). BESS was shown to release stored energy when there is peak demand and to charge when the grid requires less energy, helping to minimize load spikes.

2.3.4 Operational Strength

One of the main benefits of BESS is its controllability. Unlike conventional generator, BESS can respond to control signal within a second, which is the most important during frequency events (Tan et al., 2020). This fast-ramping capability and bidirectional power flow enables BESS to act as both a load and source and contributing to both grid support and energy market functions (Varhegyi & Nour, 2024). Fast response capability is very crucial for Frequency Containment Reserves for normal (FCR-N) operation services, where activation time up to 3 minutes. This capability allows BESS to participate appropriately in real time in different energy markets and ancillary services by managing reliability of the local grid. Furthermore, during upstream outages or sudden load shifts, BESS provides flexibility and keep the network in safe margin.

2.4 Market Participation Structures for BESS

BESS is becoming increasingly important in energy markets because of its quick response time and ability to keep the grid stable. BESS involvement in ancillary service markets adds another revenue generating opportunity and enhances system flexibility. These developments help improve the collaboration between TSO and DSO in flexibility management.

2.4.1 Fingrid's Frequency Reserve Market Structure

Fingrid, the Finnish TSO, operates different types of frequency reserve markets, enables flexibility resources like BESS to support system stability. These include FFR, FCR-N, FCR-D, and restoration reserves such as aFRR and mFRR (Fingrid, 2025). Based on the type of reserve market the activation speed, duration, and response time vary. Each reserve market has certain technical and regulatory criteria for prequalification to guarantee that BESS can function as planned. The involvement of BESS in these services improves the technological stability and viability of storage deployment from an economic standpoint (Hsi & Shieh, 2024).

Each reserve product in Finland prerequisites a certain system requirement. While FCR-D is triggered during significant frequency disruptions and provides more forceful corrective action, FCR-N provides symmetrical and automatic frequency response during typical variations (Viola et al., 2024). On the other hand, FFR market requires sub second activation to target quick but brief reactions to under frequency events (Viola et al., 2024). For scheduled restoration and balancing, aFRR and mFRR are used.

Reserve market places in Finland

	FFR	FCR-D	FCR-N	aFRR	mFRR
	Fast Frequency reserve, Finland 20 %, In Nordics, total 0-300 MW (estimate)	Frequency Containment Reserve for Disturbances, Finland 290 MW, Nordics total 1450 MW	Frequency Containment Reserve for Normal Operation, Finland 120 MW, Nordics total 600 MW	Automatic Frequency Restoration Reserve, Finland 60-80 MW, Nordics total 300-400 MW	Manual Frequency Restoration Reserve Reference incident + imbalances of balance responsible parties
Activated	In big frequency deviations, In low inertia situations	In big frequency deviations	Used all the time	Used in certain hours	Activated if necessary
Activation speed	In a second	In seconds	In a couple of minutes	In five minutes	In fifteen minutes

5 Reserves

FINGRID

Figure 4. Fingrid Frequency Reserve Markets (Fingrid, 2025).

These solutions are appropriate for longer term interventions and specifically use a centralized activation signal. By upholding transparent pricing and performance-based compensation, these reserve market participants promote competition among resources. Lots of pilot projects have been implemented and concluded that BESS units can meet these varied technical requirements and offers flexibility to both TSO and DSO (Attar et al., 2024). The diversity of these markets provides opportunity to flexibility operators with several paths for revenue.

2.4.2 Market Access Criteria and Compliance Obligations

In Finland, a BESS must finish the Fingrid prequalification process before they may take part in any reserve market. This involves providing technical report, control system requirements, and clearing real time test considering different types of scenario analysis (Fingrid, 2023). The BESS operator must then follow the standard for continuous monitoring. Therefore, state of charge reporting, real time monitoring, and routine TSO audits are needed to be verified for approval for the participation. In this context, if any technical specifications are not met with the requirements of reserve market or after participating if that BESS unit does not provide ancillary services as per submitted bid, disqualification and penalty could be issued to the BESS aggregators (Fingrid, 2023). The resilience of this framework guarantees that only trustworthy and competent units provide essential system services.

2.4.3 Study Focus: FCR-N and Day-Ahead Spot Market Participation

According to Fingrid the FCR-N market requires BESS units to support symmetrical upward and downward frequency regulation with a response capability within 3 minutes and sustained activation for up to 30 minutes (Fingrid, 2025). Participation in this market is triggered when the grid frequency remains within the range of 49.90 Hz to 50.10 Hz (Fingrid, 2023). During these periods, the BESS responds proportionally to frequency deviations, either discharging during upward regulation or charging during downward regulation (Khajeh et al., 2023). To join the FCR-N market, aggregators must submit bids at least one day in advance, with a minimum bid size of 100 kW. In addition to remuneration for the capacity reserved, BESS units earn revenue during upward activation by discharging energy, while costs may arise during downward activation due to charging (Fingrid, 2025). The activation cost or revenue is determined by comparing imbalance and spot market prices whichever results in a lower cost for charging or greater revenue for discharging is used for compensation. This structure incentivizes accurate and timely BESS operation to support frequency containment while also ensuring fair economic returns based on prevailing market conditions.

The day-ahead spot market enables electricity trading one day in advance, where participants forecast supply and demand conditions and submit hourly bids accordingly (Kitsatoglou et al., 2024). This mechanism acts as a vital contribution in balancing short-term grid operations by setting market-clearing prices for each time interval. BESS is increasingly participating in this market to provide arbitrage opportunities by exploiting temporal variations in electricity prices. Specifically, BESS operators charge their systems during periods of surplus electricity and low prices, then discharge stored energy during high-demand hours when prices rise, thus enhancing both profitability and system flexibility. The authors also highlighted that strategic BESS operation can reduce dependency on peaking generators and contribute to flattening the demand curve. Therefore, BESS integration into the day-ahead spot market not only supports economic objectives for operators but also contributes to broader grid efficiency and decarbonization goals.

2.5 Economic Assessment

The economic assessment takes precedent when determining the profitability and feasibility of BESS in MV network. Due to the capital intensity of BESS, financial indicators are needed to support investment decisions. However, the most used metrics are: Net Present Value (NPV), Levelized Cost of Energy (LCOE) and Payback Period. These indicators enable associating the technical performance of BESS with its financial viability in different market participation scenarios including day-ahead spot market and frequency containment reserves.

2.5.1 Net Present Value

Net Present Value (NPV) measures the gap between the discounted value of expected revenues and expenses throughout the system’s operational life. The long-term benefits from the investment of BESS is evaluated by discounting future cash flows to present value using NPV which is perhaps the most common evaluation method for BESS investment (Sperstad et al., 2020). To facilitate the comparison of costs and revenues over the BESS lifecycle this metric is used. A favourable NPV outcome reflects the project's ability to produce net financial gains over its operational lifetime. Several studies used NPV to evaluate profitability under varying market conditions including pricing and market regulation. As an example, Lin et al. (2017) performed a sensitivity analysis on battery size and the market income, revealing that the NPV is sensitive to energy market price spread. Overall, NPV serves as a fundamental decision-making tool for evaluating BESS deployment under uncertainty and varying economic conditions. Its application ensures that investment choices align with both technical performance and financial sustainability in MV network planning.

2.5.2 Levelized Cost of Electricity

The Levelized Cost of Energy (LCOE) is the average cost per unit of electricity generated over the lifetime of an energy asset, considering all capital, operational, and maintenance expenses (Kabeyi & Olanrewaju, 2023). It indicates the minimum price per unit of electricity needed to cover all project expenses throughout its lifetime. In energy markets, studies have found a significant reduction in LCOE when Battery Energy Storage Systems (BESS) provide ancillary services alongside energy arbitrage (Chatzigeorgiou et al., 2024). The author further commented that time-scheduled charging strategies, when coordinated with frequency regulation services, not only improve grid performance but also optimize BESS utilization. Such strategies ensure that energy storage is aligned with periods of high demand or grid instability, thereby maximizing economic returns and contributing to more favourable LCOE outcomes.

2.5.3 Payback Period

The payback period is a commonly used financial metric to assess the return timeline of energy storage investments. Peng et al. (2021) conducted a techno-economic analysis using HOMER software for a PV-plus-BESS configuration in an industrial case in Taiwan, evaluating discounted payback period among other indicators. Their results showed that optimal contract capacity and time-of-use (TOU) pricing could shorten the payback period while increasing self-consumption. Similarly, study emphasized that in frequency regulation markets, BESS profitability improves, potentially leading to shorter payback periods due to higher utilization rates and market remuneration schemes (Y. Hu et al., 2022). Additionally, sensitivity analyses revealed that electricity price volatility and capital cost reductions significantly influence the payback duration (Y. Hu et al., 2022). These findings suggest that with supportive market conditions and optimized operation strategies; BESS can achieve financially attractive payback periods in both industrial and grid-service applications.

2.6 Summary of Research Gaps

Despite the growing body of literature on flexibility enhancement and BESS integration in MV distribution network, several gaps remain unaddressed, particularly in the context of techno-economic optimization tailored to real MV rural network.

First, while many studies have evaluated BESS for flexibility support, such as voltage regulation, peak shaving, and congestion relief, most use generalized or idealized network models. Very few works implement optimization directly using big size real MV network data, such as a Finnish 20 kV rural radial system. As a result, it is rather difficult to have the results applied directly to real life planning task of DSOs.

Second, piecewise linearized power flow models have been widely used by many researchers within optimization frameworks and these models indeed best fit to large scale radial MV networks such as the test networks used in this study. When these systems have long feeder lengths, spares load centres and voltage sensitivity, nonlinear modelling becomes computationally expensive and impractical for planning purposes. However, compared to the piecewise linearized approach, keeping compatibility with MILP optimization and the ability to model important voltage and current constraints, it offers a reasonable balance between accuracy and tractability for complex radial systems.

Third, many prior studies only concentrate on one or the other technical or economic assessment. In contrast, this thesis develops a two-stage optimization framework: the first optimization model addresses strategic placement and capacity determination of BESS based on network constraints, while the second model simulates BESS participation in energy and reserve markets specifically day-ahead spot and FCR-N reserve market and to increase profit margin. A separate financial analysis module then examines the investment's profitability using evaluation metrics such as NPV, LCOE, and Payback Period. This study intends to demonstrate a comprehensive technoeconomic analysis results utilizing optimization model for the deployment of BESS in the Finnish MV radial network. More details on the technoeconomic model and analysis method are described in the next chapters.

3 Methodology

This chapter presents the methodological approach adopted in this study to examine the effective integration of Battery Energy Storage Systems (BESS) in Porkholm 20 kV network. The work applies a model based quantitative approach using data processing, mathematical modelling, optimization and simulation along with techno-economic assessment. However, all implementation was done using Python with appropriate libraries. The methodological approach utilized in this thesis is illustrated in Figure 5.

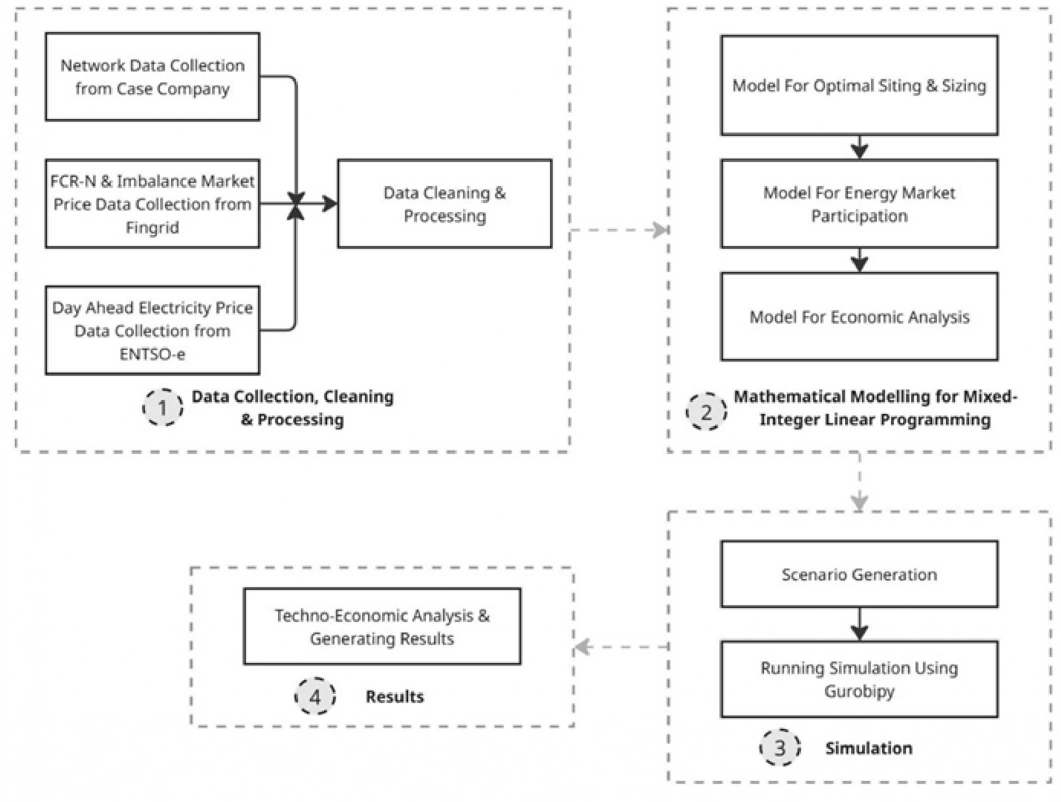


Figure. 5 An Illustration of Methodological Approach.

3.1 Data Acquisition and Preprocessing

The Porkholm MV network data has been collected from the case company, Esse Elektro-Kraft Ab. The data consists of information about node-to-node connection, length of the lines, conductor thermal ratings, resistance and reactance. To calculate per unit value of resistance, reactance, conductor thermal ratings a number of functions were constructed, and the calculation was done utilising the NumPy library of Python. Next, hourly load consumption data was cleaned using the Pandas library. This step involves delimiter correction such as commas, semi colons, for making the data consistent with the model. On the other hand, three types of electricity price data have been used in this study which are day ahead electricity price, imbalance market electricity price, and Frequency containment reserve capacity price from ENSTO-e and Fingrid (ENSTO-e, 2025, Fingrid, 2025) Moreover, yearly frequency data for FCR-N market collected from Fingrid. And finally, all data are merged with the help of pandas to fit with the model.

3.2 Mathematical Modelling

The objective of this study is to allocate optimal siting and sizing, market participation of BESS and technoeconomic analysis for the deployment of BESS in Porkholm 20 kV MV network. To mee this objective two stage piecewise linearized power flow optimization model and one economic model developed. First model provides BESS optimal location and minimum size of BESS or required flexibility of the network in the process of power flow analysis. Next, the 2nd model gives final BESS size and maximize profit by participating in energy arbitrage and ancillary service markets. Both models provide results in the process of power flow analysis to maintain network constraint. Finally in the third model comprehensive economic analysis has proposed considering NPV, LCOE and Payback Period.

Nomenclature:

$P_{x,\tau}^{U,\xi}$:	Activated upward power in kW
$P_{x,\tau}^{D,\xi}$:	Activated downward power in kW
$P_{x}^{\mathrm{C},\xi}$:	Activated power from Utility in kW
$P_{x,\tau}^{L}$:	Each nodes load consumption in kW
$P_{\chi,x,\tau}^{+,\xi}$:	Active power flowing in downstream in kW
$P_{\chi,x,\tau}^{-,\xi}$:	Active power flowing in downstream in kW
$Z_{\chi,x}^{2}$:	Impedance of the line
v_{χ}^{min}:	Minimum Voltage 0.95pu
v_{χ}^{max}:	Maximum Voltage 1.05pu
$\mathrm{v}^{\mathrm{rated}}$:	Nominal voltage 1 pu
$I_{\chi,x}^{max}$:	Maximum current
Nu^{BESS}:	Number of BESS
$R_{\chi,x,i}$:	Node to node line resistance in ohm
$SI_{\chi,x,\tau,i}^{\xi}$:	Auxiliary variable for squared current
$Q_{x}^{\mathrm{C},\xi}$:	Reactive power flowing in the network in kVar
$Q_{x,\tau}^{L}$:	Reactive power consuming in load in kVar
$Q_{\chi,x,\tau}^{+,\xi}$:	Reactive power flowing in downstream in kVar
$Q_{\chi,x,\tau}^{-,\xi}$:	Reactive power flowing in upstream in kVar
$X_{\chi,x,i}$:	Reactance of the line in ohm
$SV_{\chi,\tau}^{\xi}$:	Auxiliary variable for squared voltage
u_{x}^{BESS}:	Binary variable to locate BESS in candidate node
$\rho^{DCC}\mathcal{E}^{\zeta}$:	Capital cost in euro/kWh (Daily based)
$\rho^{M\&O}$:	Maintenance and Operation cost in euro/kWh
$P_{\omega=\mathrm{OBP},\tau,\xi}^{ch,da}$:	Charging day-ahead spot market in kW
$P_{\omega=\mathrm{OBP},\tau,\xi}^{dis,da}$:	Discharging day-ahead spot market in kW
$P_{\omega=\mathrm{OBP},\tau,\xi}^{FCR\text{-}up}$:	Upward activation capacity in FCR-N market in kW

$P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi}$: Downward activation capacity in FCR-N market in kW

$\mathrm{Cyc}^{\nu}_{\tau,\xi}$: Price of cycle ageing in euro/kWh

ρ^{FCR}_{τ}: Reserved capacity price in euro/kWh

$\mathrm{Cap}^{FCR}_{\tau,\xi}$: Reserved capacity in kW

$\rho^{reg,up}_{\tau}$: Upregulation price in euro/kWh

$\rho^{reg,down}_{\tau}$: Down regulation price in euro/kWh

ρ^{da}_{τ}: Electricity price in day ahead marker in euro/kWh

$SOE^{\mathcal{BESS}}_{\tau,\xi}$: BESS state of Energy at time slot τ of scenario ξ

$\Delta f^{up}_{\vartheta}$: Mean upward shift in system frequency in Hz

$\Delta f^{down}_{\vartheta}$: Mean downward shift in system frequency in Hz

F_t: Net cash flow in year t

D_t: Discount-adjusted return in the t-th year

R: Annual revenue

i: Inflation rate

I: Initial investment (CAPEX)

K: Total discounted cost

A: Total discounted energy output

r: Discount rate

d: Degradation rate

$\Delta\tau$: 1 hour

$\Delta f_{\zeta,\vartheta}$: Frequency deviation

O_t: OPEX in year t

C_t: Charging cost in year t

E_t: Energy discharged in year t

3.2.1 Optimal Siting and Sizing to Enhance Flexibility

The first optimization model for optimal allocation of BESS siting for the Porkholm network is carried out by simulating different load variations across several days. In this context, first optimization model has been developed with the objective function with the allocation of required size of the BESS for deployment in the network to enhance flexibility while considering technical constraints. To represent the nonlinear power flow relationships in a tractable way, a piecewise linearized formulation has been adopted following a structure consistent with established modelling approaches in the literature. On the other hand, by applying power flow analysis and evaluating the performance of different nodes in the network, the nodes with maximum voltage deviations are identified and selected for BESS deployment in such a way that their operation avoids congestion and supports the network during high-load periods, particularly in mitigating voltage or thermal limit violations. Equation (1) is the objective function which minimizes total flexibility power provided both upward and downward direction by BESS across all nodes and time steps.

$$OF = \sum_{\tau} \sum_{x} P_{x,\tau}^{U,\xi} + P_{x,\tau}^{D,\xi} \tag{1}$$

Power balance constraint equation (2) ensures active power balance at each node and time step, accounting for net load, BESS flexibility, and network power flows.

$$\begin{aligned} P_{x}^{\mathrm{C},\xi} - P_{x,\tau}^{L} + P_{x,\tau}^{U,\xi} - P_{x,\tau}^{D,\xi} - \sum_{\chi} \left(P_{\chi,x,\tau}^{+,\xi} - P_{\chi,x,\tau}^{-,\xi} + R_{\chi,x,i}\, SI_{\chi,x,\tau,i}^{\xi} \right) + \sum_{\chi} P_{x,\chi,\tau}^{+,\xi} \\ - P_{x,\chi,\tau}^{-,\xi} = 0 \forall \mathrm{x}, \tau \end{aligned} \tag{2}$$

Equation (3) defines the constraint for reactive power balance. It maintains the balance between reactive power injections and withdrawals, considering both network and BESS variables at each node and time step.

$$Q_{x}^{\mathrm{C},\xi} - Q_{x,\tau}^{L} - \sum_{\chi} \left(Q_{\chi,x,\tau}^{+,\xi} - Q_{\chi,x,\tau}^{-,\xi} + X_{\chi,x,i}\, SI_{\chi,x,\tau,i}^{\xi} \right) + \sum_{\chi} Q_{x,\chi,\tau}^{+,\xi} - Q_{x,\chi,\tau}^{-,\xi} = 0 \forall x, \tau \tag{3}$$

Equation (4) describes the voltage drop equation in linearized form using squared voltage (SV) and squared current (SI) variables. Voltage variations are estimated by considering the active and reactive power flows within the network.

$$SV^{\xi}_{\chi,\tau} - SV^{\xi}_{x,\tau} - Z^{2}_{\chi,x}\, S^{\xi}_{\chi,x,\tau,i} - 2R_{\chi,x,i}\left(P^{+,\xi}_{\chi,x,\tau} - P^{-,\xi}_{\chi,x,\tau}\right) - 2X_{\chi,x,i}\left(Q^{+,\xi}_{\chi,x,\tau} - Q^{-,\xi}_{\chi,x,\tau}\right) = 0 \forall \chi, x, \tau \tag{4}$$

Equation (5) imposes upper and lower limits on squared nodal voltages. It ensures that the voltages remain within predefined regulatory or operational thresholds.

$$\left(v^{min}_{\chi}\right)^{2} \leq SV^{\xi}_{\chi,\tau} \leq \left(v^{max}_{\chi}\right)^{2} \quad \forall \chi, \tau \tag{5}$$

Equation (6) defines the current magnitude constraints by bounding the squared line currents. This avoids thermal overloading of network lines.

$$\left(I^{min}_{\chi,x}\right)^{2} \leq SI^{\xi}_{\chi,x,\tau,i} \leq \left(I^{max}_{\chi,x}\right)^{2} \quad \forall \chi, x, \tau \tag{6}$$

Equation (7) sets an upper bound on active power flow to prevent exceeding line capacity, thereby avoiding congestion and maintaining system stability.

$$P^{+,\xi}_{\chi,x,\tau} + P^{-,\xi}_{\chi,x,\tau} \leq \mathrm{v}^{\mathrm{rated}} I^{max}_{\chi,x} \quad \forall \chi, x, \tau \tag{7}$$

Equation (8) similarly limits the total reactive power flow, thus complementing Equation (7) in maintaining network reliability under flexible operations.

$$Q^{+,\xi}_{\chi,x,\tau} + Q^{-,\xi}_{\chi,x,\tau} \leq \mathrm{v}^{\mathrm{rated}} I^{max}_{\chi,x} \quad \forall \chi, x, \tau \tag{8}$$

Equation (9) introduces the piecewise linearization of the apparent power. It approximates the squared magnitude of apparent power using linear segments of active and reactive power contributions, weighted by segment factors.

$$\left(\mathrm{v}^{\mathrm{rated}}\right)^{2} = \sum_{j}(2j-1)\ \Delta S_{\chi,x}\, \Delta P^{\xi}_{\chi,x,\tau,j,i} + \sum_{j}(2j-1)\ \Delta S_{\chi,x}\, \Delta Q^{\xi}_{\chi,x,\tau,j,i} \forall \chi, x, \tau \tag{9}$$

Equation (10) defines that the sum of all active power segments must equal the total active power flow between two nodes. This maintains consistency in the linearized approximation. (10)

$$P^{+,\xi}_{\chi,x,\tau} + P^{-,\xi}_{\chi,x,\tau} = \sum_{j} \Delta P^{\xi}_{\chi,x,\tau,j,i} \quad \forall \chi, x, \tau$$

Equation (11) maintains consistency by equating the total line reactive power with the cumulative value of its piecewise segments.

$$Q^{+,\xi}_{\chi,x,\tau} + Q^{-,\xi}_{\chi,x,\tau} = \sum_{j} \Delta Q^{\xi}_{\chi,x,\tau,j,i} \quad \forall \chi, x, \tau \tag{11}$$

Equations (12) and (13) define the bounds on active and reactive segment variables, respectively. These constraints guarantee that no segment contributes more than the maximum defined segment capacity ΔS.

$$0 \leq \Delta P^{\xi}_{\chi,x,\tau,j,i} \leq \Delta S_{\chi,x} \quad \forall \chi, j, x, \tau \tag{12}$$

$$0 \leq \Delta Q^{\xi}_{\chi,x,\tau,j,i} \leq \Delta S_{\chi,x} \quad \forall \chi, j, x, \tau, \tag{13}$$

Equation (14) defines the segment capacity ΔS based on the maximum allowable current and the number of parallel segments which ensuring a uniform piecewise linearization.

$$\Delta S_{\chi,x} = \frac{\mathrm{V}^{\mathrm{rated}} I^{max}_{\chi,x}}{N_{\mathrm{par}}} \quad \forall \chi, x, \tau \tag{14}$$

Constraints (15), (16), and (17) collectively ensure that flexible power is only injected or consumed at nodes where a BESS is installed. This is enforced using the binary variable x^{BESS}, which takes the value 1 if a BESS is installed at node x, and 0 otherwise. The upper bounds on upward and downward flexible power at each node are scaled by a large constant M and multiplied by x^{BESS}, effectively deactivating flexibility at non-BESS nodes. Additionally, constraint (17) limits the total number of BESS installations to a predefined maximum Nu^{BESS}, which is specified by the system designer.

$$P^{U,\xi}_{x,\tau} \leq M^{\mathrm{BESS}}_{x} \quad \forall x, \tau \tag{15}$$

$$P^{D,\xi}_{x,\tau} \leq M^{\mathrm{BESS}}_{x} \quad \forall x, \tau \tag{16}$$

$$\sum_{x} u^{\mathrm{BESS}}_{x} \leq Nu^{\mathrm{BESS}} \tag{17}$$

$$P^{\mathrm{up},S1}_{cn,t,s},\ P^{\mathrm{down},S1}_{cn,t,s},\ P^{+,S1}_{n,n',t,s},\ P^{-,S1}_{n,n',t,s},\ Q^{+,S1}_{n,n',t,s},\ Q^{-,S1}_{n,n',t,s},\ \Delta P^{S1}_{n,n',j,t,s},\ \Delta Q^{S1}_{n,n',j,t,s} \geq 0 \tag{18}$$

Equation (22) defines the non-negativity constraints for all decision variables related to active and reactive power flows, flexible power, and their segmented components.

$$P^{S1}_{\mathrm{BESS},min} = Max\left(P^{U,\xi}_{\omega=\mathrm{OBP},\tau,\xi}\right), Max\left(P^{D,\xi}_{\omega=\mathrm{OBP},\tau,\xi}\right) \tag{19}$$

The optimization involves solving the model defined by equations (1) to (19) to identify the worst-case scenario requiring flexibility. Equation (19) ensures that the BESS is sized adequately to support the network’s flexibility requirements. This approach determines the optimal BESS location and sizing while satisfying all technical constraints, ensuring secure and flexible network operation.

3.2.2 Market Participation Model

The goal of the model is to achieve cost minimization through strategic engagement of BESS in electricity markets. In this approach, iteratively adjusted and determined the optimal rated power and energy capacity of BESS. This iterative process identifies the BESS size that results in the lowest total cost while meeting the operational and market participation requirements.
This model is utilized when BESS participate in Daya ahead spot market, FCR-N and both markets simultaneously.

Equation (20) defines the objective function of minimizing the total expected cost of BESS operation. It includes revenues from energy arbitrage in spot market and providing frequency reserve, and costs from operating and maintaining the system, battery cycling, and by charging from spot and frequency market. It ensures optimal sizing and scheduling of the battery to maximize net profit under market and technical conditions.

$$OF = \rho^{DCC}\mathcal{E}^{\zeta} + \sum_{\xi} prb_{\xi}^{\psi} \sum_{\tau} \{ \rho^{M\&O} \left(P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{dis,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}up}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi} \right) + \mathrm{Cyc}^{\nu}_{\tau,\xi} - \rho^{FCR}_{\tau}\mathrm{Cap}^{FCR}_{\tau,\xi} - \rho^{reg,up}_{\tau} P^{FCR\text{-}up}_{\omega=\mathrm{OBP},\tau,\xi} + \rho^{reg,down}_{\tau} P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi} - \rho^{da}_{\tau} P^{dis,da}_{\omega=\mathrm{OBP},\tau,\xi} - \rho^{da}_{\tau} P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} \} \ \Delta\tau \qquad (20)$$

The constraint (21) maintains active power balance at each node and time step. It ensures that the sum of charging/discharging, frequency services, and net demand is equal to the power exchanged with the network. It reflects grid operational feasibility.

$$\begin{aligned} P_{x}^{\mathrm{C},\xi} + P^{FCR\text{-}up}_{\omega=\mathrm{OBP},\tau,\xi} - P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi} - P^{L}_{\chi,\tau,\xi} + P^{dis,da}_{\omega=\mathrm{OBP},\tau,\xi} - P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} \\ - \sum_{\chi'} \left(P^{+,\phi}_{\chi,\chi',\tau,\xi} - P^{-,\phi}_{\chi,\chi',\tau,\xi} + R_{\chi,\chi'} \cdot SI^{\phi}_{\chi,\chi',\tau,\xi} \right) \\ + \sum_{\chi'} \left(P^{+,\phi}_{\chi,\chi',\tau,\xi} - P^{-,\phi}_{\chi,\chi',\tau,\xi} \right) = 0 \quad \forall \chi, \tau, \end{aligned} \qquad (21)$$

The constraints (22) & (23) limit the total charging and discharging power according to rated power capacity of BESS. It prevents overloading the battery during operation in both markets simultaneously.

$$\mathrm{Cap}^{FCR}_{\tau,\xi} + P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} \leq P^{\mathcal{BESS}} \quad \forall \tau \qquad (22)$$

$$\mathrm{Cap}^{FCR}_{\tau,\xi} + P^{dis,da}_{\omega=\mathrm{OBP},\tau,\xi} \leq P^{\mathcal{BESS}} \quad \forall \tau \qquad (23)$$

Equation (24) & (25) define the actual power activated in response to upward or downward frequency deviations. The amount of power delivered is influenced by how much the frequency deviates from its nominal value and the reserve submitted for FCR-N support.

$$P^{FCR\text{-}up}_{\omega=\mathrm{OBP},\tau,\xi} = \frac{\Delta f^{up}_{\tau,\xi}}{0.1} \cdot \mathrm{Cap}^{FCR}_{\tau,\xi} \quad \forall \tau \qquad (24)$$

$$P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi} = \frac{\Delta f^{down}_{\tau,\xi}}{0.1} \cdot \mathrm{Cap}^{FCR}_{\tau,\xi} \quad \forall \tau \qquad (25)$$

Equations (26) and (27) compute the total frequency deviation in the downward and upward directions, respectively, over a full scenario duration. Each equation sums the absolute deviations in 1 hour resolution frequency measurements that are below or above 50 Hz, capturing the extent of activation needed for FCR-down and FCR-up. Equation (28) defines the instantaneous frequency deviation as the difference between 50 Hz and the actual value at each second. Equation (29) introduces a capping condition: if the frequency goes beyond 50.1 Hz or below 49.9 Hz, the deviation is clipped at 0.1 Hz, which reflects the maximum range over which the BESS can proportionally adjust its output under FCR commitments. This set of equations ensures that frequency response is accurately and safely mapped into the optimization.

$$\Delta f_{\vartheta}^{up} = \sum_{\zeta=1}^{N_{\zeta}} \left|\Delta f_{\zeta,\vartheta}\right| \cdot \Delta\zeta \quad \text{if } \Delta f_{\zeta,\vartheta} \geq 0 \quad \forall \tag{26}$$

$$\Delta f_{\vartheta}^{down} = \sum_{\zeta=1}^{N_{\zeta}} \left|\Delta f_{\zeta,\vartheta}\right| \cdot \Delta\zeta \quad \text{if } \Delta f_{\zeta,\vartheta} < 0 \quad \forall \tag{27}$$

$$\Delta f_{\zeta,\vartheta} = 50 - f_{\zeta,\vartheta} \quad \forall\vartheta \tag{28}$$

$$\Delta f_{\zeta,\vartheta} = 0.1 \quad \text{if } f_{\zeta,\vartheta} \geq 50.1 \text{ or } f_{\zeta,\vartheta} \leq 49.9 \tag{29}$$

Equations (30) to (34) model the evolution and boundary conditions of the battery's state of energy. Equation (30) updates the energy level at each time step by adding energy charged from the day-ahead and the FCR-N market (specifically from FCR-down activation), and subtracting energy discharged to the day-ahead market and for FCR-up activation. Charging efficiency and discharging efficiency are also applied to reflect losses. Equation (31) sets the initial state of charge for each activation. Equations (32) and (33) ensure that the state of energy is high enough to deliver the committed FCR-up reserve and low enough to absorb the full FCR-down activation, respectively—these conditions ensure the BESS can fulfil its reserve obligations. Equation (34) sets the absolute minimum and maximum bounds on the state of energy, ensuring operation stays within technically safe limits.

$$\begin{aligned} SOE^{\mathcal{BESS}}_{\tau,\xi} &= SOE^{\mathcal{BESS}}_{\tau-1,\xi} \\ &\quad + \Big\{\eta^{ch}\big(P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi}\big) \\ &\quad - \frac{1}{\eta^{dis}}\Big(P^{dis,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}up}_{\omega=\mathrm{OBP},\tau,\xi}\Big)\Big\}\Delta\tau \geq 2, \forall \end{aligned} \tag{30}$$

$$\begin{aligned} SOE^{\mathcal{BESS}}_{\tau,\xi} &= SOE^{\mathcal{BESS},ini}_{\xi} \\ &\quad + \Big\{\eta^{ch}\big(P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi}\big) \\ &\quad - \frac{1}{\eta^{dis}}\Big(P^{dis,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}up}_{\omega=\mathrm{OBP},\tau,\xi}\Big)\Big\}\Delta\tau = 1, \forall \end{aligned} \tag{31}$$

$$OE^{\mathcal{BESS}}_{\tau-1,\xi} - \mathcal{E}^{\mathcal{BESS}} \cdot SOC^{min} \leq \frac{1}{2} \cdot \mathrm{Cap}^{FCR}_{\tau,\xi} \quad \forall\tau \tag{32}$$

$$\frac{1}{2} \cdot \mathrm{Cap}^{FCR}_{\tau,\xi} \leq SOC^{max} \cdot \mathcal{E}^{\mathcal{BESS}} - SOE^{\mathcal{BESS}}_{\tau-1,\xi} \quad \forall\tau \tag{33}$$

$$\mathcal{E}^{\mathcal{BESS}} \cdot SOC^{min} \leq SOE^{\mathcal{BESS}}_{\tau,\xi} \leq \mathcal{E}^{\mathcal{BESS}} \cdot SOC^{max} \quad \forall\tau \tag{34}$$

Equation (35) calculates the BESS cycling cost by accounting for energy charged from the day-ahead market and FCR-down activation, and energy discharged through the day-ahead market and FCR-up activation. These are treated as two half-cycles and multiplied by a per-cycle cost coefficient to reflect battery aging. This ensures that the optimization considers degradation when planning BESS operation.

$$\begin{aligned} Cost^{cycle}_{\tau,\xi} &= \pi^{cycle}\Big\{\frac{1}{2}\big(P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi}\big) \\ &\quad + \frac{1}{2}\Big(P^{dis,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}up}_{\omega=\mathrm{OBP},\tau,\xi}\Big)\Big\}\Delta\tau\forall\tau \end{aligned} \tag{35}$$

Finally, the variables are constrained to take only non-negative values.

$$\begin{aligned} &P^{\mathrm{ch,da}}_{\omega=\mathrm{OBP},\tau,\xi}, P^{\mathrm{FCR\text{-}down}}_{\omega=\mathrm{OBP},\tau,\xi}, P^{\mathrm{dis,da}}_{\omega=\mathrm{OBP},\tau,\xi}, P^{\mathrm{FCR\text{-}up}}_{\omega=\mathrm{OBP},\tau,\xi}, \mathrm{Cap}^{\mathrm{FCR}}_{\tau,\xi}, p^{\zeta}, \mathcal{E}^{\zeta}, P^{+,\Phi}_{\chi,x,\tau}, P^{-,\Phi}_{\chi,x,\tau}, Q^{+,\Phi}_{\chi,x,\tau,i}, Q^{-,\Phi}_{\chi,x,\tau,i} \\ &\quad \geq 0 \ \forall x, \chi, \tau, \xi \end{aligned} \tag{36}$$

The formulation composed of Equations (20) to (35) encapsulates an optimization model that simultaneously determines the optimal battery size and its optimal operation strategy. The objective function drives the solution toward maximum economic return, while the constraints ensure technical feasibility and compliance with grid service requirements. Together, these equations guarantee that the battery will be operated in a way that maximizes revenue from energy arbitrage and frequency regulation services, without violating power limits, state-of-charge, safety margins, or reserve delivery obligations. This mathematical framework thus yields a co-optimized plan for how large the battery should be and how it should charge/discharge over time to achieve the best performance under the given market and system conditions.

3.2.3 Economic Assessment Model

This model provides an economic analysis of BESS participation in the energy market over the project lifetime. The primary objective is to evaluate the economic viability of BESS deployment. The analysis is based on key financial metrics, including NPV, Payback Period, and LCOE. By solving Equations (37) to (50), the model yields result that support decision-making for the Distribution System Operator (DSO), indicating whether investment in BESS is financially justifiable.

Equation (37) models how operational expenditure (OPEX) grows over time due to inflation. Here, O_0 is the base year OPEX and i is the annual inflation rate. It ensures cost realism across the project horizon.

$$O_0 = \rho^{M\&O}\left(P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{dis,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}up}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi}\right) + \mathrm{Cyc}^{v}_{\tau,\xi} \tag{37}$$

$$O_t = O_0 \cdot (1+i)^{t-1} \tag{38}$$

Equation (40) adjusts the annual battery charging cost for inflation, using the same escalation logic as operational expenses. It reflects increased energy procurement costs over time.

$$C_0 = \eta^{ch}\left(P^{ch,da}_{\omega=\mathrm{OBP},\tau,\xi} + P^{FCR\text{-}down}_{\omega=\mathrm{OBP},\tau,\xi}\right) \tag{39}$$

$$C_t = C_0 \cdot (1+i)^{t-1} \tag{40}$$

Battery performance decline over time. Each year, the battery discharges less energy due to degradation, modelled by the rate d. Yearly energy discharge is represented in equation (41.) Equation (42) ensures energy projections reflect aging of the storage asset.

$$E_0 = P_{\omega=\mathrm{OBP},\tau,\xi}^{dis,da} + P_{\omega=\mathrm{OBP},\tau,\xi}^{FCR\text{-}up} \tag{41}$$

$$E_t = E_0 \cdot (1-d)^{t-1} \tag{42}$$

From equation (40) the net annual cash flow is computed by subtracting operating and charging costs from revenue R . This value represents the system’s profit margin before discounting. It forms the basis for NPV and payback analysis.

$$R = \rho_\tau^{FCR}\mathrm{Cap}_{\tau,\xi}^{FCR} + \rho_\tau^{reg,up} P_{\omega=\mathrm{OBP},\tau,\xi}^{FCR\text{-}up} + \rho_\tau^{da} P_{\omega=\mathrm{OBP},\tau,\xi}^{dis,da} \tag{43}$$

$$F_t = R - O_t - C_t \tag{44}$$

Equation (41) converts annual net cash flows into present value terms by applying a discount rate$r$, thereby accounting for the time value of money, a core principle in investment economics. Future cash is worth less than today’s equivalent.

$$D_t = \frac{F_t}{(1+r)^t} \tag{45}$$

Equation (42) aggregates all discounted cash flows and subtracts the initial investment. A positive result denotes economic feasibility of the project. It’s a primary indicator in financial decision-making.

$$\mathrm{NPV} = -I + \sum_{t=1}^{n} D_t \tag{46}$$

Equation (43) calculates the total discounted costs incurred during the project. It includes both operating and charging expenses, adjusted for inflation and discounted for present value. It's used in the LCOE denominator.

$$K = \sum_{t=1}^{n} \frac{O_t + C_t}{(1+r)^t} \tag{47}$$

Equations (44) to (46) assess the economic performance for the BESS project. Equation (44) calculates the discounted energy output by accounting for battery degradation and time value, forming the basis for the next metric. Equation (45) expresses LCOE as the proportion of the total discounted expenditure to the total discounted energy output, reflecting the average cost per kWh over systems life time. Finally, Equation (46) determines the payback period by identifying the year when cumulative net cash flows equal the initial investment, offering insight into the project’s financial return timeline and capital recovery.

$$A = \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \tag{48}$$

$$\mathrm{LCOE} = \frac{I+K}{A} \tag{49}$$

$$\sum_{t=1}^{T} F_t \geq I \tag{50}$$

3.3 Scenario Selection

For optimal siting and sizing, 5 days with different load profiles selected to determine potential flexibility of the network. The days are for example maximum load with the days, minimum load with the days, different load variation with days, and typical load profile with the days. On the other hand, for market participation whole year considered for the simulation to evaluate the performance when BESS participates in day ahead spot market and FCR-N market.

3.3.1 Scenarios for Optimal Siting and Sizing of BESS

To reduce the computational burden of simulating 365 days of hourly net load data for each node, a clustering-based scenario reduction technique has been used. Specifically, K-means clustering has been applied to group days with similar load profiles for each node. The Elbow Method has been employed to identify the most suitable number of daily clusters for pattern sorting, ensuring that the clustering captured meaningful variations in daily behaviour. For each node, the resulting clusters reflected typical load behaviour such as high-load weekdays, low-load weekends.

Once clusters were defined for each node, the next step was to combine the daily cluster assignments across all nodes into network-wide daily scenarios. Each unique combination of cluster types across nodes is treated as a possible scenario. The frequency of each scenario's appearance over the 365 days was then calculated, producing a probability value for each. Scenarios that occurred very rarely i.e., below a set probability threshold were discarded to simplify the analysis.

Among the remaining relevant scenarios, additional days were selected to ensure that extreme conditions are covered. Specifically, the days with the highest and lowest total network loads are included to capture worst-case scenarios. Finally, the probabilities of all retained scenarios are normalized so that they added up to 100%. These selected and weighted representative days formed the basis for the simulation for optimal siting and required capacity of BESS to enhance flexibility of the network with much lower computational complexity.

3.3.2 Scenarios for Energy Market Participation

For the year of 2024, each day considered as different scenario. In this context, each day hourly load, day ahead electricity market price, imbalance market price, frequency data and capacity reserve price have been integrated in the model.

3.4 Simulation and Solver Implementation

Gurobipy solver has been used to develop simulation model for this study utilizing Python programming language in Jupiter notebook Platform. Since the model is piecewise linearized model and the data are time series float numbers, mixed integer linear programming (MILP) language has been used to build the mathematical model.

For optimal siting and sizing 5 days scenario simulation performed. The simulation is done by applying power flow analysis. In this context different load profile of the days in a year considered for simulations.

Next for market participation whole year’s each day simulation carried out to evaluate cost minimization curve with different price from different market. This simulation also performed utilising power flow analysis, but the objective function is to cost minimization by participating both markets. These simulation results give yearly cost, revenue and discharging power capacity. These parameters are indicator to calculate net present value, payback period and LCOE. Doing this calculation BESS investment decision will be presented in the next chapter.

The base mathematical model is constructed by employing mixed integer linear programming approach and a deterministic Gurobipy solver is used to generate the solution. This solver is particularly chosen because of its high reliability, efficiency, accuracy, and guaranteed optimal solutions compared to other solvers.

4 Results and Findings

This chapter provides both technical and economic analysis results by performing different scenario-based simulations. Based on the results, the flexibility potential, BESS siting, sizing, market participation possibilities, cost minimization approach and investment decision have been evaluated with detail discussion. Moreover, to integrate BESS into existing network, necessary measures have been outlined in this chapter considering technical and economic viability. Three types of prices (Day ahead electric price, Imbalance market, and Frequency reserved capacity for FCR-N market) collected from ENSTO-e and Fingrid for this study (ENSTO-e, 2025, Fingrid, 2025) Moreover, frequency data collected from Fingrid and network data collected from Esse Elektro-Kraft Ab for the study of Porkholm network. The parameters considered in this study are demonstrated table 1.

Table 1. Parameters considered in this study.

Parameters	Value
Minimum Acceptable Voltage	0.95 pu
Maximum Acceptable Voltage	1.05 pu
Power factor	0.90
Minimum State of charge (SoC)	0.05
Maximum State of charge (SoC)	0.95
Charging & Discharging efficiency	90%
Daily based capital cost	0.085 euro per kWh
Cycle cost	0.1 euro per kWh
Operation and Maintenance cost	0.001 euro per kWh
Project life	10 years
CAPEX	200500 EURO
Inflation rate	2%
BESS degradation rate yearly	2%

4.1 Optimal Siting and Sizing

In the first-stage optimisation, the Porkholm 20 kV MV radial distribution network was evaluated to identify the optimal location and minimum capacity requirements for BESS to enhance flexibility. The objective is to enhance flexibility by ensuring voltage limits are maintained within acceptable levels and to determine the capacity needed to deliver the required flexibility. The allowable voltage limits for this study considered as 0.95 to 1.05 pu and power factor is .90.

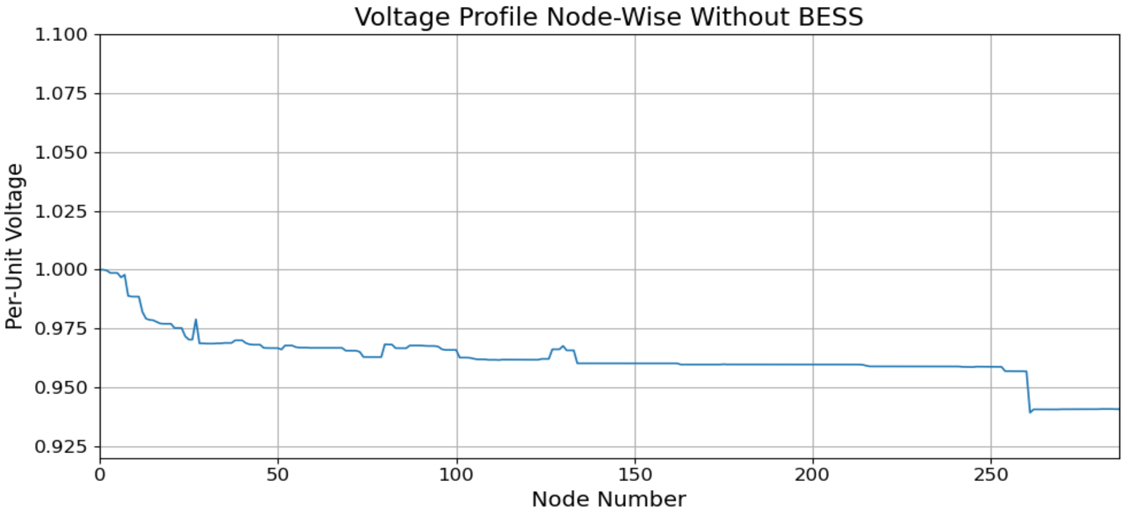


Figure 6. Voltage Profile without BESS.

At first, simulation performed to allocate required locations for the deployment of BESS in the network. The results identified multiple potential locations for BESS allocation; however, the node with the highest voltage deviation has been selected for placement. Multiple simulations performed by placing BESS at this location to evaluate the effectiveness of BESS in enhancing network flexibility. The result indicates that a single BESS installation at node number 261 is sufficient to meet the flexibility. This placement is particularly effective because node 261 experiences the most critical voltage drops during peak load conditions.

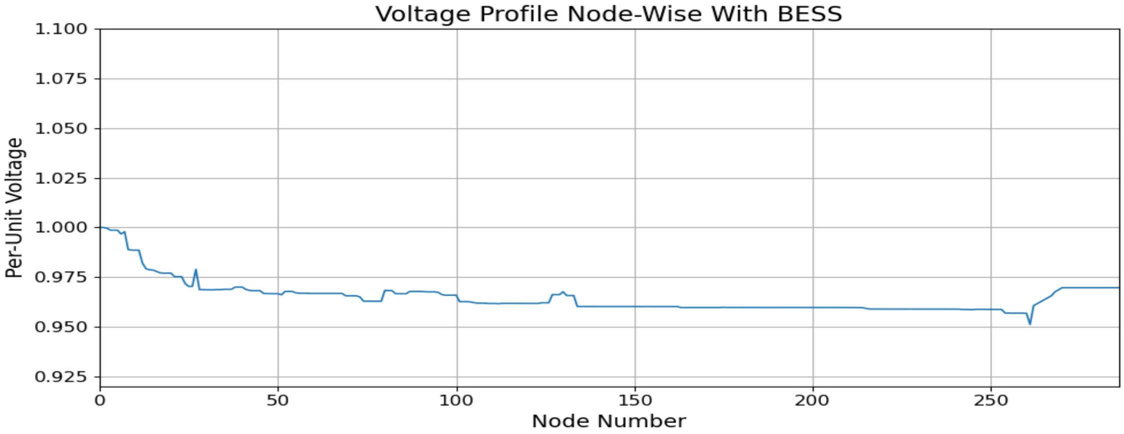


Figure 7. Voltage Profile with BESS.

Furthermore, the analysis shows that the minimum rated power capacity of the BESS is 150 kW for the flexibility requirement of the network. The installed BESS at this node significantly improves voltage stability by mitigating under-voltage conditions.

Figure-6 illustrates the voltage profile before integrating BESS in the network. According to the graph, voltage drops increase with line length starting from 1 pu reaching a minimum of 0.93 pu at node 261. On the other hand, Figure 7 illustrates the impact of integrating flexibility into the network. The visualization shows that after deploying BESS, the voltage profile significantly improves, maintaining values between 0.95 and 1.001 pu particularly the adjacent node's voltage profile improved remarkably. These findings demonstrate that targeted BESS deployment, rather than widespread allocation, is sufficient and cost-effective for enhancing operational security in rural MV networks.

After determining the minimum BESS size to enhance flexibility, the next stage involves evaluating its optimal size based on economic performance through market participation. The BESS was simulated under two market configurations: (1) participation in the day-ahead spot market and (2) combined participation in day ahead spot and FCR-N market. The objective is to maximize revenue by identifying the optimal BESS size while ensuring grid stability is maintained. To ensure robustness, the simulations were conducted for both the maximum and minimum load days of the year, capturing the full range of operational stress on the network. For each case, the active power capacity (the BESS charging/discharging rate) was incrementally increased until network constraints such as thermal limits and nodal voltage boundaries were violated. Through this iterative approach, the largest technically feasible and economically optimal BESS capacity was identified for each market scenario. During the iterative process, it has been observed that BESS can store, and network can manage more energy capacity of BESS than 500 kWh however it does not satisfy economic feasibility due to increase of associated cost CAPEX, OPEX and charging.

The results for optimal BESS sizes when participate different energy market, are summarized in Table 2.

Table 2. Optimal sizing of BESS from participating energy markets.

Energy Market	BESS Power Capacity	BESS Energy Capacity
Day ahead Spot Market	250 kW	502.75 kWh
Day ahead spot market and FCR-N	250 kW	456.81 kWh

4.1.1 Day ahead Spot Market Participation

Figure 8 illustrates the BESS's time varying charging and discharging action in response to day-ahead electricity price signals. Charging was activated in the early morning hours (0:00–4:00) when electricity prices were low, allowing BESS to store energy at minimal cost. BESS charges up to its allowable limit, constrained by its maximum SoC 0.95 and network stability conditions. Discharging was then initiated during hours 7:00 and 15:00, hours corresponding to price spikes in the spot market at its rated power of 250 kW. This behaviour reflects the ability of BESS to shift load and supply energy to match economic signals while adhering to grid constraints.

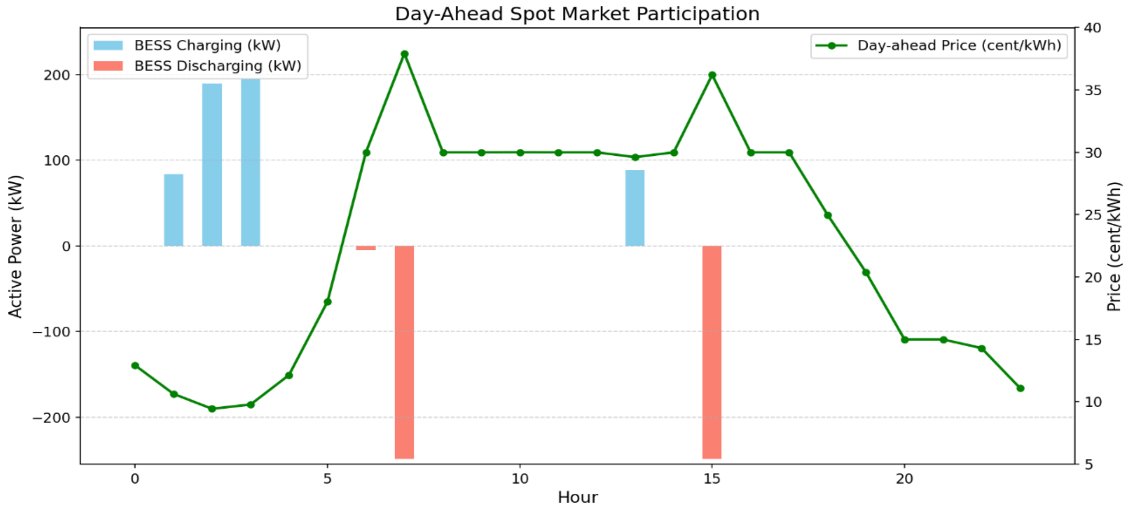


Figure 8. BESS Charging and Discharging cycle in Day-ahead Spot Market.

The revenue and cost generated from spot market for the selected day has been illustrated in Figure 9. The battery incurred a total energy purchase cost of approximately 72.13 euro by charging 554.73 kWh over the day, driven by charging during low-price hours. In contrast, the BESS generated 186.02 euro revenue by discharging of 502.75 kWh during high-price hours over the day, particularly at 7 and 15 hours, where discharging revenue reached 94.43 and 90.17 euro, respectively. Additional costs include a daily based capital cost of 55 euro, cycling degradation cost of 8.22 euro and an operational and maintenance cost of 1.03 euro. Subtracting these from gross revenue yields a net profit of roughly 47.02 euro for the day. These results confirm that the BESS can generate substantial economic value by participating in spot market through arbitrage while ensuring grid friendly operation. The model ensures profitability by avoiding operation during marginal economic conditions and prioritizing transactions that yield the most favourable cost-to-revenue ratio.

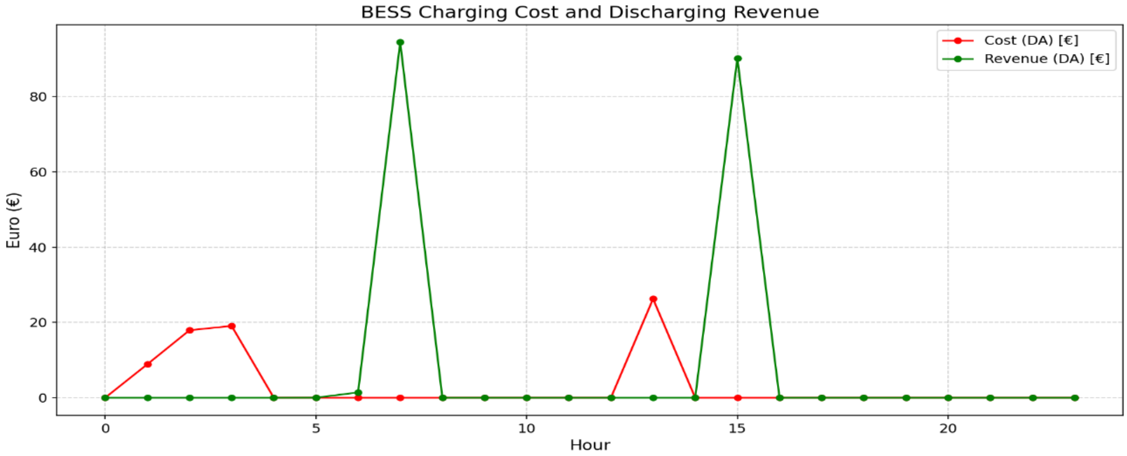


Figure 9. Revenue and Cost from Day ahead Spot Market.

4.1.2 FCR-N and Spot Market participation

The concept of FCR-N market participation is related with TSO frequency response. In this context the coordination between TSO and DSO initiates BESS activation in FCR-N. Based on TSO side frequency variation BESS activates it operation. Figure-10 illustrates a basis concept to activate BESS charging discharging cycle operation. The figure shows that when frequency reaches in between 50 to 50.10 HZ, FCR-N requires downward activation on other hand when frequency drops and stays between 49.90 to 50. HZ, BESS required to initiate upward activation.

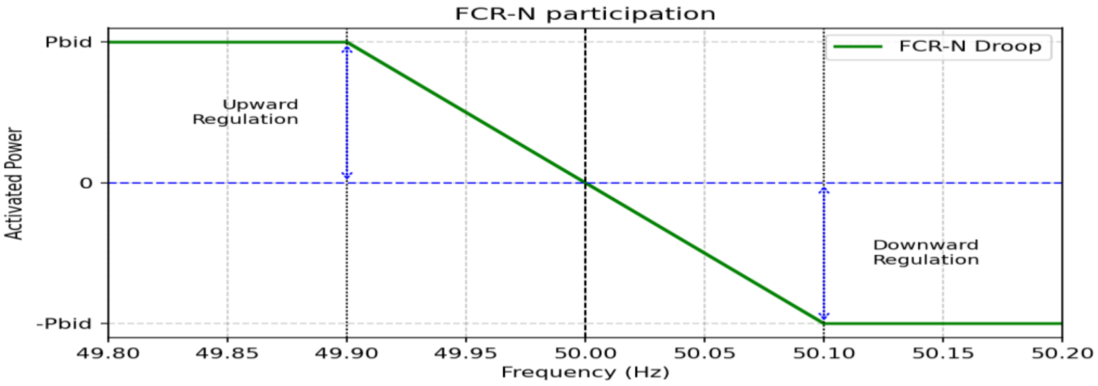


Figure 10. Activation of FCR-N according to FCR-N Market Frequency Variation.

This activation incurs cost and revenue under FCR-N market. Figure-11 illustrates FCR-N and day ahead market associated electricity price. When BESS activates charging cycle, it generates activation cost from down regulation price. Down regulation price is determined by comparing the imbalance market price with day-ahead market price and considered the lowest one. Similarly up regulation while BESS discharges remunerated from up regulation price by comparing day ahead and imbalance market price considering the highest one. Moreover, BESS gets revenue for reserving its capacity by participating in FCR-N market.

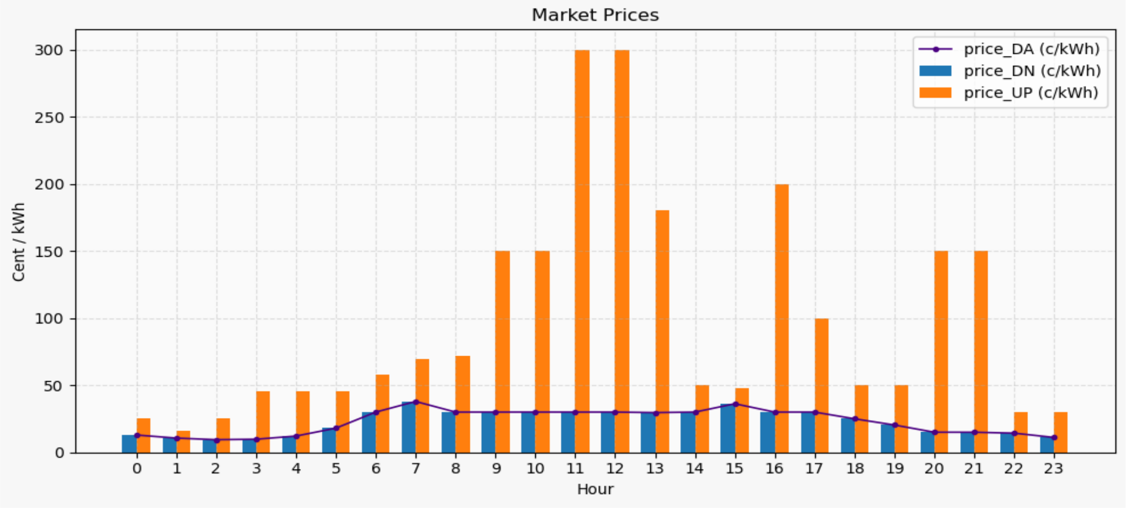


Figure 11. Day ahead Spot Market, Up Regulation and Down Regulation Price.

Figure 12 demonstrates charging and discharging activation by participating day ahead spot market and FCR-N market. At morning 0 to 2 hour the frequency reached below 50 HZ. According to FCR-N market criteria, BESS activates discharging cycle with response to frequency variation and activated active power is equivalent to reserving capacity with proportion to frequency variation. During winter period in Finland at night, electricity demand reaches peak due to activating electric heating simultaneously. For those hours as per figure 12 from 0 to 2 hours frequency reached below 50 HZ. Gradually, the frequency increased and when reaches above 50 HZ charging cycle activated at 3 AM. The graph highlights that maximum frequency reached up to 50.03 HZ and BESS charged at maximum rate within its reserve capacity. Similarly, at 13 hour frequency dropped at minimum level around 49.97 HZ and BESS discharged at its allowable maximum range. Moreover, BESS also participated in day ahead spot market simultaneously with FCR-N. BESS only can charge in day ahead spot market when BESS charge in FCR-N market and discharge only when BESS discharges in FCR-N market. Considering this cycle, BESS activated optimize charging and discharging cycle under day ahead spot market.

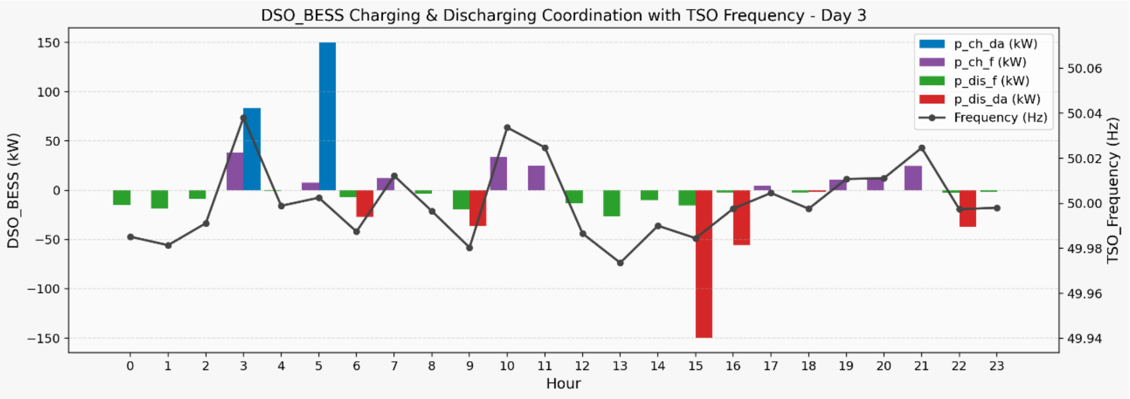


Figure 12. BESS Charging and Discharging Activation in FRC-N and Day ahead Spot Market.

Figure-13 shows how BESS participation in both the day-ahead and FCR-N markets leads to a profitable outcome. Significant revenue earned from upward regulation during hours 9.00, 12.00, and 13.00 hours, while hour 15.00 shows the highest return from the day-ahead market. The BESS also received steady revenue for simply reserving capacity in the FCR-N market when BESS activates charging or discharging cycle in FCR-N market. On other hand, charging during the day-ahead market and down-regulation periods led to higher expenses, especially at 5.00 hour from spot market and hour 10.00 hour at FCR-N market. Overall, the BESS generated 209.5 euro revenue, while total costs were 29.27 euro from FCR-N activation, 35.17 euro from day-ahead charging, 55 euro from daily based capital cost, 8.58 euro in cycling cost, and 1.51 euro in maintenance. These findings confirm that when managed properly, BESS operation across multiple markets can bring in more revenue than cost.

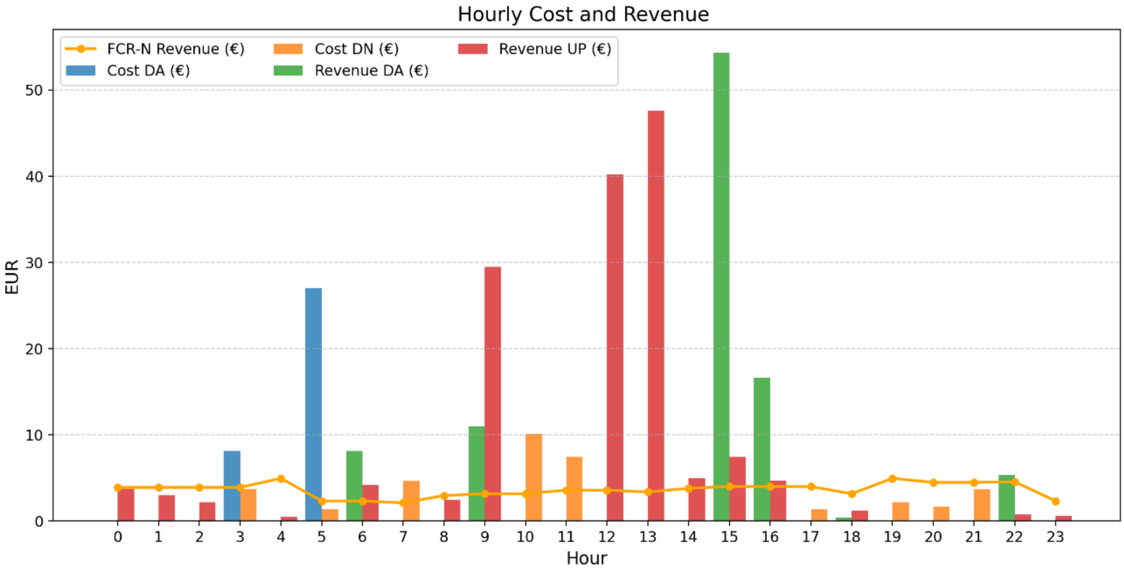


Figure 13. Revenue and Cost from FCR-N and Day ahead Spot Market Participation.

BESS participation in energy market is a power flow model. Therefore, each activation undergoes with power flow analysis with maintaining network constraint. The primary requirement is to keep local grid stable and provide stability support to TSO. Figure 14 illustrates the voltage profile when BESS participated both markets simultaneously. The simulation results confirms that the BESS operated within technical boundaries and ensures system reliability. Voltage magnitudes across all 287 nodes were maintained within the acceptable operating range of ±5% of the nominal voltage (1.0 pu). Even during peak charging and discharging periods, the voltage profiles remained stable and flat, with minimal deviation between the feeder ends and the core network. This demonstrates that the optimization algorithm effectively enforced both voltage and thermal constraints while scheduling energy transactions.

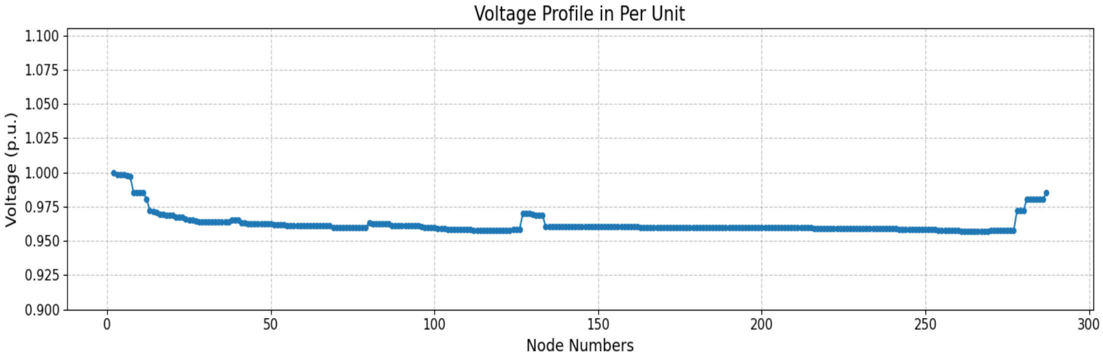


Figure 14. Node-wise Voltage Profile when Participate in Day ahead Spot Market and FCR-N Market.

On the other hand, Figure 15 illustrates the evaluation of line thermal management during the BESS operation period. Thermal limits were assessed based on the conductor with the lowest rating in the network (155 A) and the primary substation transformer capacity. The BESS operation was designed to prevent network congestion and avoid increasing thermal stress on the lines. Figure 15 indicates that, after BESS integration, neither conductor thermal limits nor transformer capacities exceeded their network limits. The transformer capacity is rated at 1000 kVA with a power factor of 0.9, resulting in a base current of approximately 28.86 A for this study. Following BESS integration, the maximum current drawn at the substation was 24.95 A, and line currents throughout the day remained below 17 A.

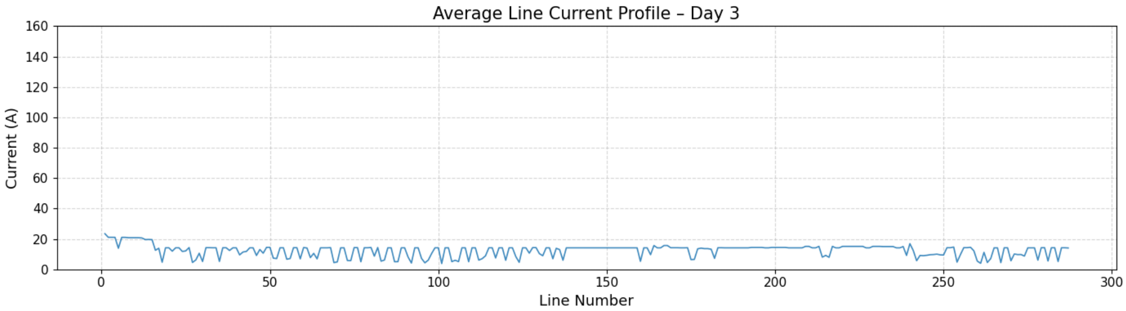


Figure 15. Node-wise Load Current when Participate in Day ahead Spot Market and FCR-N Market.

After simulating two different load variation scenarios with simultaneous participation in both markets, it was observed that the BESS generates higher revenue when participating in both markets concurrently.

Table 3. Revenue from Day ahead Spot Market and FCR-N Market.

Energy Market	Revenue (case-1)	Revenue (case-2)
Day ahead Spot Market	47.02 euro	25.68 euro
Day ahead spot market and FCR-N	209.55 euro	255.54 euro

Additionally, a year-long simulation has been performed to assess BESS involvement in the day-ahead market, the FCR-N market, as well as in combined participation across both markets.

4.2 Economic Assessment

To determine the economic viability of the investment, a comprehensive economic analysis has been conducted using full-year simulations that incorporate network, electricity price, and frequency data. The study includes taking part in day-ahead spot market, the FCR-N market, and both markets simultaneously. Figure 16 illustrates the total revenue generated from each market participation. In January, revenue was highest across all market participation due to high electricity demand in winter climate, gradually decreased until March. From March onward, revenue again started to increase and reached peak in May, after which it declined and remained relatively stable from July to December. In May, the Frequency reserve capacity price was record breaking for the year of 2024 and in FCR-N market a big amount of revenue comes from reserve capacity. Overall, the greatest revenue variation was observed when BESS participates in FCR-N market and in both markets combined. In contrast, revenues from the day-ahead spot market remained relatively constant throughout the year. The figure clearly shows that the highest revenue was obtained when BESS was involved in both the FCR-N and day-ahead spot markets. This was followed by revenue from exclusive participation in the FCR-N market, whereas the day-ahead market alone produces the least financial return.

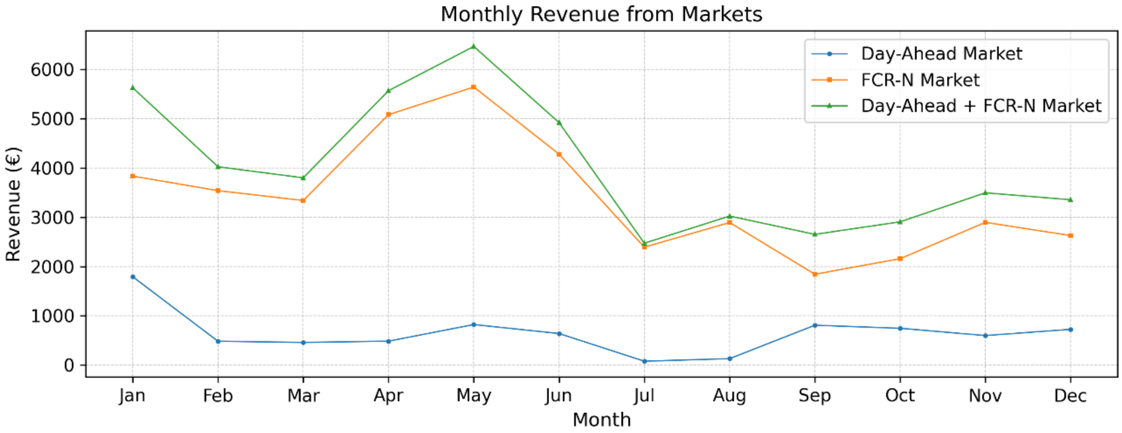


Figure 16. Yearly Revenue when BESS Participate in Day ahead Spot Market, FCR-N Market, and both Market together.

During market participation, Figure 17 shows that the day-ahead spot market incurred higher charging costs compared to the FCR-N market. However, participating in both markets simultaneously results in higher overall costs as well as increased revenue.

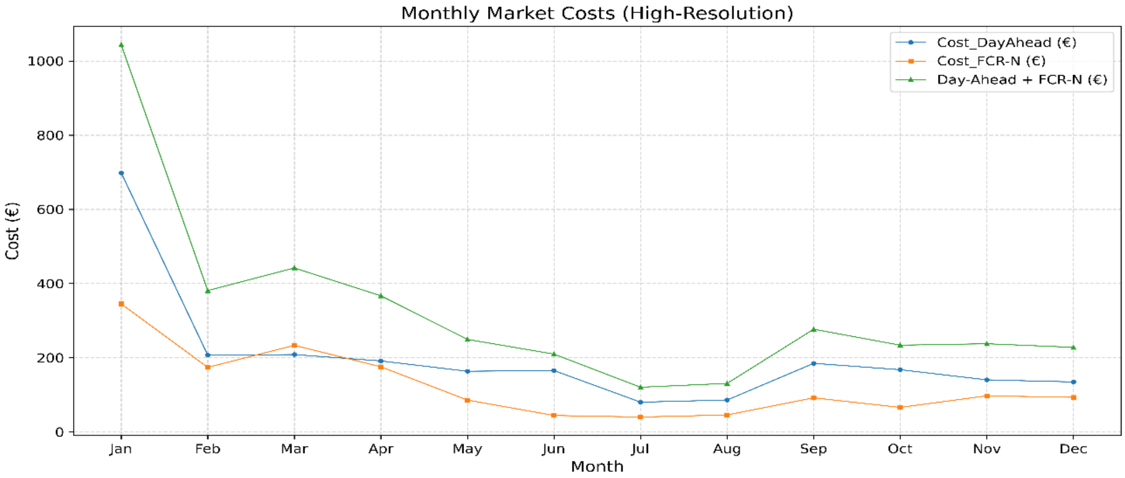


Figure 17. Monthly Cost Generated from Different Energy Markets.

Table 4 Illustrates whole year simulation results

Table 4. Yearly revenue for participating in different energy markets.

Energy Market	Revenue	Capacity utilized
Day ahead Spot Market	10673.69 euro yearly	66406.07 kWh yearly
FCR-N	37631.87 euro yearly	61393.25 kWh yearly
Day ahead spot market and FCR-N	48305.56 euro yearly	127799.32 kWh yearly

After performing whole year simulation by participating both markets, the yearly generated revenue, cycling cost, charging cost and operation and maintenance cost were integrated in economic model to calculate NPV, LCOE and payback period over the project life. The project life has been considered 10 years for this study. BESS investment (CAPEX) has been considered 200500 euro from NREL 2023 cost projections for utility-scale BESS report (Cole & Karmakar, 2023). This economic analysis performed by applying sensitivity analysis considering different discount rates for BESS project. Other parameters for example inflation rate, degradation rate are provided in table 1.

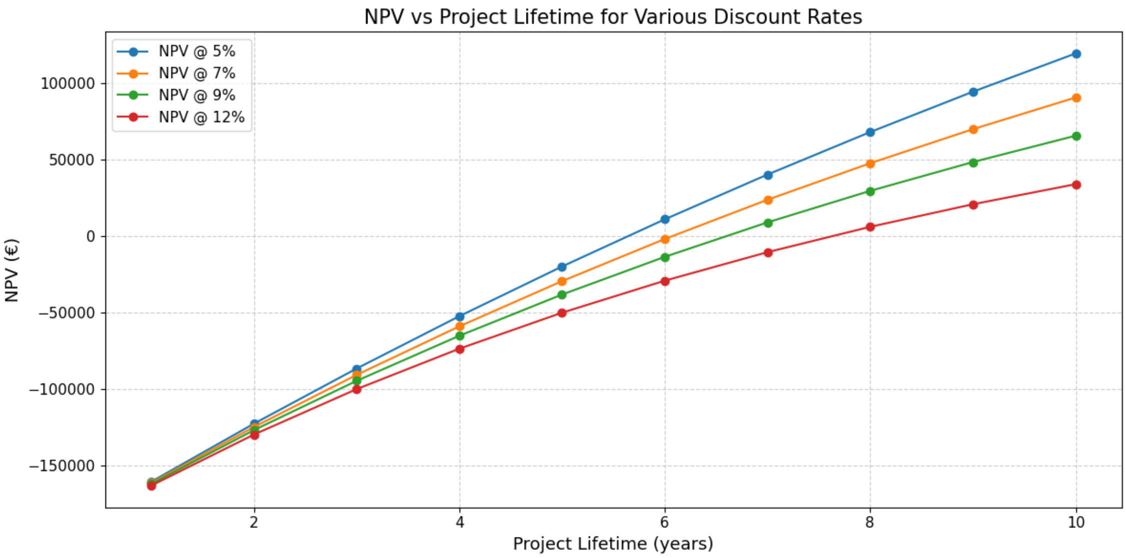


Figure 18. NPV in different Discount rates over Project Lifetime.

The NPV assessment has been conducted to evaluate the economic feasibility of the BESS. As illustrated in figure 18, NPV increased consistently with longer project durations across all discount rates. Lower discount rates, such as 5%, result in significantly higher NPV values, indicating greater financial viability. On the other hand, applying higher discount rates such as 12% reduces the NPV, as future cash flows are valued less in present terms. The project becomes profitable (NPV > 0) beyond a certain lifetime threshold, which varies depending on the discount rate applied. This trend highlights the sensitivity of BESS investment returns to both financial assumptions and operational lifespan. Conversely, the payback period reflects the time required for the BESS investment to return its upfront expenditure.

At a 5% discount rate, payback happens in about 6 years. With discount rates 7%, & 9% payback takes 7 years. In case of discount rate 12% the payback happens at 8 years. This shows that higher discount rates reduce future earnings, affecting the project's financial return.

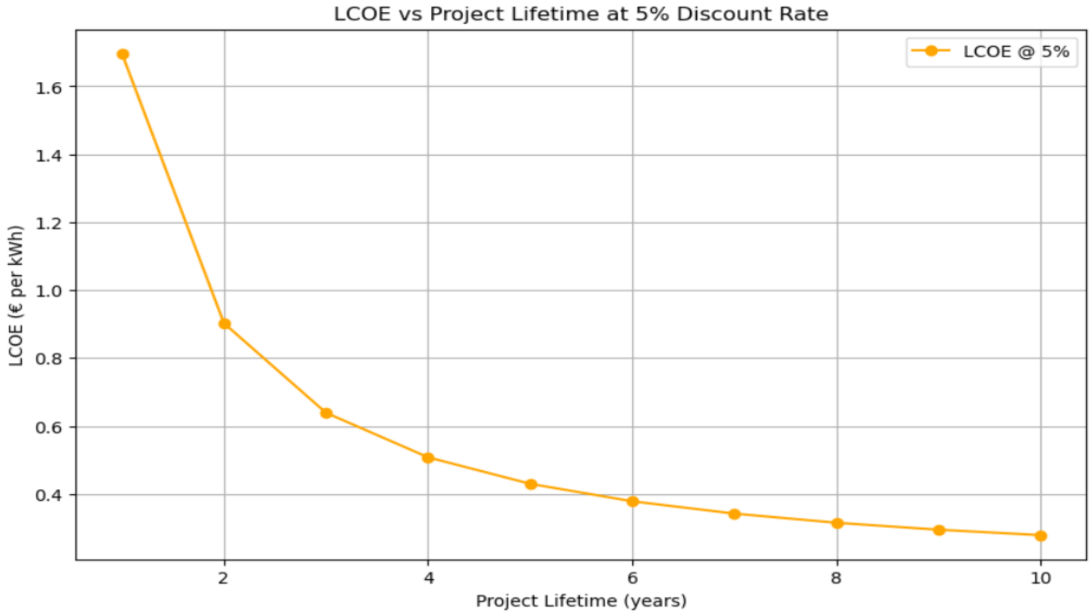
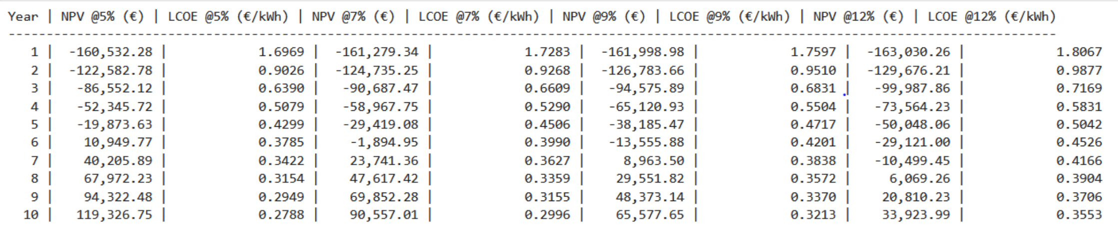


Figure 19. LCOE over Project Lifetime at 5% Discount Rate.



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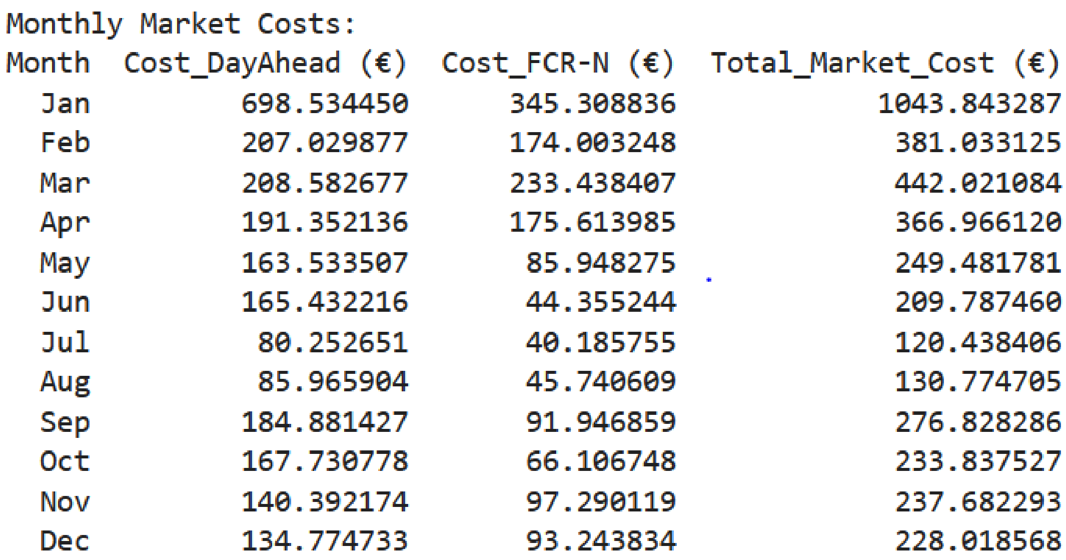
Year | NPV @5% (€) | LCOE @5% (€/kWh) | NPV @7% (€) | LCOE @7% (€/kWh) | NPV @9% (€) | LCOE @9% (€/kWh) | NPV @12% (€) | LCOE @12% (€/kWh)
----------------------------------------------------------------------------------------------------------------------------------
   1 | -160,532.28 |           1.6969 | -161,279.34 |           1.7283 | -161,998.98 |           1.7597 |  -163,030.26 |            1.8067
   2 | -122,582.78 |           0.9026 | -124,735.25 |           0.9268 | -126,783.66 |           0.9510 |  -129,676.21 |            0.9877
   3 |  -86,552.12 |           0.6390 |  -90,687.47 |           0.6609 |  -94,575.89 |           0.6831 |   -99,987.86 |            0.7169
   4 |  -52,345.72 |           0.5079 |  -58,967.75 |           0.5290 |  -65,120.93 |           0.5504 |   -73,564.23 |            0.5831
   5 |  -19,873.63 |           0.4299 |  -29,419.08 |           0.4506 |  -38,185.47 |           0.4717 |   -50,048.06 |            0.5042
   6 |   10,949.77 |           0.3785 |   -1,894.95 |           0.3990 |  -13,555.88 |           0.4201 |   -29,121.00 |            0.4526
   7 |   40,205.89 |           0.3422 |   23,741.36 |           0.3627 |    8,963.50 |           0.3838 |   -10,499.45 |            0.4166
   8 |   67,972.23 |           0.3154 |   47,617.42 |           0.3359 |   29,551.82 |           0.3572 |     6,069.26 |            0.3904
   9 |   94,322.48 |           0.2949 |   69,852.28 |           0.3155 |   48,373.14 |           0.3370 |    20,810.23 |            0.3706
  10 |  119,326.75 |           0.2788 |   90,557.01 |           0.2996 |   65,577.65 |           0.3213 |    33,923.99 |            0.3553
```

Figure 20. NPV and LCOE at different Discount Rate over the Project Lifetime.

Figure 19 presents the outcome of the LCOE evaluation at a 5% discount rate, revealing a consistent decline as the project duration extends. LCOE is initially observed to be high due to the concentration of capital and operational costs over a short duration. However, as the project lifetime extends, these costs are spread across more years and greater energy throughput, significantly lowering the LCOE. By the 10th year, the LCOE stabilizes around 0.2788 euro per kWh, indicating improved cost-efficiency over time. A longer operational lifespan contributes to improved cost-efficiency of BESS system. Some simulation results are illustrated in figure 20 and 21 when BESS participates different energy markets.

Month-wise Revenue from Day-Ahead Market (€):	**Month-wise Revenue from FCR-N Market (€):**	**Month-wise Total Revenue from Both Markets (€):**
Month 1: 1792.74 €	Month 1: 3833.74 €	Month 1: 5626.48 €
Month 2: 484.55 €	Month 2: 3539.06 €	Month 2: 4023.62 €
Month 3: 460.13 €	Month 3: 3339.51 €	Month 3: 3799.64 €
Month 4: 486.16 €	Month 4: 5080.68 €	Month 4: 5566.85 €
Month 5: 822.95 €	Month 5: 5641.07 €	Month 5: 6464.01 €
Month 6: 640.91 €	Month 6: 4278.56 €	Month 6: 4919.47 €
Month 7: 79.80 €	Month 7: 2392.78 €	Month 7: 2472.58 €
Month 8: 130.83 €	Month 8: 2892.97 €	Month 8: 3023.81 €
Month 9: 809.22 €	Month 9: 1843.15 €	Month 9: 2652.37 €
Month 10: 747.59 €	Month 10: 2158.99 €	Month 10: 2906.58 €
Month 11: 599.67 €	Month 11: 2895.79 €	Month 11: 3495.46 €
Month 12: 726.17 €	Month 12: 2628.54 €	Month 12: 3354.70 €



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Monthly Market Costs:
Month  Cost_DayAhead (€)  Cost_FCR-N (€)  Total_Market_Cost (€)
  Jan         698.534450      345.308836            1043.843287
  Feb         207.029877      174.003248             381.033125
  Mar         208.582677      233.438407             442.021084
  Apr         191.352136      175.613985             366.966120
  May         163.533507       85.948275             249.481781
  Jun         165.432216       44.355244             209.787460
  Jul          80.252651       40.185755             120.438406
  Aug          85.965904       45.740609             130.774705
  Sep         184.881427       91.946859             276.828286
  Oct         167.730778       66.106748             233.837527
  Nov         140.392174       97.290119             237.682293
  Dec         134.774733       93.243834             228.018568
```

Figure 21. Month wise Revenue and Cost from different Energy Markets.

5 Discussion and Conclusion

This study extensively analysed the integration of Battery Energy Storage System (BESS) in Porkholm 20 kV network to enhance network flexibility and economic efficiency. Employing a comprehensive methodology, the analysis included optimal siting and sizing of BESS, participation strategies in day-ahead spot market, FCR market, and dual market along with technical feasibility and economic assessment. By leveraging real network data from DSO and price and frequency data from ENTSO-e and Fingrid, the study provided a robust evaluation of the potential benefits of strategic BESS deployment. Detailed scenario simulations highlighted how targeted BESS installation not only improved network reliability and voltage stability but also generates substantial economic returns through effective market participation.

5.1 Summary and Key Findings

The first key finding from this study is that strategic BESS placement significantly enhances network flexibility. Optimal siting identified node 261 as the most beneficial location due to its highest voltage deviation. Installing BESS at this node mitigated critical voltage drops, effectively maintaining voltage levels within the allowable of 0.95 to 1.05 pu. Furthermore, it has been identified that BESS reduces peak load during on peak hour by discharging providing required power to the network. Thus, it not only mitigates stress on primary substation transformer but also manages conductor thermal limits at those hours. This simulation-based study confirms that BESS can manage potential overload of transformer, voltage and thermal issues which could be results from congestion cases. By utilizing real data and considering different scenario of the existing network, the minimum BESS power capacity required to achieve this is 150 kW, ensuring both technical feasibility and economic viability.

Secondly, by simulating BESS participation in different energy market scenarios, the optimal power and energy rating of BESS has been determined through an iterative process. This process ensured that both technical constraints such as flexibility and economic constraints such as cost-effectiveness is satisfied. The optimal BESS capacity that met these requirements was found to be 250 kW of power and 500 kWh of energy. For dual-market participation, the BESS was configured to allocate 100 kW of active power for the FCR-N reserve market and 150 kW for the day-ahead spot market for the purpose energy arbitrage as well as local network flexibility enhancement. This allocation ensured adequate power availability to enhance network flexibility across varying operating conditions, while simultaneously supporting TSO stability requirements and generating revenue from both energy markets. However, when BESS participates in dual or FCR-N market its frequent activation of charging and discharging cycle can affect Sate of Health (SOH) of the battery.

When BESS participated in day-ahead spot market, strategic charging during off peak hours and discharging during on peak intervals resulted consistent profitability of 10673.69 euro annually. In addition to that, the BESS also contributed in reducing stress on utility source during on peak hour by discharging 61393.25 kWh yearly. On the other hand, by participating FCR-N market, BESS earned more revenue comparing to day-ahead spot market. However, by participating in FCR-N market, BESS was remunerated for discharging in up regulation and for reserving capacity for TSO. This made earning more revenue than spot market. However, the combination of day-ahead market participation with the FCR-N market significantly increased revenue rather than those two market separate participation. This dual participation strategy which allows BESS to respond dynamically to both price signals and frequency fluctuations, thereby maximizing revenue of 48305.56 euro yearly and relief stress of 7.26% by discharging its stored energy of 127799.32 kWh yearly out of 1760000.345 kWh yearly total demand of the network.

Finally, the economic assessment underscored the long-term profitability of BESS investments. Using Net NPV, LCOE, and payback period assessment, it became evident that simultaneous market participation significantly improved investment returns compared to single-market strategies. Specifically, the best economic performance has been achieved at lower discount rates, indicates that longer operational lifetimes significantly reduce the cost per unit of energy delivered. Considering 5% discount rate, an annual BESS degradation rate of 2%, and an annual inflation rate of 2%, the Net Present Value (NPV) was calculated to be 119,326 euro over the project lifetime, with a payback period of 6 years. Based on economic considerations, the model proposes a strategic operational method for BESS that results in a LCOE of 0.277 euro per kWh. From this economic assessment, DSO can decide before placing bid in energy market that how much electricity price should be proposed per kWh for bidding so that no chances of losses from participating whether it’s in energy arbitrage or reserve market. Moreover, the sensitivity analysis emphasized that careful financial planning and accurate cost forecasting are critical for achieving favourable investment outcomes.

5.2 Future Direction

Future research can expand upon this work by incorporating additional flexibility markets by developing integrating TSO-DSO coordination framework. By involving BESS aggregator with coordination framework flexible market participation strategies need to be more robust to achieve system wide stability and earn maximum revenues. Evaluating the performance of larger or multiple BESS installations under diverse operational scenarios, including extreme weather events or significant grid disturbances, would also be beneficial. Additionally, integrating weather forecasting techniques in BESS, could improve accuracy in predicting renewable generation thus enabling more precise economic optimization and operational planning.

Moreover, policy-driven research addressing regulatory frameworks and incentive structures would help identify mechanisms that encourage broader adoption of BESS technologies in rural and urban distribution networks. Exploring integrated flexibility approaches that combine BESS with demand response mechanisms and decentralized renewable generation could result in more robust and holistic strategies for enhancing grid flexibility. These directions will ensure that future deployments of BESS continue to support network reliability, enhance economic performance, and contribute effectively to sustainable energy transitions.

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