



Paikallisen energiajärjestelmän kehittäminen Pohjanmaalla  
Development of the regional energy system in Ostrobothnia

## PEAK Task 1.3 Techno-Economical Calculation Related to the Renewable Energy Potential and Distribution Network Flexibility and Development needs

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## TIIVISTELMÄ/ABSTARCT

This study was carried out within the PEAK project, coordinated by the University of Vaasa in collaboration with Esse Elektro-Kraft Ab, focusing on the 20 kV Porkholm medium-voltage (MV) distribution network. Building on the results from Task 1.2, the study conducts a comprehensive techno-economic analysis of network flexibility by considering the integration of photovoltaic (PV) generation and electric vehicles (EVs) for the future operation of the Porkholm network in 2030. The main objectives are to quantify flexibility needs, increase distributed energy resource (DER) hosting capacity through Battery Energy Storage Systems (BESS), and demonstrate how BESS can provide both local flexibility and system-level flexibility through participation in Fingrid's Frequency Containment Reserve for Normal operation (FCR-N) market.

A Mixed-Integer Linear Programming (MILP) based optimal power flow model was developed to analyze flexibility needs under worst-case operating scenarios. The model integrated BESS to study their technical role in peak shaving, voltage regulation, and renewable energy utilization. Alongside this, a techno-economic analysis was conducted using investment metrics such as Net Present Value (NPV) and payback period to evaluate financial feasibility.

The results show that BESS reduced peak demand by about 29–30%, lowered PV curtailment to nearly 3% in summer, and maintained voltages within  $\pm 5\%$  of nominal limits. Economically, BESS-1 achieved an NPV of €243,913 and a six-year payback, while BESS-2 reached €211,424 NPV with €0.40/kWh and a seven-year payback at a 5% discount rate. Seasonal revenues peaked in spring and winter due to higher demand and reserve capacity prices. These findings confirm that strategically placed and sized BESS can deliver both technical and financial benefits, making them essential enablers of flexibility in future distribution networks.

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## 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                             |
| 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

The modern power system is undergoing rapid transformation as renewable energy sources and electrified loads become more widespread. In rural networks, this transition creates new challenges for stable and reliable operation. Solar photovoltaic (PV) systems and electric vehicles (EVs) are expected to play a significant role in future electricity supply and demand, but their variability and unpredictability can strain distribution grids (Zenhom et al. 2024). Traditional infrastructure upgrades are costly and often insufficient to cope with fast-changing operating conditions, which makes system flexibility a critical enabler of secure and efficient network operation. Flexibility allows the grid to respond dynamically to fluctuations, ensuring both reliability and improved integration of distributed energy resources (DERs) (Santos et al. 2023).

Battery energy storage systems (BESS) are increasingly recognized as a key source of flexibility. At the distribution level, BESS can mitigate voltage and capacity constraints by storing excess PV generation and discharging during peak demand. This not only reduces curtailment but also enhances DER hosting capacity and supports services such as peak shaving and load shifting (Martins et al. 2018). By enabling these functions, BESS strengthen the ability of local grids to accommodate higher shares of renewable energy without compromising stability.

In addition to local benefits, BESS can also provide services to the transmission system operator (TSO). One of the most promising of these is participation in the Frequency Containment Reserve (FCR) market, where batteries contribute to frequency stability. Evidence from European markets shows that such services can be highly profitable; for example, in Denmark, BESS assets achieved nearly full utilization in the FCR-N market during 2021 (Hu, Armada, and Jesús Sánchez 2022). This highlights the dual role of storage in supporting both distribution networks and system-wide balancing.

Since BESS can deliver several services at once, their economic assessment must consider all value streams together. Studies have shown that stacking services such as peak shaving, curtailment reduction, arbitrage, and reserve provision is often necessary for financial feasibility (Mohamed et al. 2023). Building on these insights, this report focuses on 20 kV Porkholm rural network. It first

assesses the flexibility needs of the system (Task 1), then investigates how BESS can enhance DER hosting capacity and contribute to Frequency Containment Reserve for Normal operation (FCR-N) participation (Task 2). Finally, it presents a 10-year project life techno-economic evaluation (Task 3), analyzing investment performance through Net Present Value (NPV) and payback period. Together, these analyses provide a comprehensive view of the technical and economic potential of BESS in enabling reliable and flexible operation of rural distribution grids.

## **1.1 Study Case and Purpose of the Study**

This study is part of the PEAK project, coordinated by the University of Vaasa in collaboration with Esse Elektro-Kraft AB, and continues the work carried out in Task 1.2 of Work Package 1. The earlier study analyzed the Porkholm 20 kV rural distribution network in Ostrobothnia by examining its existing flexibility through demand response and assessing the hosting capacity of distributed energy resources (DERs). That work highlighted how far the network could accommodate PV generation and EV while maintaining efficient utilization of existing capacity. The findings provided valuable insight into the technical limits of the network but did not fully address the additional flexibility that storage solutions could provide.

The present study (Task 1.3) builds directly on these results by expanding the analysis towards future flexibility needs and the role of battery energy storage systems (BESS). In particular, it explores how BESS can complement PV and EV integration, not only by mitigating local network constraints but also by unlocking new value through participation in reserve markets. By combining technical and economic perspectives, this study aims to offer a more complete understanding of how rural Finnish distribution networks can integrate higher shares of renewable energy and dynamic loads while moving toward the 2030 energy transition targets.

### **Task-1.3.1: Assessing Flexibility Needs for Stable Network Operation**

This objective focuses on determining the flexibility requirements of the distribution network to maintain reliable and stable operation. Flexibility is increasingly important as networks integrate higher shares of variable renewable energy sources like Photovoltaic system, electric vehicles, and other dynamic loads. By quantifying how much flexibility is needed and in what form, the study aims to ensure that sufficient system support can be provided. This includes enabling the network to handle variability, respond to uncertainties, and deliver effective flexibility services across different operating conditions.

**Task-1.3.2: Enhancing DER Hosting Capacity with BESS through Peak Shaving, Curtailment Reduction, and FCR-N Market Participation**

This objective investigates the role of Battery Energy Storage Systems (BESS) in enhancing the hosting capacity of Distributed Energy Resources DER, particularly PV generation and EV, within the distribution network. The analysis focuses on how BESS can mitigate network constraints by absorbing surplus PV generation, reducing curtailment, and enabling seasonal uncertainty management. Additionally, BESS is examined to improve local grid flexibility by supporting load shifting and peak shaving. Beyond network support, the study evaluates the capability of BESS to provide value through participation in the FCR-N reserve market. Together, these functions highlight the dual technical and market-oriented benefits of BESS in increasing DER integration while maintaining stable and efficient network operation.

**Task-1.3.3: Economic Assessment of BESS for Local Grid Flexibility and TSO-Level Services through FCR-N Market Participation.**

This objective focuses on evaluating the economic viability of BESS when providing flexibility both at the local distribution grid level and to the Transmission System Operator (TSO) through participation in the FCR-N market. Building on the technical analyses of increased DER hosting capacity and peak shaving, the study develops a model to demonstrate how the same BESS asset can deliver multiple services simultaneously. A year-long techno-economic simulation will be conducted to assess



investment feasibility using indicators such as net present value, cash flow and payback period. The findings will guide distribution system operators in making informed decisions regarding BESS deployment in the Porkholm network.

## **1.2 Structure of the Report**

The report is divided into chapters covering the background, methodology, analysis, and results. Chapter 1 introduces the study, its relevance, and objectives. Chapter 2 presents the technical background, focusing on flexibility, BESS roles, and market participation. Chapter 3 explains data collection and model development, while Chapter 4 reports the techno-economic evaluation and key findings. Finally, Chapter 5 concludes with results, discussion, and directions for future research.

## 2 Background and Concept of the Study

The present study continues the investigation of the Porkholm 20 kV distribution network within the PEAK project. Earlier phases have already described the network layout, components, and operational features in detail, providing a clear picture of its capacity and constraints. Task 1.3 focuses on a techno-economic study of flexibility in the network, with particular attention to the role of battery energy storage systems (BESS) in enabling stable operation, enhancing DER hosting, and creating value through market participation

### 2.1 Flexibility for Porkholm Network

With the integration of photovoltaic (PV) generation and electric vehicles (EVs), distribution networks begin to operate differently compared to traditional conditions. PV can bring clear benefits by supplying renewable electricity and lowering upstream demand, especially in summer when production is high. However, it also creates challenges such as reverse power flows, voltage fluctuations, and seasonal imbalances, since generation drops during winter when consumption is often at its peak. EVs add another layer of complexity by altering load curves (Linssen, Stenzel, and Fler 2017). Charging during evening hours can increase demand spikes, while uncoordinated charging may overload feeders and stress equipment, leading to new operational concerns.

To cope with these changes, networks require greater flexibility. Flexibility in power systems refers to the technical capability to maintain secure and reliable operation under conditions of variability and uncertainty (Tang, Wang, and Li 2021). It involves the ability to adjust generation, demand, or power flows to balance fluctuations and prevent violations of voltage or thermal limits (De Carne et al. 2024). In medium-voltage (MV) networks such as Porkholm, flexibility is particularly critical because these networks must integrate distributed generation while serving local demand and maintaining stable interaction with the transmission system. For this reason, the future flexibility needs of the Porkholm network are assessed under worst-case operating scenarios to ensure that reliable performance can be sustained as renewable penetration and EV usage expand.

## 2.2 BESS as Flexible Resource

Battery energy storage systems (BESS) are widely recognized as a key enabler of flexibility in medium-voltage (MV) distribution networks. Their main advantage lies in the ability to shift energy in time, balancing generation and demand while supporting secure and efficient network operation under growing shares of variable renewables. By storing surplus photovoltaic (PV) production during low-demand periods and releasing it during peaks, BESS increase the hosting capacity of DER) and reduce renewable curtailment (Conte et al. 2020).

Beyond this fundamental function, as seen in figure 1, a single BESS asset can simultaneously deliver multiple services. These include peak shaving to alleviate feeder and transformer loading, local grid flexibility to maintain voltage stability, energy arbitrage to optimize charging and discharging against market prices, and participation in reserve markets such as FCR-N (Steriotis et al. 2022). Utilizing one installation for several purposes maximizes technical benefits and improves economic feasibility. In this study, such a multi-service approach is applied to assess how BESS can enhance renewable integration and system reliability while providing market value.

Congestion relief is another important application of BESS in medium-voltage networks, where they have proven highly effective. By placing storage units strategically at critical feeder nodes, thermal stress can be reduced by supplying local loads during peak hours or absorbing excess renewable generation when demand is low (Mudaheranwa et al. 2023). Coordinated operation of BESS and distributed resources helps to ease feeder congestion, while droop control can also mitigate oscillations at HV–MV interfaces. Placement at mid-feeder locations further reduces voltage swings and assists in clearing upstream congestion under extreme conditions. When combined with electric vehicles through optimized control, BESS can also lower power losses, reduce peak demand, and decrease overall system costs.

Another key strength of BESS is their fast controllability. Unlike traditional generators, they can react to control signals within seconds, offering bidirectional power flow and quick frequency support. This fast response is particularly valuable for services like FCR-N, which require activation within a few minutes. With this capability, BESS can provide essential ancillary services, stabilize local grids,

and help maintain reliable operation even during sudden load changes or unexpected outages in the upstream network.

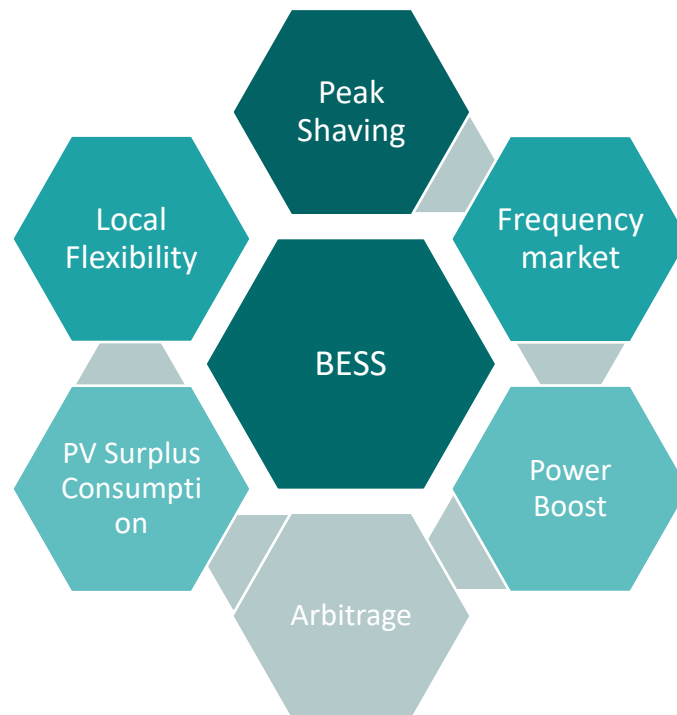


Figure 1: Multiple Services and Revenue Stacking from one BESS.

## 2.3 Energy Market Participation of 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 frequency reserve markets adds another revenue generating opportunity and enhances system flexibility. These developments help improve the collaboration between TSO and DSO in flexibility management.

2.3.1 Fingrid Reserve Markets

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. As seen in figure 2, 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 and Shieh 2024).



Figure 2: Fingrid Frequency Reserve Markets (Fingrid 2023).

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. On the other hand, FFR market requires sub second activation to target quick but brief reactions to under frequency events. For scheduled restoration and balancing, aFRR and mFRR are used.

### 2.3.2 Study Focus: FCR-N 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 which ever 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.

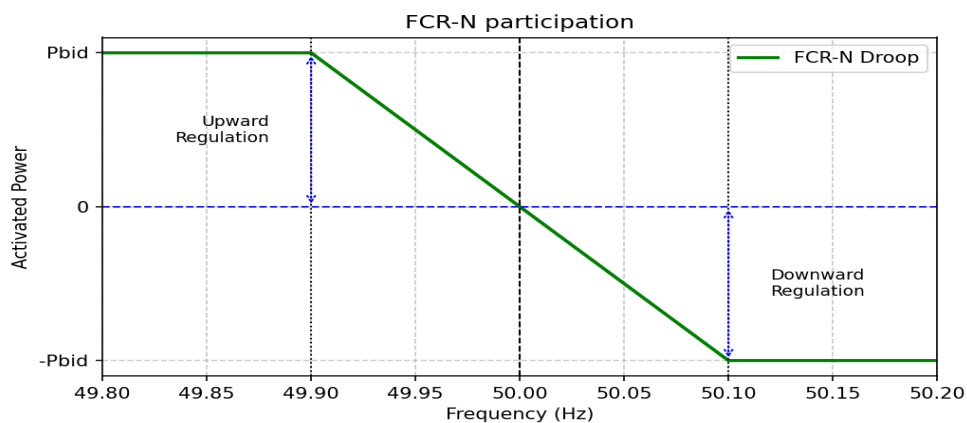


Figure 3: Activation of FCR-N according to FCR-N market frequency variation

## 2.4 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) 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.

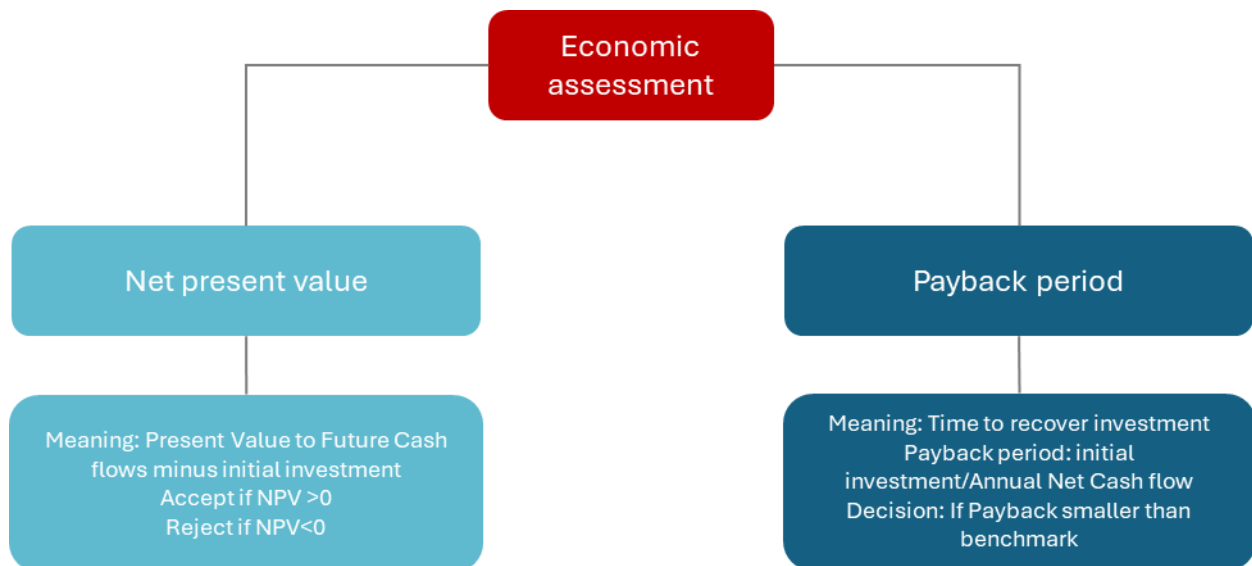


Figure 4: Economic analysis metrics

### 2.4.1 Net Present Value

Net Present Value (NPV) is one of the most widely used methods for evaluating the economic viability of BESS investments. It measures the difference between discounted revenues and costs over the asset's lifetime, allowing long-term benefits to be expressed in present value terms. A positive NPV indicates that the project can generate net financial gains, making it a fundamental tool for investment decisions. Studies have shown that NPV outcomes are highly sensitive to factors such as market prices and battery sizing (Nagel, Kirkerud, and Bolkesjø 2022).

### 2.4.2 Payback Period

The payback period is an important indicator for evaluating BESS deployment as it shows how quickly the initial investment can be recovered from operational revenues and cost savings (Zurita et al. 2018). A shorter payback period reduces financial risk and increases investor confidence, making the project more attractive. In this study, the payback period is a key part of the economic analysis, as it highlights the financial feasibility of BESS when applied to flexibility services, DER hosting capacity, and participation in the FCR-N market.

## 3 Data Collection and Model Development

This chapter presents the results of the study, following a systematic approach to analysis. The process began with the collection and preparation of the required data to ensure compatibility with the model. Subsequently, power flow optimization models were developed to represent the distribution network under various scenarios. These models were applied to assess the system's flexibility requirements, the renewable energy hosting capacity, and the techno-economic performance of the BESS.

Table 1: Data Sources

| Data                           | Source                                    |
|--------------------------------|-------------------------------------------|
| Network Data                   | Esse Elektrokraft (Esse 2025).            |
| EV charging schedule           | FME Zone (FME 2019).                      |
| PV generation profile          | Renewables.ninja .                        |
| Frequency                      | Fingrid (Fingrid 2025).                   |
| Up regulation Energy Price     | Fingrid                                   |
| Down Regulation Market Price   | Fingrid                                   |
| Reserved Capacity Price        | Fingrid                                   |
| BESS Units and Component Price | NREL 2023 Report (Cole and Karmakar 2023) |



### 3.1 Model Development

The analysis in this study was conducted using an optimal power flow (OPF) framework. To achieve this, a model was developed in Python and formulated as a Mixed-Integer Linear Programming (MILP) problem. The model was solved using a deterministic approach to ensure consistency and reproducibility of results. The standard parameters applied in the simulations are summarized in Table 2.

Table 2: 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)     | 0.20                                                                                             |
| Initial State of Charge (SoC)     | .40                                                                                              |
| Maximum State of charge (SoC)     | 0.90                                                                                             |
| Charging & Discharging efficiency | 90%                                                                                              |
| Cycle cost                        | 0.1 euro per kWh                                                                                 |
| Operation and Maintenance cost    | 0.001 euro per kWh                                                                               |
| Project life                      | 10 years                                                                                         |
| BESS-1 CAPEX                      | 330000 EURO                                                                                      |
| BESS-2 CAPEX                      | 495000 Euro                                                                                      |
| Inflation rate                    | 2%                                                                                               |
| BESS degradation rate yearly      | 2%                                                                                               |
| Discount rate                     | 5%,7%,9%,12%                                                                                     |
| BESS-1 (261)                      | P=500 kW, E= 1000 kWh (50% energy capacity reserved for Loal grid Flexibility and 50% for FCR-N) |

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|              |                                                                                                  |
|--------------|--------------------------------------------------------------------------------------------------|
| BESS-2 (133) | P=750 kW, E= 1500 kWh (50% energy capacity reserved for Loal grid Flexibility and 50% for FCR-N) |
|--------------|--------------------------------------------------------------------------------------------------|

Figure 5 illustrates the methodological framework applied in this study. The process began with data collection and preprocessing, followed by the development of an optimal power flow (OPF) model to enable subsequent analysis. As an initial step, two extreme operating conditions were examined: maximum PV generation with minimum load, and minimum PV generation with maximum load. These worst-case scenarios were used to determine the flexibility requirements of the network, thereby identifying the minimum level of flexibility needed to ensure stable operation.

In the next stage, a Battery Energy Storage System (BESS) was integrated into the OPF model. The BESS was employed to enhance PV hosting capacity, store surplus PV energy, provide peak shaving, and supply local flexibility services.

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For the economic assessment, representative operating scenarios were generated using K-means clustering to capture the diversity of system conditions. These clustered scenarios were then simulated within the economic model. At this stage, a techno-economic analysis was carried out to evaluate the performance of BESS when participating in the FCR-N market.

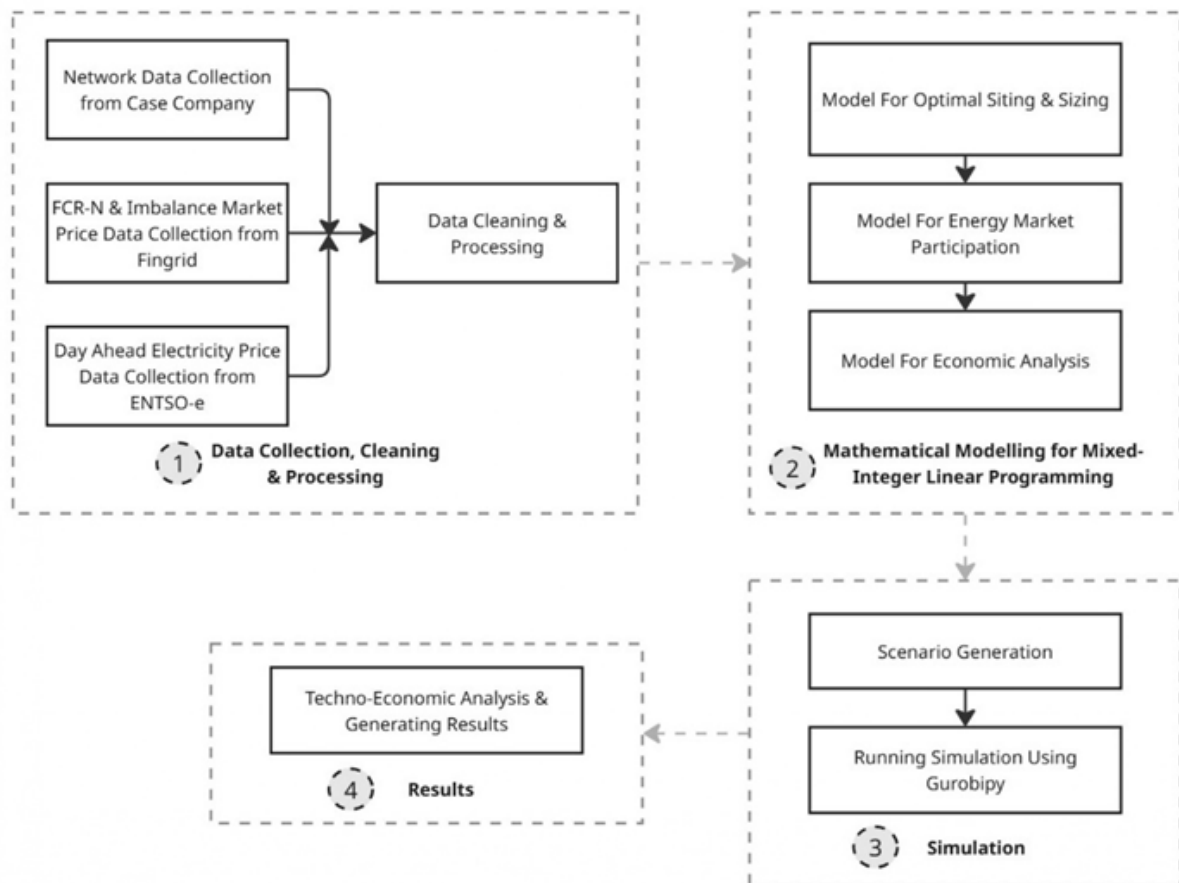


Figure 5: Methodological Approach

## 4 Results of Techno-Economic Evaluation for Flexibility

### 4.1 Flexibility Needs

In the flexibility needs assessment, two worst-case scenarios were defined to capture the extreme operating conditions of the distribution network. These scenarios were formulated to represent the boundary states where system stress is most pronounced:

- **Scenario 1:** Maximum demand combined with simultaneous EV charging and minimum PV generation.
- **Scenario 2:** Minimum demand combined with simultaneous EV charging and maximum PV generation.
- 

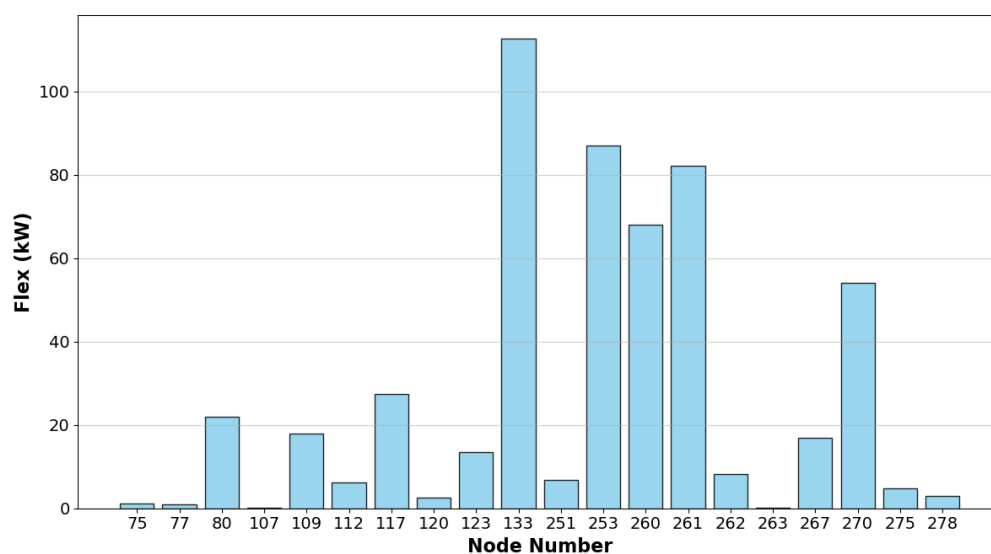


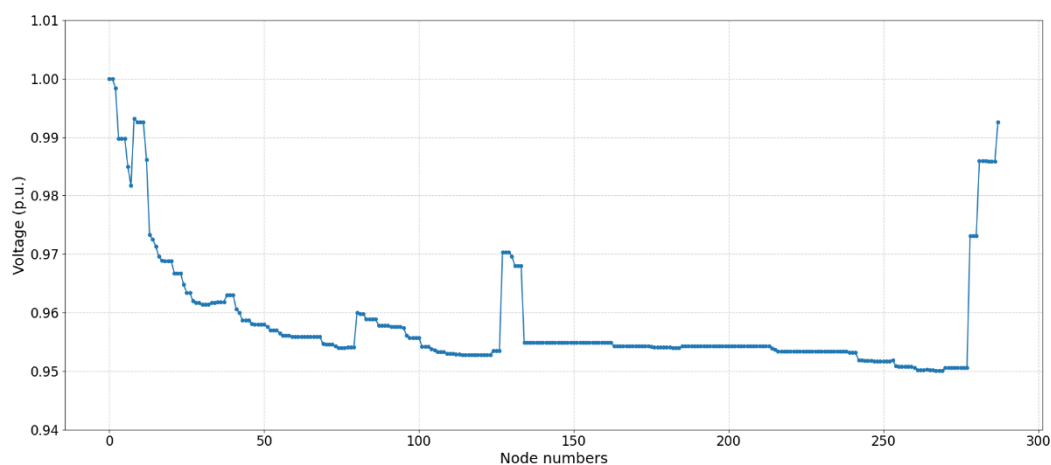
Figure 6: Flexibility Needs

These boundary conditions were selected because they reflect situations in which the network faces its greatest operational challenges. In Scenario 1, high demand with minimal PV generation leads to significant loading on the slack bus and pronounced voltage drops across the network. Under such circumstances, flexibility up is required to support the system and maintain voltages above the lower permissible threshold. Conversely, Scenario 2 represents periods of surplus renewable generation

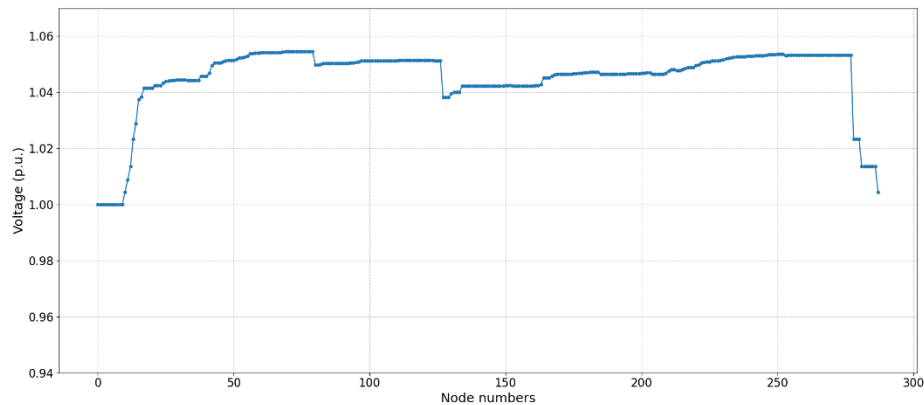
## PEAK – PEAK Task 1.3 Techno-Economical Calculation Related to the Renewable Energy Potential and Distribution Network Flexibility and Development needs

during low demand, which increases the risk of reverse power flows and voltage rise. In this case, **flexibility down** is necessary to absorb or manage the excess energy and ensure voltages remain within the upper allowable limits.

By analyzing these two extreme cases, the study identifies the minimum flexibility requirements that guarantee secure and reliable network operation. The total flexibility need was quantified at 681 kW, with the maximum flexibility observed at Node 133 and the minimum at Node 253. In addition, the analysis identified Nodes 133 and 261 as the most critical low-voltage locations, making them the preferred sites for BESS installation. Satisfying these requirements at the boundary conditions ensures system feasibility under all intermediate operating states. These findings also establish the foundation for further analysis of flexibility provision, particularly the role of BESS in enhancing PV hosting capacity, mitigating voltage issues, and supporting reliable operation of the network.



(a)



(b)

Figure 7: Voltage Profile Minimum generation-maximum load (a) and maximum generation-minimum load (b)

## 4.2 BESS for Peak Shaving, Flexibility, and Hosting Capacity

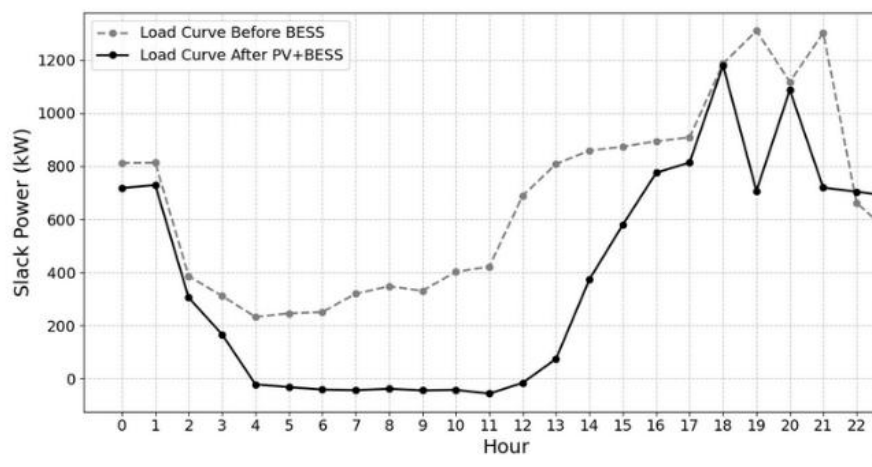
In Task 1.2, BESS was evaluated for its technical role in enhancing DER hosting capacity by absorbing surplus generation, mitigating overvoltage, performing peak shaving, and providing local flexibility. Task 1.3 extended the analysis to a techno-economic perspective, assessing BESS as a multi-service asset through participation in the FCR-N market, thereby combining network support with revenue generation opportunities.

### 4.2.1 BESS as Peak Shaving and Load Flexibility

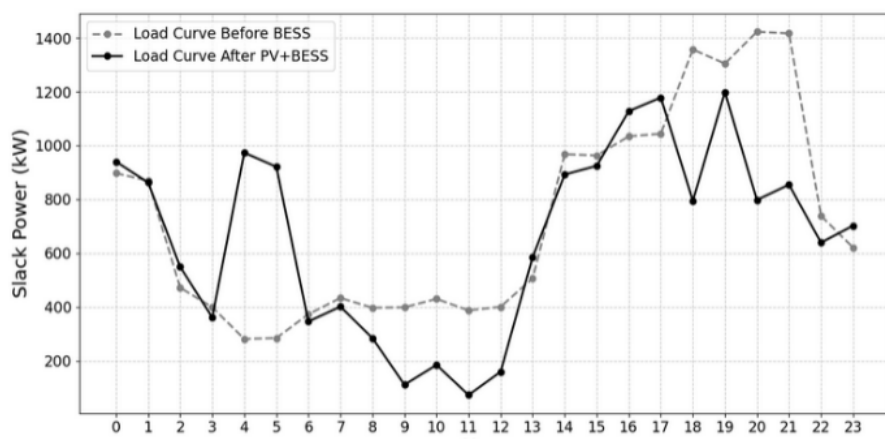
The objective of this task is to mitigate PV generation uncertainty, enhance local flexibility through load shifting, store surplus energy, and minimize overall system costs while enabling BESS participation in the FCR-N market by providing flexibility services at the TSO level. Figure 8 presents the load profiles of two representative days, one in summer and the other in autumn. These curves highlight the impact of BESS integration on daily load dynamics when coupled with PV generation.

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Prior to BESS integration, the network exhibited significant variations between minimum and maximum load. During summer, the load consumption from primary substation for couple of hours approached nearly zero between 04:00 and 12:00 due to high PV output. In contrast, in spring, the minimum load dropped to approximately 140 kW. Under these conditions, BESS operation adapted accordingly: charging occurred between 03:00 and 06:00 during low-demand periods, while discharging was activated during peak hours to alleviate system stress.



(Summer)



(Autumn)

Figure 8: Load curve before and after PV and BESS during Summer and Autumn

Considering both seasons, the results indicate that BESS achieves peak shaving of approximately 29% in summer and 30% in autumn. In addition, BESS participation in the FCR-N market enables operation during specific periods, thereby generating additional revenue. When the FCR-N response coincides with local grid flexibility needs, BESS also absorbs surplus PV power, which explains the two distinct variations observed in the load curves after PV and BESS integration.

Furthermore, as shown in Figure 9, the voltage profile of the network remains within the permissible range of  $\pm 5\%$  of the nominal value throughout the simulation. This demonstrates that BESS not only improves load management and economic performance but also contributes to maintaining voltage stability under varying operating conditions.

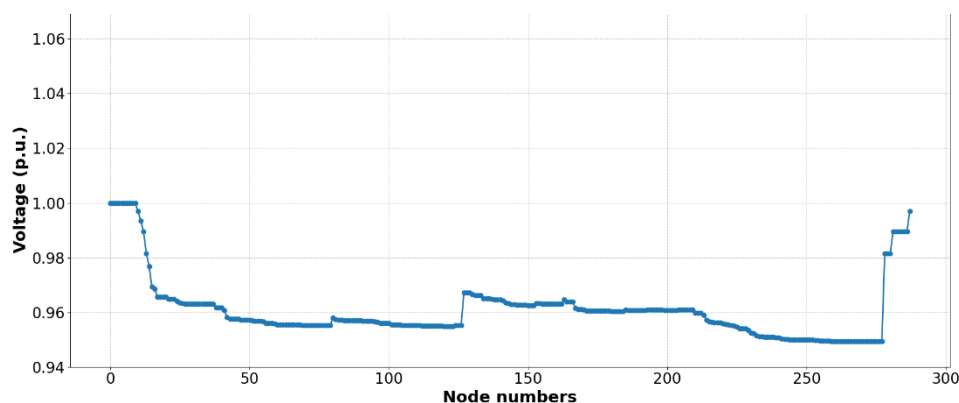
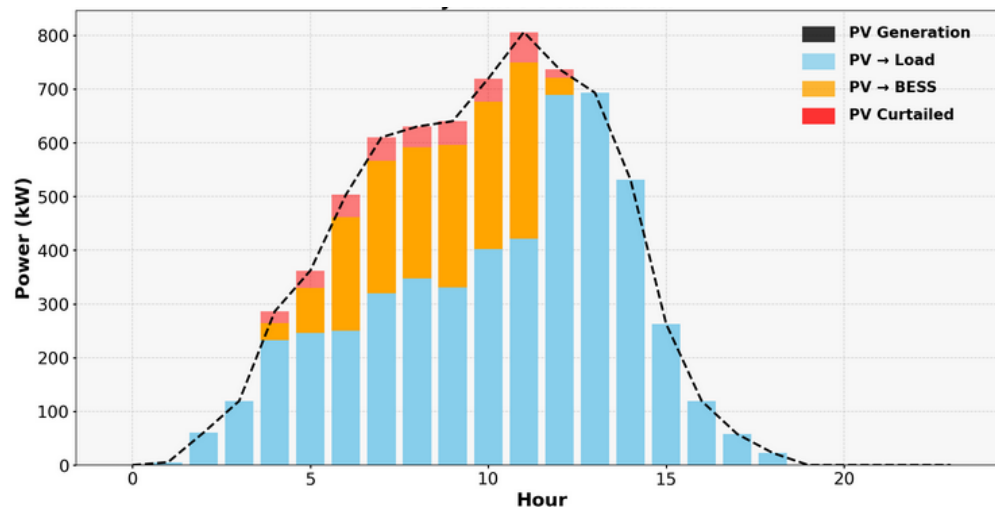


Figure 9: Voltage Profile node wise

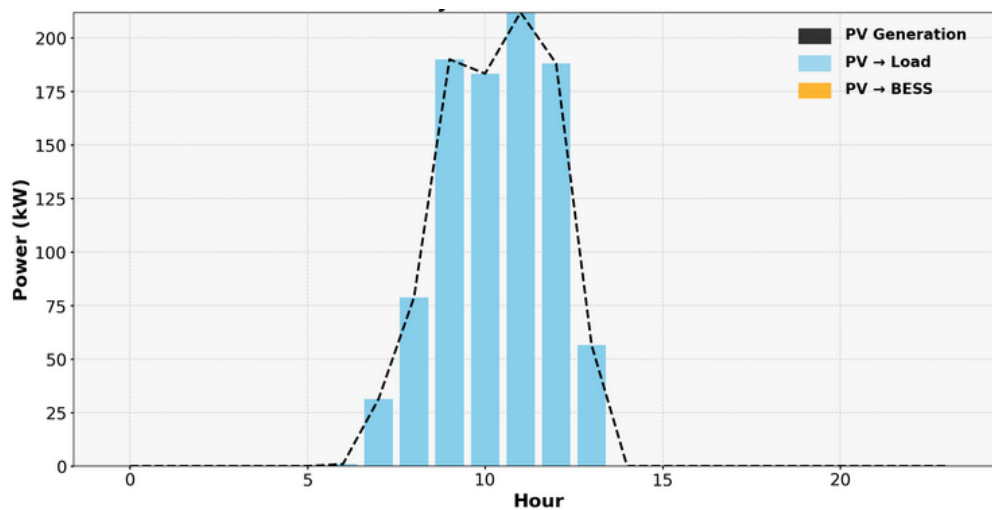
### 4.2.2 DER Hosting Capacity Enhancement

Figure 10 shows the seasonal utilization of PV generation and the role of BESS in managing surplus energy. PV output peaks in summer, often exceeding local demand. In such cases, the BESS stores excess generation up to its rated capacity, with 50% reserved for local flexibility (e.g., voltage support and peak shaving) and 50% for FCR-N market participation. Even with this allocation, around 3% of PV generation is curtailed in summer. In spring, the BESS fully absorbs surplus PV without curtailment, while in autumn and winter, PV production is lower and entirely consumed by the load.





(Summer)



(Autumn)

Figure 10: PV generation vs BESS and Load during summer and autumn

### 4.3 BESS Participation in FCR-N Reserve Market

The operation of the Battery Energy Storage Systems (BESS) in this study shows how they can support both the local distribution grid and the wider power system through FCR-N market participation. From figure 11 it is observed that in the early morning hours (0–2 h), the system frequency dropped below 50 Hz, which triggered an FCR-N down-regulation response. Both BESS units immediately

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started charging, with the activated power proportional to the frequency deviation and the contracted reserve capacity. This demonstrates the ability of BESS to provide fast frequency support while also storing energy.

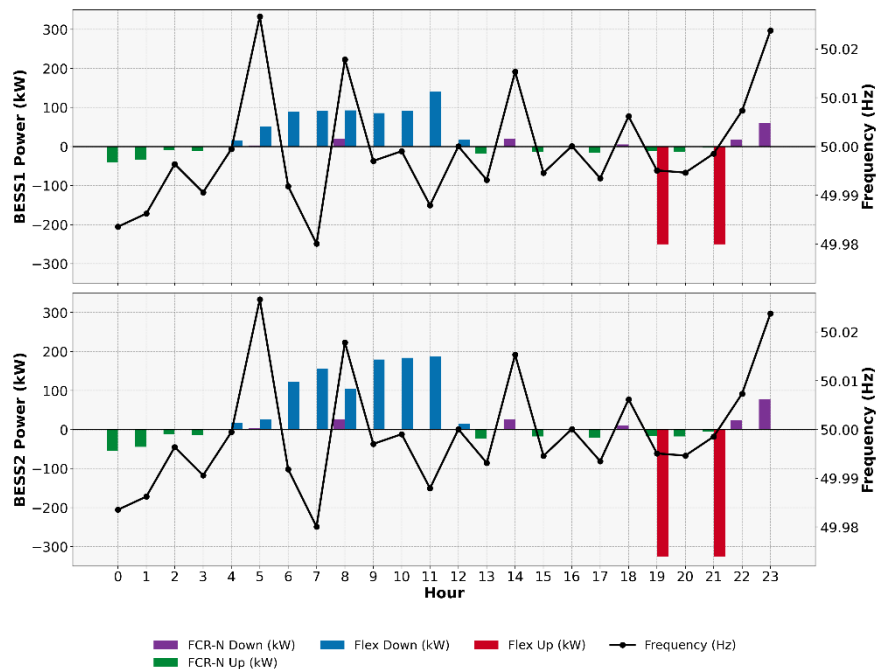


Figure 11: FCR-N Participation during summer

Between 4 h and 11 h, the BESS units mainly remained in charging mode. Even though up-regulation signals were available, FCR-N activation was not required because part of the capacity was reserved for local flexibility. Only once during this period did an FCR-N charging signal align with system conditions, leading to extra charging. At the same time, high PV generation produced surplus energy, which was absorbed by the BESS, reducing curtailment and improving renewable utilization.

Later in the day, the focus shifted to managing peak demand. At hours 19 and 21, the network reached maximum load, and both BESS units discharged at their rated capacity. This reduced stress on the grid and highlighted the multifunctional role of BESS in frequency control, flexibility, and peak shaving.

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Figure 12 illustrates the charging and discharging behavior of both BESS units under combined local flexibility and FCR-N market participation. The results confirm that the reserved capacity allocated to local grid flexibility consistently remains within its operational limits, ensuring reliable support for voltage and load management. Simultaneously, the capacity reserved for the FCR-N market is activated strictly according to system frequency deviations and reserve commitments. This demonstrates the effectiveness of capacity partitioning in enabling BESS to deliver dual services without operational conflict.

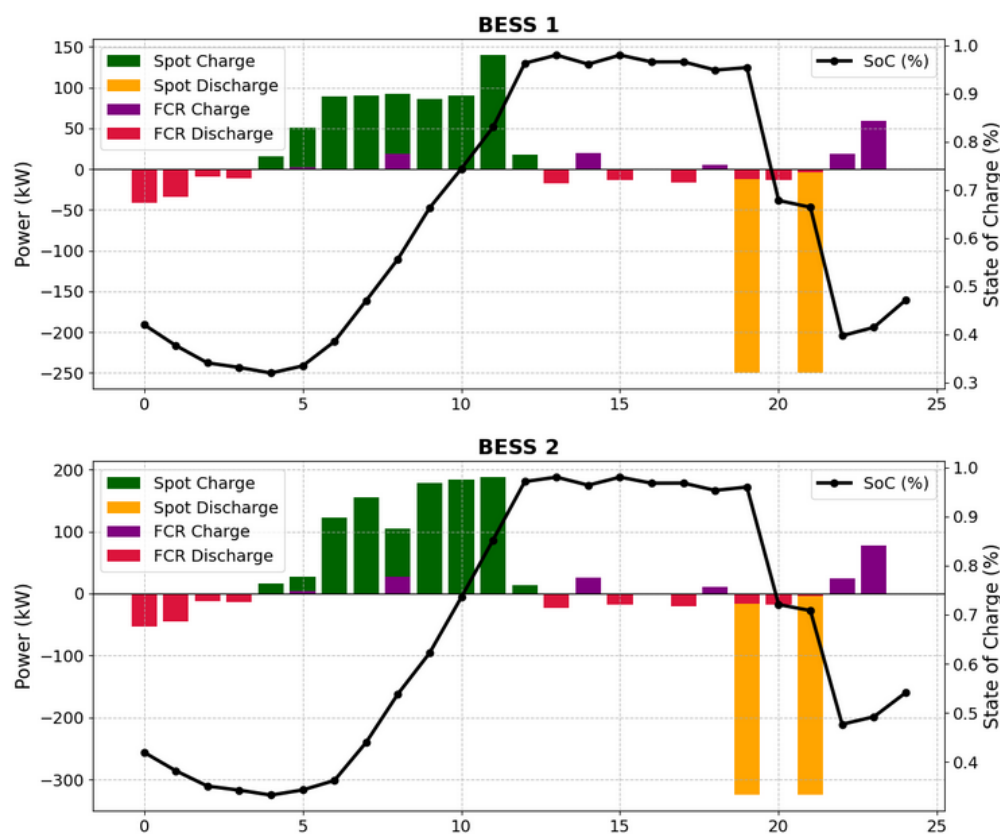


Figure 12: State of Charge of BESS while participates FCR-N market

## 4.4 Economic Insights

To evaluate the economic viability of the investment, a detailed techno-economic analysis was carried out using representative scenarios generated through clustering. These scenarios captured seasonal variations in network demand, PV generation, EV charging load, electricity prices, and frequency data. The analysis considered BESS participation in both the FCR-N market and local grid flexibility services. Figure 13 presents the total revenue earned by each BESS across the year, while Figure 14 shows the variation of the FCR-N reserve capacity price. Revenues were highest in spring and winter, coinciding with higher electricity demand and elevated FCR-N reserved capacity prices. In particular, May 2024 recorded the maximum reserve capacity price of the year, which directly contributed to peak revenue levels. Conversely, revenues in summer and autumn were comparatively lower, reflecting reduced electricity demand and reserved capacity prices, largely driven by the higher penetration of renewable generation during these seasons.

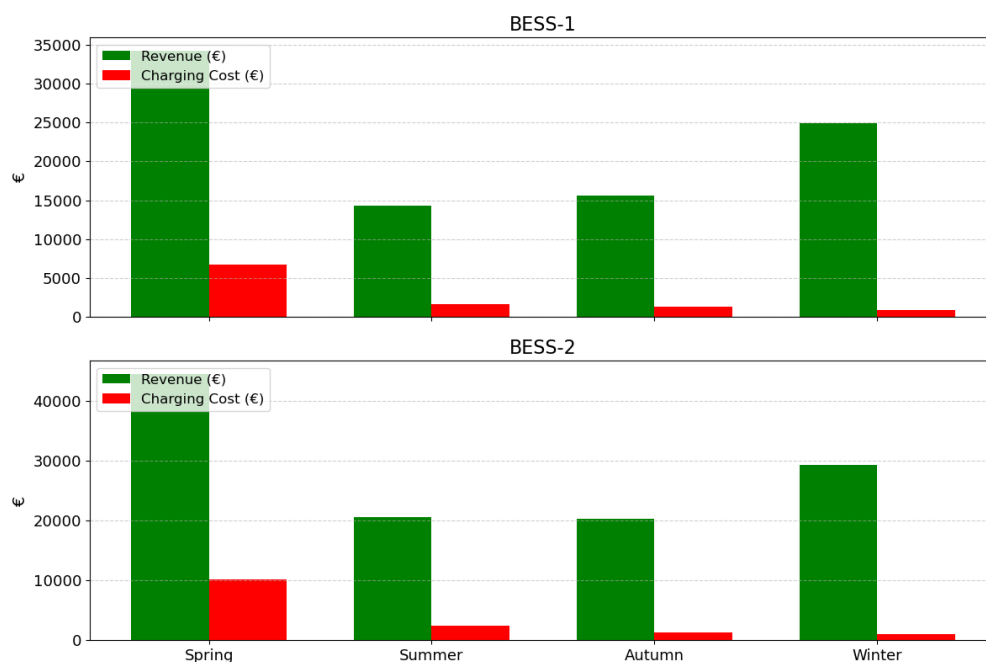


Figure 13: Revenue and cost of BESS across the year

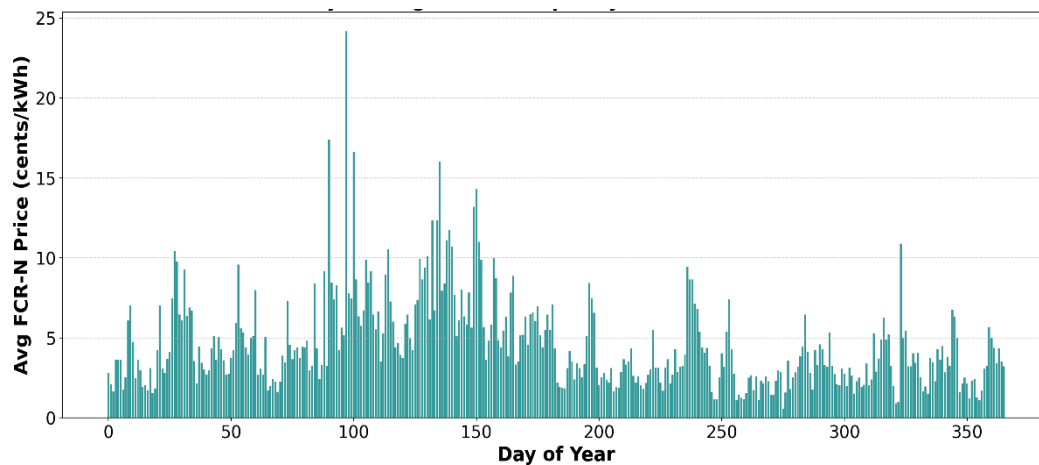


Figure 14: Frequency reserved capacity Price

After performing all representative day simulation in FCR-N market, the yearly generated revenue, cycling cost, charging cost and operation and maintenance cost were integrated in economic model to calculate NPV and payback period over the project life. The project life has been considered 10 years for this study. BESS-1 &2 investment (CAPEX) has been considered 330000 and 495000 euro from NREL 2023 cost projections for utility-scale BESS report (Cole and Karmakar 2023). This economic analysis performed by applying sensitivity analysis considering different discount rates. Other parameters for example inflation rate, degradation rate are provided in table 1.

The Net Present Value (NPV) analysis was performed to assess the economic feasibility of BESS deployment. As illustrated in Figures 14 and 15, NPV increases with longer project durations across all discount rates, reflecting the cumulative effect of positive annual cash flows over time. The cash flows considered in this study include annual revenues from FCR-N market participation and local grid flexibility services, offset by operational expenditure and charging costs, all adjusted for inflation and battery degradation effects. Lower discount rates, such as 5%, yield substantially higher NPV values, as future revenues are discounted less heavily, improving project viability. Conversely, higher discount rates, such as 12%, reduce the present value of long-term cash flows, thereby lowering NPV. The investment becomes profitable ( $NPV > 0$ ) only after a certain operational lifetime, which varies depending on the assumed rate. This highlights the sensitivity of BESS investment returns to both

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financial assumptions and cash flow dynamics, with the payback period indicating the point at which cumulative discounted revenues exceed the initial capital expenditure.

At a 5% discount rate, payback happens for BESS-1 & 2 in about 6 and 7 years. With discount rates 7%, & 9% payback takes increase the payback period. In case of discount rate 12% the payback happens at 7 and 8 years for BESS-1 & 2. This shows that higher discount rates reduce future earnings, affecting the project's financial return.

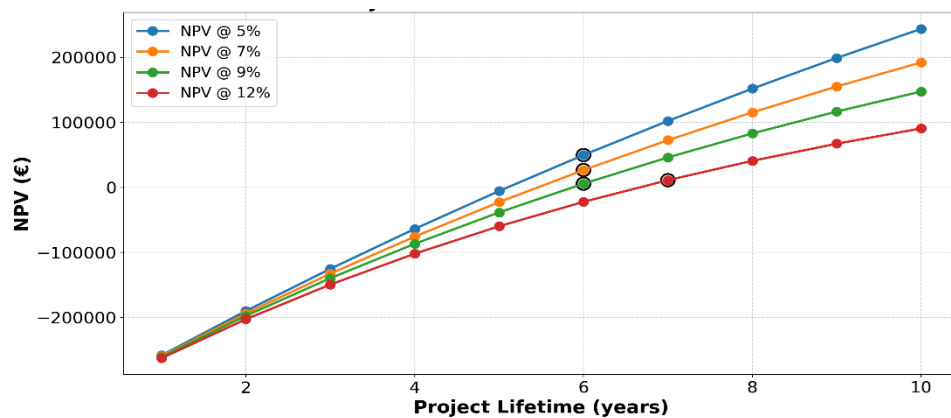


Figure 15: BESS-1 NPV vs Project Lifetime for various Discount rates

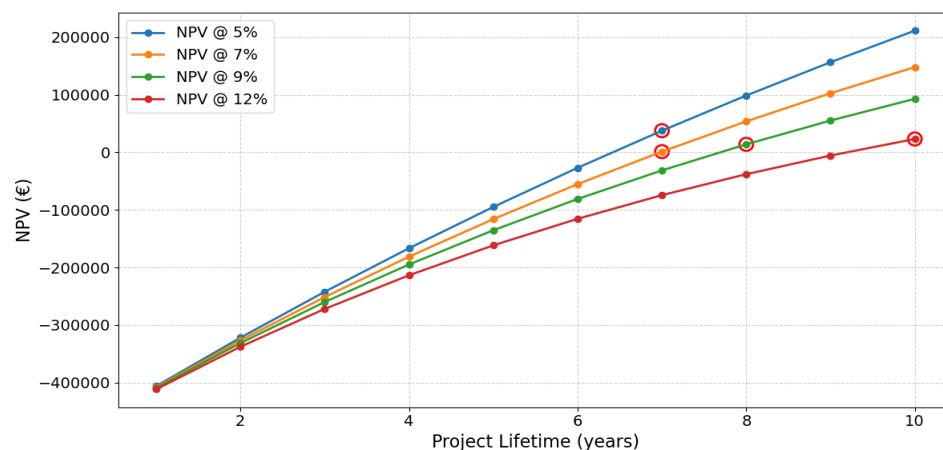


Figure 16 : BESS-2 NPV vs Project lifetime

## 5 Conclusion

This study comprehensively analyzed the integration of Battery Energy Storage Systems (BESS) into the Porkholm 20 kV distribution network, with the aim of enhancing both network flexibility and economic performance. The methodology incorporated optimal siting of BESS while accounting for photovoltaic (PV) generation, electric vehicle (EV) charging, and flexibility needs. In addition, the analysis examined the provision of flexibility services and participation in the Frequency Containment Reserve for Normal operation (FCR-N) market, combining technical feasibility with economic assessment. The determination of optimal BESS size was carried out in task 1.2.

Building on this foundation, the evaluation used detailed Porkholm network data provided by the distribution system operator (DSO), combined with electricity price and frequency data from ENTSO-E and Fingrid, to ensure realistic and reliable conditions. Scenario-based simulations confirmed that strategic BESS placement can improve reliability, stabilize voltage, and reduce the negative effects of variable renewable generation.

Furthermore, the results showed that beyond technical benefits, BESS can generate substantial economic returns by actively participating in energy and reserve markets. Together, these findings highlight the dual role of BESS in strengthening network operation and delivering financial value, supporting the case for their deployment in future distribution systems.

### 5.1 Key Findings and Discussion

- Under the extreme scenarios, the study identified the minimum flexibility required to keep voltages within 0.95–1.05 pu. When demand and EV charging were at their maximum with minimal PV, flexibility up was needed to counteract undervoltage. Conversely, during maximum PV and low demand, flexibility down was required to absorb surplus injection and prevent overvoltage. Aggregating these worst-case requirements, the minimum network flexibility need is 510 kW (combined upward and downward capability), sufficient to maintain secure operation under the defined boundary conditions.

- Integrating BESS into the system substantially improved DER hosting capacity. In summer, storage absorbed excess PV output, reducing curtailment to about 3%. In spring, surplus PV was fully utilized by the BESS without curtailment, while in autumn and winter PV production was lower and completely consumed by the load.
- Peak shaving was another key contribution of BESS. During high-demand periods, particularly in summer and autumn, maximum load was reduced by around 29–30%. The systems charged during low- hours and discharged at peak times, reducing reliance on the slack bus.
- The dual participation of BESS in local flexibility and the FCR-N market was successfully demonstrated. Reserved capacity for frequency regulation responded proportionally to deviations from 50 Hz, while capacity for local flexibility remained available to support network needs. This confirmed the effectiveness of capacity partitioning in preventing conflicts between services and daily revenue observed considering both BESS from FCR-N market from 400.05 to 900.13 euro daily.

## 5.2 Future Directions

**Dynamic revenue stacking:** Future work should develop optimization frameworks enabling one BESS asset to stack multiple services, such as peak shaving and reserve provision. Robust forecasting of weather and hidden behind-the-meter flexibility will be essential to maximize profitability while avoiding conflicts between local and market needs.

**Penalty-resilient bidding strategies:** BESS market participation requires bidding approaches that withstand penalties. Accurate flexibility quantification and probabilistic modelling under uncertainty will support reliable bids in FCR-N and other markets, ensuring economic viability even during unpredictable conditions.



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**Asset coordination:** Improved coordination among BESS, EVs, and demand response is needed to maximize hosting capacity and maintain voltage stability. Future studies should design scalable control mechanisms to synchronize these assets and unlock higher utilization of existing networks.

**Comprehensive techno-economic assessments:** Further techno-economic studies should apply sensitivity analyses to capture uncertainties in prices, degradation, and market rules. Such evaluations provide DSOs and investors with realistic insight into risks, supporting informed decisions on BESS and DER deployment.

**Integration of EVs through V2G/G2V:** Future research should examine how bidirectional EV charging complements BESS in delivering flexibility. V2G and G2V can support balancing and reserve provision but require solutions for degradation, control, and regulation.

**AI-enabled forecasting and control:** Machine learning can enhance prediction of PV output, EV demand, and frequency events, enabling more accurate scheduling of BESS. AI-driven adaptive control will be key to optimizing flexibility under uncertainty.

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