PEAK

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

Task 1.2 Improving the Reliability of Distribution Network through Renewable Energy, Electric Vehicle and Battery Energy Storage System (Part 2)

Md Ashfaqul Alam

2025
Ryhmähanke R-01335

Co-funded by the European Union
ÖSTERBOTTENS FÖRBUND POHJANMAAN LIITTO
esse elektro-kraft
AKTION ÖSTERBOTTEN
Vaasan yliopisto UNIVERSITY OF VAASA

TIIVISTELMÄ/ABSTARCT

Following the results of Task 1.2 Part 1, this report focuses on the integration of Renewable Energy Resource (RES) as Photovoltaic (PV) system, Electric Vehicle (EV), and Battery Energy Storage System (BESS), into distribution network. The aim of the study is to enhance system reliability and operational resilience by assessing hosting capacities under voltage, thermal, and transformer constraints. The analysis further considers the transition of distributed resources from passive units to active contributors in supporting grid operation.

The findings indicate that coordinated management of PV generation and EV charging significantly improves the utilization of existing network capacity. Compared to uncoordinated operation, PV hosting capacity increased by 33% and EV hosting capacity by 72%. These improvements demonstrate the potential of coordinated control to alleviate network stress and accommodate seasonal variations in demand.

In addition, the integration of BESS provided further operational flexibility. By absorbing surplus PV generation during daytime and discharging during evening peak demand, BESS reduced peak load by approximately 25% and maintained voltage levels within ±5% of nominal values. The strategic placement of BESS at low voltage nodes contributed to improved voltage stability and overall system performance. These results suggest that combining BESS with coordinated PV and EV operation strengthens both the reliability and resilience of distribution networks, while reducing the immediate need for costly grid reinforcements.

Sisällys/Table of contents

1 Introduction 6

1.1 Study Case 7

1.2 Purpose of the Study 7

1.3 Structure of the Report 8

2 Background and Concept of the Study 10

2.1 Porkholm Network 10

2.2 Hosting Capacity as a Reliability Enabler for PV and EV Integration 13

2.3 Reliability and Flexibility Gain through Coordinated PV and EV operation 14

2.4 Role of BESS in Distribution Network with PV and EV 14

3 Reliability of Energy System with PV, EV, and BESS 17

3.1 Potential Reliability from Renewables with Intelligent EV charging 17

3.1.1 Implications of Renewable Energy and EV for Potential Reliability 20

3.2 BESS Needs and Opportunities 21

3.2.1 Flexibility Provision of BESS: Implications for the System 26

4 Conclusion 27

4.1 Key Findings and Discussion 27

4.2 Future Directions 28

References 30

List of Table

Table 1: Network data Summary....10

List of Figures

Figure 1: Month-wise Load Profile of 20 kV Porkholm Network. 12
Figure 2: Hosting Capacity Estimation Process. 13
Figure 3: Coordinated Energy Management in Active Distribution Network with PV, EV and BESS. 16
Figure 4: Hosting Capacity Comparison Winter vs Summer. 17
Figure 5: Voltage profile node wise....18
Figure 6: PV and EV hosting capacity with coordination. 19
Figure 7: Hourly Load and EV consumption vs Transformer Capacity at node 50.....20
Figure 8: EV load and network load Profile....22
Figure 9: PV generation Profile. 23
Figure 10: PV Generation consumed by Load and BESS 23
Figure 11: Peak Shaving with the integration of BESS 24
Figure 12: Voltage Profile node wise....25
Figure 13: BESS size node wise....25

Abbreviations

BESS	Battery Energy Storage System
BTM	Behind the Meter
DER	Distributed Energy Resource
DSO	Distribution System Operator
EV	Electric Vehicle
G2V	Grid to Vehicle
LV	Low Voltage
MILP	Mixed Integer Linear Programming
MV	Medium Voltage Distribution Network
OPF	Optimal power Flow
OLTC	On Load Tap Changer
PV	Photovoltaic
RES	Renewable Energy Sources
SOC	State of Charge
TSO	Transmission System Operator
V2G	Vehicle to Grid

1 Introduction

The growing integration of renewable energy and Distributed Energy Resources (DERs) are driving major changes in modern power system, with significant implications for reliability, stability, and efficiency. In Medium Voltage (MV) distribution network, resources such as photovoltaic (PV) system, Electric Vehicle (EV), and Battery Energy Storage System (BESS) are becoming more common. These technologies not only increase the share of clean energy but also introduce changes that influence the daily operation of the grid. This study explores how such DER can be used to improve the reliability and resilience of distribution network. Particular emphasis is placed on the role of BESS in delivering flexibility services, as well as on the coordinated use of PV and EV resources to enhance grid stability and efficiency.

As the role of DER in MV network grows, the increasing penetration of DER is reshaping modern distribution network and creates both opportunities and challenges (Maask et al. 2025). High levels of PV generation and EV charging demand can introduce voltage fluctuation, reverse power flow, and thermal stress on key components if unmanaged (Bastida-Molina et al. 2024). At the same time, these resources also offer new flexibility options that can strengthen the network's ability to withstand variability and disturbances. By applying monitoring, control, and coordinated management strategies, DER can be transformed from sources of uncertainty into active contributors to resilience (Smith, Robinson, and Elphick 2024).

In this context, the analysis first evaluates how coordinated PV and EV integration contributes to network reliability under varying seasonal and operational conditions. It then investigates the contribution of BESS as a flexibility resource, focusing on its ability to mitigate PV intermittency, provide peak shaving, absorb surplus generation, and stabilize voltages. Together, these assessments provide practical insights into how Distribution System Operator (DSO) can leverage renewable energy, flexible resources, and advanced control solutions to strengthen resilience and enable higher levels of renewable integration.

1.1 Study Case

This report presents the results of a study conducted under the PEAK project, coordinated by the University of Vaasa in collaboration with Esse Elektro-Kraft Ab, as part of Task 1.2: *Mapping the Utilisation of the Electricity Network and Flexible Resources* within Work Package 1. While the first part of Task 1.2 focused on assessing PV hosting capacity and the role of BESS integration without considering EVs, the present study (Part 2) extends the analysis to 38 nodes by evaluating both PV and EV hosting capacities under coordinated and uncoordinated scenarios, and by examining the additional flexibility provided by BESS. The scope of this work is to determine how maximum PV and EV penetration can be achieved while maintaining reliability, and to explore opportunities for BESS integration in combination with PV and EV in supporting future power systems towards 2030.

Esse Elektro-Kraft Ab provides power distribution services to the rural region of Ostrobothnia by receiving electricity from the Transmission System Operator (TSO) as well as from its own power generation units, mainly hydropower and sola(Esse 2025). In addition, the company indirectly owns shares in several wind parks through Puhuri Oy, as well as shares in other production assets such as the Olkiluoto nuclear plant. Approximately 30–40% of Esse Elektro-Kraft's yearly production portfolio is directly connected to the distribution grid. The company operates four primary 110/20 kV substations with a total of 18 feeders. However, this particular study was carried out for the 20 kV Porkholm line, which is located in Kauhava.

1.2 Purpose of the Study

The primary purpose of this report is to identify and quantify the potential of renewable generation, smart EV charging, and battery storage to improve the reliability and operational stability of a regional distribution network. This analysis supports DSO in decision making by highlighting the technical limitations of unmanaged integration and demonstrating the benefits of coordinated flexibility strategies. To address the aim of the study the work is classified in following tasks.

Task-1.2.4: The potential for the reliability of the region's energy system and to improve resilience with renewable energy, flexible resources and new technologies monitoring and management solutions.

This task focuses on assessing the reliability of the distribution network under the integration of PV generation and EV charging. The maximum capacities of PV and EV were evaluated considering key network constraints such as voltage limit, thermal rating, and transformer capacities. Intelligent charging strategies were applied as a management solution to assess the benefits of coordinated operation. The quantification was carried out through power flow analysis to ensure that network constraints were respected throughout the study. Finally, the role of flexibility in mitigating PV intermittency and managing EV charging dynamics was examined, while a more detailed evaluation of BESS integration is addressed separately in Task 1.2.5.

Task-1.2.5: The assessment of the possibilities and flexibility services of BESS

The PV generation and EV charging profiles were integrated into the distribution network model to determine optimal BESS locations and the required flexibility. The aim was to reduce PV curtailment, manage solar intermittency, and provide services such as peak shaving and reliability support. Power flow simulations identified two nodes with the largest voltage deviations as the most effective BESS sites, and accurate sizing was carried out to ensure sufficient capacity for storing surplus PV generation, voltage regulation, peak shaving, and network stability under high DER penetration.

1.3 Structure of the Report

The report is organized into chapters that present the background, methodology, analysis, and results of the study. It begins with the context and network description, followed by technical assessments of PV, EV, and BESS integration, and concludes with key findings, implications, and recommendations.

Chapter 1 lays the groundwork for the study by outlining its background, highlighting the core issue and defining the research aim. 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 provides a technical overview of the state of play in PV, EV hosting capacity and BESS integration in distribution network, including empirical constraints, modelling approaches.
Chapter 3 discusses the flexibility solutions under investigation of PV deployment, Intelligent charging of EV and battery storage including coordination mechanism and their system level effects.
Chapter 4 concludes with a set of recommendations for future action, and further investigation.

2 Background and Concept of the Study

This study was conducted on a specific 20 kV distribution network, referred to as 02_Porkholm. The analysis focused on quantifying the hosting capacity, assessing the impacts, and evaluating the reliability of the network under the integration of PV, EV charging infrastructure, and BESS as flexible resource. In this context, a thorough understanding of the existing network structure and its key components is essential. Therefore, a complete technical study of the Porkholm network is presented in this chapter, forming the foundation for the hosting capacity assessment and subsequent analysis.

2.1 Porkholm Network

The 02_Porkholm network is a 20 kV distribution feeder connected to the Kortesjärvi 110/20 kV, 16 MVA primary substation. The feeder has a total length of approximately 55 km and consists of 287 nodes, out of which only 38 nodes are load points. Most of these load points are supplied through 20/0.415 kV distribution transformers, few of them are already operating close to their rated limits. In contrast, the conductor thermal ratings of the feeder indicate sufficient capacity to accommodate additional power transfer. Based on the 2024 load profile, the total annual energy consumption of this feeder is estimated at approximately 1,953 MWh.

Table 1: Network data Summary

Nodes	Transformer (KVA)	Conductor (Ampere)	Max Load (kW/H)	Min Load (kW/H)
20	50	999	11.19	1.13
23	50	999	10.74	0.17
32	30	999	28.09	2.71
34	30	999	18.72	0.65
37	50	999	36.33	0.98
40	16	999	0.74	0.25
45	50	999	1.85	0.06
50	100	999	86.07	10.42

54	30	999	27.91	0.84
58	50	999	48.34	0.67
72	100	999	5.61	0.26
76	100	999	49.85	8.7
79	30	999	20.25	0.76
86	30	999	2.24	0.11
90	30	999	3.85	0.05
94	30	999	7.76	0.1
100	50	999	11.38	0.74
103	16	999	8.05	0.5
108	50	999	11.16	0.69
111	16	999	4.66	0.2
116	30	999	13.98	0.77
119	50	999	2.73	0.05
122	30	999	4.71	0.44
126	16	999	7.04	0.04
129	50	999	43.14	2.95
133	30	999	5.79	0.11
152	50	999	4.56	0.37
162	30	999	4.2	0.69
184	30	999	28.96	1.1
203	100	999	75.49	4.83
231	100	999	23.59	1.47
266	30	999	0.98	0.01
269	30	999	26.48	3.94
277	50	630	2.13	0.02
280	50	999	33.34	0.75
283	30	999	18.62	0.86
286	30	999	11.68	0.6

From Table 1, a general overview of the network can be observed. It shows that several distribution transformers operate close to their maximum limits during periods of peak demand, while others still have sufficient headroom to accommodate additional loads, such as EV charging. When considering minimum load conditions, however, all distribution transformers show adequate spare capacity to host additional demand.

This overview highlights that the hosting capacity of the network is highly dependent on load variations. If these variations are not carefully considered in the quantification process, there is a risk of exceeding component limit, leading to network congestion. On the other hand, proper consideration enables the optimal utilization of the network's hosting potential.

Figure 1 illustrates the annual load consumption profile of the Porkholm network. The annual load profile further indicates that the feeder experiences its highest loading during winter months, while in summer the demand decreases to its minimum level. This seasonal variation directly influences the available hosting capacity.

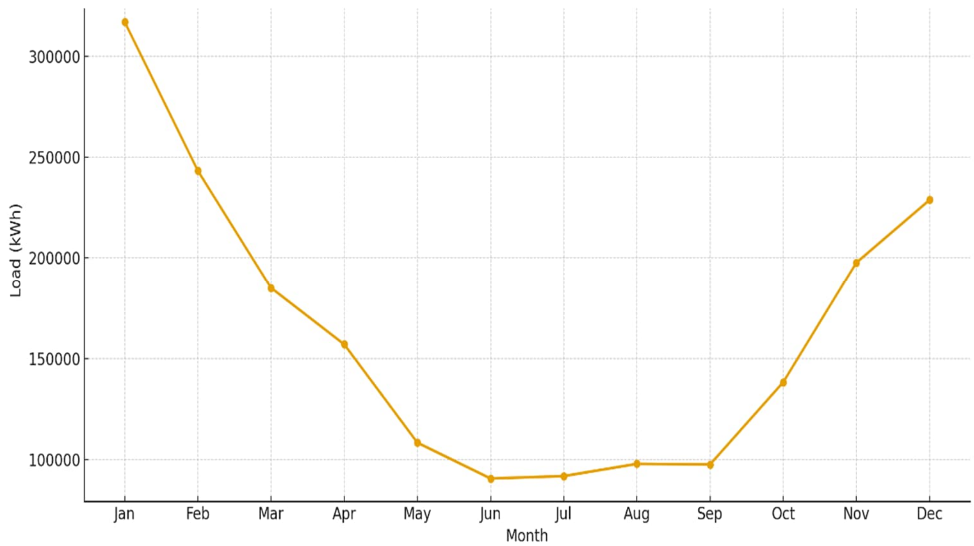

Figure 1: Month-wise Load Profile of 20 kV Porkholm Network.

Co-funded by the European Union

2.2 Hosting Capacity as a Reliability Enabler for PV and EV Integration

In modern distribution network, increasing the share of DER such as PV and EV is essential for decarbonization. However, their large-scale integration must be managed carefully to avoid violating technical limits like voltage threshold, thermal rating, and protection boundaries. Hosting capacity, in this context, serves as a fundamental metric to evaluate the extent to which PV and EV can be deployed without compromising network performance or stability (Zenhom et al. 2024). Conventionally, PV and EV hosting capacities are calculated separately, with PV limited by daytime over voltage and EV constrained by evening under voltage or transformer overload. This siloed analysis often results in conservative limits, restricting renewable and electrification potential and undermining the reliability benefits that these technologies could provide (Iqbal, Stevenson, and Sarwat 2025).

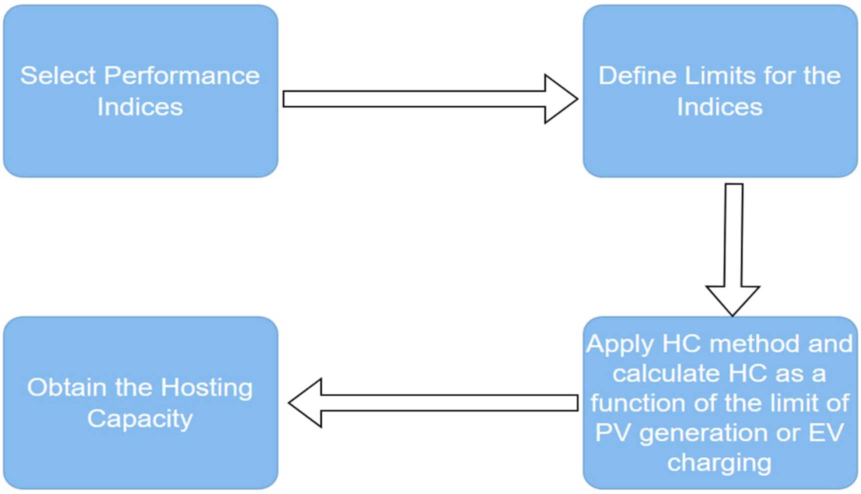

Figure 2: Hosting Capacity Estimation Process (Umoh et al. 2023).

This study frames hosting capacity not only as a planning constraint but as a pathway to operational reliability. By adopting a coordinated integration strategy, where EV charging is scheduled during peak PV output and PV generation dynamically adjusts its active power based on voltage feedback, this study demonstrates that the combined hosting capacity can be significantly enhanced (Fatima et al. 2024). Coordinated control reduces voltage excursion and enhances load generation balancing at the feeder level. This expanded hosting unlocks the reliability potential of both PV and EV by turning them into controllable, grid supporting assets rather than passive loads or generators (Li et al. 2024).

2.3 Reliability and Flexibility Gain through Coordinated PV and EV operation

Maximizing hosting capacity through coordinated PV and EV integration directly enhances distribution system reliability, particularly under high renewable penetration. PV equipped with smart inverter functionalities can provide upward flexibility by adjusting active and reactive power output in response to local voltage dips. On the other hand, EV acts as downward flexible loads by increasing their charging demand during high voltage conditions caused by solar surplus. This mutual voltage regulation mechanism helps maintain operational margin, reduces stress on transformers and feeders, and improves local power quality (Bishla and Khosla 2024).

More importantly, the flexibility offered by these resources enhances the system's ability to respond to variability and uncertainty. Even without bidirectional power flow (i.e., without V2G), intelligently managed EV charging profiles can flatten demand curves, mitigate overloads during peak hours, and absorb renewable intermittency. Therefore, the reliability potential of renewable energy in distribution networks is not merely a function of installed capacity but depends critically on how well PV and EV resources are hosted, coordinated, and controlled (Chen et al. 2025). This study positions coordinated hosting capacity maximization as a key technical enabler of renewable based reliability in modern power system.

2.4 Role of BESS in Distribution Network with PV and EV

BESS is increasingly recognized as critical enablers of reliability and operational flexibility in distribution network with high shares of PV and EV loads. In such networks, the temporal mismatch between midday PV generation peaks and evening EV charging demand creates voltage management and congestion challenges (Kelepouris et al. 2023). Over voltage can occur during periods of high solar injection, while under voltage and transformer overloading are common during peak residential and EV charging periods. BESS addresses these challenges by time shifting energy, mitigating power quality issues, and reducing reliance on grid reinforcement (Castro 2024). In this study, BESS units are integrated into a MV network model alongside high PV penetration, EV charging demand, and conventional loads. The coordinated BESS control strategy is designed to enhance the reliability and hosting capacity of the network through three main operational functions:

- Energy Absorption and Curtailment Mitigation: During midday, when local PV output exceeds consumption, BESS units charge to absorb surplus energy. This prevents over voltage and reduces the need for PV curtailment.

- Peak Shaving and Load Support: In the evening, when EV and household demand peak, BESS units discharge to relieve stress on transformers and feeders, supporting voltage and reducing congestion.

- Voltage Constrained Flexibility Provision: BESS units provide both upward and downward flexibility by responding to local voltage deviations, supporting network operation within regulatory limit (e.g., ±5% of nominal voltage).

BESS placement is optimized at nodes where voltage or thermal constraints are most binding, allowing for localized intervention that maximizes system benefit. By charging when PV output pushes voltage toward the upper bound, and discharging when voltage sags due to high evening loads, BESS dynamically balances generation and demand. This coordinated behaviour enables the network to safely accommodate higher levels of PV and EV without violating technical limits or triggering expensive reinforcements.

Within the coordinated PV, EV, and BESS framework applied in this study, BESS serves not only as an energy buffer but as a distributed reliability asset and enhances voltage stability, increases hosting capacity, and improves power quality. These functions collectively support Finland's clean energy transition by enabling higher renewable and electrification levels without compromising the reliability of distribution network operations.

Co-funded by
the European Union

Figure-3 is the visualization of the concept of this study. Which shows that the network is getting power from primary substation and distributed at nodes using step down transformer. DER as PV and BESS integrated at 20 kV network so that the power generating from PV and flexibility from BESS can distributed all over the network. On the low voltage side, intelligent charging points enable EV to act as flexible resource, while small-scale rooftop solar generation further supports this approach.

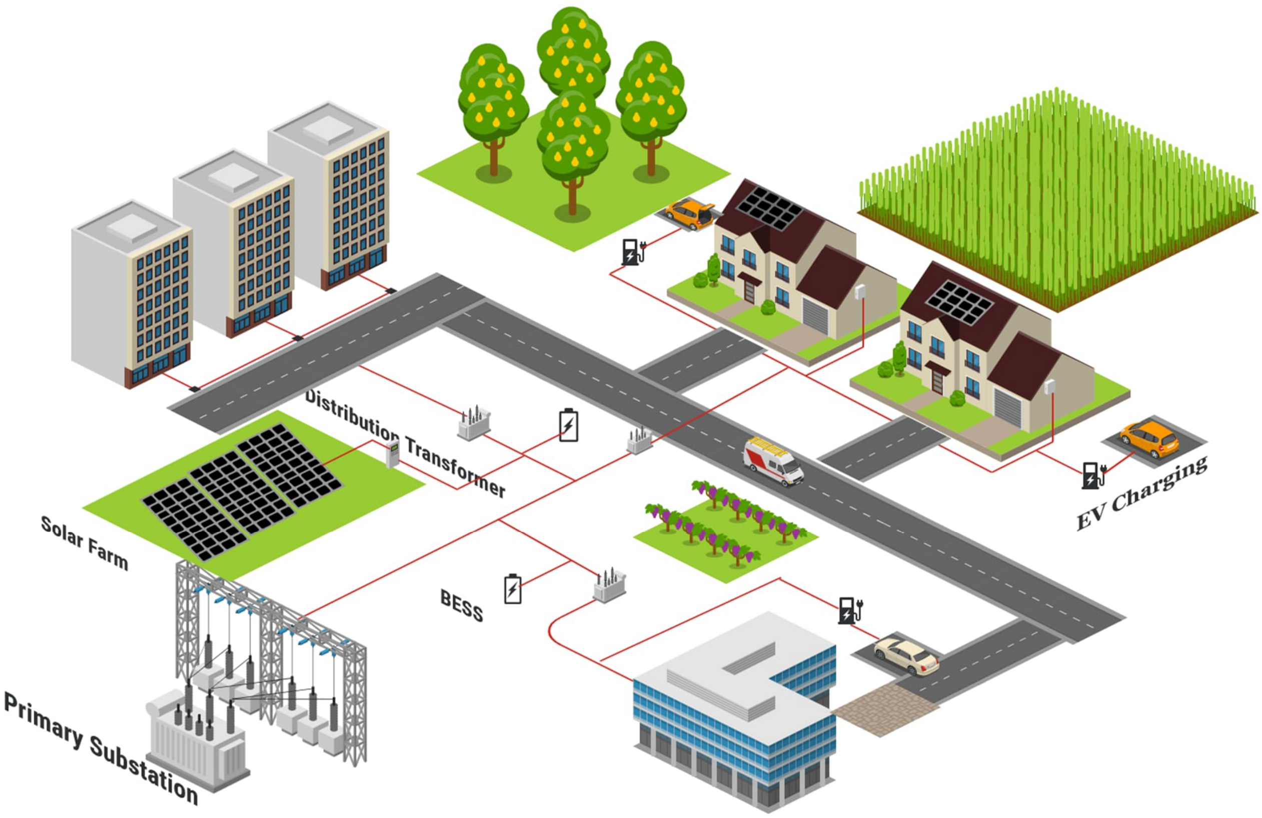

Figure 3: Coordinated Energy Management in Active Distribution Network with PV, EV and BESS.

3 Reliability of Energy System with PV, EV, and BESS

In this chapter, the simulation results of the distribution network under various scenarios are presented. The scenario analysis was conducted using representative days from both summer and winter seasons to reflect seasonal variability in PV generation and EV demand. The network data was obtained from Esse Elektrokraft, specifically from the Porkholm distribution area. PV generation profiles were sourced from *Renewables.ninja* based on the calculated hosting capacity, while the EV charging schedules were obtained from the FME ZEN project (Pfenninger and Staffell 2016) (FME 2019). All simulations were performed in Python using Jupyter Notebook. A linearized Optimal Power Flow (OPF) model was implemented within a Mixed Integer Linear Programming (MILP) framework and solved using the Gurobi optimization solver (Gurobi 2008).

3.1 Potential Reliability from Renewables with Intelligent EV charging

In Task 1.2.4, the hosting capacities of both PV and EV were evaluated under both coordinated and uncoordinated scenarios. The results, summarized in Figure 4, shows a significant improvement in hosting capacity when coordination is applied. Specifically, during the winter period, coordinating PV generation with EV charging increased the PV hosting capacity from 1,415 kW to 1,883 kW.

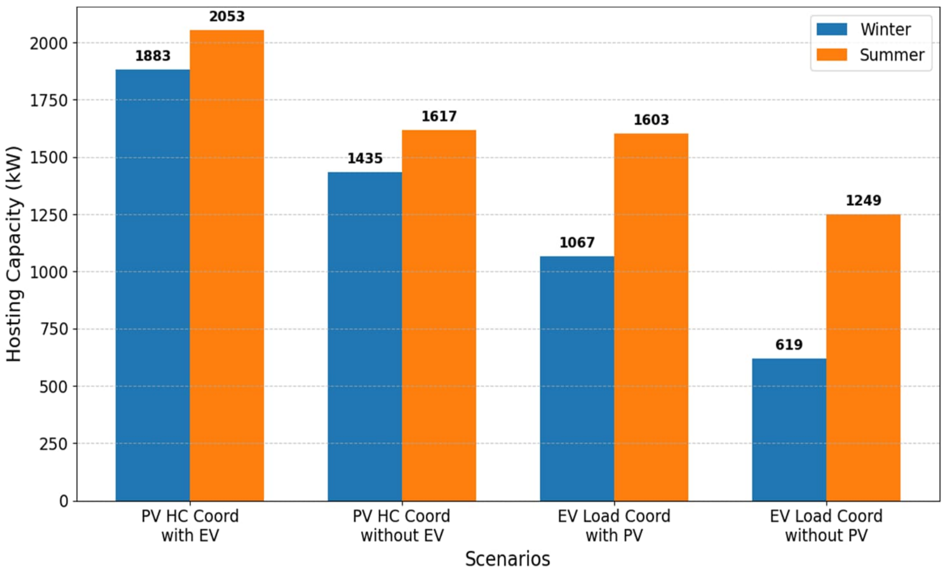

Figure 4: Hosting Capacity Comparison Winter vs Summer.

Similarly, the EV hosting capacity rose from 619.6 kW to 1,067 kW under coordinated operation. During winter, when electricity demand is at its peak, the available capacity for EV is limited, resulting in a lower EV hosting capacity. In contrast, summer typically sees lower base load consumption, which frees up distribution transformer capacity at each node. This additional capacity enables higher levels of EV charging, thereby increasing the EV hosting capacity. Furthermore, the coordination between PV generation and EV charging is more effective in summer, as greater PV output can be directly utilized for EV charging. This not only improves PV utilization but also enhances overall hosting capacity. Because both PV and EV systems are coordinated, their hosting capacities rise and fall together, while staying within the permissible voltage limit. 5.

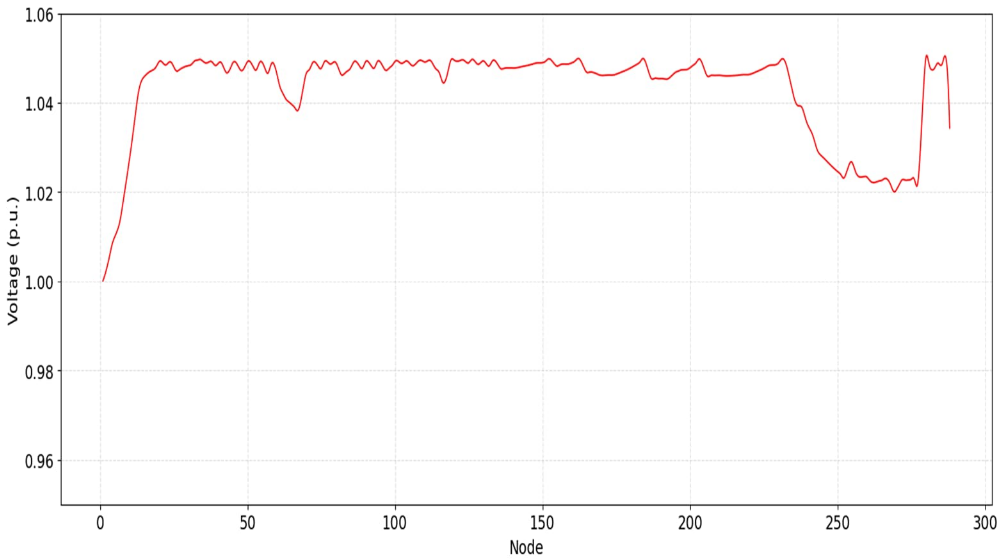

Figure 5: Voltage profile node wise.

The hosting capacity of both PV and EV was calculated by considering only the nodes with load. This approach was chosen to maximize the utilization of the available capacity without requiring network reinforcement, as only load nodes are connected to distribution transformers. Therefore, these nodes were selected for evaluating EV hosting capacity, and the same strategy was applied for PV hosting capacity quantification analysis. In the simulations, EV hosting capacity was limited by the distribution transformer capacity, whereas PV hosting capacity continued to increase until it reached the conductor thermal limits, the feeder over current rating or the maximum voltage limit. As a result, PV hosting was found to dominate EV hosting capacity in this study. This outcome is reflected in Figure 5, where the network voltage is shown to rise up to 1.05 p.u.

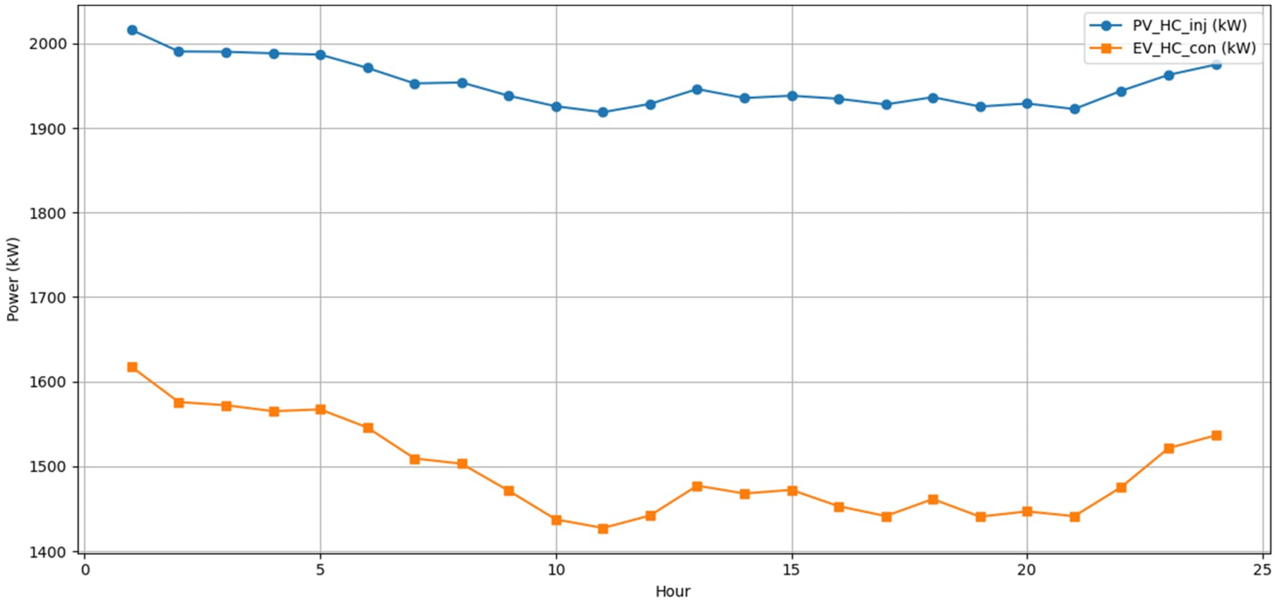

Figure 6: PV and EV hosting capacity with coordination.

As shown in Figure 6, the hosting capacities of both PV and EV increase and decrease simultaneously, reflecting the impact of their coordinated operation. When EV charging capacity increases, it creates additional room for PV to inject more power into the network, thereby enhancing the overall hosting capacity. This mutual influence activates both upward and downward flexibility. In contrast, without coordination, PV and EV systems operate independently. In such cases, once the PV reaches the maximum voltage limit, it stops increasing its output and similarly, EV charging halts when the minimum voltage limit is reached limiting their hosting capacities. The coordinated approach thus acts as an intelligent control solution that improves flexibility in both directions while enhancing overall hosting capacity and network reliability.

Figure 7 illustrates the consumption at Node 50 compared to transformer capacity during the hosting capacity analysis. It demonstrates that after serving the base load, the remaining distribution transformer capacity is efficiently used for EV charging without causing any overloading.

Co-funded by
the European Union

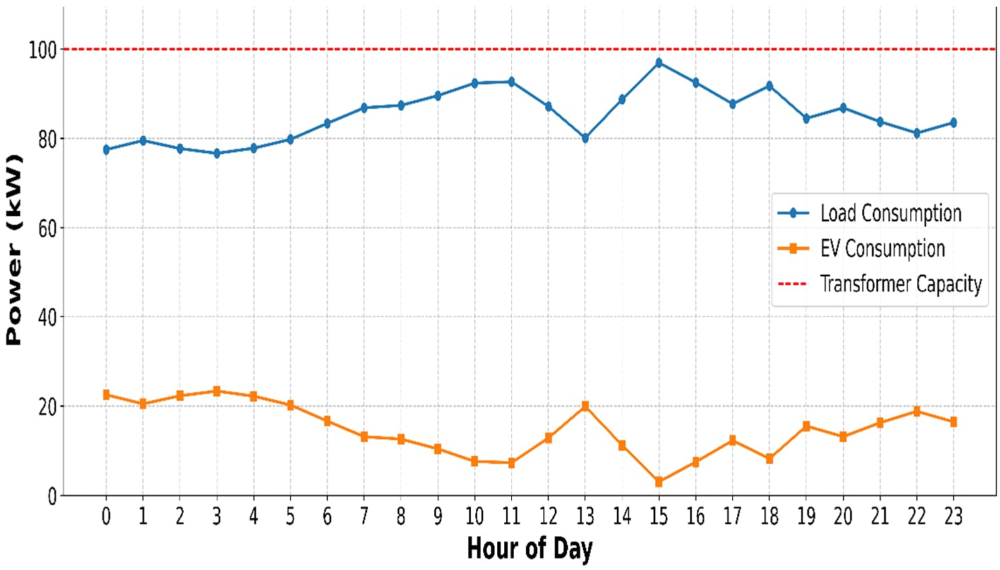

Figure 7: Hourly Load and EV consumption vs Transformer Capacity at node 50.

3.1.1 Implications of Renewable Energy and EV for Potential Reliability

- Coordinating PV and EV operations significantly increases their respective hosting capacities. For instance, during winter, PV hosting capacity increased by approximately 33%, while EV hosting capacity rose by about 72%, under coordinated operation. This demonstrates that intelligent coordination between PV and EV enables more efficient use of available network capacity, particularly under seasonal constraints.

- EV hosting capacity is notably lower during winter due to higher base load and transformer loading. In contrast, during summer, the lower base load consumption frees up transformer capacity, allowing more room for EV charging. This variation is evident in Figure 5, where EV hosting capacities are consistently higher in summer across both coordinated and uncoordinated scenarios.

- Network voltage levels rise close to the upper operational limit, particularly under high PV penetration. Throughout the simulations, voltage remained within the acceptable range (±5%) of the nominal value and ensures compliance with standard voltage regulation.

- PV injection and EV consumption fluctuate together throughout the day and reflects their coordinated behaviour. This coordination allows activation of both upward flexibility (e.g., increasing PV output when EV are charging) and downward flexibility (e.g., increasing EV charging when PV generation is high). Such dynamic balancing helps maintain voltage within limit while maximizing resource utilization.

- Without coordination, PV and EV systems act independently and are constrained once volage limits are reached. For instance, PV injection halts when it reaches Vmax, and EV charging stops at the minimum voltage threshold. This lack of mutual support leads to underutilized network capacity and less efficient operation compared to the coordinated case.

- After meeting the base load, the remaining transformer capacity is effectively used to accommodate EV charging without overloading. This validates the strategy of targeting load connected nodes for hosting EV and ensures optimal use of infrastructure without reinforcement.

3.2 BESS Needs and Opportunities

In this task, the flexibility potential of BESS was examined by integrating PV generation and electric vehicle (EV) charging loads into the network. Based on the PV hosting capacity results, a PV system size of 2,000 kW was considered, and its generation profile was obtained from the renewables.ninja database. EV integration was modelled by allocating charging loads to individual nodes based on calculated demand, using representative charging schedules from the FME ZEN research dataset in Norway. After integrating both PV and EV, a power flow analysis was performed to evaluate the system behaviour. The objectives were to store surplus PV generation and shave peak demand while maintaining network stability and delivering the necessary flexibility. To achieve this, two potential BESS locations were considered, with placement determined at nodes experiencing the lowest voltage level.

As seen in figure 8, the network load profile remains relatively steady throughout the day, with the maximum base load occurring at around 10 AM. In contrast, the EV load profile shows that most charging takes place during the evening and night, with very little charging activity during the day-time. Between 4 AM and 12 PM, almost no EV charging is observed. The highest EV demand occurs at 7 PM, creating a new peak in the overall load curve. As a result, after EV integration, the system experiences a shifted load profile with a distinct evening peak that did not exist in the base load scenario.

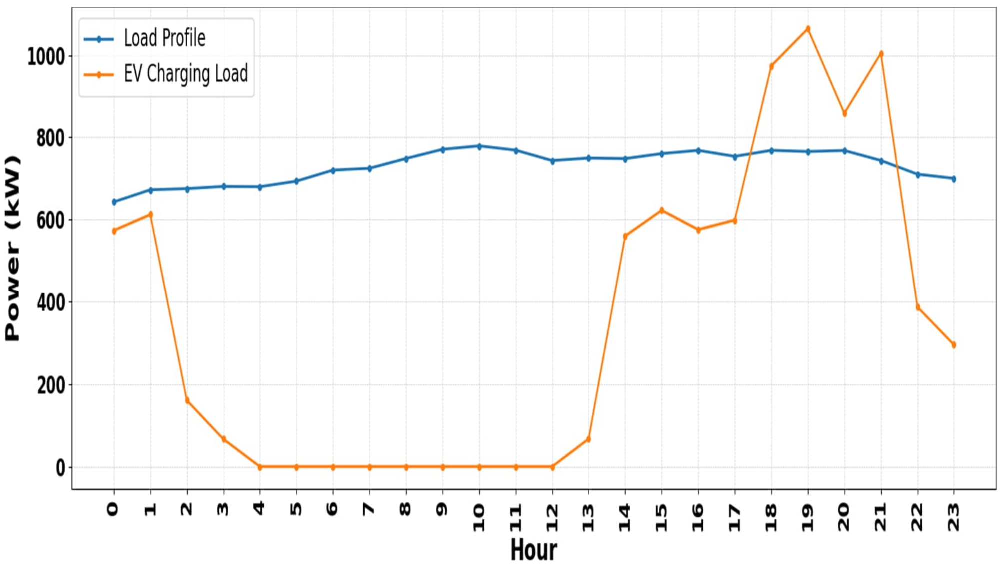

Figure 8: EV load and network load Profile

Figure 9 demonstrates PV generation profile of a day. The PV generation starts in the morning around 9 AM and lasts until about 7 PM, with the highest output at midday. During these hours, part of the load is supplied directly by PV, while the surplus is stored in the BESS so it can be used later.

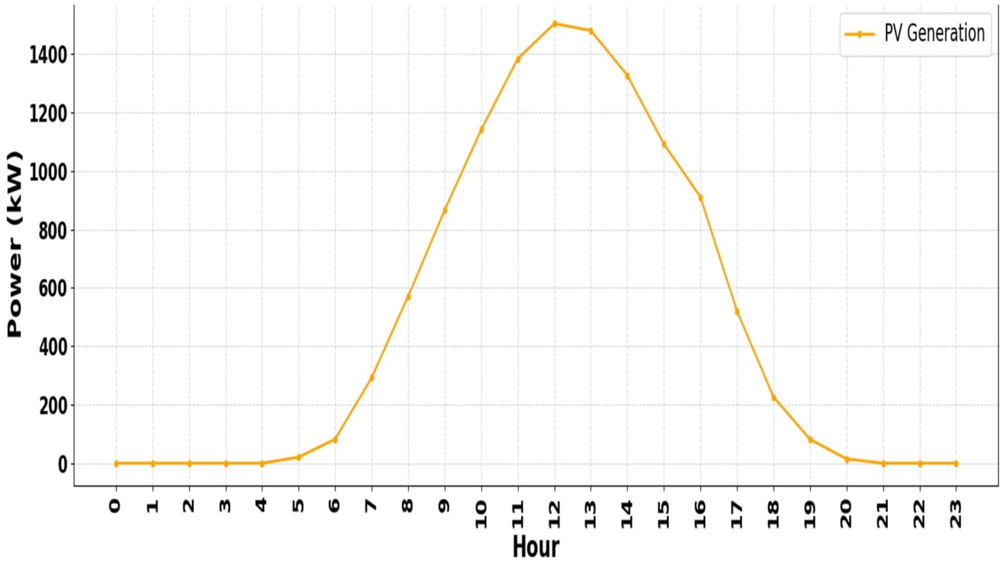

Figure 9: PV generation Profile.

The simulation was carried out with BESS initially set at a state of charge (SOC) of 35%. During the early hours (0–2 AM), EV charging demand was relatively high, which caused the BESS to discharge in order to support the load. Between 2 AM and 8 AM, when network demand was at its minimum, the BESS remained inactive to preserve its energy capacity for storing surplus PV generation later in the day. As seen figure 10, when PV production began, a share of the load demand was met directly by the PV system, reducing reliance on the grid and remaining surplus power consumed by BESS.

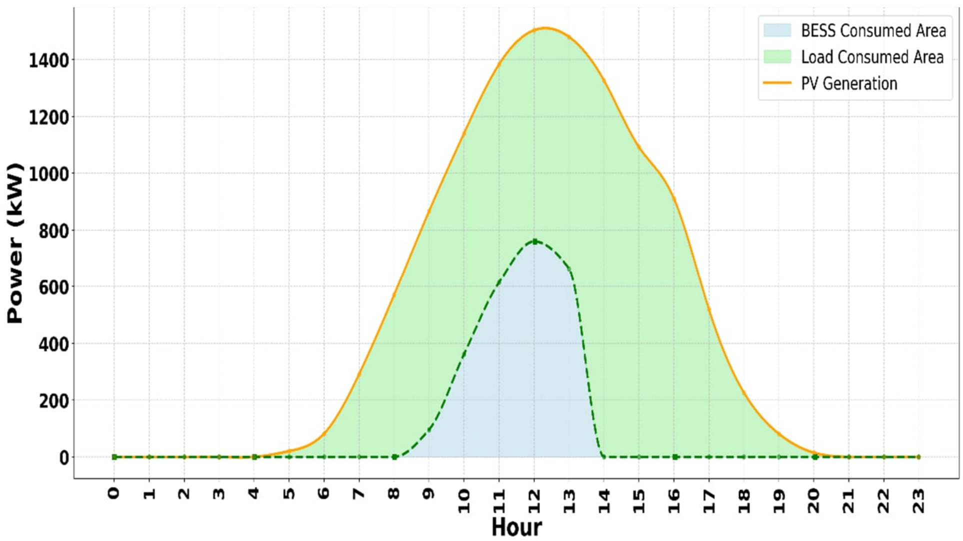

Figure 10: PV Generation consumed by Load and BESS

The surplus energy 2,500 kW out of a total daily PV generation of 11,515.13 kW was stored in the BESS. This storage ensured that excess energy was not wasted and could later be used during periods of higher demand or lower PV availability and improves both efficiency and flexibility of the network.

As seen figure 11 when the network experienced its maximum demand and PV generation was unavailable, the BESS discharged and provide flexibility. During the peak period, the system demand was reduced from 1,653.76 kW to 1,240.34 kW, corresponding to a 24.8% reduction in peak load through BESS support. This demonstrates the dual role of BESS: by storing 2,500 kW of surplus PV, it provides downward flexibility, and by reducing peak demand during high load periods it delivers upward flexibility, thereby improving overall network performance.

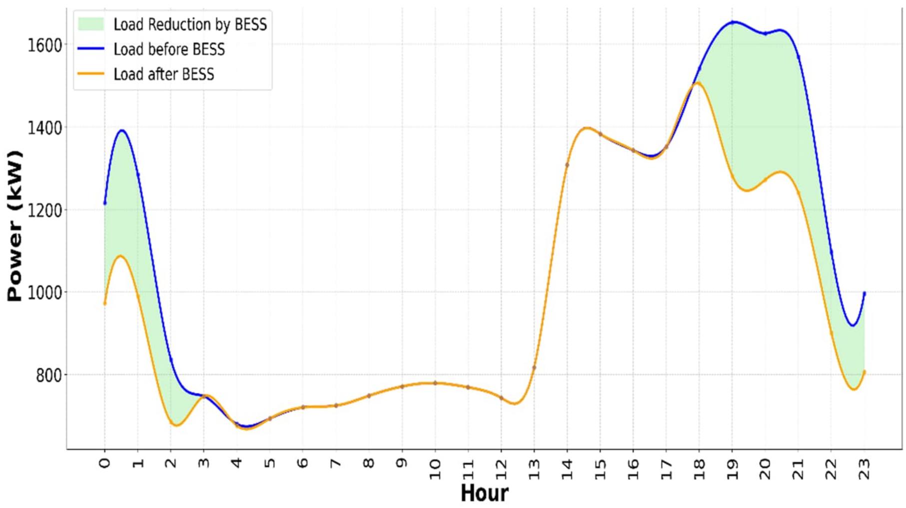

Figure 11: Peak Shaving with the integration of BESS

Figure 12 illustrates the network wide voltage profile, demonstrating that the coordinated operation of PV, EV, and BESS effectively maintains system reliability by keeping voltages within the permissible ±5% range of the nominal value.

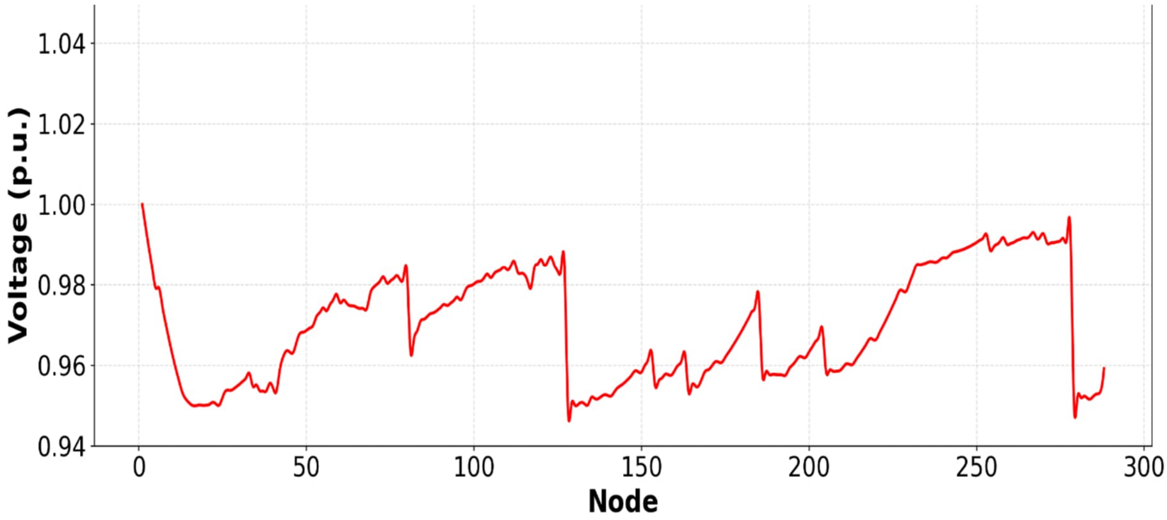

Figure 12: Voltage Profile node wise.

According to Figure 13, two BESS units were placed in the network one at node 20 and the other at node 133 based on the minimum voltage observed at those nodes. The sizing of the BESS units was determined to ensure that they could effectively store the maximum surplus power generated by PV. Their charging capacities were also designed to match the surplus PV generation, allowing the system to maximize the utilization of available renewable energy. This placement and sizing strategy ensures that both PV generation is efficiently used, and network voltage performance is improved.

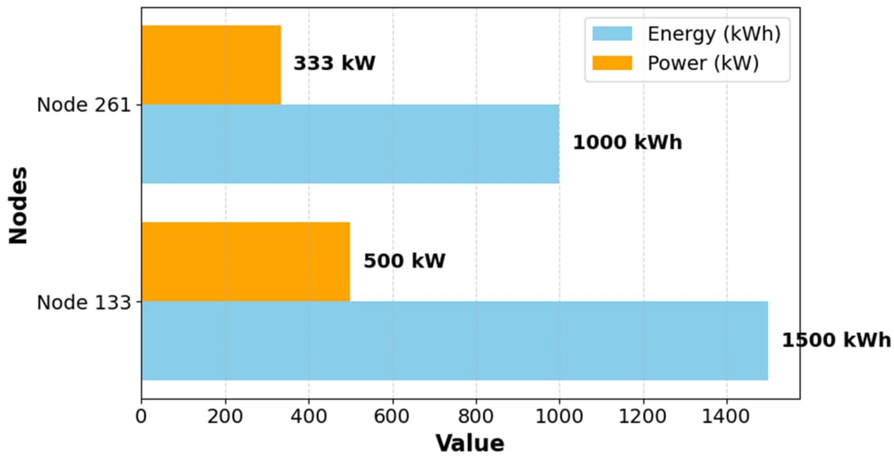

Figure 13: BESS size node wise

3.2.1 Flexibility Provision of BESS: Implications for the System

- By integrating PV with BESS, surplus PV generation is no longer curtailed but instead stored for later use. This increases the effective utilization of renewable energy in the network, improving overall system efficiency.

- The BESS significantly reduced the evening peak demand, lowering it by 24.8%. This demonstrates the important role of BESS in providing upward flexibility during high demand periods. At the same time, by absorbing 2,500 kW of surplus PV generation, the system also benefited from downward flexibility.

- EV charging introduced a new peak at 7 PM, altering the network's original load profile. Through controlled discharging, the BESS mitigated this additional stress, reducing the burden on the primary substation and helping to balance demand more effectively.

- Placing BESS units at nodes with the lowest voltages helped improve the network's voltage profile, which was affected by congestion. Through strategic charging and discharging, the BESS maintained voltages within the permissible range, preventing deviations beyond ±5% of nominal voltage. This highlights how optimal BESS placement can enhance both local node stability and overall system performance.

- The coordinated operation of PV, EV, and BESS illustrates a practical pathway toward smarter, more flexible distribution network. Such integration enhances renewable energy absorption, supports electrification of transport, and reduces stress on grid infrastructure. Collectively, these outcomes align with the broader energy transition objectives of reliability, sustainability, and efficient use of distributed resources.

Co-funded by
the European Union

4 Conclusion

This study highlights that the integration of PV, EV, and BESS can transform distribution network into more resilient and flexible system capable of supporting the energy transition. While these distributed resources can sometimes increase operational stress, they can also contribute to stability when managed effectively. Coordinated operation of PV and EV improves the balance between generation and demand, while BESS adds a crucial layer of flexibility by absorbing excess energy and reducing evening peaks. The results show that higher levels of renewable penetration and electrification can be achieved without immediate reinforcement of network assets. For distribution system operator, this demonstrates that flexibility measures such as smart charging and strategically placed storage can deliver cost effective reliability while deferring expensive grid upgrades. At the same time, the study emphasizes the importance of considering node specific conditions, as capacity limits and voltage sensitivities vary across the network.

4.1 Key Findings and Discussion

The first major finding from this study is that, coordinated operation of distributed resources strengthens network reliability. Instead of treating PV and EV as isolated elements that risk violating voltage limits or overloading transformer, this study showed how intelligent charging and generation management allow them to complement each other. By aligning EV charging with PV generation and adjusting operation around network constraints, it was possible to balance load and supply more effectively. This turns DER into active tool for maintaining operational margins and improving system stability. A second important outcome is the recognition of seasonal dynamics in network performance. Winter conditions, with high base load and peak demand, posed greater stress on transformers and voltages. In contrast, summer conditions with lower base load created more space for EV charging and higher utilization of PV generation. These variations show that reliability planning must move away from static limits and instead adopt dynamic, seasonally adaptive strategies.

The integration of BESS demonstrated its critical role as a flexibility provider. By charging during midday PV surplus and discharging during evening peaks, BESS smoothed demand curves, reduced transformer stress, and maintained voltage within operational thresholds. Beyond energy balancing, strategically placed BESS at low voltage nodes improved local voltage stability and prevented violations, directly contributing to network resilience. This dual capability absorbing excess energy and providing peak support illustrates why storage is central to future distribution system.

Finally, the results highlight that optimized use of existing assets is achievable without reinforcement. Through coordination and flexibility, the network accommodated higher renewable penetration and new demand from EV without upgrading conductors or transformers. This not only ensures technical reliability but also represents a cost-effective approach for DSO. By relying on flexibility rather than reinforcement, DSO can align grid operation with broader European goals of decarbonization and sustainability.

In this study it has been also observed that there are notable differences in available capacity across nodes. Transformers at nodes 32, 54, 58, 184, and 269 are already close to their rated limit, therefore in future additional EV charging or load should be restricted unless upgrades are made. In contrast, Nodes 20, 23, 40, 45, 72, 76, 86, 90, 94, 100, 108, 111, 119, 122, 133, 152, 162, 231, 266, and 277 still have sufficient spare capacity and are suitable for future load growth or EV integration. Meanwhile, Nodes 203 and 283 show the highest voltage drops, which could threaten reliability if more EV load is added without corrective measures. DSOs should take these node specific constraints into account when planning network expansion or flexibility solutions.

4.2 Future Directions

- Coordinated Flexibility Between MV and BTM: Though in this study, EV has been considered as behind the meter resource, however future research should focus on integrating more resources from BTM coordinating their operation with MV network assets. This requires modelling and quantifying DER and flexible resources at the Low Voltage (LV) level, then coordinating their activation with MV network operations. Such an approach would unlock additional renewable generation, improve the accuracy of flexibility provision, and strengthen overall reliability and resilience. Pilot studies targeting specific nodes at both MV and LV levels could provide valuable insights into practical implementation.

- Advanced control algorithms for coordinated flexibility: New control strategies, such as hybrid control algorithms, could be developed to enable the combined activation of multiple flexibility resources. For instance, if an On-Load Tap Changer (OLTC) initiates an action, other resources such as BESS, DER, or Demand Response (DR) should be coordinated to enhance system performance. Testing these strategies under both normal and abnormal operating conditions would demonstrate how coordinated active and reactive power flexibility can increase hosting capacity and improve reliability.

- Vehicle to Grid (V2G) and Grid to Vehicle (G2V) integration: The bidirectional operation of EV through V2G and G2V mechanisms should be investigated to assess their impact on network performance. Such studies can reveal the potential flexibility these technologies provide, the operational challenges they introduce, and the flexibility needs that arise when adopting them. Exploring these technological advancements would help identify how EV can contribute more effectively to balancing, reliability, and resilience in distribution networks.

References

Bastida-Molina, Paula, Yago Rivera, César Berna-Escriche, David Blanco, and Lucas Álvarez-Piñeiro. 2024. 'Challenges and Opportunities in Electric Vehicle Charging: Harnessing Solar Photovoltaic Surpluses for Demand-Side Management'. *Machines* 12(2):144. doi:10.3390/machines12020144.

Bishla, Sandeep, and Anita Khosla. 2024. 'Review of Power Quality and Stability of EV Charging with Grid and PV Solar'. *Energy Technology* 12(2):2300744. doi:10.1002/ente.202300744.

Castro, Luis M. 2024. 'On BESS Allocation in AC/DC Networks Using a Sensitivities-Based Loss Model Combined With Injection Shift Factors'. *IEEE Access* 12:77523–35. doi:10.1109/ACCESS.2024.3407099.

Chen, Chao, Weifeng Peng, Cheng Xie, Shufeng Dong, and Yibo Hua. 2025. 'Photovoltaic Hosting Capacity Assessment of Distribution Networks Considering Source–Load Uncertainty'. *Energies* 18(8):2134. doi:10.3390/en18082134.

Esse, Elektrokraft. 2025. 'Esse Elektrokraft AB'. https://eekab.fi/.

Fatima, Samar, Verner Püvi, Matti Lehtonen, and Mahdi Pourakbari-Kasmaei. 2024. 'A Review of Electric Vehicle Hosting Capacity Quantification and Improvement Techniques for Distribution Networks'. *IET Generation, Transmission & Distribution* 18(6):1095–1113. doi:10.1049/gtd2.13010.

FME, ZEN. 2019. 'FME ZEN'. https://fmezen.no/.

Gurobi, optimizer. 2008. 'Gurobi Optimization'. https://www.gurobi.com/?_gl=1*1tleegz*_up*MQ..*_gs*MQ..&gclid=Cj0KCQjw58PGBhCkARIsADbDilyzyFs0ezwjGd5kDpX5t23CxRfTZGZLOtbXSd7L7AjPEgIrE70m8MwaAunxEALw_wcB.

Iqbal, Hasan, Alexander Stevenson, and Arif I. Sarwat. 2025. 'Impact Analysis and Optimal Placement of Distributed Energy Resources in Diverse Distribution Systems for Grid Congestion Mitigation and Performance Enhancement'. *Electronics* 14(10):1998. doi:10.3390/electronics14101998.

Kelepouris, Nikolaos S., Angelos I. Nousdilis, Aggelos S. Bouhouras, and Georgios C. Christoforidis. 2023. 'Optimal Scheduling of Prosumer's Battery Storage and Flexible Loads for Distribution

Network Support'. *IET Generation, Transmission & Distribution* 17(7):1491–1508. doi:10.1049/gtd2.12759.

Li, Xiangyu, Christine Yip, Zhao Yang Dong, Cuo Zhang, and Bo Wang. 2024. 'Hierarchical Control on EV Charging Stations with Ancillary Service Functions for PV Hosting Capacity Maximization in Unbalanced Distribution Networks'. *International Journal of Electrical Power & Energy Systems* 160:110097. doi:10.1016/j.ijepes.2024.110097.

Maask, Vahur, Hannes Agabus, Hans Tiismus, Victor Astapov, Roya AhmadiAhangar, Tarmo Korõtko, and Argo Rosin. 2025. 'Exploring the Landscape of End User Energy Flexibility: A Systematic Review of Technologies, Challenges, and Opportunities'. *IEEE Access* 13:146579–602. doi:10.1109/ACCESS.2025.3599989.

Pfenninger, Stefan, and Iain Staffell. 2016. 'Long-Term Patterns of European PV Output Using 30 Years of Validated Hourly Reanalysis and Satellite Data'. *Energy* 114:1251–65. doi:10.1016/j.energy.2016.08.060.

Smith, Edward J., Duane A. Robinson, and Sean Elphick. 2024. 'DER Control and Management Strategies for Distribution Networks: A Review of Current Practices and Future Directions'. *Energies* 17(11):2636. doi:10.3390/en17112636.

Umoh, Vincent, Innocent Davidson, Abayomi Adebiyi, and Unwana Ekpe. 2023. 'Methods and Tools for PV and EV Hosting Capacity Determination in Low Voltage Distribution Networks—A Review'. *Energies* 16(8):3609. doi:10.3390/en16083609.

Zenhom, Zenhom M., Shady H. E. Abdel Aleem, Ahmed F. Zobaa, and Tarek A. Boghdady. 2024. 'A Comprehensive Review of Renewables and Electric Vehicles Hosting Capacity in Active Distribution Networks'. *IEEE Access* 12:3672–99. doi:10.1109/ACCESS.2023.3349235.