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Optimizing Smart Grid Flexibility and Resilience with Demand Response, Renewable Integration and Energy Storage

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ABSTRACT:

Traditional power networks' reliability and adaptability are facing serious problems as a result of the growing use of renewable energy sources and the electrification of heating system. This thesis examines how integrating photovoltaic (PV) system, battery energy storage system (BESS) and demand response (DR) technique might improve the flexibility and resilience of smart grid. Two sample Finnish distribution networks, 02_Porkholm (rural) and 03_Centrum (semi urban), are the subject of this study which is carried out under the EU funded PEAK project in cooperation with the University of Vaasa and Esse Elektro-Kraft Ab. Using hourly smart meter data, a Python based modelling and simulation framework has been developed to determine hosting capacity, optimize PV and BESS installation and size and analyze the possibility of demand response technique. Analysis of hosting capacity showed that feeder length, voltage drop and load pattern, all had an impact on the significant regional variance in PV integration potential. Peak shaving and grid dependability were all significantly improved by BESS deployment particularly when it was placed strategically close to nodes that were high voltage sensitive and had high demand. To assess the flexibility potential of residential and commercial consumers, heating optimisation, heating level DR and appliance level DR modelling were carried out on the demand side. The results showed that load shifting algorithm, smart thermostat and TOU pricing signal might lower peak loads by as much as 20% especially during the winter heating season. Smart control solutions that match energy usage with PV generation and dynamic tariff were shown to be essential for attaining demand side flexibility in heating system. The research provides a thorough, data driven methodology for improving smart grid efficiency via flexible demand management and DER integration. The technique and insight are flexible and scalable. This provides distribution system operators with useful tools to accelerate the shift to low carbon, resilient and decentralised energy system.

KEYWORDS: Smart heating systems, Demand-side flexibility, Peak demand reduction, Renewable energy alignment, Energy efficiency, Battery energy storage system

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Abbreviations

AI	Artificial Intelligence
BESS	Battery Energy Storage System
DER	Distributed Energy Resource
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EEK	Esse Elektro-Kraft
GWh	Gigawatt-hour
HVAC	Heating, Ventilation, and Air Conditioning
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
HC	Hosting Capacity
IoT	Internet of Things
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour
LV	Low Voltage
MV	Medium Voltage
P2P	Peer-to-Peer
PEAK	Pathways to Energy Autonomy and Knowledge-based Flexibility
PV	Photovoltaic
RES	Renewable Energy Source
SLD	Single Line Diagram
SoC	State of Charge
TOU	Time-of-Use
V2G	Vehicle-to-Grid
WP1	Work Package 1

1 Introduction

The modern energy system has been in a state of rapid transition during the recent decade. These changes occur because of technological enhancements and the requirements for sustainability. One of the biggest issues that can be identified in the energy system is probably load management (Rathor & Saxena, 2020). According to Rathor & Saxena, load management involves simultaneously matching the supply of energy with the demand in the best optimised way, optimum cost analysis and the environment consideration. Thus, the primary purposes of an energy system are to achieve stability of the grid, minimize energy consumption costs and reduce the negative impact on the environment. Demand side management optimization addresses these challenges by employing sophisticated methods such as demand response, renewable energy integration, smart grids, energy storage systems and energy management systems (Rathor & Saxena, 2020).

1.1 Energy flexibility in smart grids

A transformation in the modern power system occurs significantly because renewable energy integration stands alongside technological progress and the imperative to mitigate climate change. The transformation depends on implementing smart grids based on energy flexibility. A power system shows energy flexibility when it adjusts its response to changing conditions between supply and demand for successful operation and stability maintenance (P. D. Lund et al., 2015). The ability to adjust grid operation plays a vital role in accepting intermittent nature of renewable energy flows that strengthens power network stability.

Renewable Energy Sources (RESs) including wind and solar power have become increasingly prevalent thus adding major fluctuations to power generation patterns (Chakraborty et al., 2022). Traditional power grids were built for anticipating stable centralized power generation yet the shift towards decentralized power generation requires adaptable power operation system. Power system flexibility enables RESs integration into grids because it helps the network control rapid electricity production and consumption. This adaptability is vital for maintaining system stability and avoiding blackout.

The National Renewable Energy Laboratory’s report shows how flexibility can improve power system performance at all operating levels beginning with system operations through markets to demand-side resources and storage system, generation unit and transmission network (Karim et al., 2022). The access to flexible solutions demands thorough planning which enables optimized investments and guarantees system reliability for both short term and long term period.

Distributed Energy Resource (DER) consist of different technologies which include distributed generation such as rooftop solar panels, energy storage systems, demand response programs and electric vehicles (Twaisan & Barışçı, 2022). These resources are typically smaller in scale and located closer to the point of the load consumption rather than huge centralized power plants. DERs establish a crucial role in improving energy flexibility because they create decentralized power generation and energy storage functions which decrease transmission network stress and enable flexible distribution of consumer demand (G. & Edward J., 2024). DER enhance reliability by providing backup power during power outages and implement decentralized power production to prevent widespread power disruptions. These power systems enhance operational efficiency because they reduce transmission losses and possibly save the infrastructure upgrades. DER utilize renewable energy sources which delivers important environmental advantages by cutting down greenhouse gas emissions.

Despite the benefits of DER adoption, there are major challenges with developing intelligent control systems which ensure electricity bi-directionality and maintain power grid balance (Obeidat, 2018). The Distributed Energy Resource Management Systems is crucial because they enable optimization of DER functions together with their smooth connection to the smart grid (Salinas et al., 2013).

Demand Side Management (DSM) refers to the strategies to control and reduce energy consumption on the consumer side. The goal of DSM programs is to provide customers with monetary incentives alongside pricing information and educational initiatives that encourage consumers to modify power consumption habits during peak demand (Häseler & Wulf, 2024). DSM helps improve grid resilience through shifting and lower customer demand. The DR programs motivate consumers to change or decrease their electricity needs during peak times in response to price signals or grid requirements. The Energy Efficiency program reduces total energy usage by adopting more energy efficient application, efficient lighting systems and advance building design.

Reducing peak demand can lead to major cost reductions because it reduces the need for new generation capacity. Demand side management enhances grid stability by balancing supply and demand, reducing the likelihood of grid disturbances and enhancing network reliability (Drude et al., 2014). Energy consumption adjustment enables a double benefit because it mitigates environmental impact by reducing greenhouse gas emissions and the environmental footprint of power generation. Smart grids need flexibility development to reach their sustainability goals along with energy resilience in the evolving power industry.

1.2 Role of PV, BESS and Demand response in Future Smart Grids

The transition to a sustainable and resilient energy system centre on the effective integration of Photovoltaics (PV), Battery Energy Storage Systems (BESS) and Demand Response (DR). All these components serve crucial purposes to boost grid stability by improving energy consumption while enabling renewable energy integration.

Photovoltaic (PV) technology enables the direct conversion of sunlight into electricity, providing decentralized electricity with various benefits. Energy security stands as a primary benefit from PV distributed systems because decentralized deployment reduces power dependency on centralized facilities thus preventing transmission failures and large scale outage (Maghami et al., 2024). Area based solar power systems function as independent electricity generators during disasters thus providing backup power to vital facilities and residential needs. The distribution of PV systems near points of electricity consumption leads to decreased transmission losses that enhances efficiency system operation. The economic benefits of PV technology allow consumers to save money through net metering systems which enable them to reintroduce surplus electricity into the power grid. It enhances community empowerment through localized generation and manages their renewable energy network independently. The environmental advantages of PV systems are substantial because they use clean, renewable solar energy to reduce greenhouse gas emissions (Breyer et al., 2015).

The integration of Battery Energy Storage Systems (BESS) brings great benefits to modern power systems which help regulate renewable energy sources. The primary benefit of BESS technology includes frequency regulation because it enables quick power absorption or injection which maintains power supply stability to support grid frequency needs (Akram et al., 2020). This rapid response capability becomes increasingly important as energy systems transition from traditional generation to renewables. BESS decreases power demands during peak hours through peak shaving, discharging stored energy and reduces the requirement for new generation infrastructure. The better integration in renewable energy systems stores excess power during peak production and subsequently releasing this stored energy during low generation periods which ensures a cleaner and more balanced energy supply. The vital role of BESS also includes delivering emergency backup power that boosts system dependability and resistance during power grid failures. The market acceptance of BESS shows significant growth because European battery storage is projected to reach 50 gigawatts by 2030 (European Commission. Joint Research Centre., 2024). BESS plays a central role in the future energy landscape because its costs continue to decrease while utilities require better methods to handle renewable energy intermittency.

Demand Response (DR) programs implement methods to control consumer power usage which simultaneously improve power grid reliability and economic efficiency

(Rahman et al., 2020a). Consumers benefit from load shifting programs which motivate them to change electrical consumption from peak usage times to off peak hours. This helps lower the peak demand level and eliminates the requirement for additional power generation capacity. DR programs provide energy cost savings because consumers can take advantage of lower electricity rates during off-peak periods and receive incentives for reducing energy consumption during peak demand. DR improves the operational flexibility of grids because it manages supply demand through shifting loads and without relying solely on generation side adjustments (Maghami et al., 2024). The combined use of energy storage and DR systems provides operating reserves which replaces the requirement of running thermal power plants for maintaining the instantaneous penetration of variable renewable energy sources (Rahman et al., 2020a).

DR supports environmental sustainability by decreasing peak demand while reducing dependence on fossil fuel based peak generation. This reduces greenhouse gas emissions. The combined deployment of PV systems, BESS and DR enables developmental progress in power grids that are both decentralized and economically efficient and stable. Collectively, these technologies combine to protect energy security and support environmental sustainability and economic advantages, thereby playing a critical role in the ongoing transformation of the global energy landscape.

1.3 Background and Company Details

The EU Just Transition Fund provides funding for the PEAK (Pathways to Energy Autonomy and Knowledge based Flexibility) project which is directed by the University of Vaasa in partnership with Esse Elektro-Kraft Ab. It aims to support Ostrobothnia and South Ostrobothnia's transformation into resilient, sustainable and decentralised energy system. This thesis is under the PEAK project's work package 1 (WP1). Mapping the potential for renewable energy and assessing the adaptability of the local electrical grid are the main objectives of WP1. It is designed for identifying feasible and sustainable energy development possibility especially for areas that depend on regional energy network and system.

The project's geographic scope has been carefully determined to encompass the western Finnish municipalities of Kauhava in South Ostrobothnia and Pedersöre in the Ostrobothnia region (Pinilla De La Cruz, 2024). Esse Elektro-Kraft is the local energy supplier. The selected location is based on its distribution footprint and the particular these areas have the largest concentration of its customers (Esse Elektro-Kraft Ab, 2025). These two municipalities are located under Esse Elektro-Kraft service which makes them perfect for examining the functioning of the distribution network, patterns of energy use and the possibility of incorporating flexibility solution. This geographical delimitation not only facilitates access to detailed consumption data, smart meter reading and network topology from a single distribution system operator but also ensures that subsequent modeling, simulation and planning efforts are contextually accurate and practically applicable. The designated region provides a useful variation in energy consumption pattern, infrastructure feature and renewable energy potential since it combines semiurban and rural region. The project deliverables are guaranteed to be not only technically sound but also locally relevant and in line with regional energy objectives since focussing efforts within this specified limit enables meaningful engagement with local stakeholder, municipality and energy users. The chosen region serves as the basis for the planning and analysis task completed during the PEAK project. The project's results have more credibility, reproducibility and effect because of its planned and intentional regional emphasis.

Finnish energy company Esse Elektro-Kraft (EEK) is a privately owned company that has a significant local presence and is dedicated to sustainable power distribution and renewable energy (Esse Elektro-Kraft Ab, 2025). With a small staff of 13 workers and an annual revenue of around 8 to 9 million euros, EEK is owned by about 350 stockholders. Approximately 3,800 connected consumers receive energy via the company's 1,055-kilometer distribution network. The operating voltage levels are 20 kV and 0.4 kV. Figure 1 shows the whole network's single line diagram. About 52 GWh of power is distributed there annually and 38 GWh are sold to customers. Three minor hydroelectric power stations with a total capacity of 3.7 MW (Hanhikoski, Hattar, and Värnå) are part of EEK's energy production portfolio. With a 1.6 MW solar photovoltaic park and co-owned production assets, EEK has expanded into solar energy in addition to its hydropower assets, increasing its annual production capacity to around 53 GWh. A 1 MW energy storage facility is presently being built as part of the company's aggressive expansion of its renewable infrastructure.

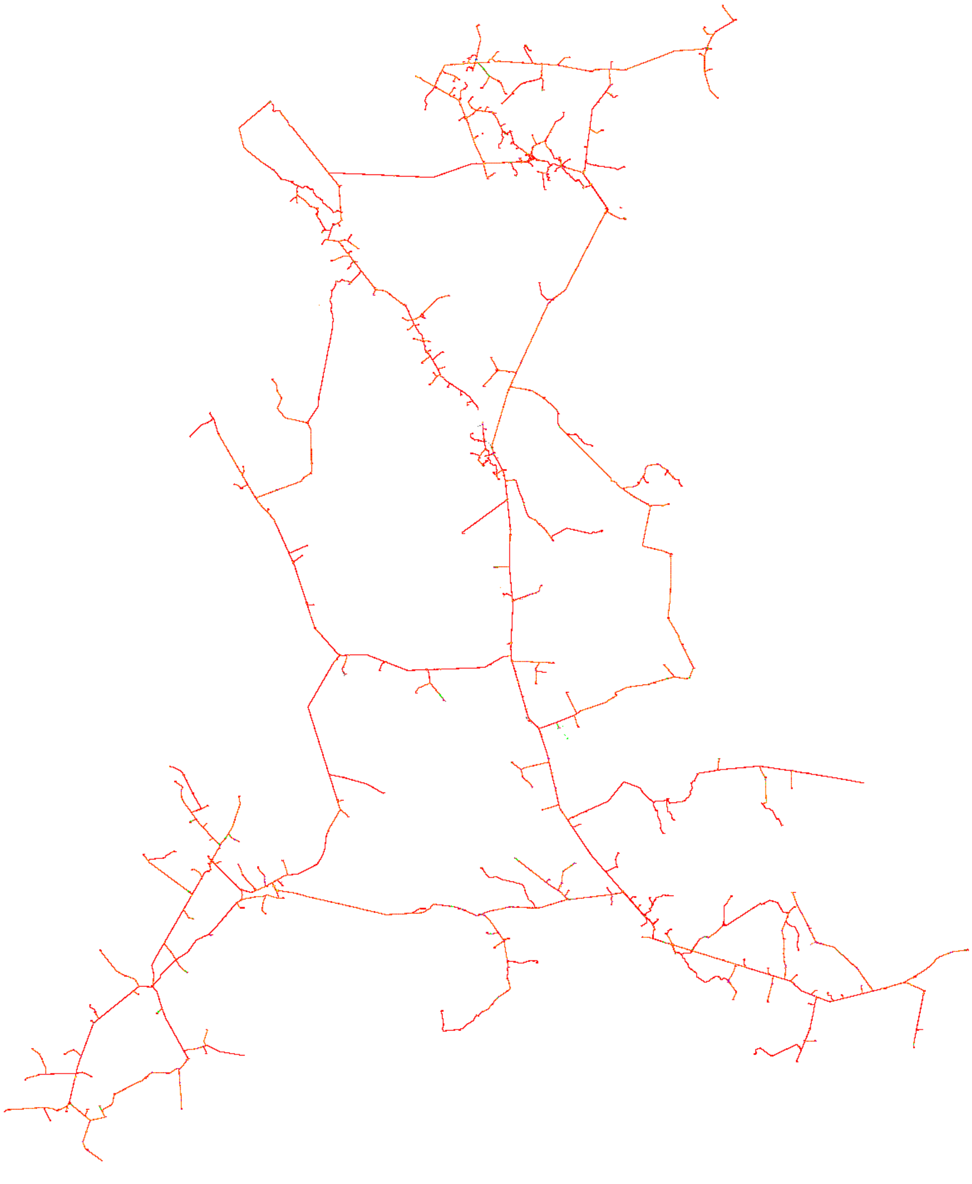


Figure 1. Single line diagram (SLD) of distribution network (Esse Elektro-Kraft Ab, 2025)

Modern power sector issues including managing peak demand, integrating renewable energy source (RES) into its distribution network and enhancing grid flexibility are being addressed by EEK. EEK emphasises the significance of sustainability, affordability and security in its operation with sector coupling, load shifting and user flexibility market. EEK is poised to meet the rising energy demand from electrification and contribute to a low carbon energy future by improving RES predictability, grid investment and optimal matching of generation with energy consumption.

1.4 Scope of thesis

This thesis evaluates energy flexibility within smart grids through PV systems and BESS and DR strategies integrated into the same framework. The study focuses on a large distribution network for optimizing PV and BESS placement and operation of household appliances and heating system for demand-side management strategies. The research has two fundamental objectives.

1. Identification of suitable PV and BESS locations and their capacities in a large distribution network:

The rise of renewable energy systems demands strategic placement of PV systems and BESS to manage grid stability and decrease energy losses while optimizing power consumption. This thesis aims to address these challenges by conducting a comprehensive analysis of a large-scale distribution network. Through the research process the study will determine the most suitable sites for PV deployment without overloading transformers or causing voltage instability. This research will establish suitable PV capacity by studying energy demand and grid operational limits. This thesis will identify suitable BESS location by considering network requirements, voltage variation and peak demand. An optimized charge discharge strategy for BESS will also be developed to optimize energy efficiency and stabilize the grid at peak and off-peak periods.

2. Development of a Demand Response Strategy for different consumer groups and an optimized Heating System:

Demand response (DR) functions as an essential tool for reducing peak demand, improving energy consumption and optimizing grid flexibility. This research examines DR strategies through energy consumption patterns for different consumer groups to improve efficiency and cost-effectiveness. The heating systems account for the majority of energy consumption throughout regions because temperatures become extreme during winter months. Enhancing heating operation provides energy efficiency and decreases expenses while improving demand side flexibility. Also, this thesis will focus on developing strategies to achieve these goals through data driven analysis and control optimization. This study will start with modeling the load profiles of common appliances by developing their usage patterns to assess their flexibility potential. The analysis results will guide the development of a DR control algorithm that moves unimportant appliance usage from peak time periods to off-peak hours to decrease grid strain and decrease consumer energy costs. Additionally, studying the relationship between heating loads and seasonal temperatures along with household vacancies to discover crucial demand factor. A response strategy for heating systems will be developed that modifies power usage according to electricity prices, external temperature condition and use pattern.

The evaluation process will consist of running statistical simulations assessing their impact on overall energy consumption patterns, peak load reduction efficiency and cost saving. Additionally, this research will measure how efficient optimized heating operations perform when compared to standard operational patterns. This study aims to contribute to developing intelligent DR solutions and optimized heating operations for power system efficiency and grid resilience. This thesis aims to provide a comprehensive framework for improving smart grid flexibility through optimized PV and BESS integration and demand response implementation along with heating system optimization. This study will develop methods for improving distribution networks' flexibility and reliability as well as support for sustainable energy transformation by using a Python based modeling and simulation framework.

1.5 Structure of the report

In order to provide a thorough knowledge of how photovoltaic (PV) systems, battery energy storage systems (BESS) and demand response (DR) technique may be integrated to improve smart grid flexibility and resilience, this thesis is structured into five chapters. The research background, the study's motivation and important topics like energy flexibility, smart grid and the functions of PV, BESS and DR in future energy system are all covered in chapter 1. It also specifies the objectives and parameters of the study.

The grid structure and limitation of Finnish distribution network, the technical difficulties and integration techniques for solar PV, the operational advantages of BESS, the concepts of demand response and energy management and the role of heating system in achieving demand side flexibility are all covered in detail in chapter 2. This chapter also provides a comprehensive literature review. This review identifies current research difficulties that the thesis addresses. The study's methodology is described in chapter 3. It explains how the particular networks were chosen, how the data was gathered and how the Python based modelling framework was used for DR simulation, BESS optimisation, HC analysis and heating load control. Every modelling stage is in line with the research's aims to guarantee a data driven and reliable analysis.

Chapter 4 presents the findings for PV integration, demand response, heating system optimisation and BESS optimisation. Each network's hosting capacity is extensively examined. The optimal nodes for PV deployment are determined. BESS optimization investigates the technical and economical implication of battery location. The simulation result presents several load circumstances for BESS installation. Demand response tactics focus on technological management and pricing system This suggests the option of transferring load and heating for both business and residential consumers. Heating system optimization analyzes seasonal trends in heating demand. It also finds the possibility for smart heating regulation to decrease peak load and improve grid flexibility.

Chapter 5 summarizes the key findings and provides recommendation for utility, lawmaker and future smart grid designer. It also concludes by outlining future research direction focusing on emphasizing technological advancement, regulatory issues, the function of advance technology such decentralized energy market and vehicle to grid connectivity.

2 Literature Review

2.1 Overview of Distribution Networks and Grid Constraints

Electricity distribution networks are the backbone of power delivery from generation to consumers. The electricity distribution networks in Finland operate through two separate systems which include low-voltage (LV) and medium voltage (MV) networks. Power distribution grids face significant challenges because of voltage fluctuations, power losses and transformer loading problems.

2.1.1 Structure of Low and Medium Voltage Distribution Networks in Finland

Finland's electricity distribution system is structured into various voltage stages to power supply across the grid efficiently. The power grid of Finland includes four main sections which are transmission networks with 400 kV and 220 kV lines and distribution networks with 110 kV and medium voltage with 10 to 20 kV networks and low voltage (LV) with 400 V networks (BELLERA, 2018).

Medium voltage (MV) networks (10 to20 kV) link high-voltage transmission lines to low-voltage consumers. The distribution networks utilize overhead power lines as well as underground cables while transformers stepping down voltage levels for final distribution (Chaves et al., 2021). Residential buildings, industrial consumers and commercial consumers receive their power through LV (400 V) and MV (10-20 kV) network. These networks operate through a three-phase four-wire system for ensuring voltage stability and reliable power supply (Dovgun et al., 2020). Finland has highly decentralized power distribution system through its 77 local distribution system operators (DSOs) who manage the distribution network operation (Oksanen, 2011). The network design prioritizes reliability; therefore, Finland invests significant in underground cabling form to minimize weather-related disturbances. The decentralized framework and modern infrastructure increase power grid reliability and ensures a stable electricity supply nationwide.

2.1.2 Key Grid Constraints in Finnish Distribution Networks

1. Voltage Fluctuations: The robust electricity distribution network of Finland has many operational limitations that affect reliability, stability and efficiency. The main operational challenge is the voltage fluctuations which arise from variations in load demand and distributed power generation from renewable energy sources (Holmgren et al., 2009). The Finnish LV network encounters voltage variations mainly from uneven load distribution among phases. Additionally, the integration of solar PV systems create voltage rise during peak generation times as well as fluctuations in electricity consumption patterns primarily in residential areas. Research shows that rural Finnish medium-voltage networks experience voltage changes from 5% to 10% beyond nominal value at times when demand reaches its peak (Repo et al., 2004).

Distributed energy resources (DERs) such as wind and solar power continue to grow in number and this has made voltage regulation more difficult to manage. The management of voltage issues has focused on implementing advanced solutions like on load tap changers (OLTC) and reactive power compensation according to Sarimuthu et al. (2016). These strategies aim to enhance voltage stability and ensure the seamless integration of renewable energy into Finnish electric power grids.

2. Power Losses in Distribution Networks: The distribution network of Finland faces several operational limitations which negatively influence operational efficiency, reliability and stability (Holmgren et al., 2009). Power losses in distribution networks are categorized into technical losses and non-technical losses. Technical losses arise from resistance in conductors and transformer inefficiencies. Non-technical losses are created from measurement errors, electricity theft and data inaccuracy.

Total power losses in Finland’s LV and MV networks fall within a range of 3.5% to 6.2% as reported by Haapaniemi (2022). Several factors influence these losses like longer overhead MV lines in rural areas have higher losses due to greater impedance. The level of transmission losses depends on load density rates; urban areas have lower losses due to higher electricity consumption per unit area compared to rural area. The implementation of underground power cables results in a reduction of technical losses by 25% compared to overhead lines due to less cable resistance and good insulation capabilities (Argaut, 2021).

Finland reduces distribution losses through its power distribution automation systems and balanced phases with demand-side management approaches. Smart measurement technologies with real time monitoring systems have accomplished a 30% decrease in non technical losses (Jafari et al., 2023). This improvement helps make the grid more efficient and reliable.

3. Transformer Loading and Overloading Issues: Distribution networks rely heavily on transformers for stepping down voltages for end users. In Finland, the loading capacity of distribution transformers ranges from 50 kVA to 1 MVA and it depends according to consumer density (BELLERA, 2018). However, challenges related to overloaded conditions and underutilization impact their efficiency and operational life. The winter season in Finland results in extreme residential heating requirements that cause transformers to operate beyond 85% of their maximum capacity (Nortamo, 2023). The transformer utilization decreases significantly during summer because power consumption levels remain below capacity. The peak load changes in rural MV networks reach up to 120% which reducing operational lifespan and raises the possibility of overheating (Rafati et al., 2024). Finnish distribution system operators (DSOs) use advanced technologies to improve transformer reliability and efficiency against specific challenges. Dynamic transformer rating (DTR) systems handle real time performance adjustments according to load demand and ambient temperature dynamics (Lai & Teh, 2022). The integration of hybrid transformers with energy storage systems develops potential solutions to strengthen load balancing and system efficiency. These strategies maintain vital importance to reduce network limitations and maintain electrical stability throughout various network conditions.

2.1.3 Mitigation Strategies

Finland has implemented various mitigation techniques to strengthen power grid reliability and minimize transmission losses and enhance transformer efficiency. Manual voltage regulators known as automatic voltage regulators actively regulate electrical voltage to achieve network stability (Haapaniemi, 2022). The implementation of reactive power compensation devices improves power factor correction and reducing voltage deviations in smart grid. Smart inverters function as stability systems to regulate voltage fluctuations by incorporate substantial solar PV resources in distribution system and it also helps for smooth management of decentralized power generation.

High tech underground power cabling has become widespread in Finland and reduce 40% lower power losses in urban areas (Tuikka, 2024). Real time monitoring systems with predictive analytics enable grid operators to detect inefficiencies and proactively address potential issues for improving power flows. Advanced load forecasting algorithms enable grid operators to track demand changes and this technology helps prevent transformer overload conditions (Ramesh et al., 2022). Battery Energy Storage Systems (BESS) play a fundamental part in peak shaving applications which benefit areas that incorporate many distributed energy resources (Maghami et al., 2024). BESS operates during low demand times by storing electricity which gets released during peak times. Therefore, BESS enhances grid flexibility and reduces transformer stress. Finland can achieve better electricity distribution system resilience through combined strategic implementation which also improves efficiency and adaptability.

2.2 Solar PV Integration in Distribution Networks

Solar photovoltaic (PV) systems integrated into distribution networks presents a unique set of advantages and technical issues. The Nordic nations (Denmark, Finland, Norway and Sweden) do not have the same ample solar resources and experience seasonal variations that significantly affect PV energy generation throughout the year (Narayana, 2023). The rising adoption of distributed solar PV faces operational obstacles from choosing suitable locations, capacity determination, power quality and grid stability. This section explores the possibilities and challenges for PV implementation in distribution systems and their effects on both power stability and quality.

2.2.1 Challenges in PV Placement and Capacity Determination

The successful placement of solar PV systems combined with determination of hosting capacity leads to optimal energy output without compromising grid reliability standards. The Nordic region's PV deployment suitability depends significantly on three main factors which include weather patterns and electricity grid limitations and regulatory policies (Narayana, 2023). The main barrier for PV implementation is geographic conditions and extreme climate variations. Summer days in the Nordic region are lengthy while winter days are short which affect PV generation predictability (Klyve et al., 2023). The generation efficiency of PV panels can reduce between 30-50% when snow covers them for 20-40% of wintertime in northern regions (Narayana, 2023). The variables in PV output require adaptive energy storage systems and grid management strategies because cloud effects and diffuse radiation further contribute to fluctuations in generation (Klyve et al., 2023).

Another major challenge is determining the grid’s hosting capacity of solar PV. Distribution grid hosting capacity indicates the highest level of PV penetration that a power system can handle through operational constraints (Khajeh et al., 2025). Research shows that Swedish and Danish regions currently handle between 10% to 15% PV penetration which creates problems of overvoltage and reversed power flow in their electricity grids (Narayana, 2023). Long distribution lines in rural distribution network are at higher risk of voltage instability when PV penetration exceeds 5–10% of peak load in Finland (Haapaniemi, 2022). Advanced hosting capacity assessment method such as probabilistic load flow analysis uses to optimize PV integration without minimizing the need for costly grid upgradation (Mousa et al., 2024).

The implementation of PV systems faces various technical problems regarding their proper placement and appropriate sizing systems. Severe voltage fluctuations and reverse power flows occur in weak grid areas with long radial feeders which need dynamic voltage regulation solutions (Ibrahim & Hossain, 2021). Electric power systems contain large PV installation without storage mechanisms produce voltage spikes during peak times which reduce overall grid efficiency. Research in Finland and Sweden show that urban power distribution systems exhibit better PV hosting capacity than rural networks because they feature superior voltage control functionality and shorter power feeder lengths (Khajeh et al., 2025).

The placement of PV systems faces barriers because of regulatory controls. The Nordic grid codes enforce strict voltage and frequency stability standards on distributed generation (DG), thus creating additional challenges for PV installation compliance (Narayana, 2023). Different feed-in tariff schemes and net metering rules between Nordic countries determine how profitable PV system investments can be. Some utilities also resist high PV penetration due to concerns over grid reliability and loss of revenue from conventional electricity tradeoff.

2.2.2 Impact of PV on Power Quality and Stability

The implementation of solar PV systems in power distribution systems creates multiple impacts on the quality of supplied power and network stability. The deployment of solar PV systems in distribution networks causes four main technical issues: voltage fluctuations, harmonics, frequency variations and system stability risks (Rahman et al., 2020b). The stability of voltage ranks as the foremost important issue. Solar PV operations generate sporadic power that causes frequent voltage fluctuations particularly in low-inertia networks with weak grid connections. The integration of PV exceeds 10% of peak demand creates voltage variations beyond ±5% that violate European grid codes (Visser et al., 2022). On-load tap changers, dynamic voltage regulation and reactive power compensation operate as solutions to fluctuating conditions in PV dense regions (Korpikiewicz & Mohamed-Seghir, 2022).

PV inverters create several difficulties for power quality and harmonic distortion in distribution network. The introduction of harmonics by solar inverters leads to reduced performance of the entire power grid. Studies show that PV system installations cause harmonic voltage departures exceeding 2% to 3% in week grid systems that exceed accepted standards (Ahsan et al., 2021). Grid operators use smart inverter technology and active harmonic filtering to reduce these negative effects. High PV penetration creates additional challenges for both reverse power flow management and frequency stability. The occurrence of surplus solar generation during daylight hours leads to backward power flows which disrupt conventional power grid networks. The Norwegian power grid has shown that increased PV integration leads to over-frequency occurrences which requires fast-response demand-side management and batteries for stabilizing electricity systems (Bana, 2024). Nordic utility companies conduct tests on grid-forming inverters because these devices supply synthetic inertia and boost frequency stability within networks that rely heavily on photovoltaics.

The uncontrolled consumption of reactive power creates another vital operational challenge. The Nordic power distribution network did not have built-in capabilities to handle large PV power generation leading to voltage instability and reactive power mismatches. Research conducted in Finland shows that 25% of rural feeder lines face reactive power issues because of PV generation especially when networks have radial structures (Haapaniemi, 2022). The installation of static synchronous compensators and local energy storage system serves as a countermeasure of these problem.

2.2.3 Mitigation Strategy

Several strategic measures have been established to allow smooth integration of solar PV into distribution networks. Dynamic voltage control systems and reactive power compensation work as effective methods. Smart inverters that provide dynamic reactive power support are being introduced, alongside voltage regulators and OLTCs to smooth out fluctuations in PV integrated networks (Varma, 2021).

Battery energy storage systems absorb excess PV generation during low demand periods then release it during peak time. The testing of hybrid energy storage systems that contain lithium-ion and flow batteries takes place in Sweden and Finland for enhancing power grid stability (Väliahde, 2024). New methods of estimating hosting capacity are being developed to maximize the integration of PV systems. Utilities implement machine learning based forecasting models which anticipate how PV power generation affects the power system grid (Mousa et al., 2024). The implementation of probabilistic load flow analysis serves to identify proper PV placement spots which avoid grid overloading. The increased use of demand side management (DSM) and flexible loads are critical solutions to handle PV integration problem (Drude et al., 2014). Smart appliances and dynamic pricing systems are being introduced to load shifting according to PV availability. Electric Vehicle (EV) charging stations serve as flexible loads to take in additional solar energy. It works as a virtual battery energy storage system.

2.3 Role of Battery Energy Storage Systems (BESS) in Grid Stability

The power grid now depends on Battery Energy Storage Systems (BESS), because it helps power grid to resolve stability issues, regulate frequency and meet peak demand requirements. With the growing penetration of intermittent renewable power sources like wind and solar energy, the need for flexible energy storage solutions has intensified. BESS provide rapid frequency control capabilities and peak reduction functions which strengthen power grid stability through their ability to compensate for supply and demand variations (Shafiei et al., 2024). This section examines BESS grid solutions through frequency control and peak demand reduction while presenting optimization techniques for their placement and capacity selection to achieve the best possible results for both operational effectiveness and economic viability.

2.3.1 Frequency Regulation and Peak Shaving

Power grid stability requires continuous frequency regulation. The Nordic electricity grids function at 50 Hz nominal frequency but any frequency deviations cause power imbalances as well as equipment failures that might result in blackouts (Modig et al., 2022). Renewable energy penetration growth has led to BESS becoming a superior alternative over the traditional frequency control systems which relied on hydropower plants and fossil fuel-based generators (Shafiei et al., 2024). The battery energy storage system functions as a primary, secondary and tertiary frequency regulator through rapid energy charging and discharging operations during grid frequency fluctuations. Studies conducted in Sweden and Finland indicate that BESS can stabilize frequency deviations within milliseconds which outperform conventional power plants in response time (Hollinger et al., 2018). A 1 MW BESS installed in the Åland Islands project in Finland which demonstrated the capability to fulfill 90% of primary frequency regulation requirements while decreasing reliance on imported electricity (Kumar et al., 2020).

The Nordic power system benefits from BESS because it enables participation in Frequency Containment Reserve (FCR) and Frequency Restoration Reserve (FRR) markets (Laine-Ylijoki, 2024). Storage systems that participate in these markets earn revenue and provide additional benefits for stabilizing the power grid. Peak shaving techniques decrease electrical power consumption during times of high demand. The Nordic region experiences its highest electricity use during cold winter months because people raise their heating consumption. The BESS technology stores power during occasions of low consumption while supplying it throughout periods when usage reaches its highest level (Samiayya et al., 2023). In Norway, a study on industrial peak shaving demonstrated that a 2 MWh lithium-ion BESS could reduce peak demand charges by 25–30% which leads to significant cost savings for industrial consumers (Schumann, 2023). The integration of BESS to Swedish commercial buildings achieved peak demand reductions of 40% and it minimized the need for fossil fuel based peaking stations (Sköld, 2023).

The economic feasibility of peak shaving implementation depends on the existing energy pricing structures and demand charges. Peak shaving implementation stands or falls on both the existing energy charge rates and demand related fees. Finland has implemented dynamic electricity pricing which BESS utilizes to enhance energy consumption efficiency and decrease electricity expenditures (Väliahde, 2024). BESS systems combine with solar PV systems in commercial buildings generate 50% higher levels of self consumed solar power thus delivering better financial benefits for peak shaving (Sköld, 2023).

2.3.2 Methods for Optimal BESS Placement and Sizing

1. Optimal Placement of BESS in Distribution Networks:

Power grid operators need to determine optimal BESS locations because this ensures maximum system performance and effectiveness. The placement of BESS in distribution networks depends on grid congestion, renewable energy penetration and demand distribution pattern (Shafiei et al., 2024). Several analytical approaches can be used to optimize the placement and operation of BESS for ensuring grid stability, cost effectiveness and efficient energy management. The assessment of grid constraints through load flow analysis lets operators to determine specific locations suitable for implementing BESS to prevent load congestion and stabilize voltage. The power flow simulation under diverse conditions helps utilities to choose optimal BESS locations and maximize network efficiency. The economic dispatch model enhances these processes by performing a profit loss evaluation which considers both electricity prices and market participation opportunities. BESS operates most profitably when installed at locations with extreme price variations and grid imbalances which allows operators to maximize financial returns while improving energy reliability.

Artificial intelligence (AI) driven algorithms developed in Finland to anticipate peak demand locations which enables utility companies to place BESS systems with maximum effectiveness (Ahmed, 2025). These machine learning based models use historical consumption record, weather condition and grid dynamic to enhance decision making. Strategic BESS placement proves its effectiveness through various studies of actual power grids. Sweden achieved a 15% improvement in system efficiency when it positioned BESS units within load centers and renewable energy hubs (Hollinger et al., 2018). A 10 MW BESS system positioned in a Norwegian wind facility increased power stability and minimized wind-generated power disruption by 25% (Bendel & Ahrens, 2024). These examples prove that combining sophisticated analytical techniques and data analysis approaches significantly improve the effectiveness of BESS in modern power systems.

2. Sizing Strategies for BESS :

Multiple analytical methods help determine the perfect battery capacity to maximize economic and technical benefits. Energy arbitrage model prediction help operators to determine optimal battery storage capacities by charging the battery when prices are low and discharging when prices are high. The optimization process becomes more precise through stochastic optimization methods because it handles unpredictable renewable energy patterns and ensure that BESS is neither underutilized nor over-capacitated. Multi-objective optimization considers both economic profitability and technical performance. It also considers balancing factors such as investment costs, operational efficiency and grid support (Laine-Ylijoki, 2024).

Real world implementations show effective battery capacity estimation and overall success. A 500 kWh medium scale BESS deployed in a Norwegian commercial facility improved grid stability and decreased annual power expenses by 18% (Bendel & Ahrens, 2024). The precise battery sizing of a 1.2 MWh BESS which was added to a district heating system in Finland which led to a 20% increase in energy efficiency(KOSKELA, 2024). These findings emphasize the need for data-driven approaches in designing BESS solutions which meet economic requirements and fulfill technical specifications.

3. Hybrid BESS Integration with Renewable Energy Systems:

Research has demonstrated that BESS combined with renewable power systems including solar PV and wind becomes a powerful solution in distributed energy networks. The combination of BESS with a 10 MW solar farm in Sweden incresed local energy independence to 35% which reduced energy grid reliance and improved local energy resilience (Sköld, 2023). Placing BESS units adjacent to wind and PV farms improves renewable energy operation flexibility and minimizing the necessity of fossil fuel backup systems. According to (Hvelplund et al. (2017), the combination of BESS and wind power in Denmark, improved wind energy utilization by 22% and ensured more stable electricity supply even during low wind condition.

BESS has become essential for improving grid stability and frequency control while mitigating peak load condition. By responding rapidly to frequency deviations and managing peak load, BESS helps balance intermittent renewable generation and reduce electricity cost. The effectiveness of BESS depends heavily on finding its best installation location and proper sizing because these factors determine its maximum potential benefits through advanced load flow analysis solution, AI based optimization algorithm and hybrid integration model. BESS plays an essential role in achieving sustainable energy, enhanced economic performance and improved energy reliability.

2.4 The Role of Demand Response and Energy Management Systems

The increasing electrical power requires improved controlled power supply and optimized consumption. The demand response (DR) programs become a solution which directs consumers to modify their electricity consumption patterns during price fluctuations, peak load situations and demand side flexibility incentives. Demand response functions as a crucial energy management tool throughout Nordic nations because these markets present both high deregulation and significant renewable energy integration. Demand response contains three essential elements, demand side flexibility and peak load shifting and strategies for residential participation

2.4.1 Demand Side Flexibility and Peak Load Shifting

Demand side flexibility refers to the ability of end users to modify their power usage according to price indications and utility requirements or incentives. In Nordic countries, demand side flexibility is essential for integrating renewable energy sources like wind and PV which have variable generation pattern (Söder et al., 2018). Residential consumers play a substantial role in demand side flexibility through shifting their electricity use during peak hours to minimize peak load on the grid.

Among all demand response (DR) strategies peak load shifting remains the most popular method. The process of distributing electrical consumption from high demand periods during morning and evening hours to less demand period (noon or late night). The residential demand response programs in Finland prove successful at decreasing peak electricity demand by 10% to 15% during wintertime (Ju et al., 2021). Cold climate conditions require special attention because electric heating systems contribute to peak power consumption. Consumers shift their energy usage due to dynamic tariffs and time of use pricing schedules which help lower electricity cost and increase grid efficiency.

Real time pricing (RTP) functions as the key element which enables successful execution of demand response programs. The RTP pricing method reflects electricity prices at intervals from one hour up to fractions of an hour which enables consumers to change their energy usage based on price fluctuations (Nezamoddini & Wang, 2017). According to Schmidmayer (2015), households that participate to RTP and DR plans in Sweden managed to cut their electricity expenses by 8% to 12% relative to customers maintained on fixed-tariff agreements. However, challenges like consumer engagement and effective automation of DR remain key factors in determining the success of RTP based demand response programs.

2.4.2 Strategies for Demand Response Participation

For successful demand response programs, it is necessary to use financial rewards, advanced automated systems and user’s behavioral interventions. The Nordic nations use different techniques to improve customer participation in demand side management activity.

1. Time Based Pricing Mechanisms: Nordic countries implement various time-based pricing models to encourage end users to participate in DR and optimize their electricity consumption patterns. The Danish time of use (TOU) pricing scheme motivates customers to move energy usage from peak times (16:00 to 20:00) to off-peak periods. User’s engaged in TOU price programs achieve an average 10% to 15% decrease in their yearly electricity expenses (Zhao et al., 2017). Critical Peak Pricing (CPP) represents an effective pricing model in Norway specifically because it uses higher electricity prices during extreme peak demand (Park et al., 2015). The implementation of CPP programs leads enrolled consumers to lower their peak-time electricity usage by 20% which reduces load on the power grid during critical demand situations (Li et al., 2018).

Real Time Pricing (RTP) is becoming increasingly popular in Sweden and Finland because of the widespread deployment of smart meters which enhanced its effectiveness (Jonsson & Målsten, 2023). The RTP system gives users immediate access to electricity data which lets them modify their usage according to fluctuating market prices. Time-based pricing structures as a whole improve the efficiency and flexibility of power systems and support grid capacity while enabling greater renewable energy penetration. These time based pricing models collectively contribute to a more flexible and efficient power system which reduces grid congestion and enables higher renewable energy penetration.

2. Smart Home Appliances Technologies and Automated HVAC System: The widespread implementation of smart home appliances technology and efficient Heating, ventilation and air conditioning (HVAC) system functions as the essential mechanism to handle demand response system activation. Smart thermostats in combination with automated lighting systems and smart appliances allow customers to move their power consumption automatically without manual intervention (Ayan & Turkay, 2018). Smart thermostats installed in Finnish households decrease heat energy usage by 15 to 20% through temperature adjustments controlled by real time electricity price (Ivanova, 2024).

Home energy management systems (HEMS) boost demand response participation through their ability to unite several smart devices into a centralized control system (Rahman et al., 2020a). HEMS pilot projects in Sweden demonstrated a 25% decline in peak electrical usage by program participants according to Adeli & Hedman (2020). Consumers can use these systems to develop preset energy use schedules according to price. The combination of smart home technologies with automated HVAC systems revitalizes energy efficiency in residential and industrial areas across Nordic nations where extreme climate conditions demand optimal heating and cooling solutions. The combination of Internet of Things (IoT) connections, AI driven analytical and machine learning enables modern HVAC systems to automatically change indoor temperature settings based on actual weather input and occupancy statistics and energy consumption data which achieves substantial energy savings (Shah et al., 2022). Finland has adopted smart ventilation systems integrated with geothermal heat pumps which improves indoor air quality and enhances energy saving (Mäkelä, 2020). This shift towards smart and energy efficient energy management not only contributes to lower carbon emissions but also aligns with Nordic sustainability policies and carbon neutrality goals for 2035 (Pedersen et al., 2020).

3. Demand Aggregation and Community Based Programs: Several end users unite their electricity usage flexibility in aggregated pools which results in increased stability benefits for the power grid. Third-party companies and utilities known as aggregators, operate as intermediaries to manage flexible demand resources which take part in electricity markets and ancillary service programs (Rahman et al., 2020a). Denmark's demand aggregation pilot studies proved that residential consumer groups can supply a flexible 5 MW of load capacity during peak usage hour (Andersen et al., 2017). People from different neighborhoods are now working together to handle their power usage through community-based demand response programs. The Norwegian research demonstrates that when residents link through community microgrids, they both improve their energy engagement and improve their demand response participation up to 30% (Alvial-Palavicino et al., 2011).

4. Incentive Based Demand Response Programs: The compensation of consumers through incentive-based programs during peak consumption times both stabilizes grid demand and provides payment incentives to them. Through Direct Load Control (DLC) across Finland and Sweden offer monetary benefits to citizens who authorize distant control of heating devices, water heaters and electric vehicle chargers during the periods of high demand (Tikka, 2024). These programs provide a method to adjust power usage in short term and stabilize power systems without needing any new generation resources. The Capacity Subscription Programs concept is developing as a new strategy through ongoing trials in some Nordic countries. Under this model, consumers select a maximum power capacity for their household or industry and receive lower electricity prices if they stay within the designated limit. The model promotes electricity savings by enhanced behavioral performance while letting customers manage their utility expenses. The combination of DLC models with capacity subscription plays a crucial role in enhancing demand-side flexibility, peak load reduction and grid efficiency.

5. Behavioral Interventions and Consumer Engagement: Consumer awareness and engagement are the most critical for demand response success. Research indicates that providing real time consumption data through mobile applications and in-end user displays can reduce power consumption between 5% and 10% (Khan et al., 2024). Educational campaign and gamification strategy where consumers earn rewards for reducing peak time energy consumption have been effective in encouraging sustained participation in DR programs.

2.4.3 Challenges and Future Directions

Many obstacles continue to challenge the progress of DR initiatives across Nordic nations. Consumer awareness and trust is a major obstacle because many people do not understand the benefits of DR programs and have privacy and control concerns about their participation. On the other hand, integrating flexible demand side resources with renewable power sources presents a challenge while demand response helps balance the variability of renewable energy sources. Advanced forecasting and grid management technology must be implemented to achieve a reliable and efficient system. Diverse electricity market regulations in Nordic countries complicate the standardization of implementation of DR program.

Nordic countries work toward overcoming these obstacles by developing future-oriented DR solutions. AI powered energy management technology optimizes consumption patterns independently which offers users enhanced convenience along with improved efficiency. Electric vehicles under Vehicle to Grid (V2G) integration can act as adjustable energy sources to supply the grid during peak time. Blockchains are currently tested for developing the decentralized energy markets through which users can execute peer to peer energy deals (Chen, 2022). These advanced solutions aim to enhance the grid flexibility, efficiency and accessibility of DR programs. It also helps to make them more appealing and feasible for consumers and utilities. The sustainable and resilient energy future of Nordic countries depends strongly on the implementation of demand response programs in their future smart grids and renewable energy integration.

2.5 Heating Systems and Their Impact on Demand Flexibility

Heating systems remain essential for managing Nordic household energy use due to extensive cold winters that create extensive heating requirements. In Nordic countries such as Finland, Sweden, Denmark and Norway, residential heating accounts for a significant portion of total energy consumption. Therefore, making it an important focus area for demand side management (DSM) and flexibility programs. Heating systems with flexible demand are essential for managing supply and demand while minimizing power peaks and maximizing energy efficiency. An analysis of heating utilization in the Nordic area and the practical applications of heating systems for demand-side management occurs throughout this research review.

2.5.1 Energy Consumption Patterns for Heating

The heating systems of Nordic region use district heating as well as electric heating together with heat pumps and bioenergy. High demand in urban centers drives the widespread adoption of district heating systems but electric heating and biomass heating dominate the heating system of rural areas (Soltero et al., 2018). The share of heating systems differ across nations because Finland and Sweden use district heating for more than half of their heating requirements but Norway depends mainly on electricity based system. The Nordic countries utilize heating for 50% to 70% of their total energy usage each year and peak consumption of energy normally happens during the winter season (Allard et al., 2013). The Finnish electricity demand for heating rises three times higher in the coldest winter months which creates major challenges for the power grid (Söder et al., 2018). According to Andersen et al. (2017), in Sweden, household electricity demand during peak winter season is 50% higher than in summer season. This seasonal variation highlights the importance of flexible heating solutions that adapt to fluctuating power use patterns.

2.5.2 Potential of Heating Systems in Demand Side Management

The heating sector demonstrates major demand side flexibility capabilities through peak demand reduction strategies and renewable integration and load shifting opportunities. Several methods exist to improve heating flexibility such as thermal energy storage systems with smart temperature control and demand response program.

1. Thermal Energy Storage and Heat Pumps: Heat storage systems known as Thermal energy storage (TES) effectively boost the adaptability of residential and industrial heating systems. The TES system enables end users to gather surplus heat during low electricity demand then access it when electricity demand reaches its highest point thus decreasing the amount of congestion in the power grid. According to Narayana (2023), the combination of TES technology with district heating infrastructure enables Denmark to reduce its peak electricity consumption by 15% to 20%. Heat pumps function as essential components for the implementation of demand response management (DSM) strategies. Heat pumps supply between 30% to 40% of heating needs within Norwegian households while increasing operator interest for their capability to support demand-side flexibility (Söder et al., 2018). Through smart heat pump controls residential buildings can shift their electric heating requirements to the low demand periods and avoid high electricity prices during peak hours. A research project from Sweden demonstrated that residential buildings could decrease peak power use by 20% through heat pump controlled DSM system (Zator & Skomudek, 2020).

2. Smart Thermostats and Automated Heating Control: Smart thermostats have brought improved heating flexibility as an addition to Nordic users. Real-time control of indoor temperatures occurs by the smart thermostats and the combination of price signals with user behavior patterns and weather predictions. The installation of smart thermostats in Finnish residences leads to a decrease of 10% to 15% in electricity consumption for heating purposes according to Ivanova (2024). The implementation of automated heating control technology enables users for preheating home and industry during off peak hour and maintains lower temperatures during peak times while maintaining the comfort level which is 18^0c to 22^0c (Kruusimagi, 2017).

3. District Heating and Demand Aggregation: District heating networks operating in the Nordic region are among the most advanced in the world because they create possibilities for big scale demand side flexibility. Swedish multi-apartment buildings use district heating for 80% of their facilities thus allowing operators to control heating demands as a centralized system (Toropov, 2024). Through aggregating customer demands, district heating operators maintain real-time temperature control for heating systems which allows them to match electricity market fluctuations and use renewable energy surpluses effectively. Demand aggregation functions as a mechanism to connect various households, buildings, offices, departmental stores and firms under a single flexible operation system. The Danish research showed that combining the heating requirements across multiple users resulted in a 25% better electric power system stability and lowered total electricity expenses (R. Lund & Mathiesen, 2015). District heating networks now implement artificial intelligence (AI) along with machine learning for optimizing their energy consumption patterns.

4. Time of Use Tariffs and Incentive Programs: Different time based pricing strategies installed throughout Nordic nations aim to achieve heating flexibility. Time of use (TOU) tariffs offer reduced electricity pricing to consumers during off peak times, yet higher prices during peak demand hours. The research conducted in Sweden demonstrates households in TOU heating programs manage to save between 12 and 18 percent on their annual electricity expenses (Nilsson et al., 2018). Critical peak pricing (CPP) and DR contracts have started to be utilized in both Finland and Denmark. Such programs pay customers to lower their heating dependent electricity consumption during peak usage hours. A case study in Finland showed that the end user who participate in the heating based DR programs and cut their electricity consumption throughout winter peak times receive up to 150 € in yearly savings according to Söder et al. (2018).

5. Integration with Renewable Energy Sources: The ability to control heating systems plays an essential role in allowing power grids to incorporate volatile power generation from wind and solar sources. Heating loads can be dynamically adjusted to consume surplus renewable electricity during peak generation hours thus reducing curtailment and enhancing overall system efficiency. According to Johansen and Werner (2022), wind powered district heating facilities in Denmark succeed in balancing heating demands and minimizes fossil fuel usage. The attention has recently shifted toward heat to power conversion technology through the implementation of the power-to-heat (P2H) system. Heat systems use excess electricity from renewable energy to create heated water that is stored for later distribution using district heating network. A research study in Denmark discovered that applications of P2H technology improved renewable power consumption by 30% which decreased the dependence on imported electrical power during high demand times (Sorknæs et al., 2020).

Heating systems play a vital role in demand flexibility and energy efficiency in Nordic grid systems. When heating utilizes thermal energy storage systems combined with smart controller, district heating network and time based electricity rates, it substantially supports grid stability while managing electricity demand. Despite existing barriers such as consumer awareness, high investment cost and regulatory barriers, the heating system's impact on Nordic energy transition will be strengthened by new demand response solutions and advance AI optimization. These implemented strategies will simultaneously decrease peak power demand and support the integration of renewable energy which leads to a more sustainable and resilient energy system.

3 Methodology

3.1 Distribution Network Selection and Data Collection

3.1.1 Overview of the Selected Distribution Networks

The two medium voltage distribution networks were chosen for flexibility and capacity analysis in this study (02_Porkholm and 03_Centrum). Those networks are maintained by Esse Elektro-Kraft. These networks reflect a combination of rural and semi-urban energy consumption patterns. These networks were selected because of their disparate structural and load feature. The analysis approach provides an in-depth overview of how flexibility initiatives might help distribution network in various technological and demographic situations.

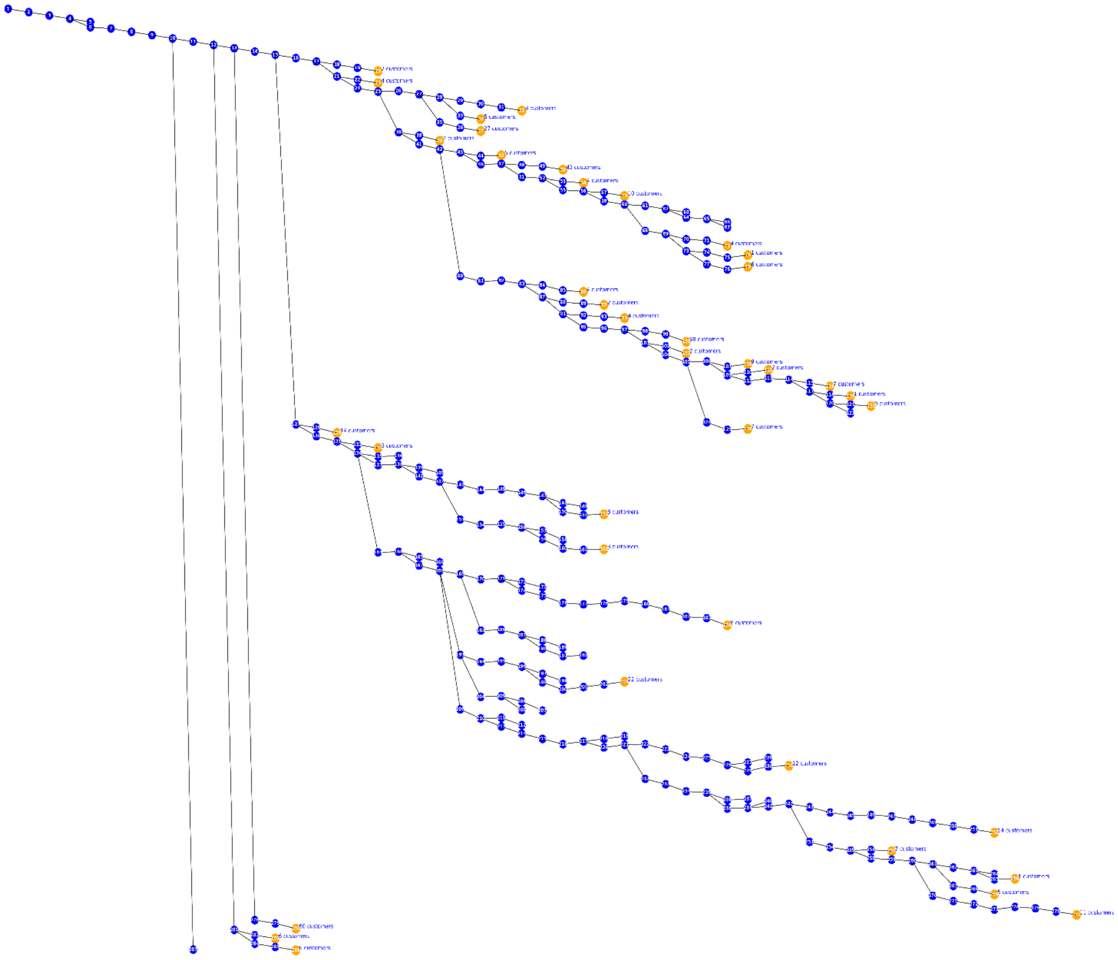


Figure 2. SLD of 02_Porkholm

The 02_Porkholm network is characterized by its rural structure. It has 39 secondary substations, 287 nodes and a total network length of 55.39 km. 277 customers are connected in this network. The single line diagram of the 02_Porkholm network is presented in figure 2. Its annual electricity consumption is approximately 1953.11 MWh with high seasonal variation largely for the electric heating in winter months. The 03_Centrum network represents a more compact and urban setting. It has 11 substations and 176 nodes. The network length is 9.01 km and 202 customers are connected. The annual consumption is 1800.56 MWh. The single line diagram of the 03_Centrum network is presented in figure 3. Despite its smaller geographic footprint, 03_Centrum displays high peak demand during business hours because of its commercial, public and residential consumers.

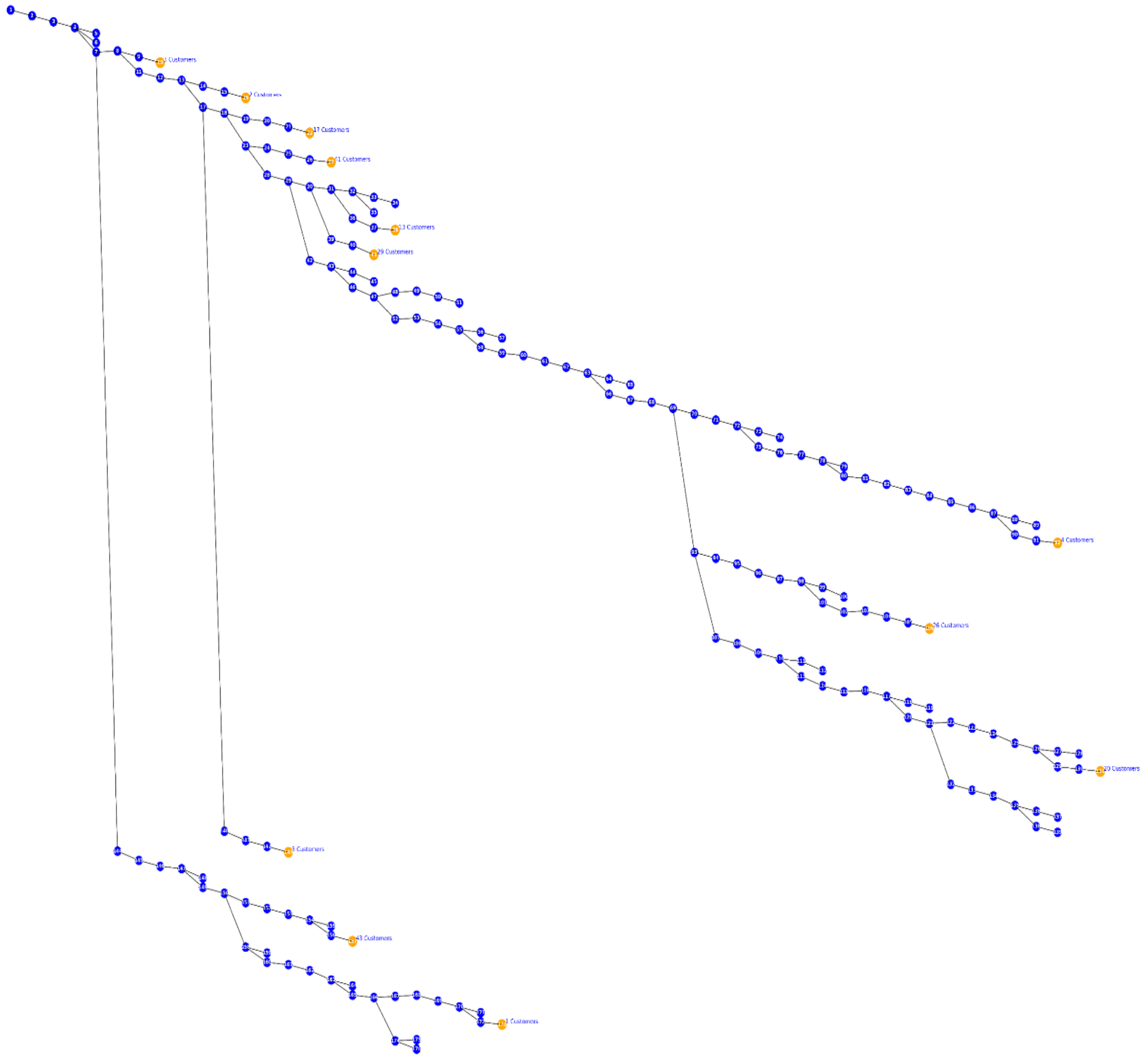


Figure 3. SLD of 03_ Centrum

3.1.2 Data Sources and Methodology

This study uses a methodical and data driven methodology in order to simulate energy consumption, battery storage allocation, heating optimisation and demand response (DR) technique across different distribution network. The system is based on hourly resolution consumption data taken over a one year period. Esse Elektro-Kraft Ab provides smart meter data (hourly resolution), network map, customer classification and line characteristic while ENTSO-E provides energy pricing data (hourly resolution) (ENTSO-E., 2025).

3.1.2.1 Data Sources and Preprocessing

Every simulation is based on a large data set that includes hourly power usage data for a year (8,760 hours) for various user types within the selected network. As part of data preparation, user and node specific data for each distribution network (02_Porkholm and 03_Centrum) were filtered and separated. The network topology's corresponding nodes were matched with consumption data for node level analysis (relevant to hosting capacity and battery allocation task). Customers were categorised by consumer segment (households, commercial users) for user level analysis (related to demand response and heating optimization). Profile clustering was then used to create aggregated load model that preserve representative demand pattern while lowering computational complexity.

3.1.2.2 Demand Response (DR) Modeling Methodology

The DR simulation was based on one year of hourly consumption data. Users were first categorized by network and then by user type for example, residential and commercial. Aggregated load model was created for representative groups after clustering method used to find comparable consumption characteristic for each group. To evaluate the possibility of load shifting, the demand response model was then run on this combined load and the average DR effect was calculated.

A probabilistic appliance consumption model with a rule based disaggregation approach has been used to replicate actual appliance behavior. In order to shift peak demand to off peak hour, these models made it possible to estimate the TOU trends for important equipment. Each customer segment's DR shifting algorithm has been developed using observed consumption trend, user behavior assumption and appliance flexibility. For example, loads associated with washing machine or dishwasher in homes were considered to be more shiftable than loads associated with cooking or lighting.

3.1.2.3 Hosting Capacity and Battery Energy Storage Systems Modeling

One year of hourly power consumption data was used to evaluate hosting capacity (HC) and battery energy storage systems (BESS). The raw dataset was processed to provide node specific load profiles for each distribution network, 02_Porkholm and 03_Centrum.

To ensure resilient planning, the research included two separate scenarios:

- Maximum Load Condition: This scenario takes into account the maximum hourly demand observed at each node throughout the duration of the year. It is a worst case test designed to establish the network's maximum ability to support additional distributed energy resource (DER) or renewable power without exceeding voltage or heat limitation.

- Average Load Condition: Calculated based on average hourly demand for each node throughout the duration of the year. It represents normal operational circumstance. It is important in determining daily adaptability.

Simulation was done under both scenarios to evaluate network performance with a particular focus on finding nodes that are best suited for BESS implementation. Each node's allotted peak demand (kWh) and battery power capacity (kW) have been calculated and evaluated. Importantly, the best HC finding was obtained at the highest load scenario which provided a more stringent and relevant boundary for planning. This scenario allowed for the identification of crucial demand areas in the network as well as the optimization of battery deployment approaches in order to improve grid stability and avoid overload risk factor. The maximum load condition scenario addressed the most demanding operational situation, ensuring that HC estimations were accurate and realistic. This gives a useful information for grid planner and investment decision maker.

3.1.2.4 Optimum Heating Demand Modeling

Heating demand optimisation used hourly electrical consumption data throughout the year. Users were initially separated by network and user type, as in the DR technique, then clustered based on their consumption habit. Aggregated load models were subsequently created for each cluster and fed into the heating optimization algorithm. This approach ensured that simulation showed both diversity and commonality in thermal behavior across customer segment. The average simulation results were subsequently calculated to reflect the optimal heating load across each sample group. The result represent the potential load reductions and enhanced thermal comfort levels through a more effective control approach.

3.2 Python Based Modeling Approach

The complete modeling framework used in this research was developed using Python. This programming language is popular and flexible in the field of energy systems analysis. Flexible, transparent and repeatable power system dynamic modeling, optimization and data-driven decision-making are made possible by Python's large ecosystem and domain specific module. Demand response (DR), distribution network design, hosting capacity, battery energy storage system (BESS) location and optimum heating technique were all designed implementing Python module. It specifically designe to meet this study's analytical requirement.

3.2.1 Hosting Capacity Analysis

To model hosting capacity (HC), the cvxpy, pandas and numpy libraries were used. Determine the greatest distributed generation such as solar PV can be connected to a node without going against voltage or thermal limits by using CVXPY. CVXPY is an efficient optimization modeling tool that enables the formulation and solution of convex optimization problem. In order to manage the hourly consumption data and node level characteristic, pandas and numpy provide effective data management, manipulation and array based calculation.

3.2.2 Battery Energy Storage System (BESS) Sizing and Placement

In the BESS related simulations, Pandas and Numpy were used to handle network level data, determine energy storage requirement and evaluate performance under maximum and average load scenario. In addition to supporting the simulation of load shifting and peak shaving scenarios under both deterministic and averaged situation, these libraries made it possible to aggregate node wise profile.

3.2.3 Demand Response (DR) Modeling

The libraries seaborn, pandas, and numpy were essential for DR modeling. Cluster patterns, load shifting effects and DR participation behavior across user groups were visualized using Seaborn. In the meanwhile, rule based and probabilistic load disaggregation models were implemented, user types were segmented, consumer behavior profiles were clustered and time series energy data was handled using pandas and numpy.

3.2.4 Optimal Heating Strategy Modeling

LinearRegression from sklearn, scipy.optimize, pandas and numpy were used to analyze the best heating solution. While scipy.optimize allowed parameter fitting and optimization for load smoothing and schedule planning, regression model contributed in identifying consumption pattern. The creation of aggregated user profiles and the optimization of thermal load distribution across various heating settings were made easier by these libraries.

3.2.5 Distribution Network Power Flow Analysis

The power system component was mainly reliant on pandapower, a specialized open source Python software for power system modeling. The submodules pandapower.topology and pandapower.network were used to build the 287 node distribution system, model secondary substations and simulate load flow using backward/ forward sweep and optimum power flow technique. Pandas and NumPy were once again required for maintaining network characteristic and customer profiles.

3.3 Metrics for Evaluating PV, BESS and Demand Response

Several technical and operational measurements were used to assure a consistent and relevant evaluation of the performance and effect of photovoltaic (PV) integration, battery energy storage systems (BESS) and demand response (DR) methods in the regional electricity network. These indicators give quantifiable information on system dependability, flexibility, increased hosting capacity, peak reduction and economic efficiency.

3.3.1 Photovoltaic (PV) Hosting Capacity Metrics

Maximum Hosting Capacity: Maximum Hosting Capacity refers to the maximum amount of distributed PV generation that may be linked to each node without exceeding voltage or temperature constraint. The numbers are determined for different load condition.

Voltage Deviation: To maintain an appropriate voltage range (usually ±10%), the system evaluates the change in node voltage caused by PV integration.

Node Reliability: The Node Reliability (Pre/Post PV) compares system reliability before and after PV installation, focusing on metrics like voltage stability and load supply continuity during peak demand time.

Thermal Loading: Transformers and lines are monitored during PV capacity situation. The thermal loading meter measures whether increased PV causes line overload or transformer stress.

3.3.2 Battery Energy Storage System (BESS) Metrics

Peak Load Reduction: Peak Load Reduction indicates how successfully BESS decreases peak demand at specific nodes and system wide. This helps to assess the influence of BESS on flattening demand curve.

State of Charge (SoC) Profile: The State of Charge (SoC) Profile tracks battery storage use, depth of drain and charge/discharge cycles over time.

Energy Shifting Capacity: Energy Shifting Capacity (kWh) measures the amount of energy saved during off-peak times and released during peak hours. It describes the BESS's function in load balancing and arbitrage.

3.3.3 Demand Response (DR) Evaluation Metrics

Load Shifting: Load Shifting represents the peak hour load effectively moved to off-peak times by customer category.

Peak Demand Reduction: Peak Demand decrease measures the decrease in system or node level peak demand as a result of DR operation particularly for residential and retail sector.

Flexibility: The Flexibility measures the willingness and ability of various consumer categories (e.g., residential, retail) to adjust their load profile. Based on appliance use models and user behavior.

These criteria allow for a complete and multidimensional assessment of the potential, effect and practicality of integrating PV, BESS and DR methods into the regional distribution grid. They also function as decision making tools for designing robust and efficient energy system.

4 Result and Discussion

4.1 Distribution Network Analysis & PV Integration

The structure and load profile of a distribution network play a crucial role in determining its potential to incorporate distributed energy resources such as PV installation. In this study, two separate types of distribution networks are analyzed (Porkholm and Centrum) each having differing characteristics in term of topology, regional distribution and consumer load pattern. The Porkholm network has a typical rural distribution architecture, consisting of 39 secondary substations and running over 55.39 kilometers. This configuration means longer feeder length, greater impedance and more significant voltage change especially under variable load or power generation condition. On the other side, the Centrum network shows a dense urban topology, with just 11 substations which covers only 9.01 kilometers. Its compact design predicts shorter feeder line, increased node density, and better voltage control under common operational circumstance. These structural variances considerably impact not only the technical functioning of each network but also their hosting capability for PV generation.

Demand distribution across the two networks also reflects the varied user bases and geographical arrangements. In the Porkholm network, power usage is predominantly dominated by residential user with high use of electric space heating especially during the winter months. The overall yearly energy consumption of 1953.11 MWh is scattered across a vast geographic region which results in lower average demand per node. It increases variability because of isolated peaks in individual household usage. Centrum network consumes a slightly lower yearly total of 1800.56 MWh which shows a greater per-node and per area consumption. This is partially due to its mixed client profile which includes residential, public and commercial customer clustered within a narrow metropolitan area. Centrum's load profile is characterized by high daily peaks notably during business hours which reflects the regular activity cycles of stores, offices and public services. This concentration not only leads to increased localized load but also increases the heat and electrical stress during peak time.

Seasonal fluctuation in demand further underlines the operational issues and planning implications for both networks. Porkholm has residential orientation and significant use of electric heating which suffers a substantial spike in power consumption throughout the winter season. The heating load creates significant and sustained consumption peaks which can lead to voltage dips at remote nodes and higher losses across the system. These periodic peaks also limit the network's capacity to absorb surplus PV power during non winter months unless effectively controlled by smart grid management or energy storage device. Conversely, the Centrum network's load profile displays fewer noticeable seasonal fluctuation but it shows regular summer and winter pattern. In summer, cooling loads and longer daylight hours contribute to greater daytime consumption which can more easily line with PV generation profiles. During winter, although the total increase in load is low compared to 02_Porkholm, the shorter daylight hours and greater peak demand nonetheless impose operational restrictions for PV integration.

The structure and load features of the 02_Porkholm and 03_Centrum networks provide various challenges and possibilities for PV hosting. 02_Porkholm has rural topology and winter dominated load profile complicate voltage management and limit PV hosting during off peak seasons. 03_Centrum has urban density and business driven load provide better alignment with daytime PV generation but present peak congestion challenges. Comprehending these variances is essential for assessing the technical hosting capability and creating suitable control plan for every network.

4.1.1 Identifying Suitable Locations for PV

Identifying acceptable sites for PV integration into a distribution network includes a technical study based on electrical performance requirement. In this research, electrical load flow models are performed to evaluate optimum PV location throughout networks. These simulations analyze voltage level, heat loads of line and transformer and reactive power behavior under different PV penetration scenarios. Nodes maintain appropriate voltage profiles and do not induce reverse power flow or overloads are regarded as suitable option for PV connection. This strategy ensures that chosen sites have the electrical resilience to manage the related generation without affecting system stability.

The identification method takes into account a number of constraints. An important element is grid integration capability which involves proximity to existing infrastructure such as secondary substations and medium voltage line. Sites placed too distant from the grid may need expensive infrastructure upgrades or extensive feeder expansion diminishing their economic viability. Integration also relies on the flexibility of local component like voltage regulator and transformer to accept unpredictable and possibly reversing power flow especially during low demand time. This technique focuses on technical hosting capacity and network compatibility. It provides a dependable foundation for selecting electrically acceptable areas for PV deployment inside the distribution network.

4.1.2 Determining Optimal PV Capacity

A distribution network's ideal PV capacity must be accurately determined which is a complex process. It includes evaluating technological limitation, examining energy demand pattern and making sure grid constraints are not compromised. In this research, the best PV hosting capacity was assessed for two structurally distinct networks. The technique combines node by node load flow analysis with hosting capacity calculation. It uses a simulation based approach to establish the highest feasible PV integration at each node without violating voltage, temperature or operational limitation.

The simulation methodology created for this study examines each node's capacity to host PV by progressively increasing the PV injection until operational constraints are reached. This was done using an iterative program developed in Python. Python automates the testing of incremental PV levels and analyzes the resultant voltage profile, thermal loads of cable and overall system stability. For each node, the ideal PV capacity is defined as the highest value at which all voltage magnitudes stay within ±5% of nominal values (usually 1.0 per unit) and no thermal overload occurs on any connected line or transformer. This technique provides for the discovery of technical restrictions in a controlled, node specific way which allowing an exhaustive overview of geographical distribution of hosting capacity throughout the whole network.

4.1.2.1 02_Porkholm Network Analysis

The 02_Porkholm distribution network consists of 39 secondary substations and a total line length of roughly 55.39 km. It links 277 consumer points through 287 nodes, emphasizing its sparse and geographically spread out structure. The rural structure and scattered demand patterns greatly impact the PV hosting capacity distribution. Annual energy consumption in 02_Porkholm amounts at 1953.11 MWh with a significant increase during the winter months.

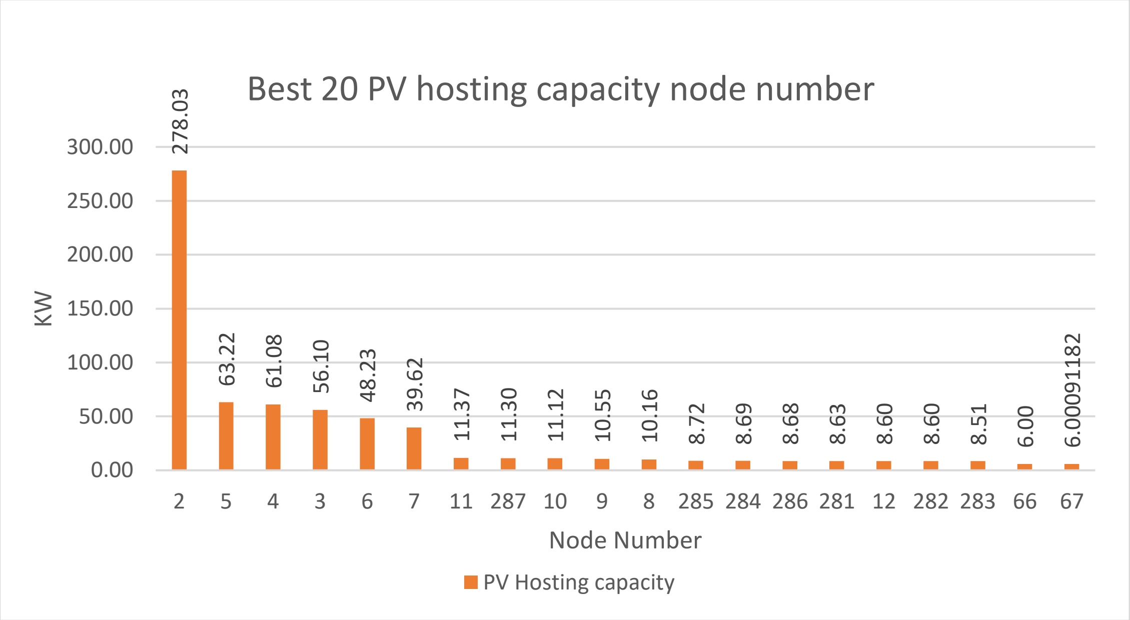


Figure 4. Top 20 hosting capacity and node location of 02_ Porkholm network

The findings demonstrate a substantial range in hosting capacity among the nodes, with values ranging from as low as 2.4 kW to as high as 278 kW (Figure 4). Node 2 notably has the largest hosting capacity which is 278.03 kW. Node 2 has a robust connection and low impedance link to the main feeder. Several additional nodes close to primary substation show moderate to high capacities (e.g., Nodes 3 to 6 with capacities of 50–60 kW) which indicates their advantageous location in the network architecture and load sharing potential.

However, a significant number of nodes in the mid and tail regions of the network (Nodes 50 to 287) demonstrate very modest hosting capacity (HC). The HC generally ranges between 2 to 6 kW. This decrease is related to longer line lengths, increased impedance and voltage sensitivity at remote nodes. In rural networks like 02_Porkholm, such voltage losses are a significant limiting issue. The PV injection at remote nodes may rapidly increase the voltage above permissible limit. Furthermore, many of these nodes serve isolated families or tiny clusters where local demand is inadequate to absorb surplus energy, raising the danger of reverse power flow.

One of the main takeaways from the 02_Porkholm scenario is the discovery of clusters of high-capacity nodes which might be prioritized for PV deployment. For instance, nodes 2 to 10 create a corridor with relatively high and consistent capacity. It makes them appropriate for community scale PV system.

4.1.2.2 03_Centrum Network Analysis

The 03_Centrum network has 11 substations and lengths just over 9 km which shows a compact urban structure. This network servs 202 consumers through 176 nodes. Annual consumption is somewhat lower than 02_Porkholm with 1800.56 MWh. It shows more constant demand throughout the year with notable peaks during business hours caused by commercial and institutional loads.

The result for 03_Centrum has great diversity in HC. From Figure 5, the largest value observed is around 122.36 kW at Node 2 while the majority of the other nodes indicate hosting capabilities between 4 to 11 kW with few peaking slightly over 10 kW (e.g., Nodes 170 to 175). Unlike 02_Porkholm, the 03_Centrum network lacks significant low capacity tail primarily due to its compact structure and shorter cable line. This minimizes the voltage drop effect of distributed generation which provides a slightly higher average HC across nodes.

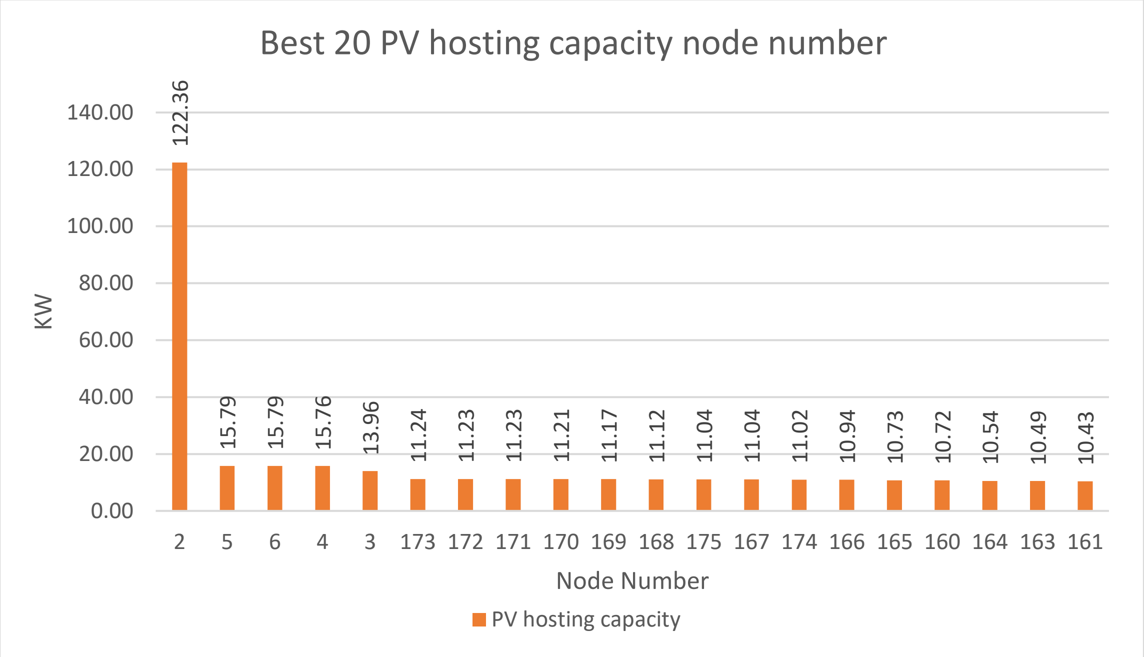


Figure 5. Top 20 hosting capacity and node location of 03_Centrum network

That said, urban networks like 03_Centrum are subject to distinct restriction. While electrical HC may look more beneficial because of reduced impedance and more durable transformer, practical constraints such as limited rooftop space, structural load bearing capacity and regulatory zoning rule generally restrict the deployable PV scale. From an electrical viewpoint, the 03_Centrum network offers a potential capacity for rooftop solar integration, particularly at commercial buildings and public infrastructure with flat roof.

4.1.3 Comparative Analysis and Interpretation

Comparing these networks demonstrates the importance of grid design and load variable on PV hosting potential. 02_Porkholm's lengthy, radial feeders and unequal load distribution provide limitations for extensive PV deployment particularly in far rural branches. By comparison 03_Centrum's meshed topology and concentrated load center result in more homogeneous HC but with lower peak values due to space limit.

The use of simulation based HC study also showed several crucial dynamics. In both networks, hosting capacity at a node is not only a function of its own demand but is heavily impacted by upstream transformer capacity, line impedance and the operational limitation of the surrounding nodes. For example, high capacity nodes in 02_Porkholm are commonly at substation or branching point where back feeding may be handled. However, 03_Centrum has clusters of high demand nodes near commercial areas show higher hosting potential despite lower line rating.

Seasonal variance plays a vital influence in establishing the practical PV hosting capability. In 02_Porkholm, peak demand comes in winter when solar availability is lowest which possibly leading to underutilization of installed PV. Conversely, in summer when PV generation peaks, the local demand is modest. This situation worsens concern of voltage increase and backfeed which are especially essential for long radial feeders. These dynamics must be addressed when sizing PV system and creating for energy storage or demand side management measurement.

The research also highlighted the significance of dynamic HC assessment tools which update capacity in near real time depending on network loads and voltage profiles. As loads change daily and yearly, static values risk under or overestimating real integration capabilities. Integrating smart inverter, voltage control method and flexible load coordination may further boost HC without costly infrastructure investment.

The simulation based analysis supported by node level data from the code which offers a credible and practical framework for finding appropriate PV capacity in distribution networks. It increases technically competent and economically effective PV integration, coordinating with the wider targets of decarbonization and distributed energy production.

4.1.4 Impact of PV Integration on Network Performance

The incorporation of PV system into distribution network significantly impacts their operating property. These implications appear across multiple performance parameters including voltage profile, power losse, thermal load and dependability. In this research, simulations and load flow analysis were done to analyze how growing PV penetration levels effect the technical performance of the 02_Porkholm and 03_Centrum networks which represent rural and urban design respectively.

One of the most direct affects of PV integration is on the voltage profile of the network. Typically, in passive distribution network, voltages decline steadily with distance from the substation because of cumulative load. With the incorporation of distributed PV generation particularly at downstream nodes reverse power flow might occur which leads to voltage increase.

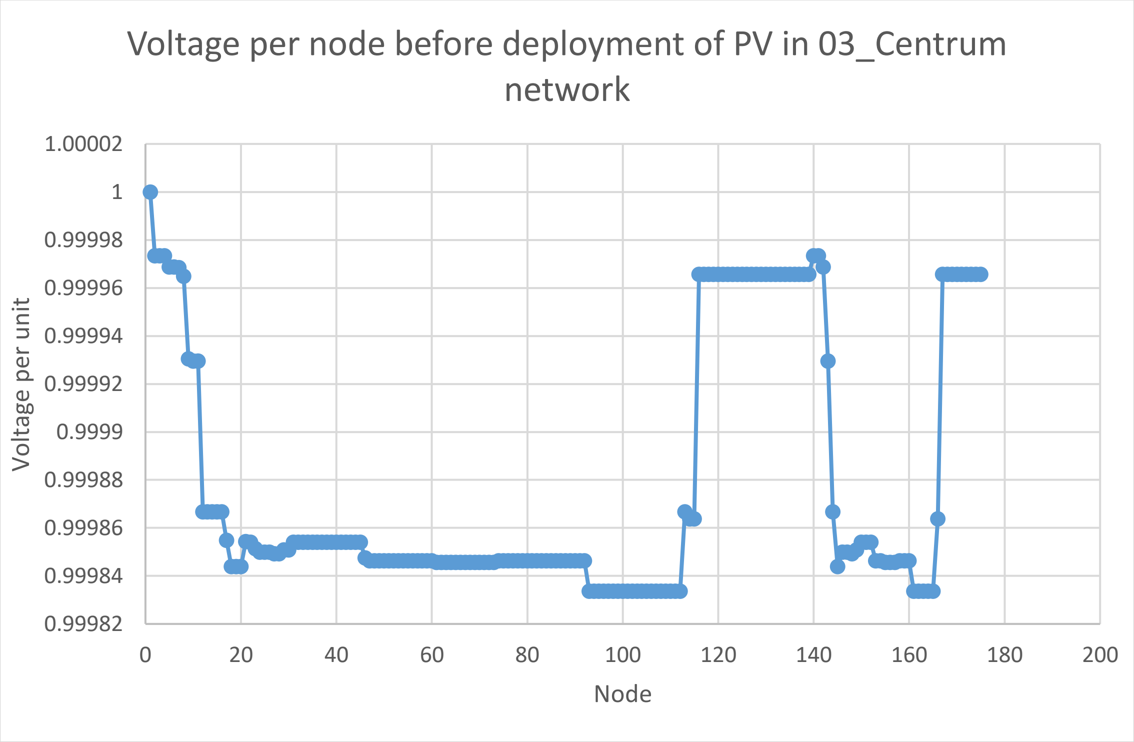


Figure 6. Voltage per node before deployment of PV in 03_Centrum network

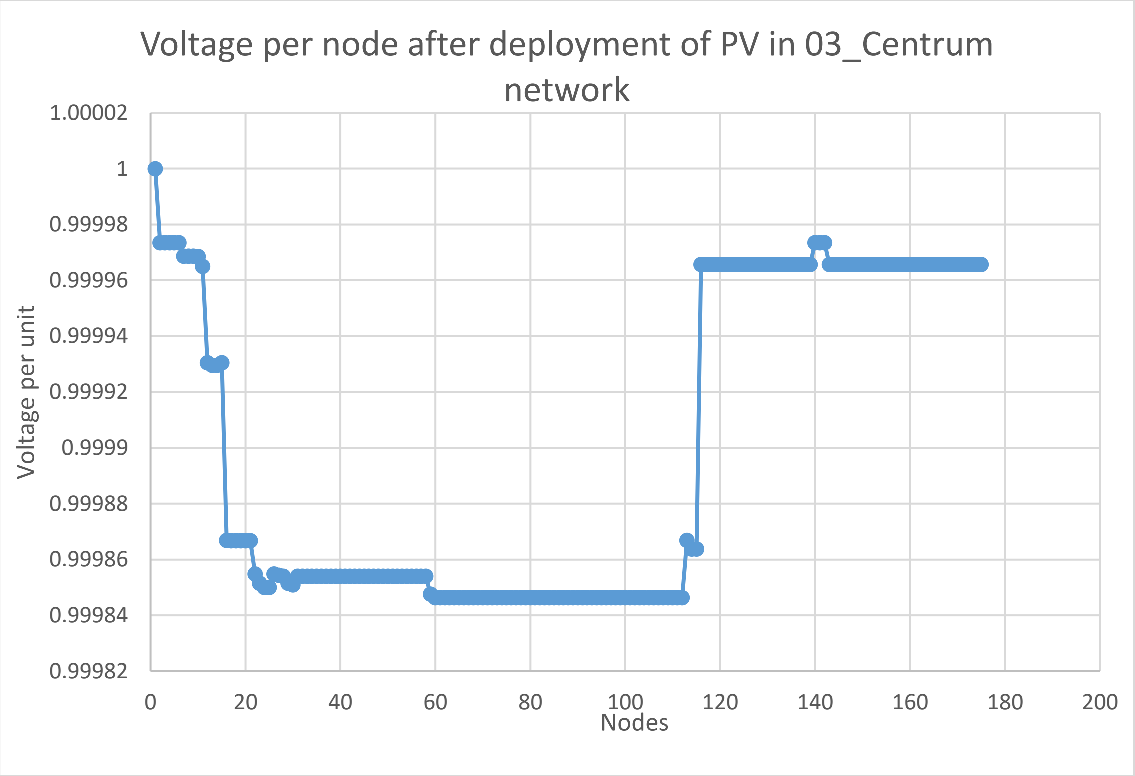


Figure 7. Voltage per node after deployment of PV in 03_Centrum network

The 02_Porkholm network is geographically wide and low loaded in summer. The addition of PV power helped improve the voltage profile at distant nodes at this network. However, excessive PV production might result in overvoltage situation. The HC data indicates this clearly. Numerous nodes display a hosting limit just below the point where voltages would surpass 1.05 p.u. The algorithms implementation carefully assesses this threshold and terminates PV injection whenever voltage limitation is surpassed. 03_Centrum has shorter lines and greater load density. Therefore, the voltage fluctuations are less obvious but nodes near to the substation are more vulnerable to even minor injections of PV which posing voltage management issues. The comparison between figure 6 and figure 7, figure 8 and figure 9 highlight the positive impact of PV deployment on voltage regulation in the both network.

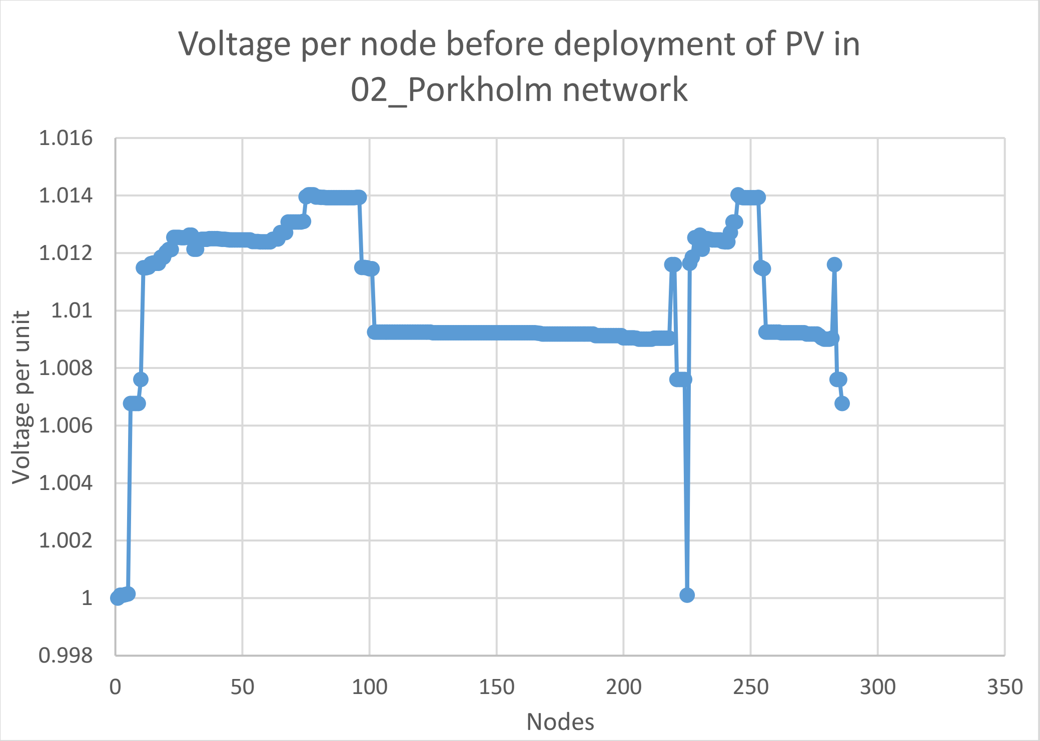


Figure 8. Voltage per node before deployment of PV in 02_Porkholm network

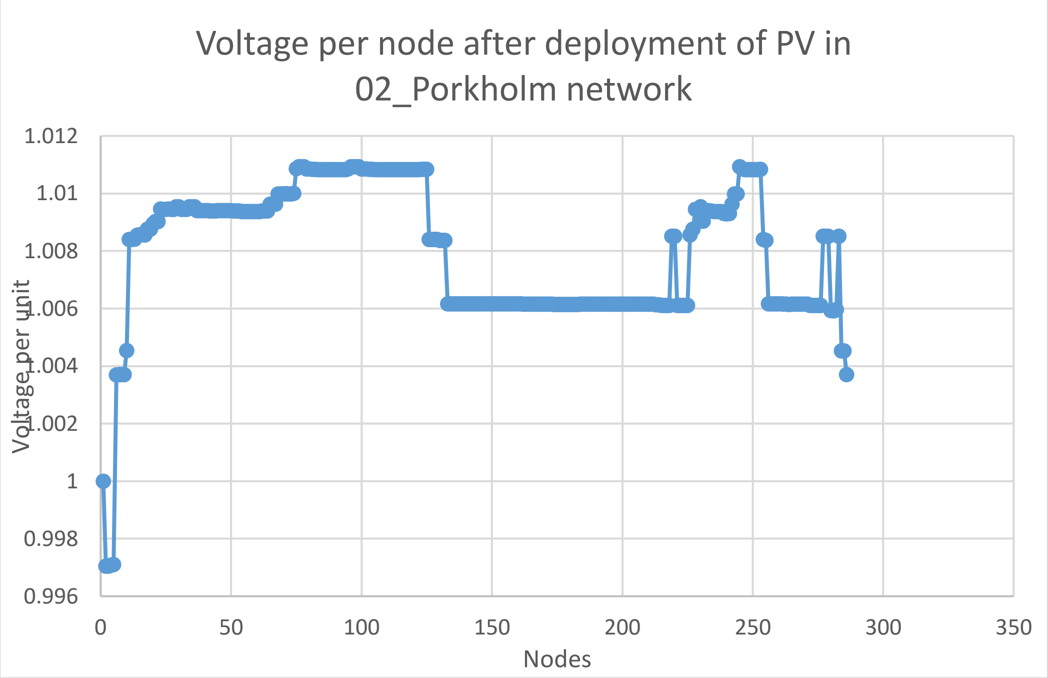


Figure 9. Voltage per node after deployment of PV in 02_Porkholm network

4.2 Battery Energy Storage System (BESS) Optimization

The integration of renewable energy source and the ongoing electrification of heating system is introducing new difficulties to traditional distribution network (Gallegos et al., 2024). Battery energy storage system (BESS) can be a crucial component in enabling operational flexibility in distribution network such as 02_Porkholm and 03_Centrum where conventional grid upgrade is costly and take a long time to implement. Batteries offer a number of benefits including the capacity to store extra renewable energy, reduce peak demand, maintain voltage stability and allow demand side management to change peak load over time (Maghami et al., 2024). This section examines the specific dimension, functionality and financial effects of implementing battery energy storage in the two network. This study considers both technological limitation and market driven prospects for flexibility service.

4.2.1 Battery Storage as a Flexibility Solution

Several issues can be resolved by placing BESS at different points across the distribution network. Batteries can lower power flows on overloaded line and support voltage at the grid edge (Chidambaram & Paramasivam, 2013). They can act as bulk energy storage near substation, reducing transformer stress and smoothing the net load profile. Additionally, BESS integrated with smart meter and DR ready devices can participate in advanced control scheme where both load and generation are dynamically optimised in response to real time price signal (Chakraborty et al., 2022).

The emphasis is on using BESS not as backup power source but as active grid participant capable of enhancing reliability, reducing energy cost and improving the efficiency of renewable integration. It is intended for these batteries to function in hybrid control mode that include frequency regulation, load shifting and peak shaving. Although Finland's ancillary services markets are still in their infancy at the distribution level. The anticipated regulatory change and market design reform could soon allow distribution connected asset to participate in multiple value streams.

4.2.2 Load Profiles and Battery Sizing Methodology

The initial stage was to simulate the hourly load characteristic of both networks over typical peak day in order to design the BESS for best performance. A maximum load day such as a cold winter's workday with significant heating demand and an average load day such as moderate load circumstances usual in spring or fall were the two main scenarios taken into consideration.

For each scenario, the analysis includes the calculation of the following:
- Total energy required to be supplied during peak hours (kWh)
- Duration of peak periods (9 hours)
- Battery energy capacity (kWh) needed to fully cover peak load
- Battery power rating (kW) required for delivery over the peak window

The models assumed complete charging during off peak hours utilising excess renewable or cheaper grid electricity. This study also took into consideration the normal round trip battery efficiency of 90%. In 2025, it was anticipated that batteries will be stationary lithium-ion system with performance attributes comparable to those of commercially available option (Bubulinca et al., 2023).

4.2.2.1 Battery Sizing Results: 02_Porkholm Network

The highest recorded peak demand in the 02_Porkholm network was 6181.10 kWh. An estimated 1854.33 kWh of battery supply over a 9 hour period was needed to successfully minimise this peak demand which results in a 2225.20 kW power capacity need. The necessary battery energy for the same time period was 631.23 kWh or a power capacity of 757.47 kW under the average load scenario while peak demand was around 2104.09 kWh.

Therefore, 757.47 kW to 2225.20 kW is the ideal working range for battery systems in 02_Porkholm. Without running the danger of overloads or voltage instability, the network might accommodate flexibility requirement under both normal and exceptional load levels by deploying BESS within this range. These batteries are set up to charge in the middle of the day when demand is often low, solar PV generation is at its highest and the energy price is low.

4.2.2.2 Battery Sizing Result: 03_Centrum Network

During the 9 hour peak period, the 03_Centrum network's highest demand of 5045.37 kWh necessitated a battery drain of 1513.61 kWh. 1816.33 kW was the corresponding power capacity. Battery energy and power needs decreased to 552.53 kWh and 663.03 kW respectively under the typical load profile.

This implies that despite its short network size, the 03_Centrum network still requires a high degree of flexibility support because of its dense load cluster and feeder topology's lack of redundancy. Similar to 02_Porkholm, the suggested battery capacity range 663.03 kW to 1816.33 kW enables a scalable envelope that allows storage deployment to be adjusted in accordance with changing network requirements and economic feasibility.

4.2.3 Economic Evaluation of Battery Operation

A simple cost benefit analysis was conducted with a cut off price for demand flexibility set at €0.06/kWh in order to evaluate the financial effect of BESS deployment. Based on current electricity tariff and preventing network loss, this price is the anticipated value of shifting consumption or injecting energy during critical hour. The charging cost and total discharging income for the typical load scenario are €32.77 and €56.72 per day, respectively (Table 1). This indicates a moderate financial gain from battery operation with a total cost reduction of €23.95 per day. Because of the increased energy use under the maximum load scenario, the charge cost rises to €104.28/day. The discharge income is €166.84 per day which results in €62.55 in cost reductions per day. The highest saving under maximum load highlight the potential for higher return when the battery is used more intensively. Each situation demonstrates the economic benefits of battery operation.

Table 1. Cost Analysis of 02_ Porkholm

Topic	For Average Load	For Maximum Load
Total Charging Cost	€32.77/ day	€104.28/ day
Total Revenue from Discharging	€56.72/ day	€166.84/ day
Total Cost Savings	€23.95/ day	€62.55/ day

According to the statistics, significant cost savings may be achieved by optimising charging and discharging schedule. For the typical load in 02_Porkholm, Figure 10 displays the income from discharging and the cost of charging the BESS during a 24 hour period. When energy costs (orange dashed line) are below the threshold (purple line), charging often takes place during this off peak hours (blue zones). In order to maximise income, discharge occurs during the peak hours (red zones) when prices surpass the threshold. Energy price affects the charging expenses (blue line) and the revenue from charging (green line). By taking advantage of pricing variation throughout the day, this tactic raises trade and investment. Figure 11 shows the charging cost and discharging income for the maximum load in 02_Porkholm network with charging taking place during low priced off peak hour and discharging during high priced peak hour. Based on the price threshold, the cost and revenue patterns optimise profit by following the energy price curve.

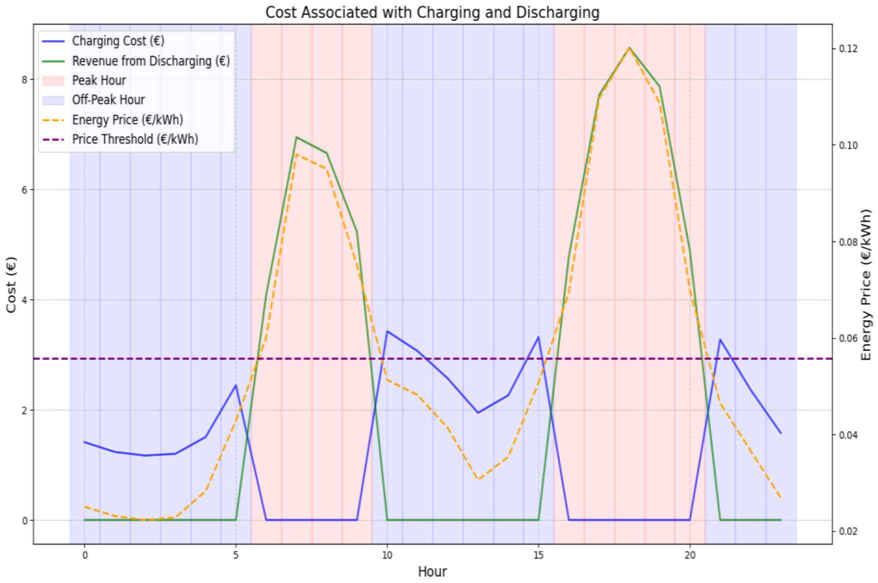


Figure 10. Cost associated with charging and discharging for average load in 02_ Porkholm

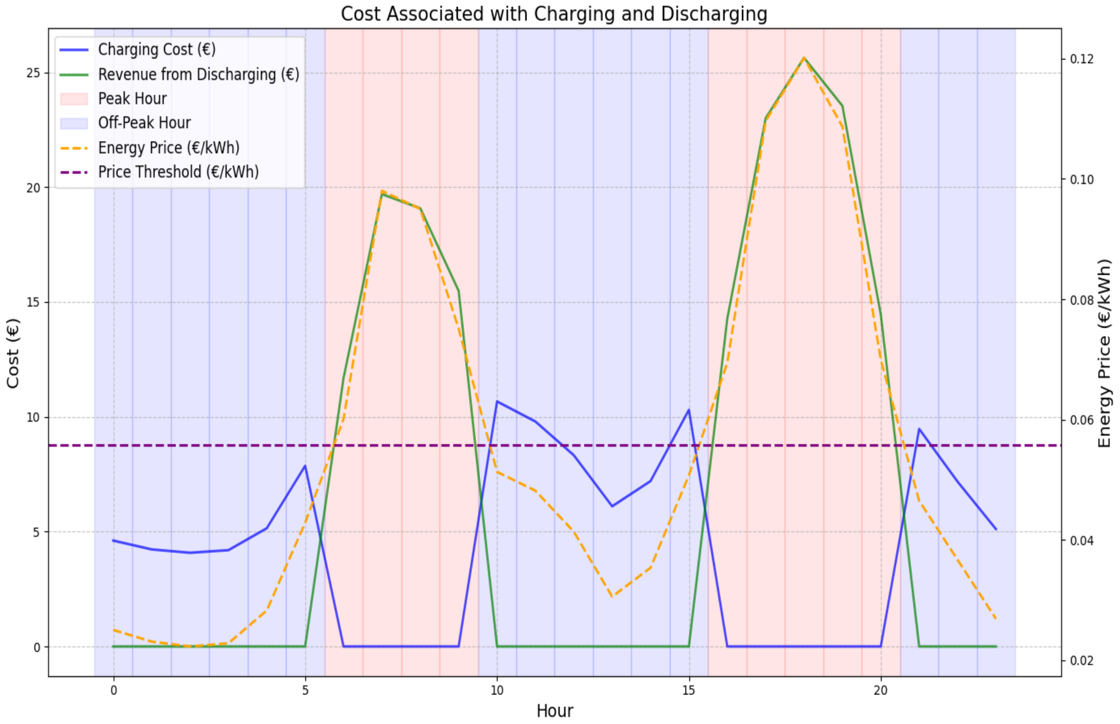


Figure 11. Cost associated with charging and discharging for maximum load in 02_ Porkholm

Table 2. Cost Analysis of 03_Centrum

Topic	For Average Load	For Maximum Load
Total Charging Cost	€29.95/ day	€83.76/ day
Total Revenue from Discharging	€49.86/ day	€136.52/ day
Total Cost Savings	€19.91/ day	€52.76/ day

Savings were relatively reasonable under normal load condition (€19.91 in 03_Centrum and €23.95 in 02_Porkholm). However, they were still economically justified especially when scaled over several peak occurrences per year. The true economic benefit would be greater when grid reinforcement, decreased outage risk and increased DER HC are taken into account.

The economic assessment of BESS operation at 03_Centrum under average and maximum load circumstances is shown in table 2. The battery costs €29.95/day to charge under normal load condition. It makes revenue of €49.86/day when discharged which results of the saving €19.91/day. Higher expenses (€83.76) and revenues (€136.52) at maximum load result in larger saving of €52.76 per day. This proves that BESS operation is profitable, particularly in situations with larger loads.

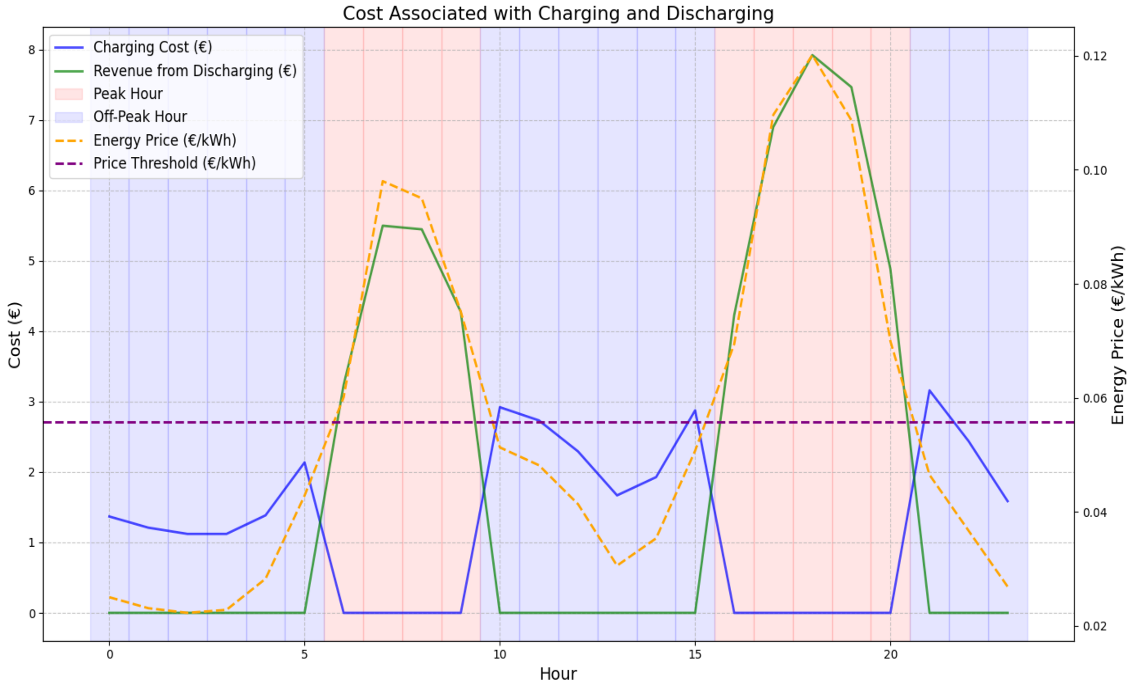


Figure 12. Cost associated with charging and discharging for average load in 03_Centrum

The batteries' payback periods might be further extended by participating in balancing service, traffic management initiative and energy trading in local flexibility market among other value stream. The charging expense and discharging income for the typical load in 03_Centrum during a 24 hour period is shown in Figure 12. In order to save costs, charging is mostly carried out during off peak time (blue zones) when energy prices are lower than the threshold. In order to maximise income, discharge takes place during peak hours (red zones) when prices are higher than the threshold energy price. Hourly pricing fluctuation is successfully used by the technique to operate economically. The cost of charging and the income from discharging for the highest demand in the 03_Centrum network over a 24 hour period are shown in Figure 13. The majority of charging occurs during off peak hours (shaded blue) particularly 0 to 6, 10 to 15 and 21 to 23 when the energy price drops below the predetermined cutoff of 0.06 €/kWh (shown in the purple dotted line). Because of the increased demand for energy during these hours, the charge cost (blue line) reaches its maximum values around hours 10 and 15. In this situation, it surpasses 10 € charging cost per hour. During peak hours (shaded red) especially between hours 7 to 9 and 17 to 20 when energy cost above the threshold, strategic discharge takes place. The highest energy price of the day which is around 0.12 €/kWh at hour 18 when the discharge revenue (green line) rises at almost 22 €. The discharge pattern is closely followed by the orange dashed line that represents energy price. This indicates that the control technique is successfully price driven. In general, this strategy maximises the financial gain from storage operations by guaranteeing that energy is stored during periods of low price and sold during periods of high price.

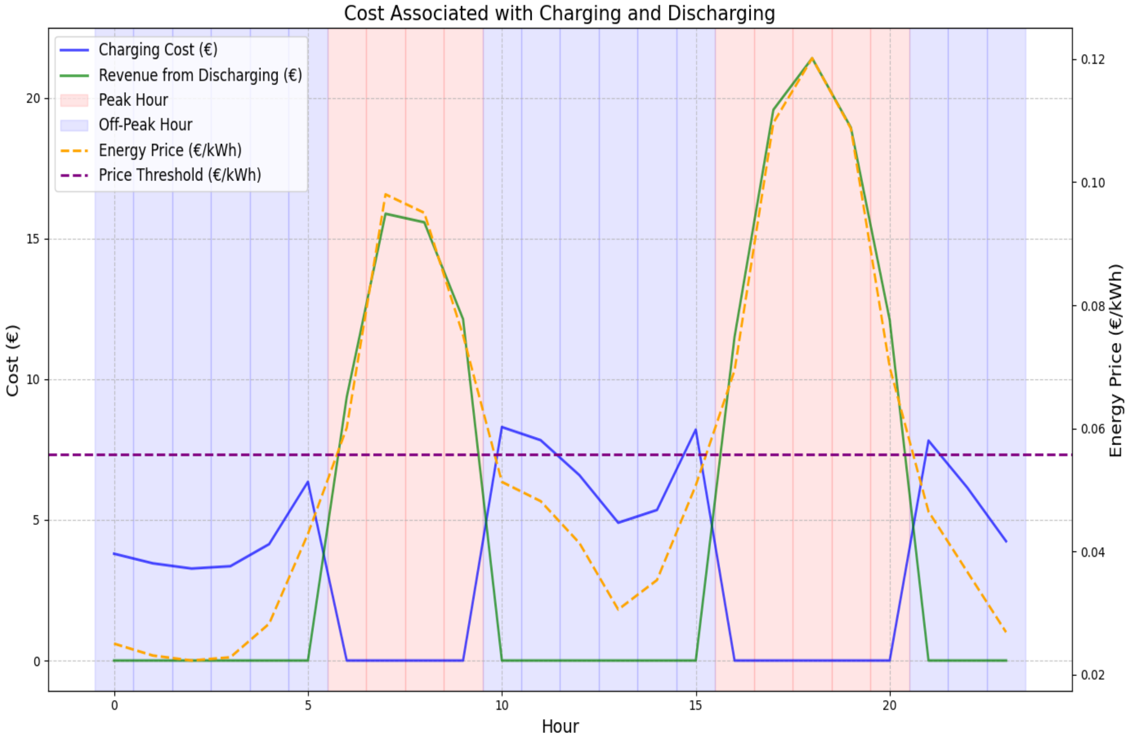
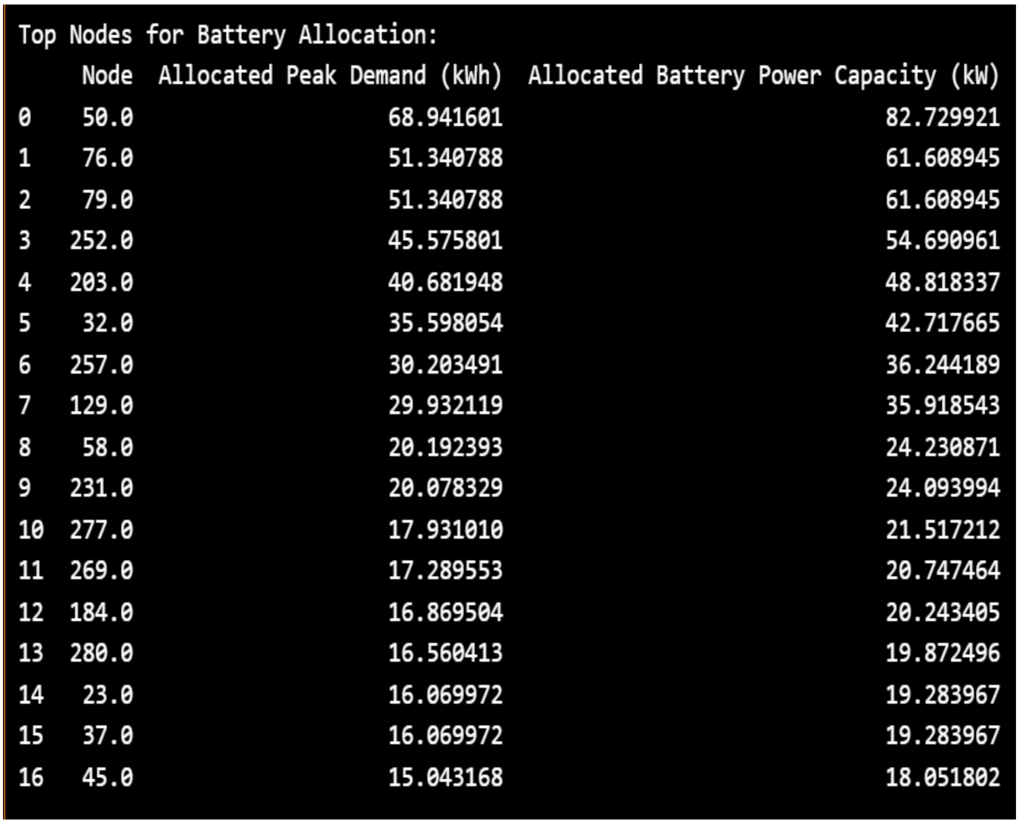


Figure 13. Cost associated with charging and discharging for maximum load in 03_Centrum

4.2.4 Strategic Deployment and Locational Optimization

The location of battery energy storage system (BESS) inside the network topology has a significant impact on how well they support distribution network operation. To optimise technical advantages such loss minimization, voltage support and peak load reduction, locational optimisation is crucial (Nottrott et al., 2013). For the 02_Porkholm and 03_Centrum networks, this study involved a node level allocation analysis to determine the best potential site for BESS deployment under both average and maximum load scenarios. Based on the assigned peak demand and corresponding battery power capabilities at every node, these findings show distinct trend that guide tactical deployment strategy.



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Top Nodes for Battery Allocation:
     Node  Allocated Peak Demand (kWh)  Allocated Battery Power Capacity (kW)
0    50.0                    68.941601                              82.729921
1    76.0                    51.340788                              61.608945
2    79.0                    51.340788                              61.608945
3   252.0                    45.575801                              54.690961
4   203.0                    40.681948                              48.818337
5    32.0                    35.598054                              42.717665
6   257.0                    30.203491                              36.244189
7   129.0                    29.932119                              35.918543
8    58.0                    20.192393                              24.230871
9   231.0                    20.078329                              24.093994
10  277.0                    17.931010                              21.517212
11  269.0                    17.289553                              20.747464
12  184.0                    16.869504                              20.243405
13  280.0                    16.560413                              19.872496
14   23.0                    16.069972                              19.283967
15   37.0                    16.069972                              19.283967
16   45.0                    15.043168                              18.051802
```

Figure 14. Battery capacity associated with node location for average load in 02_ Porkholm

The figure 15 represent the battery's charging and discharging behavior over a 24 hour period under average load conditions at node 50. Charging occurs primarily during night time and late morning hours and the charging power levels reach up to approximately 8.28 kW. BESS is discharge during peak demand hours (6:00 to 9:00 and 16:00 to 21:00) and power output is peaking at around -8.17 kW. This ensures efficient energy utilization by storing energy during off peak hours and supplying it during peak load periods.

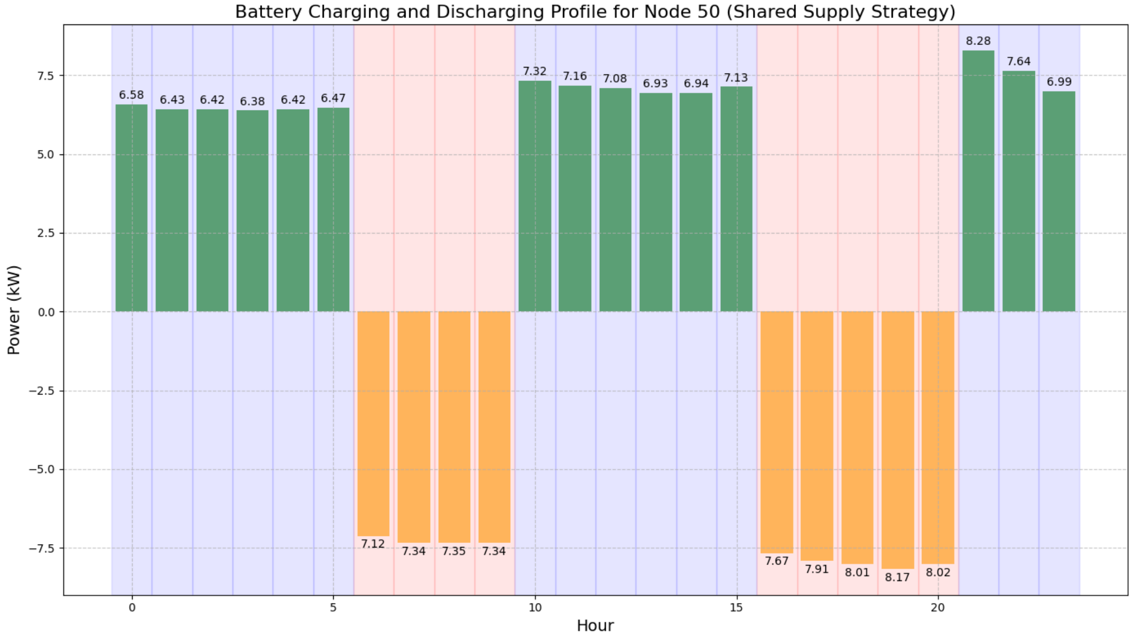
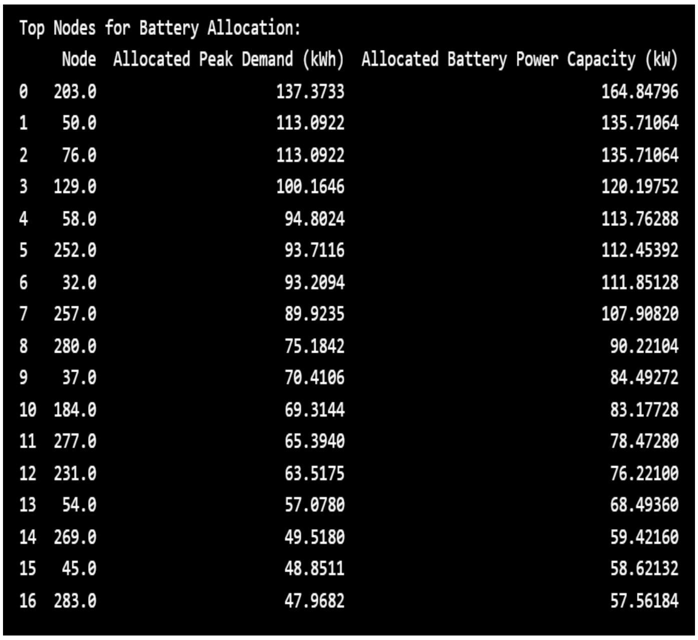


Figure 15. BESS charging discharging for node 50 in 02_ Porkholm network under average load condition

The 02_Porkholm network has 287 nodes and covers 55.39 km and battery distribution is fundamentally more distributed. Nodes 50, 76 and 79 are the best performing nodes under typical load circumstance with peak demand surpassing 50 kWh and needing battery capacity in the range of 61 to 83 kW (Figure 14). These nodes are typically located around the middle or end of feeder branch where upstream utility find it difficult to absorb peak demand and voltage dips are more noticeable. Nodes 203, 50 and 76 show the greatest allotted peak demand up to 137.4 kWh under maximum load circumstance and required 164.84 kW, 135.71 kW and 135.71 kW respectively of battery capacity (Figure 16). These numbers imply that these sites should be given priority for first phase storage deployment as they are essential for controlling winter peak demand. The BESS at Node 203 in the 02_Porkholm network shows distinct charging and discharging behavior under maximum load condition (Figure 17). Charging primarily occurs during low price hours (0–5 and 10–15), with a peak charging power of 16.12 kW at hour 10.

Discharging happens during high demand periods from hours 6–9 and 16–21, and maximum discharging power is -19.14 kW at hour 19.



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Top Nodes for Battery Allocation:
     Node  Allocated Peak Demand (kWh)  Allocated Battery Power Capacity (kW)
0   203.0                     137.3733                              164.84796
1    50.0                     113.0922                              135.71064
2    76.0                     113.0922                              135.71064
3   129.0                     100.1646                              120.19752
4    58.0                      94.8024                              113.76288
5   252.0                      93.7116                              112.45392
6    32.0                      93.2094                              111.85128
7   257.0                      89.9235                              107.90820
8   280.0                      75.1842                               90.22104
9    37.0                      70.4106                               84.49272
10  184.0                      69.3144                               83.17728
11  277.0                      65.3940                               78.47280
12  231.0                      63.5175                               76.22100
13   54.0                      57.0780                               68.49360
14  269.0                      49.5180                               59.42160
15   45.0                      48.8511                               58.62132
16  283.0                      47.9682                               57.56184
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Figure 16. Battery capacity associated with node location for maximum load in 02_ Porkholm

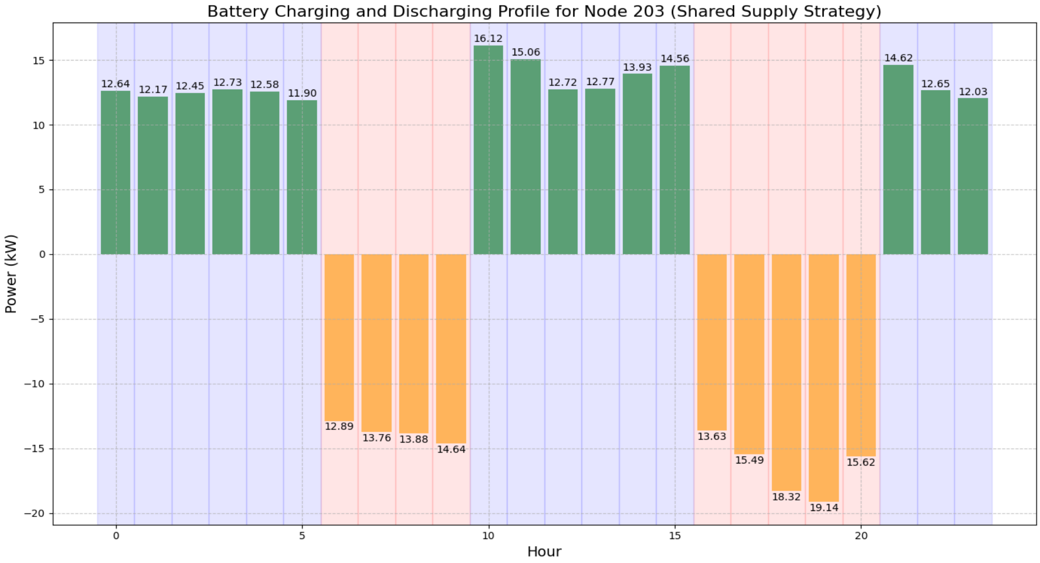
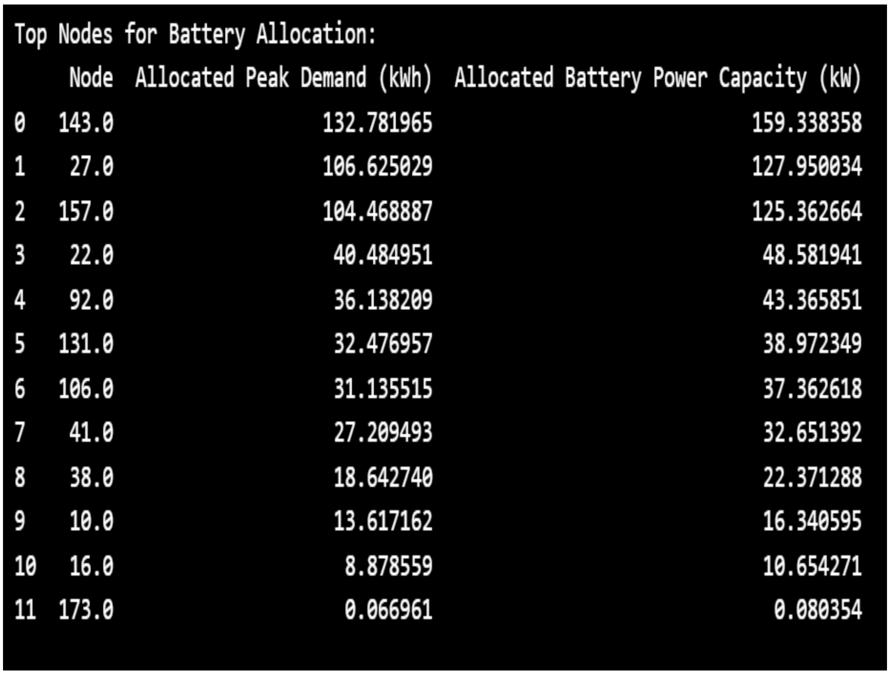


Figure 17. Battery Charging and Discharging Profile for Node 203 under Maximum Load Conditions in the 02_Porkholm Network

It's interesting to note that nodes that rank well for both average and maximum load (such as Nodes 50, 76, 129 and 203) indicate a strategically important location where

BESS can provide flexibility under a range of load scenarios. Since storage may mitigate both heat and voltage limitation, these nodes most likely correspond to residential clusters or small business customers situated farther from primary substation.



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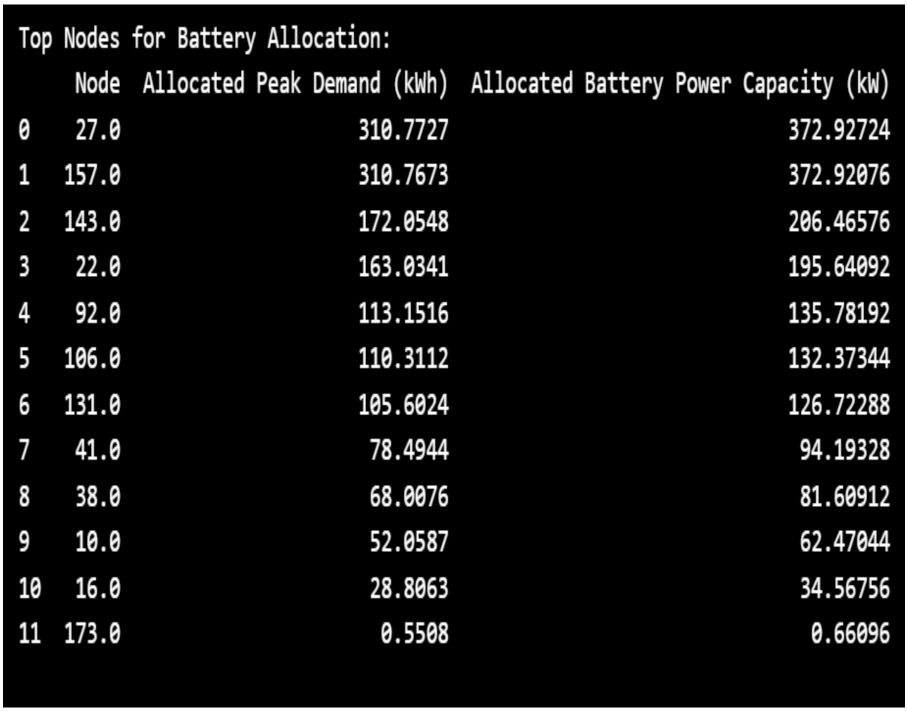
Top Nodes for Battery Allocation:
     Node  Allocated Peak Demand (kWh)  Allocated Battery Power Capacity (kW)
0   143.0                   132.781965                             159.338358
1    27.0                   106.625029                             127.950034
2   157.0                   104.468887                             125.362664
3    22.0                    40.484951                              48.581941
4    92.0                    36.138209                              43.365851
5   131.0                    32.476957                              38.972349
6   106.0                    31.135515                              37.362618
7    41.0                    27.209493                              32.651392
8    38.0                    18.642740                              22.371288
9    10.0                    13.617162                              16.340595
10   16.0                     8.878559                              10.654271
11  173.0                     0.066961                               0.080354
```

Figure 18. Battery capacity associated with node location for average load in 03_Centrum

A more centralised battery allocation is showed by the 03_Centrum network which is smaller and has just 176 nodes. Nodes 143, 27, and 157 are the best options under typical load circumstances with a peak between 104 and 132 kWh and battery capacities of up to 159 kW (Figure 18). Peak demand surpassing 310 kWh and battery capacity above 370 kW indicate that Nodes 27 and 157 dominate the allocation under maximum load scenarios (Figure 19). These numbers indicate network segment are highly loaded and may serve public facility, commercial building or educational institutions with high daytime usage. Nodes like 22, 92 and 131 are present in both load circumstances, indicating that these regions are frequently under demand and have to be taken into account when making storage investment.



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Top Nodes for Battery Allocation:
     Node  Allocated Peak Demand (kWh)  Allocated Battery Power Capacity (kW)
0    27.0                     310.7727                              372.92724
1   157.0                     310.7673                              372.92076
2   143.0                     172.0548                              206.46576
3    22.0                     163.0341                              195.64092
4    92.0                     113.1516                              135.78192
5   106.0                     110.3112                              132.37344
6   131.0                     105.6024                              126.72288
7    41.0                      78.4944                               94.19328
8    38.0                      68.0076                               81.60912
9    10.0                      52.0587                               62.47044
10   16.0                      28.8063                               34.56756
11  173.0                       0.5508                                0.66096
```

Figure 19. Battery capacity associated with node location for maximum load in 03_Centrum

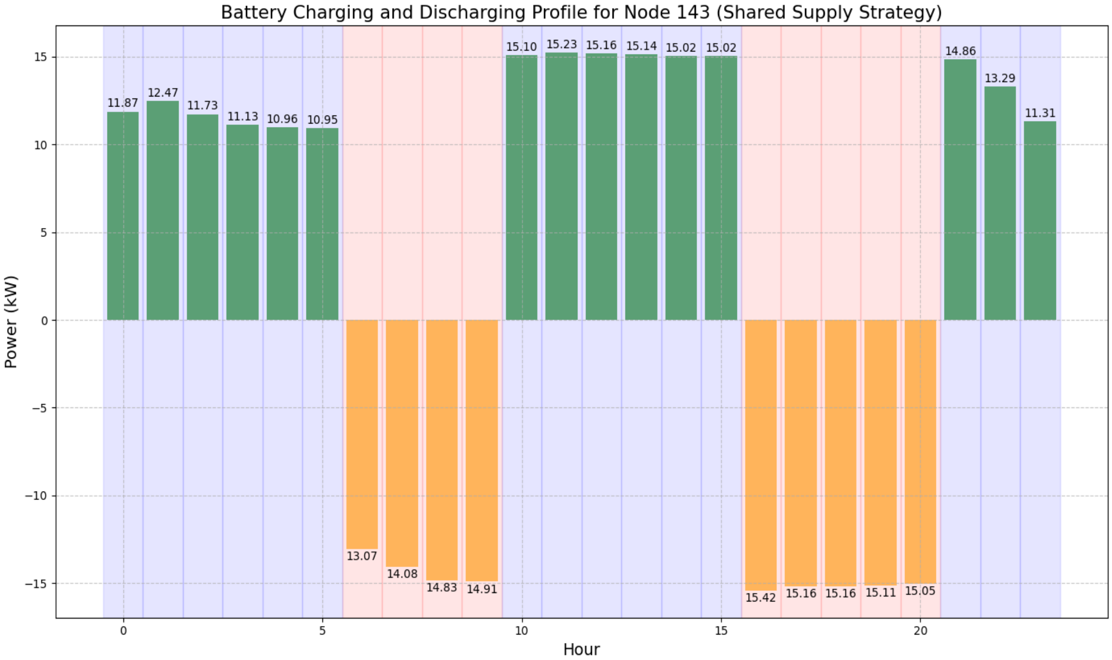

Figure 20. Battery Charging and Discharging Profile for Node 143 under Average Load Conditions in the 03_Centrum Network

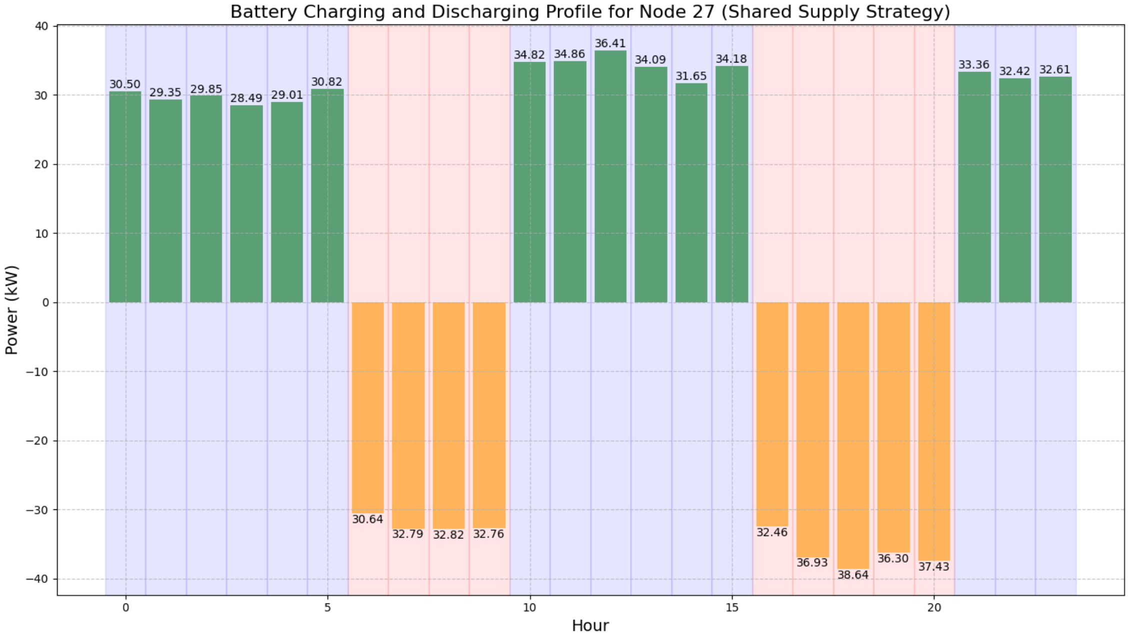

Figure 21. Battery Charging and Discharging Profile for Node 27 under Maximum Load Conditions in the 03_Centrum Network

Figure 20 displays the battery behavior at node 143 under average load condition and figure 21 shows the same for node 27 under maximum load condition. In both cases, the BESS charges during low price hours (blue shaded) and discharges (pink shaded) during high demand period (morning peak and evening). For node 143, charging peaks at 15.23 kW during hour 11 and discharging reaches -15.42 kW at hour 16. For node 27, the charging rate is significantly higher, peaking at 36.41 kW at hour 10 and discharging hits a maximum -38.64 kW at hour 18. The higher discharging values at node 27 suggest more aggressive peak shaving under max load condition. Both figure shows effective alignment with price signals, enhancing cost efficiency and reducing grid stress.

The 03_Centrum network focusses on region with concentrated demand and minimal voltage headroom which enables fewer but larger BESS installation due to its smaller geographic spread and higher node density. In contrast, a more dispersed deployment of BESS could be needed in 02_Porkholm to cover longer feeder length and a larger range of regional variability. Since nodes that score highly for both load situation is most likely to endure constant strain throughout the year and daily cycle. It is suggested that those nodes in both condition be given priority.

From a practical planning perspective, these findings can guide distribution system operator (DSO) investment strategy by identifying high impact location where BESS can provide immediate operational benefit and long term flexibility value. Additionally, DSO supports the flexible incentive system or locational pricing model which might attract community organisation or consumers close to crucial nodes to host BESS or take part in DR program. By using power flow modelling and geospatial analytics, further study will expand on this work and create a node level flexibility heat map. This will help municipalities and DSO decide where BESS investments will have the biggest financial and impactful effect.

4.2.5 Conclusion

Battery storage is an essential tool for improving grid flexibility and accelerating the transition to more sustainable and decentralized power system. The analysis conducted in this research confirms that both 02_Porkholm and 03_Centrum networks can benefit significantly from BESS implementation. This implementation is technically viable and economically acceptable. Strategic deployment of these resource together with demand side flexibility and smart grid technology can help to reduce peak load, avoid capital investment and encourage greater renewable energy integration.

As the government continues to adapt its energy policy and market structure to meet current demand in power system, the integration of flexible resources such as BESS will become a critical component of distribution system development. This research establishes the groundwork for a scalable, data driven storage deployment strategy, emphasising the need of integrating technical analysis with long term planning objective. The insights presented here will contribute particularly to evaluating system dependability, long term scenario planning and policy suggestion for flexible grid evolution.

4.3 Demand Response for Household Appliances and Heating

Demand response (DR) is a significant component of a load management system. It includes programs that encourage consumers to shift their electricity usage during periods of high energy demand. This system uses a response to time-based energy price. The primary objective of DR is mainly to lower the demand for electricity during specific times of the day and improve the stability of the grid. This reduces the need for additional power generation, saving energy and cutting energy costs for consumers. DR programs are valuable because they offer an adjustable cost efficient method to reduce peak electricity usage. DR helps stabilize the grid system by shifting or decreasing load as and when needed. They also reduce the use of peaking power plants and encourage energy efficiency.

There are several methods of demand response program, each of which has different characteristics and features. TOU pricing means that the electricity price is a function of the time of electricity use with relatively high rates at peak demand periods and a low price at other times. This encourages consumers to shift their usage to other times of the day. Critical Peak Pricing uses energy pricing strategies that include rate increases to a customer’s bill only for a few days in a year. Consumers are informed beforehand so that they can either lower their power usage or shift their consumption during these critical periods. Real-time Pricing programs change the tariff of electricity depending on energy supply and energy demand. Prices are frequently updated, for instance, hourly, to reflect the actual cost of generating and transmitting electricity (Nezamoddini & Wang, 2017).

Various researches have shown that DR programs are effective in controlling peak demand while maintaining grid reliability at the same time. According to a recent study by Tiwari and Pindoriya (2022), the optimum flexibility in DR programs could achieve up to 15 percent of peak demand with consumer engagement and advanced metering infrastructure. In a multiple pilot programs design by Dutta & Mitra (2017), dynamic pricing was found to be effective in cutting electricity costs as well as peak loads, though consumer engagement was crucial for success. RTP bring down electricity prices by 10 to 20 percent, although consumer acceptance can be challenging due to the variability and complexity of the modern energy system (Jonsson & Målsten, 2023).

The incorporation of renewable energy sources into distribution network adds unpredictability in both generation and consumption pattern. This leads to increasing problem in maintaining grid stability especially during peak demand period (Rahman et al., 2020b). In this scenario, demand response (DR) appears as an essential way to boost flexibility without needing fast infrastructure reinforcement. This section includes a complete examination of the DR potential across various consumer groups within the 02_Porkholm and 03_Centrum network with the purpose of identifying opportunities for peak load reduction, energy cost reduction and load shifting.

4.3.1 Demand Response and Load Profile for Household Appliances

Demand response refers to the change of energy use by end users in response to supply situation. This could include lowering use during peak hours or shifting usage to times when renewable power is more abundant or when grid capacity is underutilized. DR can be incentivized by technique like as time TOU tariff, real time pricing or automated load management system that are connected with smart meter infrastructure (Häseler & Wulf, 2024).

The research originated with a categorization of customers according to their operational behavior and load type in order to evaluate the DR potential in the network. Residential housing (with and without heat pumps), cottages, farms, small offices, schools, hotels, retail shops, industries and garages were among the eleven groups into which consumers were divided (Esse Elektro-Kraft Ab, 2025). Table 3 displays the number of consumers by consumer category. Appliance loads such as irrigation pump and household appliance and heating loads such as Heating, ventilation and air conditioning (HVAC) system, electric heater, hot water tank and heat pump where the two categories into which consumption was further divided within these groups (Table 3) (Carmichael et al., 2020; Pipattanasomporn et al., 2014; Wohlfarth et al., 2020). Since heating systems usually provide more load shifting capability because of their thermal storage capacity, this classification allows for a more comprehensive study of flexibility.

Table 3. Consumer type and number in 02_Porkholm and 03_Centrum networks

Consumer Type	Consumer Number
House, electric heating + hot water tank	289
House with heat pump	55
Apartment	43
Farming	27
Offices	7
Schools	1
Cottage	51
Retail store	2
Hotels	1
Industry	2
Garage	1
Total	**479**

Classifying the yearly operating hours into peak and off peak periods performed as a framework for the sequential part of the research. In accordance with high national demand and grid stress, peak hours were established for the majority of residential and commercial users as the times between 7:00 to 10:00 and 16:00 to 21:00 on weekdays. Weekends, evenings and daylight hours outside of peak times were all considered off peak hours. The quantity of energy that could be moved from peak to off peak time was estimated using simulation model. Hourly consumption data and the corresponding cost reductions have been calculated using the real time electricity pricing structure. Preheating solutions which include turning on heating before peak times begin and storing thermal energy for later use which also taken into consideration in this research.

Table 4. Demand Response participation between consumer groups

Consumer Type	Demand Response Participation	
	Appliances	Heating
House, electric heating + hot water tank	Washing, Dishwasher	Full Heating System
House with heat pump	Washing, Dishwasher	Full Heating System
Apartment	Do not participate in DR	Do not participate in DR
Farming	Irrigation Pumps	Full Heating System
Offices	Do not participate in DR	HVAC (Heating)
Schools	Do not participate in DR	HVAC (Heating)
Cottage	Washing, Dishwasher	Full Heating System
Retail store	Do not participate in DR	HVAC (Heating)
Hotels	Laundry	HVAC (Heating)
Industry	Do not participate in DR	HVAC (Heating)
Garage	Do not participate in DR	Do not participate in DR

4.3.2 Segment Wise Results and Insights

The findings of the simulation showed that different groups of customer had different pattern of DR potential. Peak shifting led to a 5.8% decrease in total energy cost and an annual savings of around €23.43 per family for residential customers which have electric heating and hot water tank. These savings are predicated on shifting around 4221 hours of peak use per year to off peak time. Cost reductions in homes and cottages with pre-heating capabilities were around €23.23 year. Additionally, energy saving increases to 196.27 kWh annually which results in a 16.45% decrease in total energy cost.

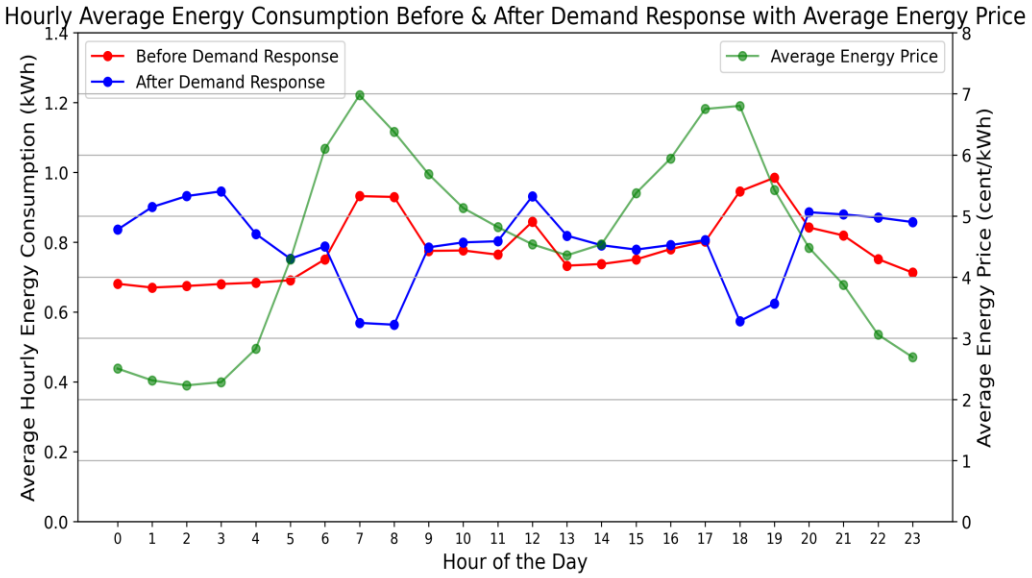

Figure 22. Hourly average energy consumption before and after appliance based DR in residential buildings

These results show the unexplored possibility of using the current heating infrastructure in conjunction with basic automation technique. This also provides grid optimization and a financial advantage. The hourly average energy usage in residential buildings before and after appliance based DR is shown in Figure 22. The load is moved to off peak hours when energy prices are high.

Due to their increased efficiency and flexibility, consumers who own heat pumps showed a higher level of flexibility. Heat pumps are becoming more and more common in modern Finnish homes. DR simulation showed savings of €21.49 on heating per year (16.89% decrease) and €38.49 per year on appliance load (7.06% reduction) for this group. Also, it shows an annual energy shift of 185.11 kWh for heating alone. These results imply that heat pump users constitute a high potential demographic for DR initiative. The hourly average heating power in residential buildings before and after DR approach is shown in Figure 23. The DR moves consumption to lower priced time and lowers heating power during peak pricing hours (7AM to 8 AM and 5PM to 7 PM). This maintains comfort while reducing energy expenses. Figure 24 explains the monthly usage of heating electricity in residential buildings both before and after the deployment of DR.

Heating demand is continuously decreased by the DR approach particularly in the winter months.

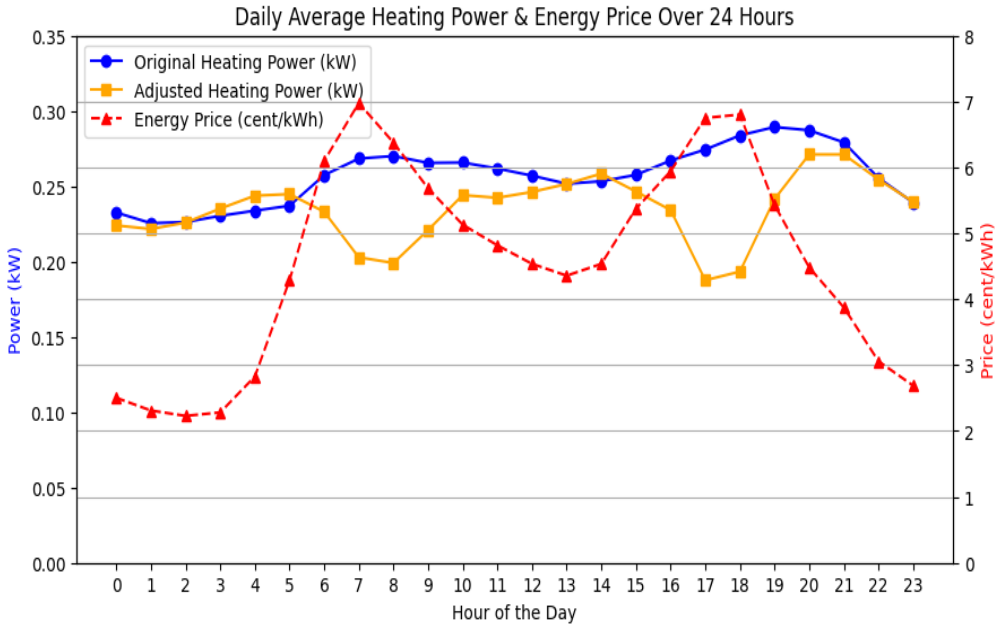

Figure 23. Hourly average energy consumption before and after heating-based DR in residential buildings

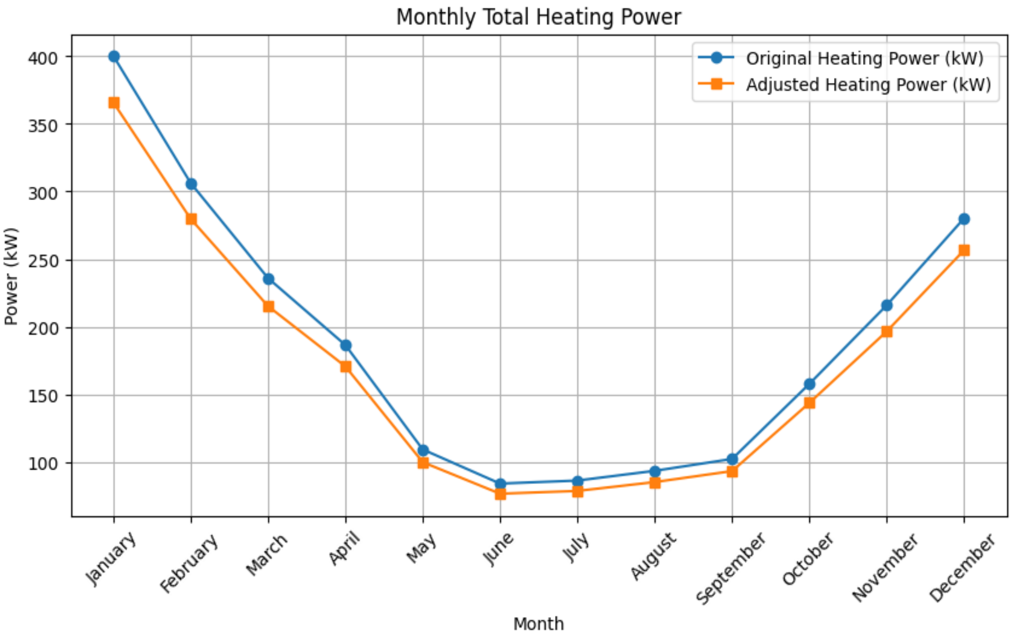

Figure 24. Monthly energy consumption before and after heating-based DR in residential buildings.

A great possibility for flexibility was the agricultural sector which is frequently overlooked in DR studies. By moving loads like the irrigation pump, farming users reduced the cost of by 14.42 %, saving €48.43 per year. The cost reduction for heating application in the agricultural sector amounted to €41.03 per year. Over 707.46 kWh of appliance energy was shifted by applying DR.

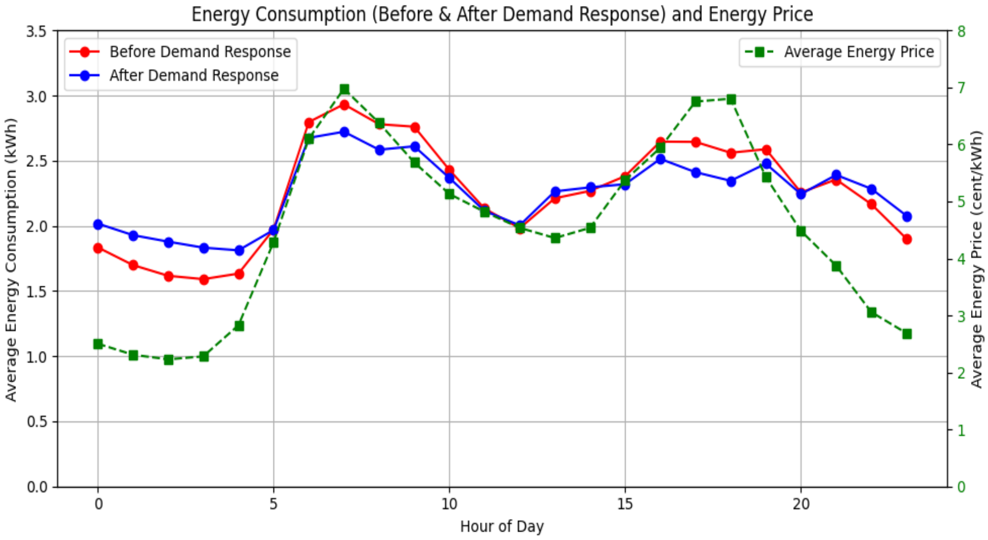

Figure 25. Hourly average energy consumption before and after appliance-based DR in farm

Agricultural operations are repetitive and planned; therefore, there is a lot of room for automated DR solution in the agricultural sector, especially with the help of digital monitoring and control system. A farm's hourly average energy use before and after implementing appliance based DR is shown in Figure 25. The blue line shows decreased use after DR. The red line shows increased consumption at times of highest price. The green dashed line shows the average energy price which peaks between 7AM to 8 AM and 5PM to 6 PM. In order to decrease expenses, DR efficiently shifts and lowers demand during peak hours.

Figure 26 represents the hourly average energy consumption in the farm before and after implementing a heating based DR strategy. The orange line displays the modified heating power after the application of the DR strategy. The blue line represents the initial heating power usage. The hourly energy price in cents/kWh is shown by the red dashed line. The price of energy rises between 7AM and 8 AM and again between 5PM and 7 PM in the evening.

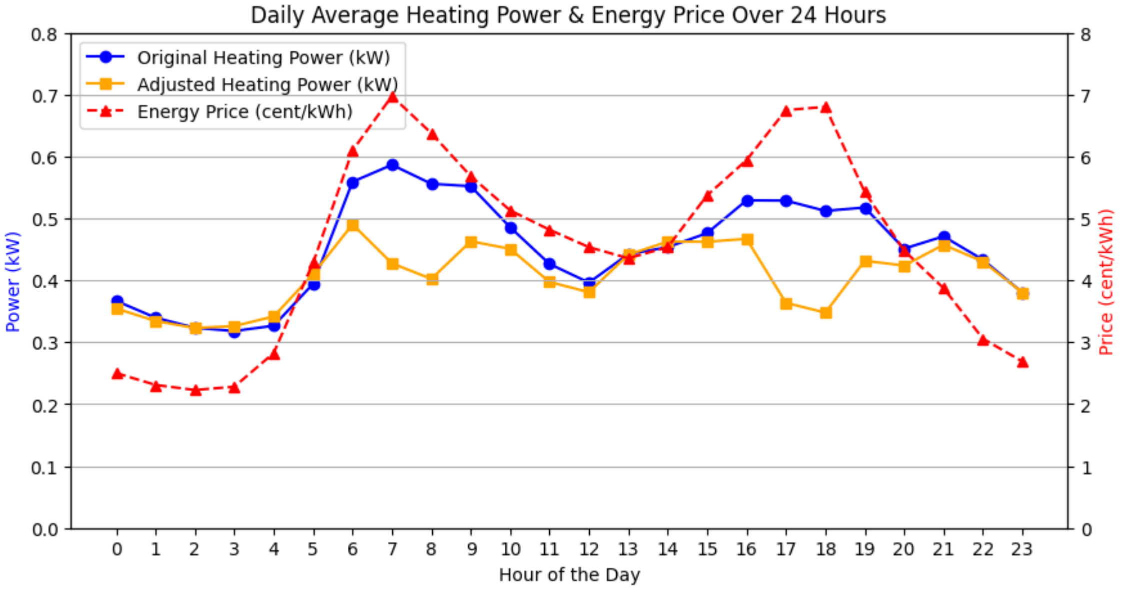

Figure 26. Hourly average energy consumption before and after heating-based DR in farm

In order to minimise energy expenditures during these high price times, the DR method lowers heating power use. On the other hand, when energy costs are reduced, the heating load is increased due to pre heating strategy. This change in heating demand supports cost effectiveness while maintaining indoor comfort by balancing energy consumption with more reasonable price time and flattening peak load.

Institutions in both the public and private sectors also showed significant DR potential. For instance, schools with set hours and high winter heating needs might save up to €51.56 a year (12.57% cost reduction) by applying pre heating and modifying heating schedule. This corresponds to over 422.60 kWh (1.67% energy reduction) of energy savings, a notable contribution when scaled across several buildings. The original and modified heating power usage in school buildings during a 24 hour period is compared with energy cost in Figure 27. During peak pricing hours (about 7 to 8 AM and 5 to 6 PM), the adjusted heating power (orange) is decreased by the demand response approach. This change maintains comfort levels while reducing energy expense.

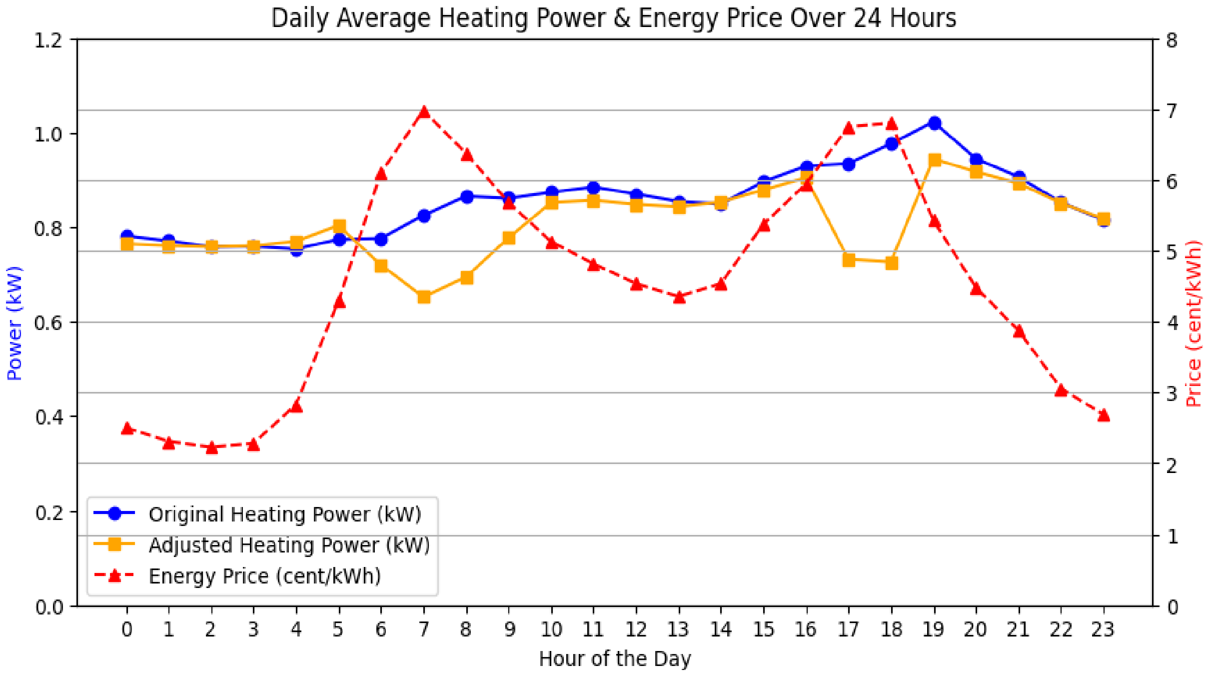

Figure 27. Hourly average energy consumption before and after heating based DR in school buildings

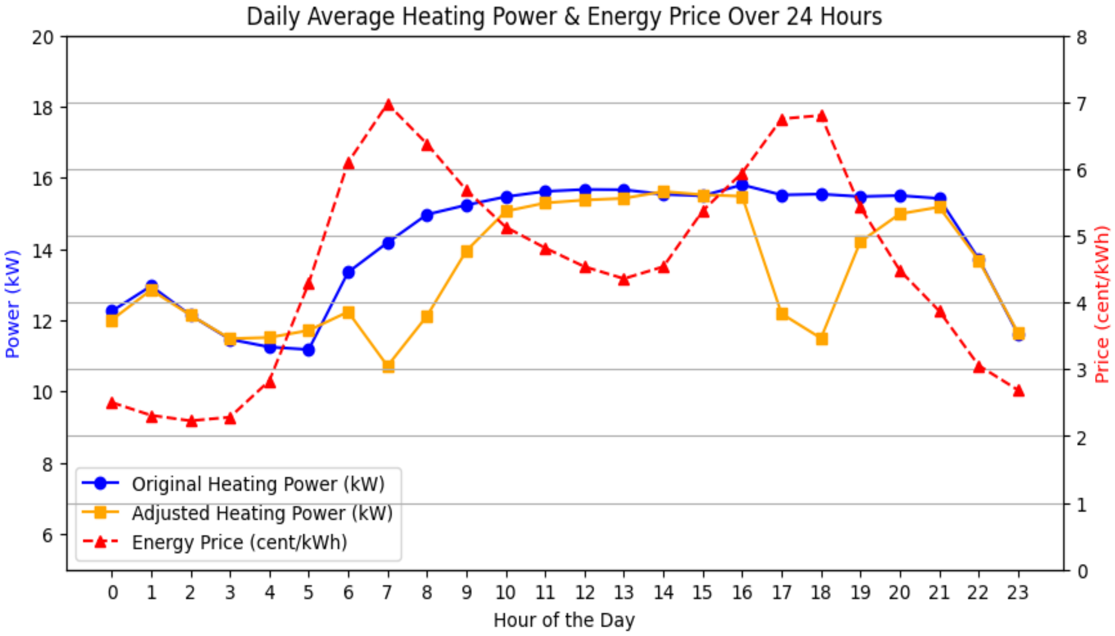

Figure 28. Hourly average energy consumption before and after heating-based DR in retail store

The most significant outcome was in the retail shop where heating loads were optimised to save €695.29 per year by reducing costs by 13.33%. The DR in retail shop shifts a remarkable 7006.47 kWh of energy from peak hours. These results show that the need for energy saving and adaptable measures are top priority in commercial buildings especially when using automated building energy management system. A retail store's hourly average heating power before and after using a heating based DR method is shown in Figure 28. Throughout the day, the initial heating power is constant but at times of high demand particularly between 6 to 8 AM and 5 to 6 PM, the adjusted power (orange) is decreased. These decreases show cost optimization behaviour as they correspond with increases in the price of energy (red dashed line). The adjusted heating demand rises during off peak hours for pre heating. This suggests an effective load shifting technique that lowers energy expenses without sacrificing comfort.

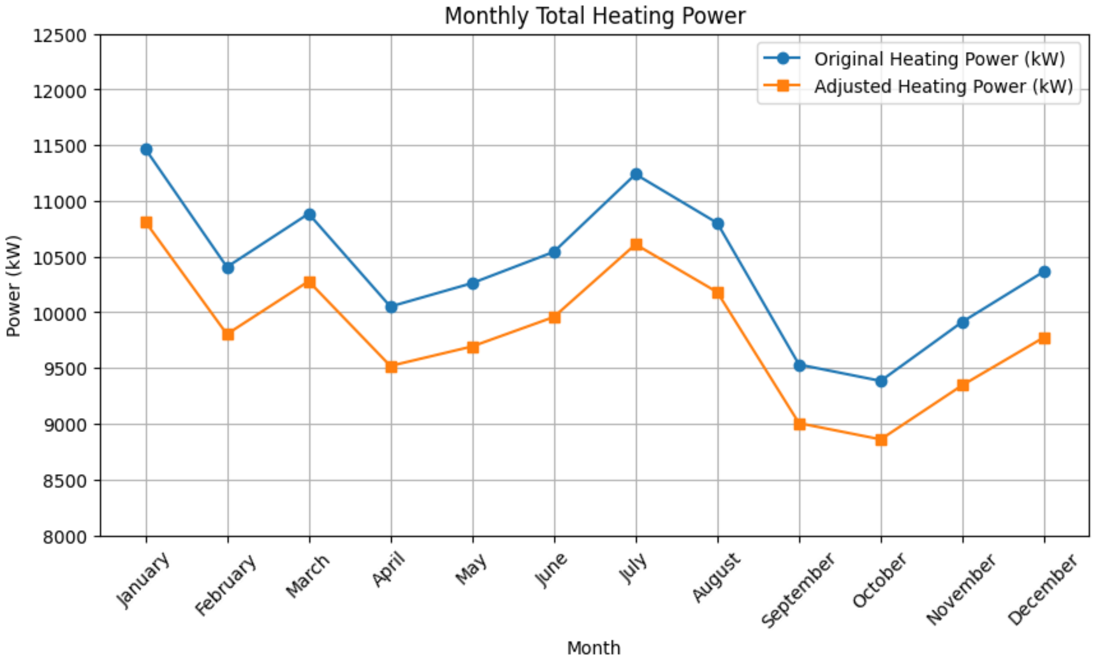

Figure 29. Monthly average energy consumption before and after heating-based DR in retail store

The monthly total heating power at a retail store before and after a demand response strategy was shown in figure 29. Throughout the year, the adjusted power (orange) is always lower than the initial heating power (blue). Notable decreases have been achieved by the DR approach especially during the colder months of January, February and December. The DR method successfully lowers monthly heating energy use while taking seasonal fluctuations into account.

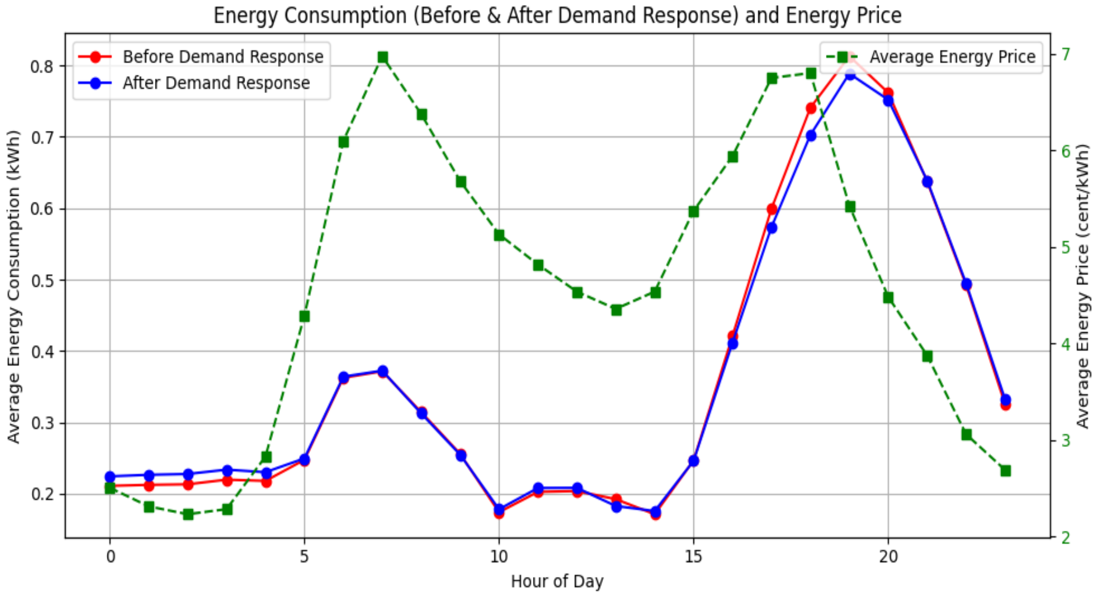

Figure 30. Hourly average energy consumption before and after appliance based DR in hotel

Smaller segments such as cottages, hotels and small offices also showed measurable benefit. Hotels saved €2.96 on appliances and €13.87 on heating, for a total shift of 173.41 kWh. Cottage user saved €15.47 on appliance consumption. Despite having lower total energy consumption, small offices nonetheless made a contribution to the flexibility landscape by shifting 9.32 kWh of energy and saving €1.19 per year. Even though each of these amounts might seem small when added up over hundreds or thousands of customer taking part in a local flexibility program, they become important. Figure 30 displays the average energy price and hourly energy use in a hotel before and after appliance based DR was implemented. Following DR, energy use is moved to lower priced times and decreased during peak pricing hours (17:00 to 21:00). This suggests efficient load shifting to save energy expenses. Figure 31 shows the changes in energy prices and the corresponding hourly average heating power usage in a hotel, before and after the implementation of heating based DR. The adjusted heating power shows a discernible decrease during those peak price times while the original heating output peaks during high price hours (18:00 to 21:00). Particularly in the early morning and the afternoon hours, heating demands are moved to a less expensive period due to pre heating strategy. The change makes energy use more consistent with times of lower price. This proves efficient load control and cost reduction using DR technique.

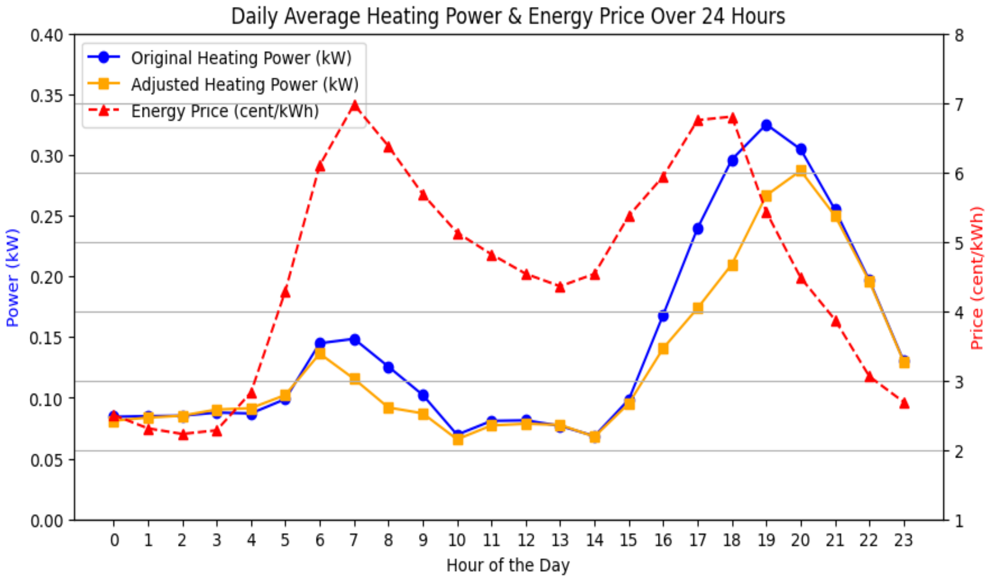

Figure 31. Hourly average energy consumption before and after heating based DR in hotel

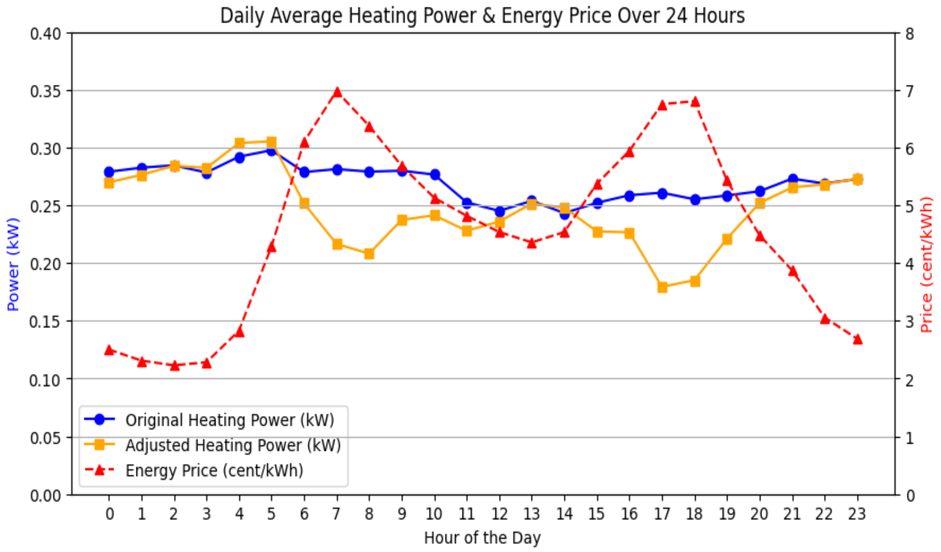

Figure 32. Hourly average energy consumption before and after heating based DR in industry

Finally, the research found that industrial users saved €34.75 per year on heating (15.05% cost reduction) and saved roughly 193.33 kWh of peak period energy. Dur to industry's continuous operation and process driven nature, DR may need advance technology integration and real time management. However, even small-scale initiatives such as thermal energy storage or demand forecasting may result in significant operational gains. Figure 32 depicts industrial heating power use before and after heating based DR. The regulated heating power is significantly lowered during peak hours (6:00 - 8:00 and 17:00 - 19:00). This load is transferred to lower-cost hours particularly in the early morning and evening for preheating. The DR strategy effectively reduces energy costs by aligning consumption with pricing signal.

4.3.3 Implications and Aggregated Impact

The demand response study results show that peak shaving and load shifting may be successfully implemented in diverse customer categories using existing infrastructure and basic control logic. The visual representations created for the project reveal that retail, agricultural and residential users have the most possibility for grid support and cost optimisation via DR. Residential customers particularly those who use heat pumps or electric heating, make a major contribution especially during the winter months when peak demand is high and grid stability is crucial.

While the savings per user may be modest in many categories, the cumulative effect across a region wide program involving hundreds of end users can be substantial (Reeve et al., 2022). For example, shifting just 1 MWh of peak period consumption to off peak period per day across a community can significantly reduce strain on substation and transformer capacity. For this saving, there is no need for costly network upgrades. The finding strongly support investment in DR enabling technology, including smart thermostat, programmable logic controller and dynamic pricing model. Adoption may also be accelerated by raising awareness among end users about the financial and environmental advantages of taking part in DR initiative. Stakeholders including DSO, municipal energy agency and technology suppliers must work together to implement scalable DR program driven by data platform, flexibility market and consumer engagement strategy in order to maximize the DR potential.

4.3.4 Conclusion

The analysis of the 02_Porkholm and 03_Centrum networks provides valuable insight into identifying target segment for implementing DR strategy. Applying clustering approaches based on user profile and utilising a full year of hourly energy consumption data, the study found that different user types especially those in the residential and commercial sectors had diverse consumption behavior.

The results show that the most promising target group for DR adoption are retail store and residential building. The majority of users on both networks are residential and they show an extensive amount of flexibility in their load pattern particularly in the evening when demand is usually at its highest. Because of their adaptability, they are good possibilities for load shifting using DR technique like smart appliance control and TOU pricing. Additionally, Residential consumers have a greater chance of participating in DR program since they frequently use electric heating and other movable equipment.

Retail stores with consistent operating hours and relatively high energy use are the only one found in the networks under this analysis. Therefore, they are ideal option for planned load reduction or targeted DR initiatives that focus on peak shaving. One retail shop in the network makes it easier to coordinate and monitor demand side actions. This makes the implementation of DR in such situation more manageable. Due to its size and diversity, the 02_Porkholm network provides potential for more segment specific and detailed DR strategy. On the other hand, the 03_Centrum network is ideal for larger, community level DR project because it’s more uniform and lower load profile.

In conclusion, residential buildings are the main target for DR deployment because of their large customer base and operational flexibility. Additionally, a single retail outlet stands out as a high impact and manageable DR option. By applying DR technique to these segments, network efficiency may be greatly increased. Also, peak load can reduce and support the energy system's broader objectives of flexibility and sustainability.

4.4 Optimization of Heating System Usage

Residential heating alone accounts for between 40 and 60 % of yearly home energy usage in Nordic nations like Finland where heating accounts for a significant portion of overall energy consumption (Ju et al., 2021). Extreme cold during the winter months causes significant electrical usage which increases strain on the grid's flexibility and stability. In Finland, peak load stress on distribution network is greatly increased during the winter month due to an unprecedented rise of demand for energy for heating (Söder et al., 2018). Therefore, optimizing heating system usage is critical for enhancing demand side flexibility, reducing energy cost and supporting renewable energy integration.

This chapter examines the use of optimized heating system usage techniques, TOU pricing signal and smart control technology for more effective heating load. Smart thermostat and thermal energy storage are two examples of technology that enables household to move heating load from peak to off peak hours without sacrificing comfort. According to research, smart heating control may lower peak demand by up to 25% and cut electric heating energy consumption by 10% to 20% (Liu et al., 2025). A more robust and sustainable power system may be achieved by incorporating these approaches into home energy management system to match heating demand with the availability of renewable energy sources and different grid scenarios.

4.4.1 Heating Load Profiling and Seasonal Variations

In Finland's extremely cold climate, heating constitutes a considerable share of home and business energy demand especially during long winter months. This study evaluates heating demand trend across diverse customer category including residences with electric heating, heat pump, flat and different commercial facilities. The heating load was grouped according to user group characteristics and the average consumption per cluster was used for the simulation to create a generalized heating load profile.

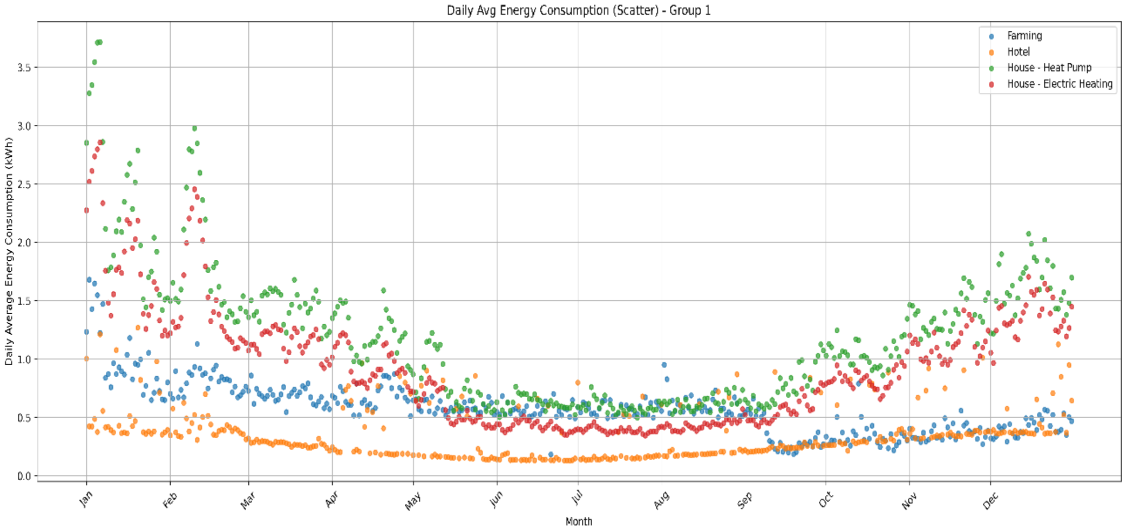

Figure 33. Daily average energy consumption of group 1

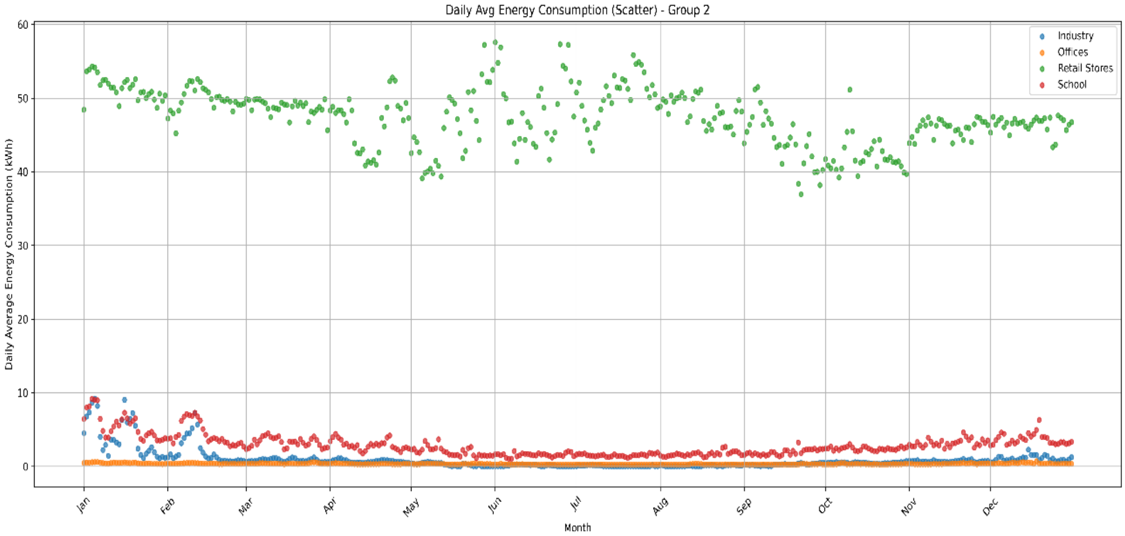

Figure 34. Daily average energy consumption of group 2

Figures 33 and 34 show the daily average energy consumption (kWh) for different types of buildings and facilities across each month of the year. Figure 33 represents group 1 which includes farming, hotel, house with heat pump and house with electric heating. In this group, energy use is the highest during the colder months (from January to March and November to December). Houses with electric heating peaks at over 3.5 kWh. Hotels and farming show relatively stable consumption with slight seasonal variation. Heat pump with houses show moderate seasonal fluctuation. Figure 32 shows group 2 which includes industry, offices, retail stores and schools. Retail stores have the highest and the most stable energy consumption year round, averaging around 45 to 55 kWh daily. Industry, offices and schools show much lower and more variable consumption (often below 10 kWh). School energy use decreases significantly during summer months due to closures and rises again in fall. Offices and industrial facilities show modest seasonal changes with slight dips in the mid year for summer holidays. Residential buildings show strong seasonal dependence while commercial facilities such as retail store maintains high and steady energy demand across the year.

The study distinguishes between winter and summer seasons characterised by outside temperatures. As indicated in the simulation logic, any outside temperature below 10°C is deemed as a wintertime. This distinction is crucial for considering that Finland has long winters where outside temperatures regularly dip below -20°C. During these winter months, heating demand rises substantially to ensure indoor thermal comfort across all types of buildings.

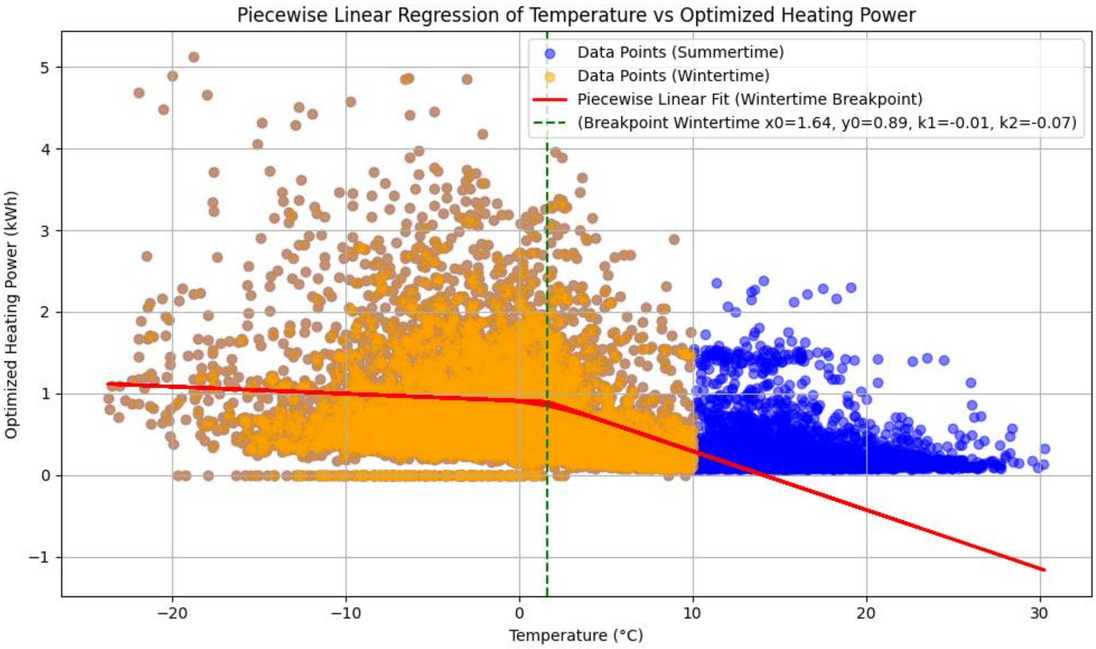

Figure 35. The relationship between temperature and optimized heating power

The scatter plot of optimal heating power vs temperature (Figure 35) highlights this seasonal reliance. Data points labeled for winter (in orange) and summer (in blue) show a clear disparity in heating demand. Wintertime data clusters around higher energy usage rate typically surpassing 3 to 4 kWh. On the other hand, midsummer consumption reduces dramatically which indicates little heating demand.

Consumer groups display various demand characteristics based on their building type and heating method. For instance, buildings with heat pumps usually exhibit more gradual rises in consumption due to the efficiency of the heat pump's coefficient of performance which declines at very cold temperature. In contrast, electrically powered heating systems such as those in cottages or older flats display greater demand spikes at lower temperature.

Schools and companies also exhibit significant weekday vs weekend trend. However, for this average profile study, temporal patterns were normalized. Despite these discrepancies, all groups followed a similar seasonal trend, demonstrating the validity of clustering and averaging in this circumstance.

4.4.2 Optimized Heating System Operation

The flowchart indicates that the study begins with inputting data on energy usage, outside temperature and energy price. One essential assumption is that heating consumption is 40% of total energy usage which is a realistic estimate for buildings with electric heating system. The heating profile is further optimised using piecewise linear regression particularly for wintertime. This technique accurately captures the nonlinear response of heating power to temperature fluctuation when temperatures outside approach freezing.

From the regression data, a breakpoint is observed at around 1.64°C (Figure 35). This breakpoint reflects a shift in the heating system's response time. Above this breakpoint, heating demand declines steadily. However, below this threshold, the slope steepens which indicates a quicker increase in heating demands as the weather turns colder. This behavior is consistent with the thermal properties of building and the performance curves of heat pump and resistive heating system.

To enhance energy efficiency and minimise costs in Finland's heating sector, the study applies an optimum control method for electric heating system. The idea is to preserve customer comfort while shifting energy consumption to periods with reduced electricity pricing. This is particularly essential in places with dynamic pricing and large seasonal demand oscillation.

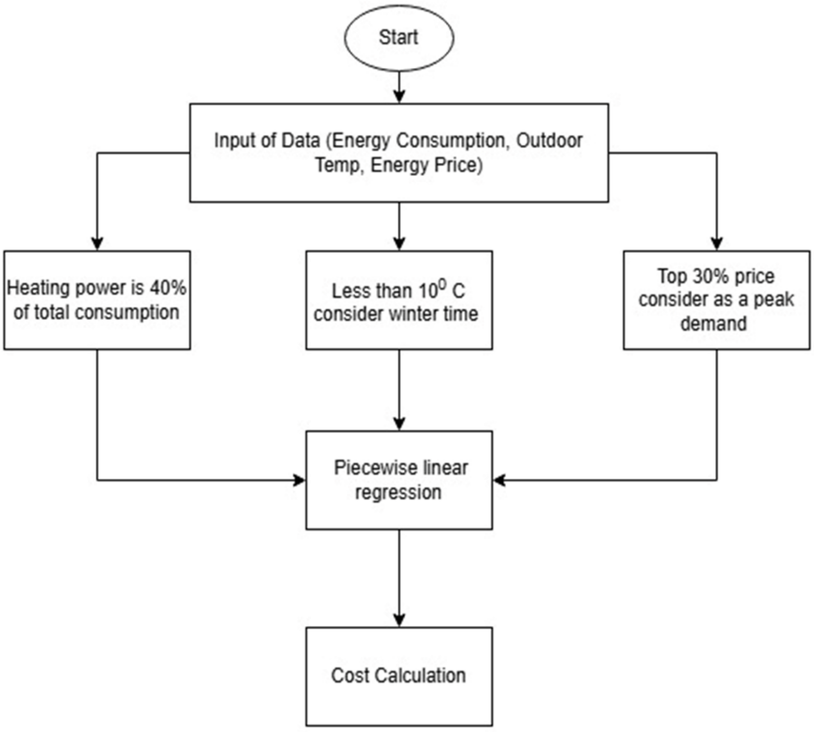

Figure 36. Flowchart of the working process of optimized heating

The optimization process begins with the collecting of three basic datasets (total energy use, outside air temperature and hourly power cost). These variables are crucial in deciding when and how much energy should be used for heating system. As indicated in the flowchart (Figure 36), data is processed to extract heating power defined as 40% of the overall energy usage. This assumption reflects typical energy usage in electric heating house and public building in Finland. A major stage is detecting wintertime circumstance based on ambient temperature which are defined in this study as periods when outside temperatures dip below 10°C. Wintertime circumstances are essential since heating demand, energy pricing and system restriction all increase during winter season.

Electricity pricing in Finland generally changes hourly with the highest 30% of costs considered as peak demand hours. The system finds these high price windows and moving heating operation during these times by the optimization of load operation as long as thermal comfort limits are satisfied. Using historical and predicted data, the system intelligently cuts heating output during high pricing hours and runs the heating system in optimum condition. The assumption is that buildings can hold heat for several hours without a noticeable decline in inside temperature which is particularly applicable in well insulated Finnish structure.

To represent the nonlinear nature of heating demand related to temperature, the method adopts a piecewise linear regression model. The model that was fitted (see Figure 35) suggests two separate heating behavior patterns with a breakpoint approximately 1.64°C. Below this threshold, heating demand grows more steeply with decreasing temperature necessitating more rigorous regulation to avoid expense spike. This regression model assists in calculating the ideal setpoint temperatures and working times, aligning system functioning with pricing and thermal dynamics. The regression coefficients (k1 = -0.01, k2 = -0.07) indicate the rate of change in heating power over temperature segment and guide the load optimized strategy.

Each consumer category, for example homes, offices, schools, was simulated using average load consumption data. By applying the improved control logic equally across the groups, the simulation caught overall cost saving trend while smoothing out building specific irregularities.

In reality, this technique may be linked to smart thermostats or home energy management systems. This provides an automatic reaction to real time pricing indication. With extensive implementation, such devices might help for flattening the national load curve which lowers peak demand stress on the grid.

The implementation of an efficient heating control technique resulted in large savings in both power expenditures and usage throughout the winter season. The result was reached by load optimization and intelligent scheduling, applied across diverse consumer groups including private residence, apartment, public building and commercial facility. The simulation used average load profiles for each group, found that the initial total wintertime heating cost of 196.99 € could be lowered to 70.32 € through optimization which gives a cost savings of 126.67 €, comparable to a 64.3% decrease per user. In addition to cost reductions, the method generated total electricity savings of 871.63 kWh throughout the winter month. These results underline the potential of algorithm based management to dramatically reduce heating related energy usage without compromising thermal comfort.

The amount of savings varies per user group. Buildings with direct electric heating such as flats or cottage show the biggest relative savings due to their more sensitive and less efficient heating system. In contrast, households with heat pumps exhibited more moderate saving as heat pump already work effectively yet benefit from price sensitive scheduling. Public facilities like school and workplaces shown prominent weekday load pattern which allowed the optimization algorithm to take advantage of low price times during off hours. Retail outlets and industrial customers also profited from tailored scheduling that curtailed activity during high power pricing window.

At the foundation of the approach was the selective avoidance of high price periods which are defined as the top 30% of hourly power prices. At this time period, heating loads were lowered at optimized level operation. This strategy harnessed the thermal inertia of buildings, allowing them to hold heat for short intervals without requiring continual energy input. The system was further strengthened by a piecewise linear regression model which properly projected heating power need depending on external temperature with a breakpoint at roughly 1.64°C. Below this level, heating demand scaled dramatically which causes the system to perform more aggressive load management.

Beyond individual consumer saving, the optimization technique leads to greater systemic advantage. Reducing peak demand helps reduce stress on the power grid especially during harsh winter condition. It also assists environmental goals by minimising power use particularly during hours when fossil fueled generating may be more frequent. Additionally, matching heating demand with lower price period often coincides with increased renewable energy availability that improves the overall sustainability of the heating system. In summary, the simulation demonstrates that smart regulation of heating systems is a very successful, scalable way to achieve both economic and environmental gains in cold climate energy system.

4.4.3 Comparison with Existing Studies

To validate the effectiveness of the suggested thermal optimization technique, results were benchmarked against finding from existing literature. Numerous studies have studied heating energy optimization, particularly in cold climate nations such as Finland, Sweden, Germany and Canada. In those regions, seasonal heating load forms a considerable fraction of overall energy demand.

A research by Nilsson et al. (2018) on load control in households indicated that intelligent heating management utilising spot price signal which might cut electricity expenses by 20% to 35% without impacting occupant comfort. Similarly, Allard et al. (2013), evaluating Finnish homes equipped with heat pump, showed that preheating and load optimization methods might cut wintertime power demand by up to 30% which depending on building insulation levels and thermal inertia.

In comparison, the proposed optimization framework produced a 64.3% reduction in heating expenses and saved 871.63 kWh throughout the winter simulation period. These results reflect a substantial improvement above usual reported value in past research. Two primary variables contribute to the larger saving observed.

Targeted avoidance of peak pricing by expressly optimizing the top 30% of power prices from heating operation. The system applies a more aggressive and cost responsive load optimization strategy compared to standard approaches that generally depend on averaged or smoothed pricing signal. Rather than concentrating on individual buildings, the simulation employed clustered average load profiles for numerous user categories, including residential, business and public sector structures. This enabled a larger system level assessment of possible saving.

Moreover, the adoption of piecewise linear regression to estimate heating power in relation to temperature gave enhanced accuracy over typical linear or rule based demand model. Breakpoint analysis allowed for more precise control tactic particularly around crucial outside temperature which improves both energy and cost efficiency.

While the simulated findings exceed the usual savings mentioned in literature, they remain within a practical range. The larger cost savings may represent idealized modeling setting such as optimal system reaction times, consistent price signal and well insulated building. Practical installations may provide slightly lower but still considerable. The findings are consistent with the prevalent view in the literature. Dynamic load optimization and price responsive heating regulation are successful technique for decreasing energy consumption and cost in cold region. The upgraded modeling and simulation approaches further indicate that large increases are feasible with modern AI based optimization technique and real time model.

5 Conclusion & Recommendations

5.1 Summary of Key Findings

This thesis observed strategy to integrate demand response, battery energy storage system and photovoltaic system into regional distribution networks in order to maximise smart grid resilience and flexibility. Esse Elektro-Kraft's 02_Porkholm and 03_Centrum networks in western Finland reflect rural and semi urban environment respectively. Those networks were the study's primary focus area. The study examined network hosting capacity, ideal location and user side flexibility technique using hourly resolution smart meter data, a Python based modelling and simulation framework.

One of the main results is the finding of considerable difference in PV hosting capacity across various nodes which is largely impacted by load parameter, network structure and node resistivity. The 02_Porkholm network has a scattered residential base and lengthy radial feeders. The hosting capacity of this network ranges from 2.4 kW to 278 kW. Furthest nodes showed energy restriction whereas nodes with low line impedance or close to primary substations were best suited for PV integration. The 03_Centrum network showed more reliable PV hosting capacity due to its denser urban layout. Variations in seasonal demand, particularly 02_Porkholm's winter heating requirement had an important effect on the viability and advantage of PV deployment.

Additionally, the thesis showed that battery energy storage system is essential for increasing grid flexibility especially through frequency management and peak shaving. The best BESS unit location and size were made possible by the simulation conducted under both maximum and average load circumstances. The use of BESS at voltage sensitive, high load nodes in 02_Porkholm decreased transformer stress and increased dependability. Battery installation in 03_Centrum showed economic potential in handling peak demand during office hours. The efficiency of BESS under actual operating setting was confirmed by key performance indicator such state of charge profile, energy shifting capacity and peak load reduction.

User segmentation and appliance level flexibility modelling provided a basis for the development of demand side DR method. Different DR potentials and consumption pattern were shown by residential and commercial customers. Simulations of load shifting revealed that although heating loads offered the greatest potential for reducing peak consumption, appliances like dishwashers and washing machine could be rescheduled with little inconvenience to users. In both networks, automated HVAC system, TOU pricing and smart thermostat are needed for successful DR implementation. Heating optimisation also showed that by adjusting heating load to suit PV availability and dynamic pricing, peak winter demand may be reduced by as much as 20%. Overall, this thesis presents a thorough framework for merging network side and user side solutions to improve smart grid resilience. It has been shown that integrating PV, BESS and DR improves energy sustainability, minimizes upgrading infrastructure and reduces operating risk.

5.2 Future Research Directions

Although this thesis provides a thorough framework for using PV, BESS and demand response to increase smart grid flexibility. There are still a number of areas that might use more research to enhance and expand its usefulness. Technical understanding, enhance scalability and new development in power system should be the focus of future study.

Static simulation and historical load data serve as the foundation for the current study. In order to enhance load forecasting, optimise BESS operation and provide adaptive demand response technique, future research might integrate real time data stream and predictive analytics with advance machine learning method. Additionally, seasonal alignment between generation and consumption would be improved by including weather prediction in power system.

This thesis focusses on technological optimisation in a particular regulatory and geographic location. Future studies should assess the financial and regulatory implication of integrating PV with BESS on a big scale. This covers commercial model for DR participation and battery storage ownership (such as utility owned vs customer owned system), life cycle cost estimate and tariff design optimization.

Additional study is required on vehicle to grid (V2G) and peer to peer (P2P) energy trading within local energy community. Decentralised energy systems are growing to include electric car and blockchain enabled energy marketplace. A more comprehensive approach to grid management may result from research on their interaction with DR, PV and BESS.

Furthermore, as DER penetration increases further research may extend the modelling framework to incorporate low voltage grid dynamic particularly power quality concerns like harmonics and unbalanced load. Incorporating multi energy systems such connecting gas and district heating networks with electricity would offer a more comprehensive perspective on integrated flexibility. A sociotechnical study that looks at consumer behavior, engagement tactic and legislative incentive would help create DR programs that are more successful and demand side flexibility.

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