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Techno-Economic Analysis of Solar and Battery Systems

A Comprehensive Analysis of Key Parameters

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**Techno-Economic Analysis of Solar and Battery
Systems: A Comprehensive Analysis of Key
Parameters**

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Abstract

Sweden has experienced a significant increase in installed solar power capacity between 2010 and 2020, driven by decreasing installation costs, government subsidies and widespread public interest. However, Sweden's geographical distribution of electricity generation and consumption presents challenges for the national grid. Recent instability in the electricity supply due to the war in Ukraine has prompted increased interest in residential battery energy storage systems (BESS) as a means to enhance energy resilience and reduce electricity bills. The rapid growth of the European residential BESS market is expected to continue, driven by the need for flexibility and energy-shifting services in response to increasing renewable energy production. BESS can provide economic benefits to households with installed PV systems through peak shaving, allowing them to store excess electricity during periods of high production and use it during peak demand.

This thesis investigates photovoltaic (PV) and BESS performance and profitability for Swedish households under various conditions. The study considers parameters such as system costs, energy prices, grid tariffs and dynamic battery management strategies to investigate the profitability of the systems. The research aims to provide guidelines for households to maximize the benefits of their PV and BESS installations and minimize their dependence on the grid. The effectiveness and practicality of the developed method are demonstrated through verification in two real-world installations.

The study's findings demonstrate that electricity prices, household consumption and roof orientation highly influence the profitability of PV systems. If future electricity prices align with present forecasts, installations on north-facing roofs will not be profitable under any circumstances investigated in this study. A distinct correlation is also discernible between larger loads and improved economic viability for PV and BESS installations, while a smaller battery capacity results in higher economic viability. This reveals that BESS profitability currently is limited due to high installation costs. However, the potential for future BESS profitability is shown if battery costs are reduced and more advanced battery dispatch strategies are developed.

Keywords: Photovoltaic systems, battery energy storage systems, techno-economic analysis, dispatch strategies, electrical pricing areas, energy management, grid independence

Sammanfattning

Sverige har upplevt en betydande ökning av installerad solkraftskapacitet mellan åren 2010 och 2020, drivet av faktorer som minskande installationskostnader, statliga bidrag och ett brett folkligt intresse. Geografiska skillnader mellan elproduktion och konsumtion i Sverige innebär utmaningar för elnätet. Instabilitet i elförsörjningen till följd av kriget i Ukraina har ökat intresset för batterilagringssystem i bostäder som ett medel för hushåll att öka deras energiresiliens och minska elkostnaderna. Den snabba tillväxten på den europeiska marknaden för batterilagringssystem förväntas fortsätta, drivet av behovet av flexibilitet i elnätet och energiomställningstjänster till följd av ökad produktion av förnybar energi. Batterilagringssystem kan ge ekonomiska fördelar för hushåll med installerade PV-system genom utjämning av effekttoppar, vilket gör att överskottsenergi kan lagras under perioder av hög produktion och användas under toppbelastning.

Denna rapport undersöker prestanda och lönsamhet för solcells- och batterisystem för svenska hushåll under olika förhållanden. Studien utforskar betydande parametrar såsom systemkostnader, energipriser, nättariffer och dynamiska batterihanteringsstrategier för att undersöka lönsamheten för systemen. Detta ämnar till att ge riktlinjer för hushåll att maximera fördelarna med solcells- och batteri-installationer och minimera dess beroende av elnätet. Effektiviteten och praktikaliteten av den utvecklade metoden demonstreras genom verifiering i två verkliga installationer.

Resultaten visar att elpriser, hushållsförbrukning och takorientering i hög grad påverkar lönsamheten hos solcellsanläggningar. Om framtida elpriser stämmer överens med nuvarande prognoser kommer installationer på tak mot norr inte att vara lönsamma under några omständigheter som undersökts i denna studie. En tydlig korrelation kan också urskiljas mellan större elkonsumtion och förbättrad ekonomisk lönsamhet för PV och batteri-installationer, medan en mindre batterikapacitet resulterar i högre ekonomisk lönsamhet. Detta visar att batteriers lönsamhet för närvarande är begränsad på grund av höga installationskostnader. Potentialen för framtida lönsamhet för batterier visas dock om batterikostnaderna sänks och mer avancerade batterihanteringsstrategier utvecklas.

Nyckelord: Solcellssystem, energilagringssystem, tekno-ekonomisk analys, elprisområden, energihushållning, självständighet från elnätet

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Nomenclature

Notations

Symbol	Description
Φ^{sc}	Self-consumption
Φ^{ss}	Self-sufficiency
CF	Cash flow
C_t	Charging cost
E_{tot}	Total energy produced by the solar installation
E_{exp}	Energy exported to the grid
i	Discount rate
I_t	Investment cost
M_t	Operation and maintenance expenditures
N	Period number
n	Expected lifetime of the system

Abbreviations

BESS	Battery Energy Storage System
BMS	Battery Management System
CAPEX	Capital Expenditure
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
DOD	Depth of Discharge
EMS	Energy Management System
End of Life	End of Life
EU	European Union
GHI	Global Horizontal Irradiance
IEA	International Energy Agency
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
NPV	Net Present Value
PV	Photovoltaic
SLP	Standard Load Profile
SOC	State of Charge
TMY	Typical Meteorological Year
VRE	Variable Renewable Energy

1 Introduction

The installed PV power in Sweden has experienced a significant increase from 250 kW in 2005 to almost 1,600 MW in 2021, with an annual market growth of 25 percent. This can be attributed to decreasing prices, government subsidies and a large interest amongst the population. Despite this growth, PV only accounts for 1 percent of the total Swedish electricity production, leaving a large potential for expansion. The potential for electricity produced by roof-mounted solar cells in Sweden is estimated to be over 40 TWh per year, representing approximately 24 percent of Sweden's electricity consumption. The Swedish PV market is dominated by self-owned and decentralized PV (IEA, 2022a). In 2017, Sweden adopted a new national climate policy framework which is a critical component of Sweden's efforts to contribute to the Paris Agreement. Measures in the policy framework supporting the development and expansion of solar power are individual support for investments in solar energy, the introduction of a net metering system allowing households to sell excess electricity and increased research and development in the field (Government Office of Sweden, 2018).

In Sweden, most of the electricity generation occurs in the northern regions, whereas the consumption of electricity primarily is concentrated in the metropolitan areas located in the southern and central parts of the country. In periods of peak demand, the capacity to transfer electricity from the northern to the southern regions can be constrained by technical limitations. Therefore, the implementation of countertrade practices, along with the establishment of four electrical areas, has been employed to enhance the stability and efficiency of the national electricity supply. The areas are named SE1, SE2, SE3 and SE4, where SE1 is in the northern parts of Sweden and SE4 is in the southern region. The different areas have individual spot prices with the goal of regulating the locations of new electricity production and consumption as well as controlling the strengthening of the main grid to a certain extent. The market prices for each electrical area are set on a day-ahead market where purchase bids are matched against producers' sales bids in an auction (Energimarknadsinspektionen, 2021a).

For a long time, the energy supply in Sweden has been stable, however, as a result of the war in Ukraine, the electricity supply in Sweden has become insecure. This has led to high electricity prices and a risk of power shortages during peak hours (Energimyndigheten, 2023). This drastic change from the previous stable energy supply has increased the interest in hourly time-of-use electricity prices since customers want to control their consumption and lower their electricity bills (Hallman, 2022). The change in electricity prices has also made

residential BESS a more attractive means to increase energy resilience and reduce electricity bills. BESS also extends the application and usage of solar PV, which has created the foundation for great market expansion. In 2021, the European residential BESS market grew 107 percent compared to the previous year. Due to the economic and political landscape in 2022, the residential BESS market is expected to maintain a very high growth (Christiansen et al., 2022). Figure 1 shows how the European residential BESS market is expected to increase until the year 2026 for three different scenarios.

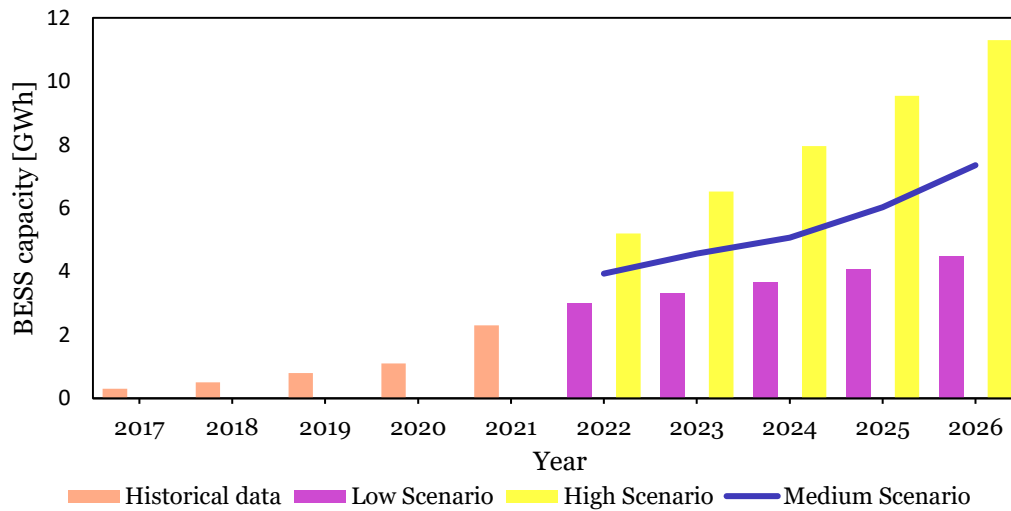


Figure 1: Predicted increase of residential BESS (Christiansen et al., 2022).

As efforts to achieve net zero carbon dioxide emissions accelerate, the energy system is under transformation. Driven by climate targets, renewable energy production is rapidly increasing, bringing new challenges due to the inherent variability of variable renewable energy (VRE) sources. To accommodate the rising share of renewables, there is a need for a more flexible system and energy-shifting services as provided by energy storage solutions. Energy storage is indispensable for maximizing the utilization of local renewables while alleviating the high electricity prices seen all over Europe (EASE, 2022). Through peak shaving, BESS can also provide economic benefits for households with installed PV systems. Due to the intermittent nature of solar radiation, the PV electricity produced in residential houses cannot always be self-consumed since the most radiation often occurs in the middle of the day when people are at work. By storing electricity during hours of high electricity production during the day and using it during peak demand in the evening, the household’s self-consumption can be improved and the electricity bill can be reduced (Fiedler and Matas, 2022).

The cost of BESS has experienced significant reductions in recent years due to lower material costs and more efficient manufacturing processes. Moreover, the price is predicted to continue decreasing by 50 percent between 2020 and 2030 (Augustine and Blair, 2021). BESS often

aims to maximize consumer self-consumption, which does not consider the electric market conditions or grid load. Many new battery storage inverters today include intelligent capabilities such as remote-control features and active reactive power management. Through these features, new opportunities in smart energy management and intra-day energy market trading arise. Intelligent BESS can, for example, predict future energy demand and supply patterns, which can help energy providers and retailers to make more informed decisions about how and when to trade energy on intra-day markets. They can also respond quickly to changes in the energy demand and supply, storing excess electricity during times of low demand, which can improve grid stability (Olaszi and Ladanyi, 2017).

1.1 Background

This chapter provides a background of important concepts, policies and describes the climatic and market conditions for PV and BESS in Sweden.

1.1.1 The Swedish Electricity Market

In Sweden, the electricity trade occurs on the marketplace Nord Pool Spot. Nord Pool is owned by the member countries that use the market, which in Sweden is Svenska Kraftnät. Different actors purchasing electricity are electricity producers, large electricity users and electrical dealers. The market prices for each electrical area are set by matching purchase bids from electricity users against producers' sales bids in an auction. The common system price and the individual spot prices are decided one day ahead. In addition to the day-ahead market, there is also an intraday market where the contracts can be adjusted after how the production and demand change during the day (Energimarknadsinspektionen, 2021b).

Power grid companies are responsible for transferring electricity from producers to electricity users. They expand and maintain the electricity grid to adapt to the need for electricity transmission. The electricity grid in Sweden consists of transmission grids and distribution grids. Svenska Kraftnät owns the transmission grids and transfers large amounts of electricity from the large producers to the regional distribution grids. Different electricity grid companies own the distribution grids and redistribute the electricity from the large transmission grids to the users (Svenska Kraftnät, 2022).

1.1.2 Household PV and Battery Installations

Through tax reductions, the Swedish government supports households investing in green technology, such as PV panels and BESS. The tax reduction for solar panel installations is set at 20 percent of the eligible costs and the tax reduction for the energy storage system is set at

50 percent of the eligible costs. Eligible expenses include the purchase and installation of the solar panels and battery system, as well as any additional components required for the system to function properly, such as inverters. The maximum tax reduction for investments in green technologies is 50,000 SEK per year. To qualify for the tax reduction, the solar panel installation must be carried out by a certified technician and the system must meet certain technical specifications and safety requirements. Furthermore, the tax reduction can only be claimed on income tax returns and is subject to approval by the Swedish Tax Agency (Skatteverket, n.d.).

1.1.3 Solar PV

When designing a PV system, solar irradiance is a crucial parameter that significantly affects the system's production. As such, it is imperative to consider this parameter while evaluating the predicted output of the intended system. Various approaches exist for determining solar irradiance in specific locations across the globe and corresponding forecasts may vary considerably. The solar irradiance can, in turn, be divided into direct normal irradiance (DNI), diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI). DNI is the radiation that reaches the panel without being scattered or absorbed by the atmosphere, DHI arrives at the plane after being reflected and GHI is the sum of the direct and diffuse radiance. The placement of the solar panel also affects its performance since the angle at which the solar irradiance hits the panel affects how much energy can be retrieved. Therefore different tilt and azimuth angles of the roof are essential parameters that require consideration (Othman et al., 2018).

Furthermore, the configuration of the PV system, including the array and wiring arrangement, also has a notable impact on the system's performance. Panels connected in series increase the voltage, while parallel coupled panels increase the current, affecting the system losses and overall performance. By optimizing the configuration, it is possible to enhance the system's efficiency and reduce associated costs. Therefore, thoroughly assessing these critical parameters is necessary to design an optimal PV system that meets the desired production goals (Ingle et al., 2017).

1.1.4 Residential BESS

In addition to the actual battery, a BESS consists of a battery management system (BMS), an inverter and an energy management system (EMS). The BMS is the central control unit of the battery pack, communicating both within the packs and to the external systems. The values provided by the BMS are protection against short-circuiting, overcharging, over-discharging and unwanted temperatures as well as optimization and maximization of the batteries

performance (Warner, 2015). The EMS decides when and how much energy should be dispatched. It considers factors such as demand-charge management, BMS limitations, long-term cycling and capacity degradation to use the BESS most effectively. To produce an alternating current that is used in buildings, the lithium-ion battery also requires an inverter. When coupled to the battery, a hybrid inverter is needed to operate bi-directional, allowing the BESS to charge and discharge (Gavenonis, 2020).

A residential PV BESS can have either a DC or AC-coupled system. In DC-coupled systems, the battery is connected to the DC link of the PV inverter, while the battery in an AC-coupled system is connected directly to the PV system consisting of the PV generator and inverter. DC-coupled systems are often cheaper since only one inverter is needed, however, in an already existing solar installation, it is easier to install an AC-coupled system since the connection from the solar panels to the inverter does not have to be rewired (Weniger et al., 2014).

The voltage in a battery affects the charge and discharge rate, whereas a high-voltage battery charges faster. Low-voltage batteries have a voltage below 100 V and because of the slow discharge rate, they often require additional assistance to cover quick demand surges from starting equipment and to support higher loads. Advantages with low voltage batteries are that they are cheaper, easier to install and can run continuously without exceeding temperature limits. On the contrary, high-voltage batteries can support quick supply and demand surges due to the faster charge and discharge rate. Additionally, the DC power from a PV system is usually between 300 to 500 V and if connected to a high-voltage battery, the inverter does not have to reduce that voltage. This results in less energy losses and increased efficiency of the entire system, contributing to the growing popularity of high voltage batteries when connected to a solar system (Deege Solar, 2022).

1.1.4.1 BESS Characteristics

State of Charge (SOC): The SOC in a battery is the currently available capacity as a function of the rated capacity. The SOC can vary between 0-100 percent and the maximum SOC decreases as the battery ages (Abdi et al., 2017).

Depth of Discharge (DOD): The DOD is expressed as a percentage of the total battery capacity and refers to how much the battery is charged and discharged on a given cycle. A DOD is often recommended by the manufacturer since fully discharging a battery can significantly shorten the cycle life and decrease safety. Lithium-ion batteries' usually have a recommended DOD between 20 to 90 percent of the available energy (Warner, 2015).

C-rate: The C-rate is the rate at which a battery can charge or discharge its energy. The C-rate is expressed in relation to a 1-hour charge or discharge and a 1C rate therefore implies that the battery is fully charged or discharged in 1 hour (Warner, 2015).

End of Life (EoL): A battery is often considered to have reached its end of life when its maximum power has been reduced to 80 percent of its original state. The general rule of 80 percent is often considered a limit for when it is no longer satisfactory to the customer, however, it depends on the application (Warner, 2015).

1.1.4.2 Sizing and Installation of a BESS

When optimizing the size of a BESS, a large variety of sizing criteria and techniques are available, all with varying complexity. The different optimization criteria can be divided into three categories: financial, technical and hybrid. Examples of economic indicators are the net present value (NPV) and levelized cost of electricity (LCOE), while a technical indicator is to improve the features of the power profile, such as peak shaving. However, lately there has been a growing emphasis on using a hybrid approach, including both financial and technical indicators. Similarly, many different techniques are used to optimize the size of a BESS. Some of the most commonly used techniques are probabilistic, analytical, directed search-based and hybrid methods (Yang et al., 2018). The most important parameters to consider when deciding the size of a BESS are the electricity generation from the PV system, type of storage and electric load profile (Hoppmann et al., 2014).

A BESS implies a safety risk, mainly through the danger of electric shock and fire and therefore the Swedish electrical safety authorities have regulations and general advice on the electrical installation work. The placement of the battery storage is also crucial to ensure safety and should comply with the local building regulations. Only a registered electrical installation company with an internal control program can perform the installation and a written application must be made to the electricity grid operator before installation. The installation should be documented and the unit should be properly labeled and marked to ensure safety. The owner is responsible for the maintenance and regular inspection of the system to ensure compliance with the regulations (Swedish electrical safety authority, 2020). According to the Swedish electrical safety authority, small-scale energy storage is defined as installations connected to customer installations with a rated voltage of 230/400 volts and in terms of power, less than or equal to 11 kW (Swedish electrical safety authority, 2016).

1.1.4.3 Operation Strategies

There exist a large variety of operation strategies for PV BESS, of which the most common ones are to improve consumer self-consumption and to have a fixed SOC limit to reduce battery aging. Maximizing self-consumption aims to cover the electricity demand by PV-produced electricity to a greater extent. If the BESS is fully charged, excess electricity is sold to the grid and electricity is only imported from the grid if the battery is fully discharged. Moreover, a fixed SOC limit is often implemented to increase the battery's lifetime. The operation strategy often remains the same, except that the battery is considered to be fully charged and discharged when reaching the SOC limits. Even though this can improve the battery lifetime, it can lead to a non-optimal use of the battery if the SOC limit is reached before it has stored enough energy to satisfy the energy demand during peak hours (Angenendt et al., 2018).

One common approach utilized to mitigate peak power consumption during periods of high demand is the peak shaving dispatch strategy. This strategy aims to mitigate peak power consumption by relocating loads from periods of high demand to periods of low demand and thereby decreasing energy consumption during peak hours. Reducing the load during peak hours can avoid additional charges often associated with peak consumption. Another dispatch strategy is price arbitrage which aims to store electricity when the price is low and use the stored electricity during hours of higher prices. This strategy aims to optimize the cost-effectiveness of energy storage by capitalizing on price differentials in the electricity market. This strategy is expected to play a key role in the competitiveness of energy storage in the future (Campana et al., 2021).

1.2 State-of-the-art

Grid-connected PV battery systems under Swedish conditions have been researched with various case studies. Many of these studies have also focused on optimizing the capacity of a PV and BESS installation and investigated different operation strategies. Zhang et al. (2017) have performed a Swedish case study of battery sizing and rule-based operation of a grid-connected photovoltaic-battery system. The study develops a method for optimizing the battery capacity and investigates three rule-based operation strategies. The operation strategies evaluated are a conventional operation strategy, a dynamic price load-shifting strategy and a hybrid operation strategy. The result indicates that the hybrid operation strategy outperforms the other investigated strategies. However, the dynamic price load-shifting strategy could also be profitable with a significant variation in the electricity price. A study by Nyholm et al. (2016) optimizes solar PV BESS capacities in Swedish households. They

develop a model for the operation of batteries where 2104 different Swedish households are analyzed. The study concluded that a battery could increase household self-consumption by 20-50 percent and self-sufficiency by 12.5-30 percent.

Moreover, Campana et al. (2021) analyzed aspects of a PV system and compared them with a PV and BESS. The dispatch strategies investigated are peak shaving and price arbitrage for systems in the commercial sector. They developed a spatial map of Sweden based on an optimization for 310 cities. Based on the electricity price structure, dispatch strategy, battery price and PV system investigated, the result shows that batteries are still not an economically viable option. The study also concludes that BESS is a good option for increasing self-consumption and that batteries would be financially feasible if electricity prices increased or battery costs decreased to 250 US\$/kWh. Lastly, Fiedler and Matas (2022) investigated grid-connected PV BESS for holiday houses in Sweden. They sized and optimized the system based on the NPV, where electricity prices, incentives, load patterns and tariff structures were investigated. The study concluded that when the battery was sized to shave many peaks of demand, the PV BESS system was slightly more profitable than a PV system without batteries.

In summary, much research has been conducted in this area, with several case studies in different locations in Sweden. However, due to the rapid decrease in BESS prices and the recent changes in electricity prices and volatility in Sweden, there is a need to update this topic's financial results. Moreover, the identified studies do not investigate how Sweden's electricity pricing areas affect the PV and BESS's profitability.

1.3 Objective

This thesis aims to assess the performance and profitability of residential PV and BESS installations in Sweden using a parametric simulation approach. In the optimization, relevant parameters such as system costs, energy prices, grid tariffs and the dynamic battery management strategies peak power reduction and price arbitrage will be considered. The effectiveness and practicality of the developed method will be demonstrated through verification in a real-world installation, with the ultimate goal of providing a practical solution for households to maximize the benefits of their PV installations and reduce their dependence on the grid. In support of this objective, the following list of research questions will be answered under a range of conditions specific to different households:

- Which are the most critical variables affecting PV and BESS's profitability?
- What is the techno-economic optimum capacity of a PV and BESS given different conditions?
- Which impact do the battery dispatch strategies have on the profitability of a BESS?

1.4 Purpose

To reach net zero emissions by 2050, there is a need to increase the share of electricity generation from renewable sources such as wind and solar PV. To address the intermittent nature of these energy sources and increase flexibility in the power sector, the installed capacity in energy storage systems needs to experience a rapid increase. This required increase is dependent on direct support through policies. However, it is also essential to develop markets for flexibility, capacity and ancillary services, as well as make regulations transparent and open for them to be able to compete with other measures and technologies. Moreover, strategies and policies will work better if they align with urban planning and mobility, for example, scaling up rooftop solar PV and residential battery systems for buildings to become active service providers to grids (IEA, 2022b).

Since BESS can reduce renewable power fluctuations and increase frequency stability, they can contribute to reaching the sustainable development goal (SDG) 7, which aims to ensure access to affordable, reliable, sustainable and modern energy for all (UN, n.d.a). A rapid increase in sustainable PV and battery production can also improve economic growth and create job opportunities supporting SDG 8, aiming to promote sustained, inclusive and sustainable economic growth and decent work for all (UN, n.d.b). Finally, by contributing to integrating and utilizing renewable energy, battery systems can also contribute to achieving SDG 13, which is devoted to taking action to combat climate change (UN, n.d.c).

2 Methodology

A primary script has been created with the programming language Python, which retrieves necessary information from various sources, including historical electricity prices, solar radiation data and system and electricity costs. The data creates input parameters for an optimization model that performs parametric simulations for thirty variables shown in Table 1. The optimization model evaluates the techno-economic performance of a PV and BESS installation for all combinations of varied parameters, creating a total of 19,200 simulations. The study will address the research questions through a quantitative approach, utilizing optimization modeling and sensitivity analysis. The simulated PV production will be verified by applying it to real-world installations, where the model's validity will be confirmed.

Table 1: Parameters varied in parametric simulations.

Parameters	Tested values					
	Luleå	Sundsvall	Stockholm	Malmö		
Location						
PV capacity [kW]	4	8	12	16	20	
Battery capacity [kW]	0	2	4	6	8	10
Electricity price [year]	2018	2019	2020	2021	2022	
Dispatch strategy	Peak shave			Price signal forecast		
Loads [MWh]	5	10	15	20		
Azimuth angle [°C]	0	90	180	270		

The system developed for this study comprises four major components: the PV system, BESS, electric load and the electric grid. The energy produced from the PV system can either directly meet the electric load, charge the BESS, or be exported to the grid. The battery will charge and discharge energy based on the dispatch strategy investigated. Additionally, the system will allow power to be exported to the grid from either the PV system or the BESS and energy from the grid will be utilized to meet the electric load or charge the BESS.

2.1 Key Performance Indicators

This section describes the technical and economic KPIs used for optimizing the model. The technical indicators investigated are self-consumption, self-sufficiency and solar fraction to capture different aspects of the relation between the produced PV electricity, consumed PV

electricity and load. The economic indicators investigated are NPV and levelized cost of storage (LCOS).

2.1.1 Net Present Value

The NPV is an economic indicator that illustrates the present value of a project, calculating the value that future cash flows would have today, given a specified discount rate. The NPV is useful for investment decisions, financial modeling and financial analysis since the present value of different investments can be compared. A positive NPV indicates that the investment is profitable. When using NPV for decision-making, it is important to remember that future cash flow predictions often have insecurities that can significantly affect the result (Hanafizadeh and Latif, 2011). The NPV consists of yearly savings and expenditures as well as the investment cost of the system and is shown in Equation 1

$$NPV = \sum_{t=1}^n \frac{S_{t,el} + S_{t,income} - M_t}{(1+i)^t} - I_t + S_{sub} \quad [1]$$

where I_t represents the total investment of the PV system, BESS and inverter, S_{sub} the government subsidies, $S_{t,el}$ the value of the electricity savings, $S_{t,income}$ the income from sold electricity, M_t the cost for maintenance and repairs, i the discount rate, n the expected lifetime of the system and t the year. A nominal discount rate of five percent is assumed since the European Union (2016) has recommended that as a minimum limit for solar PV projects. Considering a long-term inflation rate of two percent, which is the inflation target of the Swedish Riksbank (2022), this translates to a real discount rate of three percent. The value of electricity savings ($S_{t,el}$) is given by Equation 2

$$S_{t,el} = B_{t,no\ system} - B_{t,system} \quad [2]$$

where $B_{t,no\ system}$ is the electricity bill without the system and $B_{t,system}$ is the electricity bill when the system is installed. The electricity bill includes all bought electricity used to meet the load and to charge the battery. The variable part of the bill for purchased electricity consists of an electricity trade cost, a transfer cost, taxes and fees. The electricity trade cost is the price for the electricity purchased on Nord Pool Spot marketplace and varies every hour depending on supply and demand. An energy tax of 0.49 SEK/kWh and a cost for electricity certificate, often set to 0.032 SEK/kWh including VAT, is also charged on the variable fee. (Energimarknadsbyrå, 2022a). The transfer fee is the cost associated with the transportation of electricity from the generation source to the end users. In Sweden, Ellevio and Vattenfall, two of the largest electricity distribution companies, have established a transfer tariff of 0.300 SEK/kWh and 0.305 SEK/kWh respectively, including VAT (Ellevio, 2023; Vattenfall, 2023). In the present study, a transfer fee of 0.3025 SEK/kWh is utilized in the simulations,

representing the average of both companies' costs. To illustrate the total hourly electricity price with an example, if the Nord Pool spot price is 0.5 SEK/kWh, the total cost for bought electricity is given in Equation 3

$$\text{Buy price} = 0.5 + 0.49 + 0.032 + 0.3025 = 1.3245 \quad [3]$$

The transfer fee can also be partly capacity based, a pricing structure that the electricity distribution company Göteborg Energi (2023) utilized. They have a variable transfer fee of 0.255 SEK/kWh and an additional effect fee which is also a variable cost, affected by the customer's consumption. The effect fee is calculated on the average value of the three highest peaks of consumption in kW spread over three different days. That average value is multiplied by 36.25 SEK and added to the monthly bill.

The surplus production from the PV panels is sold to an electricity retailer company. Prosumers with a system smaller than 43.5 kW get a tax relief of 0.6 SEK/kWh from the energy tax, with a maximum amount of 18,000 SEK. However, the prosumer can only be credited with a maximum of as many kWh as they have purchased from the grid themselves (Energimarknadsbyrå, 2022b). The tax relief plays a significant role in enhancing the profitability of solar installations. Today, the duration of the tax relief remains uncertain but in a report addressing Sweden's prospective energy system, the Swedish Energy Agency (2021) assumes that it will persist until 2050. It is important to note that this is just a projection, still it is seen as an indication that the tax relief will remain for a longer period, which is why this study also operates under the assumption that it will last throughout the whole lifetime of the system. If the tax relief is included and the Nord Pool spot price is 0.5 SEK/kWh, the price for the sold electricity is then given by Equation 4

$$\text{Sell price} = 0.5 + 0.6 = 1.1 \quad [4]$$

2.1.2 Levelized Cost of Storage

The LCOS represents the average revenue for the discharged electricity required for the NPV to be zero. It is thus the minimum revenue needed per dispatched unit of electricity for the storage investment to be considered profitable, given a specific discount rate. The LCOS is calculated by taking the total lifetime costs of the storage divided by the total lifetime energy output of the battery using the following equation:

$$LCOS = \frac{\sum_{t=1}^n \frac{I_t + M_t + C_t}{(1+i)^t}}{\sum_{t=1}^n \frac{E_{batt,tot}}{(1+i)^t}} \quad [5]$$

where C_t is the charging cost and $E_{\text{batt,tot}}$ is the total energy discharged by the battery. The interest in calculating the LCOS has been growing due to its suitability to compare different storage technologies with each other and to generation technologies. Important parameters affecting the LCOS are discharge duration, annual cycles and nominal power capacity, which are affected by the dispatch strategy (Schmidt et al., 2019).

2.1.3 Self-Consumption

Self-consumption is defined as the share of electricity produced by the solar installation that the power producer owner consumes. Optimizing a system from self-consumption can be profitable since costs such as electricity taxes and grid fees can be avoided. With the declining cost of PV panels and increased electricity prices, the interest in PV self-consumption has elevated. In a typical residential household without storage, the self-consumption often varies between 17-44 percent. With a BESS, self-consumption can be increased by storing surplus PV production and using it during higher demand hours. If self-consumption is increased, it can provide economic benefits for the household and lower the pressure on the electricity grid (Dehler et al., 2017, p. 27). The self-consumption can be calculated according to the following:

$$\Phi^{sc} = \sum_{h=1}^n \frac{E_{PV,tot} - E_{exp}}{E_{tot}} \quad [6]$$

where Φ^{sc} is the self-consumption, $E_{PV,tot}$ is the total energy produced by the solar installation and E_{exp} is the amount of energy exported to the grid.

2.1.4 Self-Sufficiency

The self-sufficiency of a household has a strong relation to self-consumption. Self-sufficiency is defined as the share of the total demand that is supplied by the PV-generated electricity given by:

$$\Phi^{ss} = \sum_{h=1}^n \frac{E_{PV,tot} - E_{exp}}{E_{load}} \quad [7]$$

where Φ^{ss} is the self-sufficiency and E_{load} is the electric load of the household (Gudmunds et al., 2020). The level of self-sufficiency greatly depends on different factors, such as geographical location and the household's load curve. One of the main benefits of increasing self-sufficiency is that it allows the household to reduce their reliance on the grid which can provide economic benefits and grid relief (Nyholm et al., 2016).

2.1.5 Solar Fraction

The solar fraction refers to the percentage of the total building demand supplied by solar energy. It can be calculated using various methods, including simulation modeling and monitoring of actual system performance. The solar fraction can be used to compare the performance of different solar energy systems, as well as to evaluate the cost-effectiveness of these systems. The formula for the solar fraction is:

$$SF = \frac{E_{PV,tot}}{E_{load}} \quad [8]$$

where SF is the solar fraction. If the solar fraction is zero, it means that no solar energy is produced and if the solar fraction is one, the household is a net-zero energy home (Brownson, 2014).

2.2 Delimitations

The thesis is limited to residential BESS connected to roof-mounted solar systems in Sweden. Thus, the Swedish electricity market and political landscape will be analyzed and implemented in the method developed. Residential villas are investigated since self-owned decentralized systems dominate the Swedish PV market. Furthermore, the study is limited to lithium-ion batteries since that is the most commonly occurring on the market today. In the model of the solar installation, monocrystalline collectors are investigated and each simulation is performed using one roof tilt, although multiple orientations are considered in the different simulations. This assumption is made to limit the number of simulations. The economic calculations consider hourly time-of-use tariffs driven by the spot market.

2.3 Software Development Tools

This section describes the software development tools used to produce the result.

2.3.1 Python

Python is a high-level programming language widely utilized across numerous disciplines, including data science, machine learning, web development and scientific computing. Initially released in 1991, it has gained widespread adoption and is now considered one of the most widely used programming languages globally. Python boasts a variety of tools and libraries that provide powerful data manipulation, analysis and visualization capabilities. Furthermore, it is renowned for its ability to effectively construct and train machine-learning models (Anaconda, 2023).

2.3.2 SAM

The System Advisor Model (SAM) is a comprehensive software tool that provides performance and economic analysis for renewable energy systems developed by the National Renewable Energy Laboratory (NREL). SAM is a powerful modeling tool that provides users with detailed information about the performance, economic viability and environmental impact of various energy technologies designed to assist researchers, developers and decision-makers. The software also offers exhaustive data on system design, cost and performance, which is important for decision-making and policy development (NREL, n.d.).

The NREL has developed a Python library called PySAM, providing an interface allowing users to access SAM's modeling capabilities within Python. With its intuitive syntax and extensive library of modules, a wide range of renewable energy systems can be modeled, including solar, wind, geothermal, biomass and hydropower. Its compatibility with Python makes it an attractive choice for data scientists and researchers who require a flexible and customizable toolset. Additionally, PySAM's open-source nature allows for continued development and improvement by its active community of contributors (NREL, 2021).

2.4 Data Collection

This section describes and discusses the reliability and validity of the data used for the model.

2.4.1 Weather Data

The weather data used in the simulations is retrieved from PVGIS, a platform that retrieves meteorological data to aid in the planning and designing of solar energy systems. It is a free web-based tool that provides high-quality and high-resolution meteorological data for various locations in Europe, Africa and parts of Asia. The data is derived from satellite imagery, ground-based measurements and meteorological models (Huld et al., 2018). The data retrieved from PVGIS is hourly data for a Typical Meteorological Year (TMY). The TMY dataset is generated using a statistical method that combines historical meteorological data to create a typical year's weather pattern. The TMY dataset generated by the PVGIS TMY generator includes several meteorological variables, including temperature, humidity, wind speed and solar radiation. The dataset also includes derived variables such as the direct and diffuse radiation components, the solar zenith angle and the air mass (European Commission, n.d.).

The locations chosen for the simulations are Luleå (SE1), Sundsvall (SE2), Stockholm (SE3) and Malmö (SE4). These cities were selected since each electrical area often is referenced to

these cities (Energimarknadsinspektionen, 2021a). Figure 2 illustrates the average temperature and the sum of GHI of the TMY data generated for each location each month.

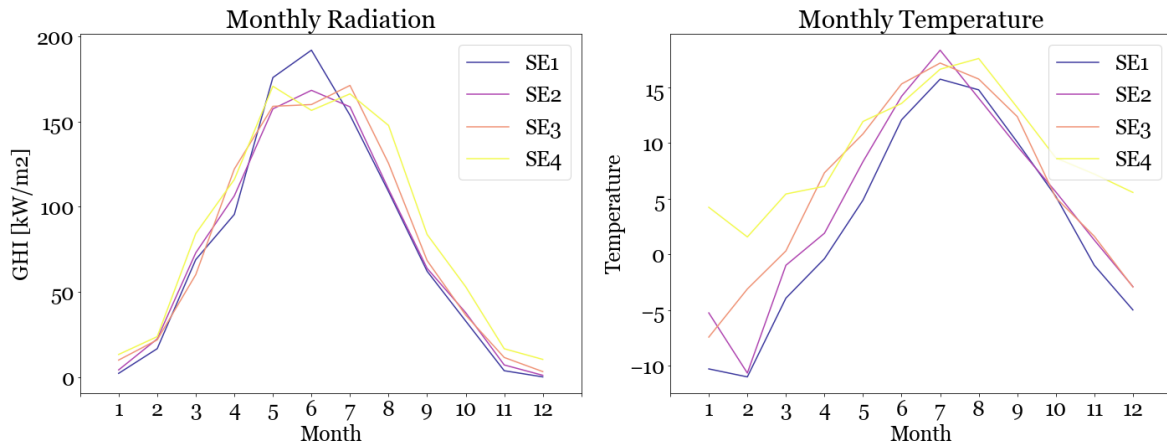


Figure 2: GHI for the simulated locations (European Commission, 2022).

Snow accumulation on PV modules can reduce energy production by blocking the sunlight from reaching the solar cells. Energy losses due to snow cover can range from 10 to 50 percent in a typical winter month, depending on different factors such as the amount and duration of snow cover and the tilt angle of the modules. Energy losses due to snow cover can be highly variable and difficult to predict. The values for snow losses utilized are retrieved from an investigation of 239 locations where south-facing systems oriented at a tilt between 0 and 60 degrees have been considered (Ryberg and Freeman, 2017). Four different values for monthly snow losses are used in the simulations depending on the location’s latitude shown in Table 2.

Table 2: Snow coverage losses [%] (Ryberg and Freeman, 2017).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
SE1	59	41	11	5	0	0	0	0	0	12	27	27
SE2	49	33	9	4	0	0	0	0	0	0	8	21
SE3	42	25	8	3	0	0	0	0	0	0	4	16
SE4	18	18	6	2	0	0	0	0	0	0	2	10

2.4.2 Load Profile

Four hourly load profiles are investigated, all are metered data from households in the Swedish city of Karlstad. The loads have varying annual energy consumption rates of 5, 10, 15 and 20 MWh/yr. The loads are chosen to evaluate the proposed system's performance under different operating conditions and are shown in Figure 3.

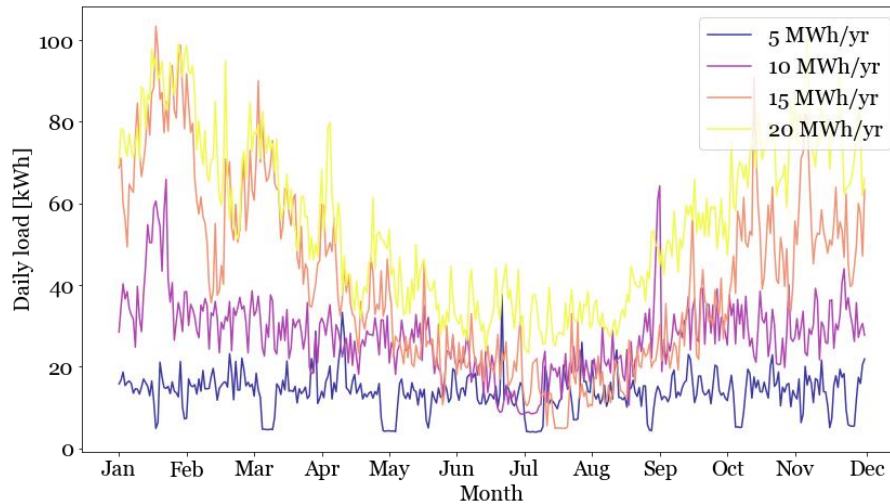


Figure 3: Daily consumption for the different loads.

2.4.3 PV Model

The PV model investigated is the PVWatts model in SAM. The model estimates the energy production of a grid-connected PV system, making assumptions about the configurations and operation of the system. The model is continuously updated to reflect the actual performance of a modern PV system. The most significant specifications needed to accurately simulate the system's performance are system capacity, system losses, array type, tilt angle, azimuth angle and hourly weather data. The sun's position is calculated each hour based on the location to find the zenith and solar azimuth angle.

To simulate the system's performance, a thermal model is implemented to account for losses due to the module temperature. A first-principles heat transfer energy balance model is used to calculate the operating cell temperature considering the effects of the thermal capacitance of the module, irradiance, wind speed and the dry bulb temperature. The modules installed nominal operating cell temperature is assumed based on the system's mounting configuration. For a roof-mounted system, it is assumed to be 45 °C. The model then calculates how much DC power is produced by the system using the following equation:

$$P_{dc} = \frac{I_{tr}}{1000} P_{dc0} (1 + \gamma(T_{cell} - T_{ref})) \quad [9]$$

where I_{tr} is the transmitted irradiance, γ the temperature coefficient with a value of $-0.20 \text{ \%}/^{\circ}\text{C}$ and using a reference irradiance of $1000 \text{ W}/\text{m}^2$. A total of 14 percent losses is assumed in the system, representing the impact of shading, soiling, mismatch, wiring, light-induced degradation, connections, system age, operational availability and nameplate rating. Lastly, an inverter model had been created by analyzing inverter performance data. By finding the average part-load efficiency curve and fitting it to a quadratic loss model, a typical behavior for an inverter was found and used for the simulations (Dobos, 2014). The tilt angle of residential houses typically varies between 18 to 36 degrees (Hollister Roofing, 2023). Therefore, a tilt angle of 27 degrees has been applied in the simulations.

2.4.4 Battery Model

SAM has a high temporal resolution BESS performance model, which can predict the energy output of a system. The model has been validated against other existing models and physical testing of battery equipment (DiOrio et al., 2015). Several performance sub-models, such as a capacity model, a voltage model, a thermal model and a lifetime model of the battery behavior have been integrated to provide a realistic interface for any lithium-ion battery. The lifetime model mainly depends on the number of elapsed cycles and the DOD. The dynamic voltage model is a generic electrochemical model which characterizes the voltage at any point, where the most important factors are the capacity, current and SOC. The C-rate of the discharge curve must be known to determine the amount of discharge at any given time. Moreover, a voltage loss model is included, mainly depending on the SOC and the charging and discharging current. The voltage model is as follows:

$$V = V_o - R \cdot I - K \left(\frac{q_{max}}{q_{max} - \int I dt} \right) + a \cdot e^{-B I dt} \quad [10]$$

where V is the terminal voltage, V_o the battery constant voltage, K the polarization voltage, q_{max} the battery capacity, q the actual battery capacity, a the exponential zone amplitude, B the exponential zone time constant inverse, R the internal resistance, I the battery current and dt the time step. The thermal model directly affects the battery's performance since its temperature impacts its lifetime and capacity. Generally, the battery capacity drops with lower temperatures, however, excessively high temperatures can result in corrosion and reductions in the battery lifetime. The thermal model depends on the thermal storage in the battery, heat generation due to internal resistance and heat transfer to and from the room. The equation for the thermal model is:

$$m \cdot C_p \frac{dT_{batt}}{dt} = h \cdot A (T_{room} - T_{batt}) + I^2 \cdot R \quad [11]$$

where m is the mass, C_p the specific heat, h the heat transfer coefficient, T_{room} the storage room temperature, A the battery surface area and R the battery internal resistance (DiOrio et al., 2015).

2.4.5 Dispatch Strategies

The battery dispatch models investigated in this paper are one peak shave model and one price signal forecast model, both with a 24-hour perfect look-ahead forecast. The peak shaving model calculates the net load to identify peaks and understand how to dispatch the battery. Moreover, the model tracks the current to ensure that the battery does not discharge too fast and thus damaging the battery's lifetime. The energy that can be extracted from the battery is then calculated using the voltage at the beginning of the 24-hour period, the available power and the maximum and minimum SOC (DiOrio, 2017).

The price signal forecast dispatch strategy considers a 24-hour forecast of the PV production, load, degradation data and utility rates. The dispatch model can hence be seen as a combination between energy arbitrage and demand charge management where both the cost of energy and if the battery degradation imposes a significant cost is considered. For each 24-hour time horizon, 13 possible dispatch alternatives are generated with discharge periods varying from 0 to 12 hours, where no battery cycling is represented by a zero. The alternatives assume one full discharge cycle during the forecast period but consider different time steps and distribution of the discharge power. The trade-offs between discharging during the highest cost periods and adhering to the battery's constraints can therefore be balanced, optimizing the use of the battery and minimizing the overall costs (Mirletz and Guittet, 2021).

2.5 Economic Calculations

The PV system is analyzed over 25 years, while the battery lifetime is considered to be when its maximum power has been reduced to 80 percent of its original state. In the simulations, the hourly electricity prices in the years 2018 to 2022 are investigated. Each simulation is run using the electricity price from one year for the whole lifetime of the system. The average electricity price for all electrical areas for the different years is shown in Table 3 and all the data is gathered from Nord Pool (2023).

Table 3: Average electricity price in the years 2018-2022 [SEK/kWh] (Nord Pool, 2023).

Year	2018	2019	2020	2021	2022
SE1	455	401	150	432	634
SE2	455	401	150	433	664
SE3	458	405	221	672	1379
SE4	477	421	270	819	1620

To illustrate the price volatility, Figure 4 shows how the average electricity price for all electricity areas varies daily. It can be seen that the prices have higher volatility in the years with higher prices while it stays relatively consistent throughout the day in the years 2018 to 2020. Nordic Energy Research (2021) has made future energy forecasts and predicted that the annual average Swedish electricity price in 2050 will vary between 0.422 to 0.455 SEK/kWh depending on the development of nuclear and the electricity area. Moreover, The Swedish Energy Agency (2021) has made an electricity price forecast predicting that the price will vary between 0.450 to 0.550 in the year 2050. This indicates that long-term electricity prices will likely be similar to those in 2018, 2019 and 2021. However, it is important to note that these studies were developed before the Ukraine conflict and the European energy crisis. These events can significantly impact future electricity prices, altering the forecasts.

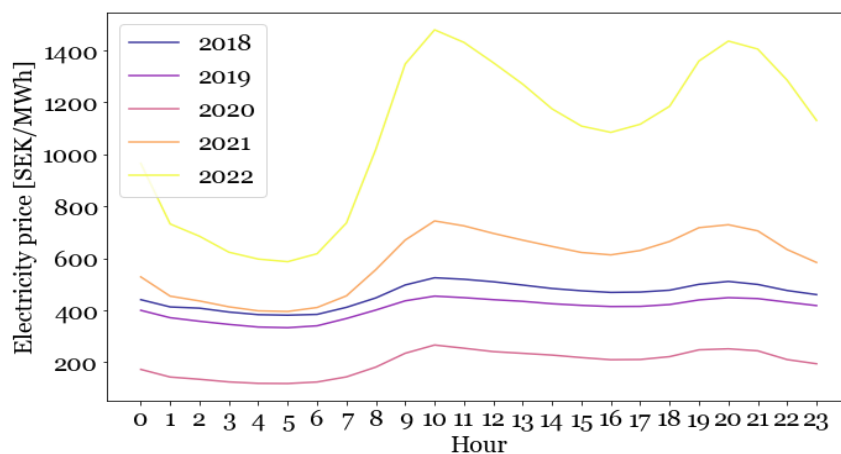


Figure 4: Average daily electricity price (Nord Pool, 2023).

The system price for the PV installation is gathered from a report by the International Energy Agency (2022). It includes the cost of the module, inverter, mounting materials, other electronics, installation work, permits and reporting, working travel time, planning and sales, shipping to the customer, travel costs and supplier margins. Moreover, the average yearly cost for system maintenance and repair is 150 SEK/kW, which includes the cost of inverter replacement (Lazard, 2023). The battery installation costs are gathered from a report published by the NREL (2021), including the cost for installation, inverter, battery and other soft costs. The report also estimates a fixed yearly fee of 113 SEK/kWh to cover maintenance and repairs (Augustine and Blair, 2021). The costs for the PV and BESS installations are shown in Table 4 and all values reported in USD have been converted to SEK using the conversion rate of 10.62.

Table 4: System prices for PV and BESS.

Capacity [kW]	2	4	6	8	10	12	16	20
PV system [k SEK]	-	78.7	-	128.7	-	168.4	195.8	213.4
BESS system [k SEK]	17.8	34.6	51.9	61.2	71.8	-	-	-

3 Results

In this chapter, the results are presented and discussed, focusing on the parametric simulations conducted. A sensitivity analysis is also performed on critical variables to understand their impact on the systems better.

3.1 Model Validation

To investigate the accuracy of the model and system inputs, the production from two real installations has been compared to the simulated production generated by the model. Both households have installed PV panels and battery storage and are located in the electrical area SE3. Household 1 has a total installed PV capacity of 6.8 kW on a roof facing southeast. Household 2 has a total installed PV capacity of 5.9 kW on an east-facing roof. The losses in the installation due to external conditions such as snow and shading are unknown and assumed to be the values as described in the methodology section. The analysis was conducted for the electricity prices and weather conditions of the year 2022 and Figure 5 illustrates the hourly production from both the real and the simulated PV panels for both households.

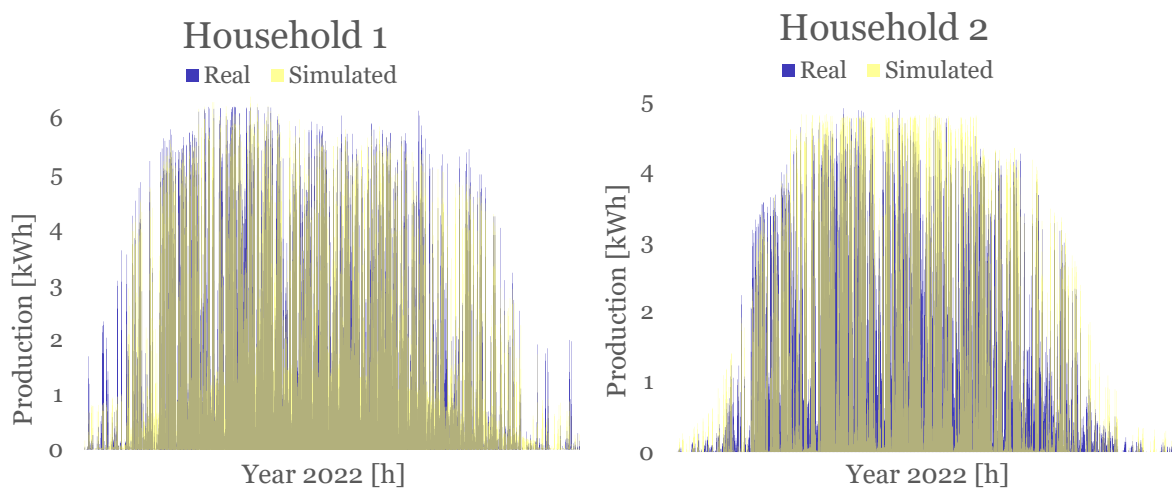


Figure 5: Real and simulated PV production for two households.

The simulated results yielded an annual production for Household 1 with a mean bias error that is 3.8 percent higher than the actual production. For household 2, the mean bias error is 0.7 percent higher for the simulated result than the actual production. When examining the hourly mean absolute error, it was found to be 1.18 kWh for Household 1 and 1.16 kWh for Household 2. This suggests a more significant variation in hourly production, whereas the yearly difference between the simulated and actual production is below 4 percent for both households.

3.2 Parametric Analysis

The parametric analysis applies an electricity pricing structure with a fixed transfer fee instead of a capacity-based pricing structure since that is Sweden's most commonly used system. Figure 6 displays the NPV generated from the simulations, with results categorized into the four different electricity price areas and electricity prices from the different years. The graph includes the results from simulations with all different PV and BESS capacities, azimuth angles and loads. The result demonstrates that the profitability of PV and BESS installations is considerably higher in areas SE3 and SE4 compared to areas SE1 and SE2. This suggests that the electricity market dynamics and weather conditions in SE3 and SE4 are more favorable for implementing solar technologies. Moreover, it can also be seen that the difference in profitability between the electrical areas becomes greater in the simulations using higher and more volatile electricity prices, such as in the years 2021 and 2022. The result also indicates that the electricity prices are highly associated with the system's profitability, as the NPV for the result produced with the electricity prices in 2022 is up to ten times higher than the once produced with the prices of 2018.

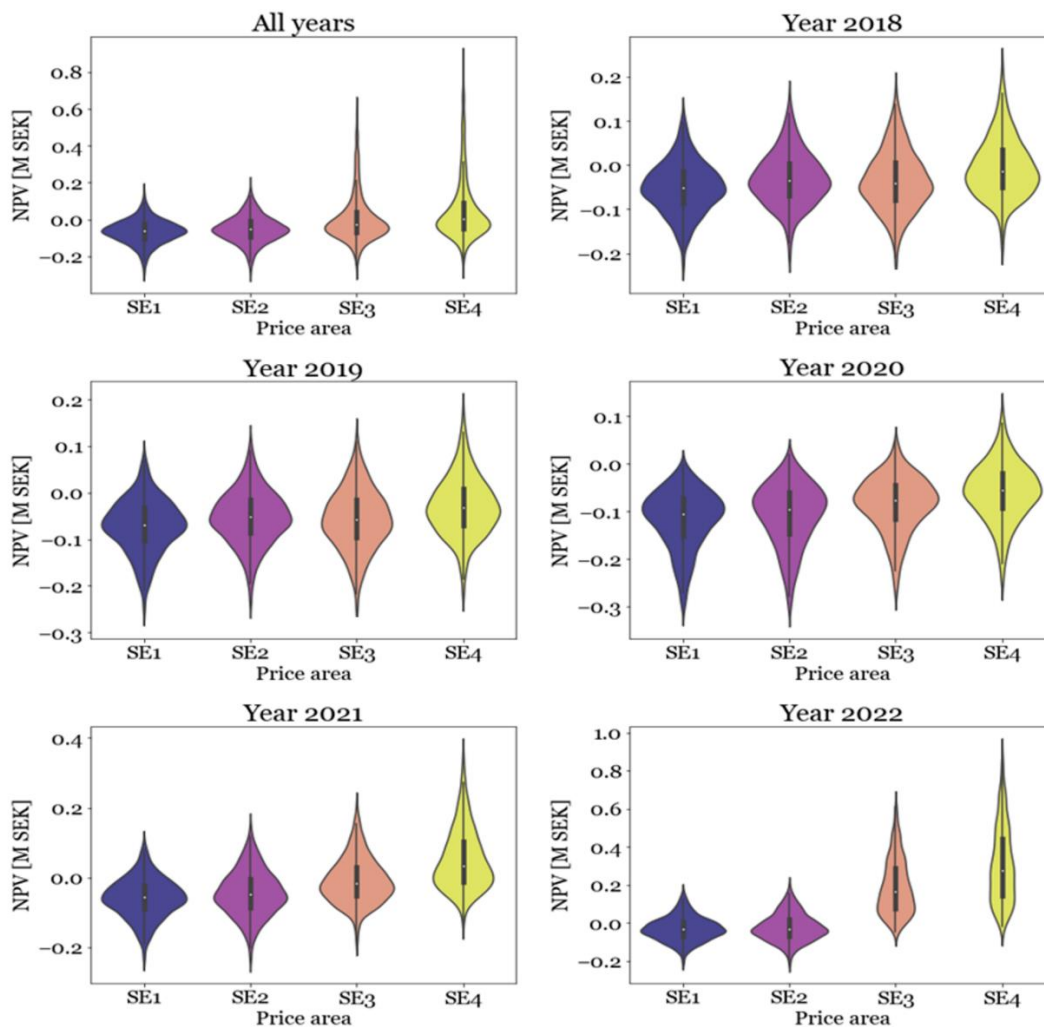


Figure 6: The NPV for different electricity price areas and electricity prices.

To further examine the effect of the azimuth angle, load and BESS on the profitability, the results from the year 2018 are investigated in more detail. The decision to further investigate the electricity prices of 2018 stems from the alignment of the average prices that year with the projected electricity forecasts for 2050. To examine the impact of the roof orientation on the NPV, Figure 7 illustrates the proportion of profitable cases for different roof orientations across all electrical areas. The first figure shows the results for all simulations, while the second figure only shows the result for simulations produced using the electricity prices from 2018. Notably, the results demonstrate a significantly higher percentage of profitable cases associated with south- and east-facing roofs.

Furthermore, the analysis reveals that north-facing roofs yielded no profitable simulations when considering the electricity prices of 2018. This highlights the importance of considering roof orientation during the planning phase of PV installations. Among the profitable simulations involving north-facing roofs in the first figure, 89 percent were generated using the electricity prices from 2022 and the remaining 11 percent utilized the electricity prices from 2021. This finding suggests that if future electricity prices align with the predictions provided by the Nordic Energy Research and the Swedish Energy Agency, PV installations on north-facing roofs will not yield profitability under any of the investigated conditions in this study.

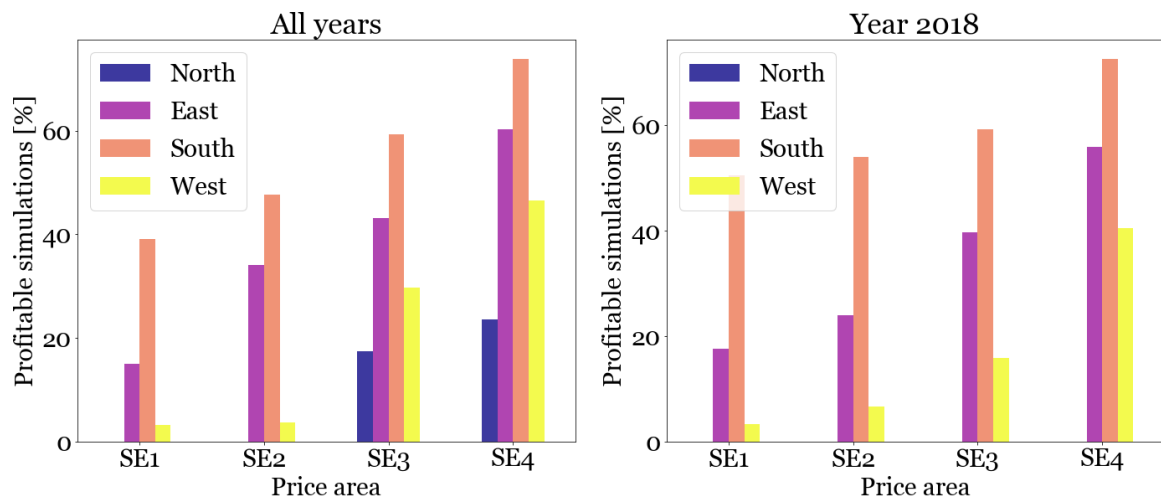


Figure 7: Percent profitable cases for different roof orientations and electrical areas.

To analyze the parameters leading to unprofitable simulations, the results for south-facing roofs with the electricity prices of 2018 are investigated further and displayed in Figure 8. The characteristics overrepresented in the figure are hence the ones contributing to unprofitability. The results indicate that the chosen dispatch strategy has minimal influence on the profitability of the installation. However, the load plays a significant role, as the smallest load examined accounts for more than half of the non-profitable simulations in the investigated scenarios. Furthermore, the simulations demonstrate that a PV capacity of 12 kW yields the fewest number of non-profitable cases, while larger battery capacities are more frequently associated with unprofitability. Simulations without a battery contribute to only 4 percent of the non-profitable scenarios.

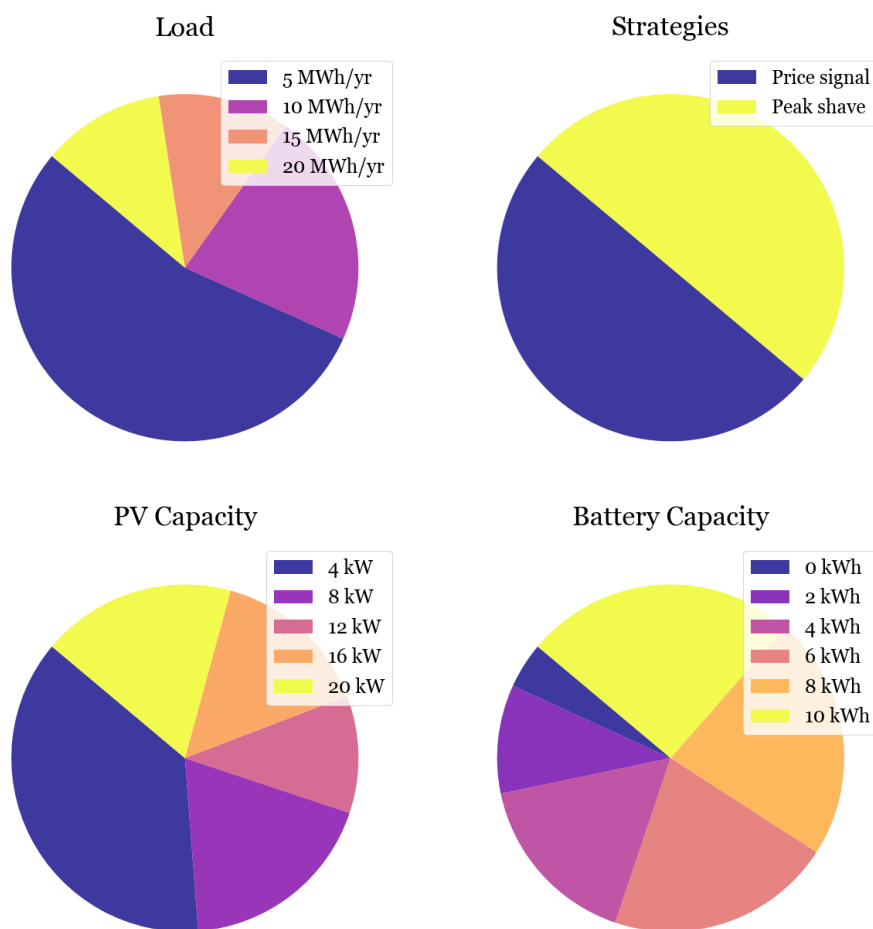


Figure 8: Attributes of non-profitable simulations.

Figure 9 portrays the NPV across different solar fractions and loads, showing results for all electrical areas for each load for the results from the year 2018 with a south-facing roof with no BESS. For a 5 MWh/yr load, the NPV maintains a relatively steady rate for solar fractions from 0.6 to 2.3, after which it begins to decline. The NPV for a load of 20 MWh/yr consistently rises with an increased solar fraction, however, the study did not explore PV systems with adequate size to disrupt this increasing trend. For both the load with 10 MWh/yr and the load with 15 MWh/yr, the NPV peaks at a solar fraction between 0.93 and 1.15, averaging at 1.03. The figure demonstrates that the profitability of PV installations increases with larger loads, suggesting that these systems are more advantageous for consumers with higher electricity consumption. The figure indicates that households with loads under 10 MWh/year have the potential to generate more energy than their consumption, even with smaller solar installations.

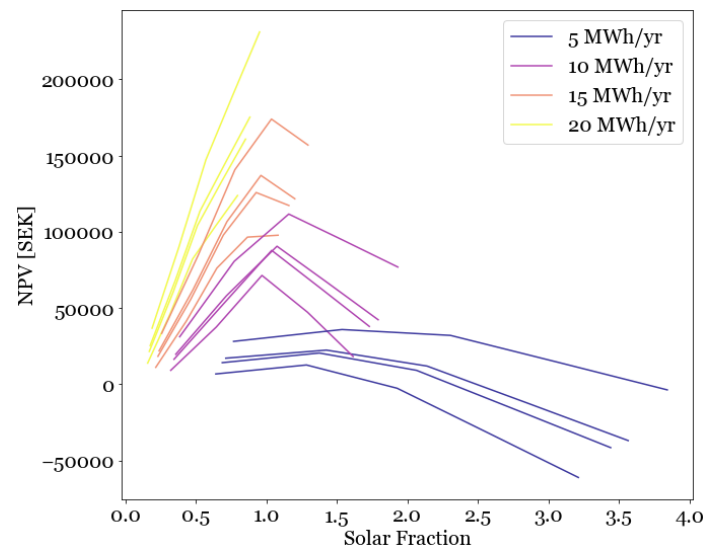


Figure 9: NPV for different solar fractions and loads.

To further examine the profitability of different PV and BESS capacities, Figure 10 presents the NPV across various PV and battery capacities for each load investigated. The result is produced for a south-facing roof with the electricity prices of 2018 and a location in SE3. SE3 has been chosen as the location since it is the most densely populated electrical area. The figure reveals a higher NPV for all the different loads when no battery is involved, indicating the current lack of profitability for batteries in the investigated scenario. It can also be seen that the load highly influences the optimum PV capacity and that the larger loads result in a higher NPV of the systems.

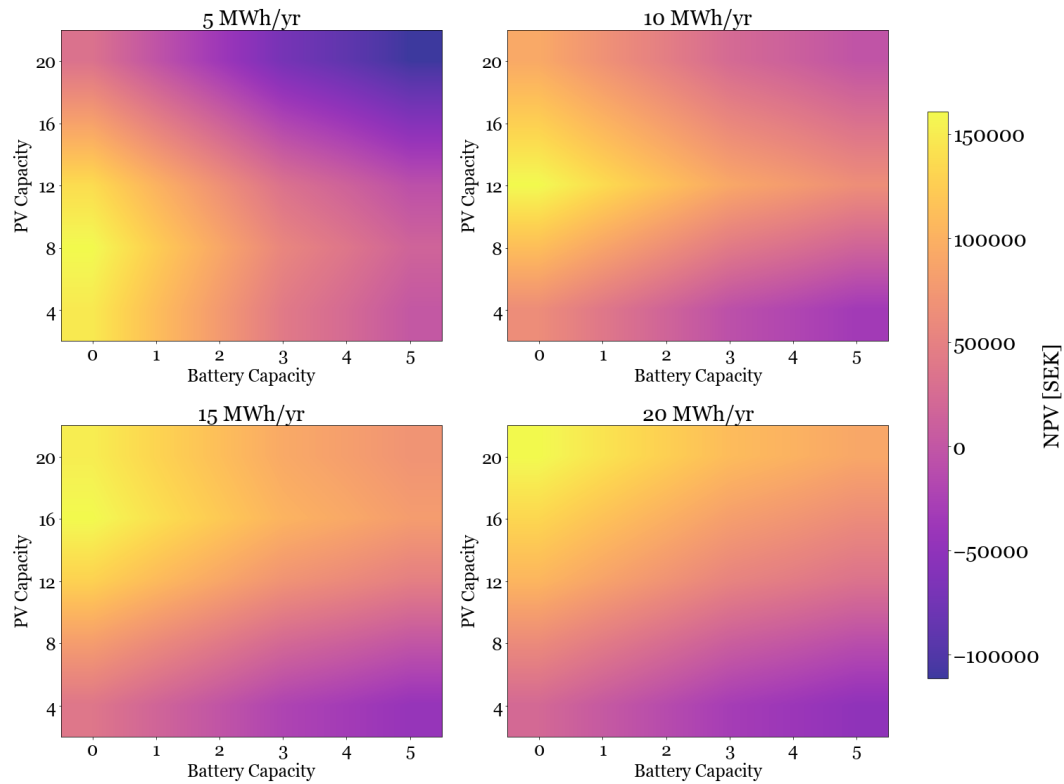


Figure 10: NPV for different PV and BESS capacities.

Figure 11 depicts the self-consumption and self-sufficiency for different PV and battery capacities. The figure is based on the same conditions as the figure above. The results show that higher self-sufficiency can be reached equally by increasing the PV or BESS capacity. If the goal is to increase self-sufficiency, the system's PV capacity could be increased since that provides the best economic benefits. However, if the goal is to increase self-consumption, it is done to a much higher degree by increasing the battery capacity. The PV capacity only has a minor influence on self-consumption.

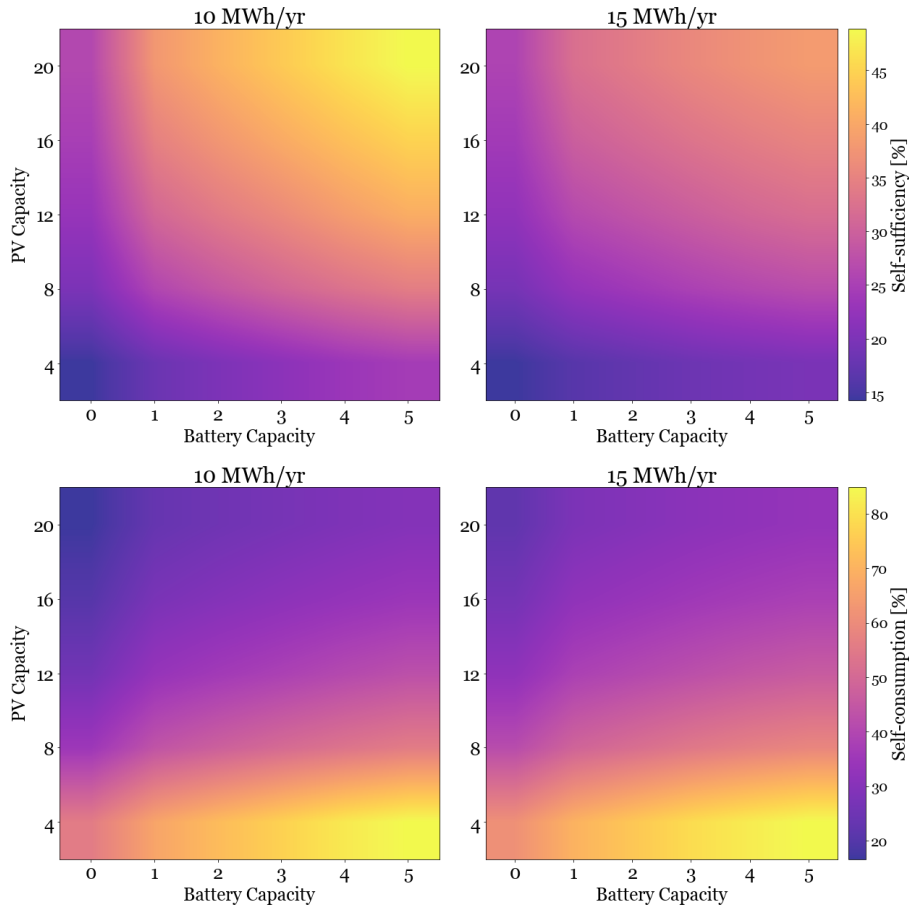


Figure 11: Self-sufficiency and self-consumption for different PV and BESS capacities.

3.2.1 Battery and Dispatch Strategy

To gain further insights into the profitability of BESS, Figure 12 illustrates the revenue per dispatch kWh of electricity from the battery for a south-facing roof located in SE3 with a 15 MWh/yr load. The average revenue of all BESS capacities is plotted for each PV capacity. The figure highlights distinct variations between the different dispatch strategies, where the price signal forecast strategy generates over five times as much revenue for every dispatched kWh. When analyzing the results across the different years, the significance of price volatility in the profitability of a BESS can be seen. Despite the overall electricity price being the lowest in 2020 among all the years considered, its higher volatility rendered it more favorable for BESS profitability compared to the relatively less volatile years 2018 and 2019. Additionally, the analysis indicates that while a larger PV capacity contributes somewhat to increased revenue, its impact is less significant than other parameters examined.

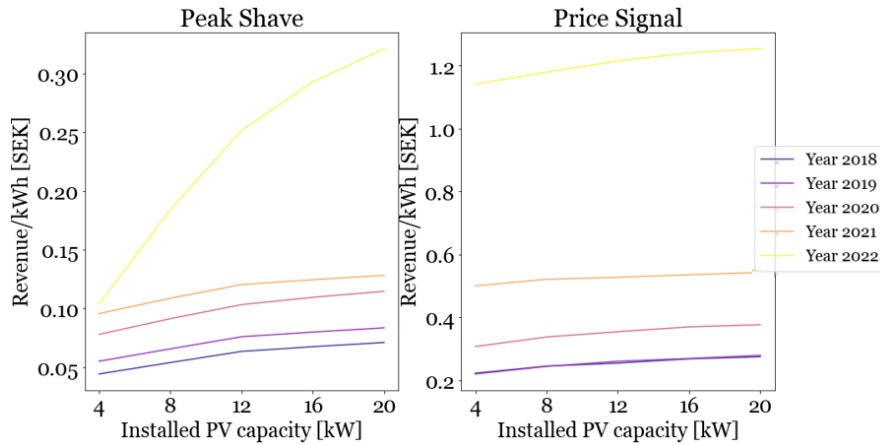


Figure 12: Revenue per kWh for the different dispatch strategies.

Table 5 displays the LCOS and the average revenue earned for every dispatched kWh of electricity for each dispatch strategy with the electricity prices in 2018. The result is shown for the scenario previously investigated with a PV capacity of 16 kW and a BESS capacity of 4 kWh. For the investment to be profitable, the actual revenue must be as high as the LCOS. The table reveals that the revenue earned from dispatched electricity is nearly negligible and would need to increase by over ten times to render the battery profitable. In the best-case scenario for a simulation in area SE4, using a load of 20 MWh/yr, a south-facing roof and a 20 kW PV installation, the difference between the LCOS and the average revenue is 1.4 SEK/kWh.

Table 5: The LCOS and average revenue for each dispatched kWh.

Dispatch strategy	Peak Shave	Price Signal Forecast
LCOS [SEK/kWh]	8.39	3.13
Actual Revenue [SEK/kWh]	0.07	0.26

In this investigated scenario with the price signal forecast dispatch strategy, the BESS installation cost would need to decrease to 748 SEK/kWh for the investment to become profitable. However, in the best-case scenario as described above, the BESS would become profitable at a cost of 3,669 SEK/kWh. This implies that the BESS cost would need to decrease by approximately 50 percent to become profitable in the best-case scenario investigated in this paper. Notably, this scenario is developed using electricity prices in 2022, which are considerably higher than future forecasts.

3.2.1.1 Comparison with a Real BESS Installation

This section compares the simulated battery dispatch in the model developed and two real installations. The installations investigated are the same ones that validated the PV model in section 3.1 Model Validation. Both households have the same battery installed with a capacity of 7,7 kWh but the dispatch strategies utilized are unknown. When investigating the dispatch strategies of the batteries, the real customer dispatch is compared to the perfect 24-hour look ahead price signal forecast in SAM and the result is shown in Table 6. The price signal forecast strategy was investigated to see the maximum amount of money the households could have saved. The results reveal that, with the current dispatch strategy employed by the households in 2022, the yearly electricity bill is higher than it would be if the households only had a PV system without a battery. Hence, the battery is increasing the household's yearly electricity bill. However, using the price signal forecast dispatch strategy, incorporating the battery would lead to an annual reduction in the electricity bill. This empirical data further confirms that batteries are not economically profitable with today's prices and technology.

Table 6: Savings in electricity bill year 2022 with a BESS [SEK].

	Real Battery Dispatch	Price Signal Forecast
Household 1	-260	1901
Household 2	-334	1888

3.3 Sensitivity Analysis

A sensitivity analysis was performed to investigate the inflation rate's effect on the NPV and Figure 13 presents the result for different discount rates for four specific PV installations without a BESS. The selected cases have a consumption of 15 MWh/yr, use the electricity prices from 2018, features a south-facing roof and have a 16 kW PV installation. The figure shows that profitability decreases with higher discount rates, although all investments remain profitable.

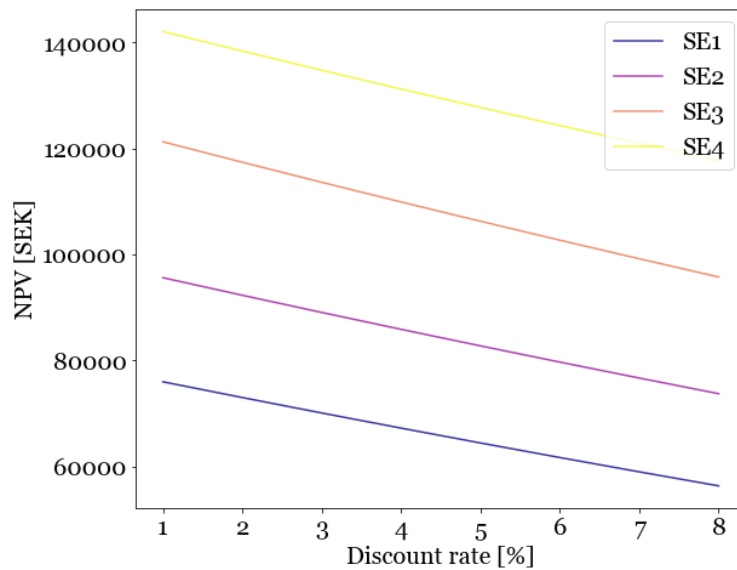


Figure 13: NPV for different discount rates.

Next, a sensitivity analysis was conducted on when the battery is considered to have reached the EoL. As stated in the background, conventional batteries are typically regarded as end-of-life upon reaching 80 percent of their original power capacity, which is applied in the parametric simulations. Nonetheless, since solar batteries do not support critical loads, they can still be deemed functional for an extended duration beyond the aforementioned threshold. Figure 14 therefore illustrates how the NPV for a south-facing roof located in SE3 using a load of 15 MWh/yr, the price signal forecast dispatch strategy and a PV capacity of 16 kW would be affected if the EoL for the battery was considered to be longer. Figure 14 illustrates the installation cost at which the BESS would become profitable for the same conditions as investigated above. The figure reveals that the price at which the BESS becomes profitable is still much smaller than what is seen in today's market. However, the profitability is still noticeably improved when a longer EoL is considered. Since solar batteries do not support a critical load, it could be valuable to reconsider the point at which batteries are considered to have reached EoL to provide a more realistic analysis of their profitability.

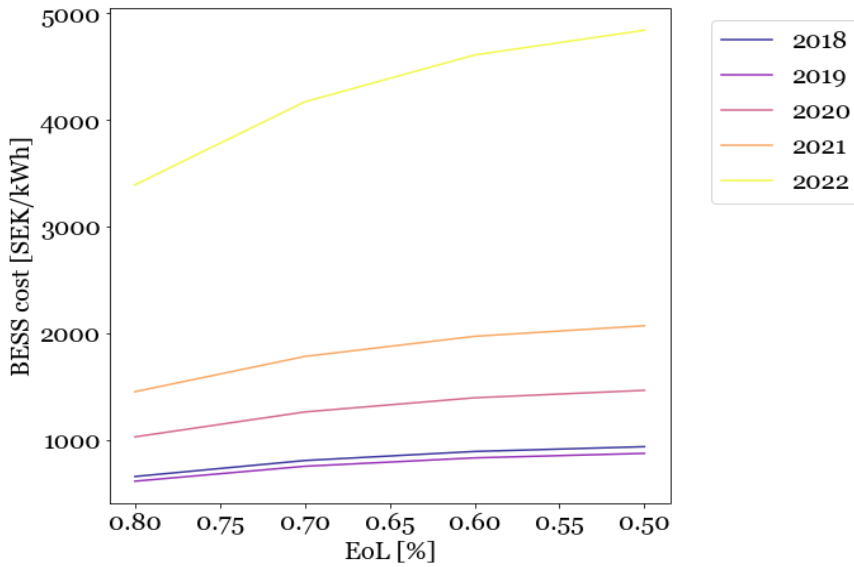


Figure 14: Installation cost at which the BESS becomes profitable.

In the parametric analysis, all results are based on a fixed transfer fee and no capacity-based pricing structure. Figure 15 examines how the profitability of the BESS would be affected if the household had an electricity contract with a capacity-based pricing structure. The graph shows that with a capacity-based pricing structure, the NPV is slightly lower than the simulations utilizing only a fixed transfer fee. However, the slope of the lines is steeper for the simulations using the fixed transfer fee, indicating that the economic gain of the battery is better for a household with a capacity-based transfer fee. However, since the battery cost as of today is approximately 7500 SEK/kWh, it is unlikely that a capacity-based transfer fee will make any significant difference in the profitability of a BESS.

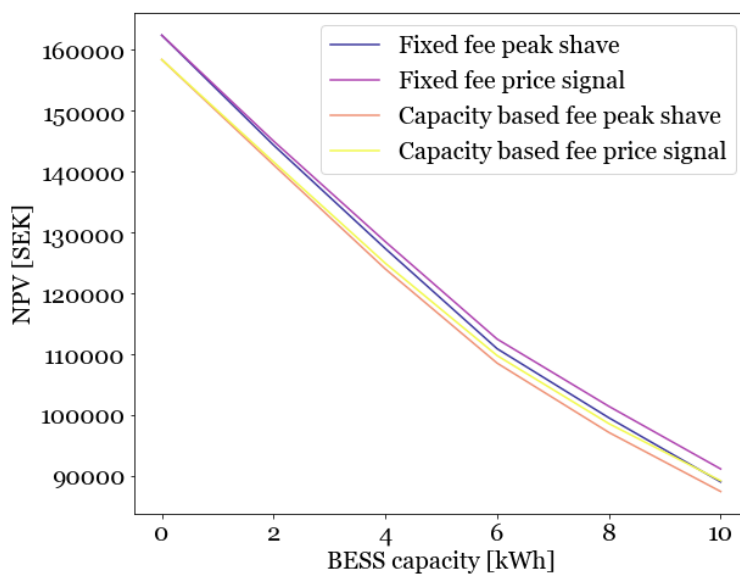


Figure 15: NPV for different electricity pricing structures.

4 Discussion and Conclusion

This section discusses the results, limitations of the study and conclusions.

4.1 Discussion

The results indicate that PV systems can generate substantial income for households, but the profitability is heavily influenced by the location, electricity price, load and roof orientation. As demonstrated in Figure 7, no simulations with north-facing roofs are profitable in the electrical areas SE1 and SE2. Therefore, it is crucial to thoroughly assess the installation conditions, particularly in northern Sweden, as many roof orientations may not be economically viable for households. Since the investigation of non-profitable simulations showed that the load has a significant effect on the profitability of a system, aspects such as if the household has electric heating or an electric car, which increases the electricity consumption, can also be important to consider. Moreover, the analysis of electricity prices reveals that installations exhibit high profitability with the elevated and volatile electricity prices of 2022, with some NPVs approaching one million SEK. However, future energy price predictions suggest that electricity prices are more likely to resemble the ones in 2018, 2019 and 2021. Despite being less advantageous than 2022, the results for these prices still show that many installations yield a positive NPV.

The self-consumption and self-sufficiency of PV systems are essential factors to consider when evaluating the overall benefits of PV installations. A high self-consumption is desirable since it implies that a larger proportion of the electricity generated by the PV system is being consumed on-site. A higher degree of self-sufficiency signifies a reduced dependency on the grid, fostering greater energy independence and resilience. Integrating BESS with PV systems can significantly enhance both self-consumption and self-sufficiency rates. By storing excess solar energy during periods of high generation and low demand and discharging the stored energy during periods of low generation and high demand, BESS can help households better match their on-site generation with their consumption patterns. However, due to the present installation costs, increasing self-consumption and self-sufficiency through a BESS does not provide economic benefits. This could become more relevant if battery prices decrease or the tax relief for selling electricity is removed.

Although BESS installation costs have decreased and electricity prices have risen, the results show that BESS is not yet profitable. In the best-case scenario investigated when the high and

volatile electricity prices in 2022 are used for the whole simulation, the battery would be profitable at an installation cost of 3,669 SEK/kWh, which is still half the cost of a typical installation in today's market. A study by the NREL (2021) predicts that future BESS costs will drop by 50 percent between 2020 and 2030. Given the anticipated rapid decrease in battery prices, some installations could become profitable within ten years if electricity prices remain as high as in 2022. However, in the simulations investigated with the electricity prices in 2018, the BESS would be profitable at 748 SEK/kWh, which is uncertain if they will ever reach. This result is confirmed in a study by Campana et al. (2021), where they found that batteries would become profitable for 250 US\$/kWh, which is within the range found in this report.

Furthermore, the results highlight the importance of battery dispatch strategies and intelligent energy management features. Examining the average earnings from different dispatch strategies reveals that the price signal forecast strategy results in approximately five times higher revenue for every discharged kWh of electricity. This was again validated in the empirical data where the households investigated increased their electricity bill due to the inefficiency of the dispatch strategy. If the profitability of a BESS is dependent on basing the dispatch strategy on the Nord Pool day-ahead market prices, this strategy could only work for a smaller number of residential installations. Electricity suppliers report to Svenska Kraftnät how much electricity they expect to use every hour the following day, which sets the hourly prices based on supply and demand. If many households instead shift their consumption based on the day-ahead price, the retailers get a penalty for making a wrong prediction of the consumption (Energimarknadsinspektionen, 2021b), which would eventually get passed on to the customers. Basing the dispatch strategy on the day-ahead prices would, therefore, only be feasible for a limited number of households when it does not have a noticeable impact on the electricity predictions.

A study by Zhang et al. (2017) further confirms the importance of the dispatch strategy, where one conventional operation strategy, one dynamic price load shifting strategy and one hybrid operation strategy were evaluated. Their findings indicated that the conventional operation strategy was not lucrative and that the hybrid operation strategy outperforms other investigated strategies. A notable discrepancy between the results found in this report and the study by Zhang et al. is that their findings suggest that battery installations under 72 kWh are profitable. The reason for this discrepancy may be attributed to the fact that their study did not consider the tax relief for selling electricity because of the uncertainty regarding how long it will persist. The tax relief significantly enhances the economics of selling electricity, reducing the benefits of having a battery that saves electricity for self-consumption. Should this tax relief be terminated in the future, the financial viability of a residential BESS could be

significantly improved. This shows the uncertainty of calculating the profitability of PV and BESS installations in Sweden since it is uncertain how long the tax relief will persist and it significantly affects the results.

4.2 Limitations and Future Work

Since the results are based on forecasts, one limitation of this study is the availability of comprehensive and accurate data for various input parameters, such as electricity prices and installation costs. Inaccurate or outdated data can affect the reliability of the results and conclusions. It is also important to recognize that even though continual advancements are being made in the fields of inverter technologies and forecasting strategies, there will always be a discrepancy between a perfect 24-hour look-ahead dispatch strategy as investigated in this study. Variations in weather conditions and unforeseen changes in load demand are among the numerous unpredictable elements that contribute to this gap. Therefore, the study's findings can be used to understand the maximum theoretical benefits that can be achieved rather than absolute targets for real-world applications.

To gain more generalized knowledge, the analysis could be expanded to other regions with different climatic conditions, electricity market structures and regulatory frameworks to gain a broader understanding of the potential benefits and challenges associated with PV and BESS installations. By examining a more comprehensive range of contexts, researchers can identify commonalities and differences in system performance and profitability, leading to more robust and generalizable insights. Moreover, alternative battery technologies or dispatch strategies could be examined to reveal new avenues for improving the overall profitability of a BESS. For example, emerging battery technologies with lower production costs may render BESS more cost-effective for residential applications.

Lastly, given the substantial influence of the tax relief on the profitability of PV and BESS, a more comprehensive exploration and examination of its total impact would be of great value. It would be interesting to see how much the profitability of the systems is affected if the tax relief is removed, but also the effect it has on households and if they are aware of its risks. For example, it could be investigated if solar companies make predictions on future earnings of their system based on the assumption that this tax relief will consist for the whole lifetime of the installation. It could also be interesting to see which impact this can have on the household's willingness to buy PV systems and if they are aware of the uncertainty of the future economic predictions due to the fact that it is unknown how long the tax relief will persist.

4.3 Conclusion

This study provides a comprehensive assessment of the performance and profitability of residential PV and BESS installations in Sweden using a parametric simulation approach. The findings reveal that the economic viability of PV and BESS installations is significantly influenced by every parameter assessed in this study. If future electricity prices align with present forecasts, installations on north-facing roofs will not be profitable under any circumstances investigated in this study. A distinct correlation is also discernible between larger loads and improved economic viability for PV and BESS installations, while a smaller battery capacity results in a higher NPV. Therefore, it is seen that with the installation costs and subsidies present today, BESS is still not an economically viable option even though electricity prices have increased and battery costs have decreased.

The data further divulges that an optimal solar fraction of 1.03 yields the maximum NPV for households with an annual load of 10 MWh and 15 MWh. The significance of the dispatch strategy on the revenue generated from dispatched electricity from the battery is also notable. The price signal forecast dispatch strategy outperforms the peak shaving dispatch strategy, yielding over five times the revenue per dispatched kWh of electricity. However, since this revenue is still over ten times smaller than the LCOS, this does not have a notable impact on the system's profitability due to the high installation costs. If the battery installation costs are significantly reduced in the future, the development of more advanced inverters that consider the hourly fluctuations in electricity prices could be crucial for BESS to ever become profitable.

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