

# Optimization and Increased Value of Solar Panels with Home Battery Systems for Swedish Households

Bachelor's Thesis in Electrical Engineering  
REX IJOMANTA

**DEPARTMENT OF ELECTRICAL ENGINEERING**

CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2025  
[www.chalmers.se](http://www.chalmers.se)



BACHELOR'S THESIS 2025

**Optimization and Increased Value of  
Solar Panels with Home Battery Systems for  
Swedish Households**

Rex Ijomanta



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY

Department of electrical engineering  
CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2025

Optimization and Increased Value of Solar Panels  
with Home Battery Systems for Swedish Households

© Rex Ijomanta, 2025.

Supervisor: Anders Hellman, Associate Professor, Chemical Physics  
Examiner: Anders Hellman, Associate Professor, Chemical Physics

BACHELOR'S THESIS 2025  
Department of Electrical Engineering  
Chalmers University of Technology  
SE-412 96 Gothenburg  
Sweden  
Telephone +46 31 772 1000

Cover photo: Sourced from STG Solar FZCO, "Off-Grid System," [Online]. Available: <https://stgsolar.ae/off-grid-system/>

Typeset in L<sup>A</sup>T<sub>E</sub>X  
Gothenburg, Sweden 2025

# Abstract

This thesis investigates the techno-economic viability of residential photovoltaic (PV) systems with and without battery energy storage under Swedish market conditions. Using MATLAB, a comparative analysis is conducted for four system configurations: 5 kW and 10 kW PV systems, each with and without a 10 kWh lithium-ion battery. The energy production potential is modeled using PVGIS data, while economic metrics, Net Present Value (NPV), Return on Investment (ROI), and payback period are calculated based on current electricity prices, feed-in tariffs, and tax incentives such as Sweden's "Grön Teknik" deduction.

Additionally, the thesis implements and compares two battery control strategies: a rule-based heuristic and a predictive model using price signals to optimize battery dispatch. Results show that PV systems without storage provide the shortest payback and highest NPV, particularly when system size is aligned with household demand. Battery integration improves self-consumption and grid independence but reduces financial performance under current market conditions. Predictive control marginally outperforms rule-based strategies in energy savings but yields limited additional economic benefit. The study concludes that while residential PV is currently a financially sound investment in Sweden, battery adoption remains constrained by cost unless justified by non-monetary benefits or future policy shifts.

Keywords: Solar PV, residential, battery energy storage, net present value, return on investment, self-consumption, predictive control, rule-based control, feed-in tariff, MATLAB.

# Sammanfattning

Denna kandidatuppsats undersöker den teknisk-ekonomiska lönsamheten för solcellssystem i bostäder, med och utan batterilagring, under svenska marknadsförhållanden. Med hjälp av MATLAB genomförs en jämförande analys av fyra systemkonfigurationer: 5kW och 10kW solcellssystem, vardera med och utan ett 10 kWh litiumjonbatteri. Energiproduktionspotentialen modelleras med data från PVGIS, medan ekonomiska nyckeltal såsom nettonuvärde (NPV), avkastning på investering (ROI) och återbetalningstid beräknas utifrån aktuella elpriser, ersättning för överskottsels och skatteincitament som Sveriges skattereduktion för "Grön Teknik".

Uppsatsen implementerar och jämför även två batteristyrstrategier: en regelbaserad heuristik samt en prediktiv modell som optimerar batterianvändningen baserat på prisvariationer. Resultaten visar att solcellssystem utan lagring ger kortast återbetalningstid och högst NPV, särskilt när systemets storlek matchar hushållets elanvändning. Batteriintegration förbättrar egenanvändning och elnätsberoende men försämrar den ekonomiska avkastningen under nuvarande marknadsförutsättningar. Prediktiv styrning presterar marginellt bättre än regelbaserad styrning i form av energibesparing, men den ekonomiska vinsten är begränsad. Studien drar slutsatsen att solcellsanläggningar i dagsläget är en ekonomiskt lönsam investering i Sverige, medan batteriinvesteringar fortsatt begränsas av kostnadsskäl, såvida de inte motiveras av icke-ekonomiska fördelar eller framtida förändringar i energipolitiken.

Nyckelord: Solcellssystem, bostäder(villa), batterilagring, nettonuvärde, avkastning på investering, egenanvändning, prediktiv styrning, regelbaserad styrning, ersättning för överskottsels, MATLAB.

## Acknowledgments

This degree project was carried out as part of the Bachelor of Science program in Electrical Engineering at Chalmers University of Technology. The work focused on smart energy management in residential buildings and the economic evaluation of solar photovoltaic systems with battery storage.

I would like to express my sincere gratitude to Daniel Elfstrand at Grid Collective, who provided me with the opportunity to undertake this project and offered valuable insights throughout its development. I am also especially thankful to my supervisor and examiner, Anders Hellman, at Chalmers University of Technology, for his constructive feedback, and guidance, all of which were instrumental in the successful completion of this thesis.

Rex Ijomanta, Gothenburg, 06 2025



# Abbreviations

AC	Alternating Current
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
DC	Direct Current
EV	Electric Vehicle
EMS	Energy Management System
Ei	Energimarknadsinspektionen (Swedish Energy Markets Inspectorate)
EMS	Energy Management System
FiT	Feed-in Tariff
GHI	Global Horizontal Irradiance
HEMS	Home Energy Management System
IEA	International Energy Agency
kWh	Kilowatt-hour
kWp	Kilowatt-peak
LCOE	Levelized Cost of Electricity
Li-ion	Lithium-ion
MPPT	Maximum Power Point Tracking
MPC	Model Predictive Control
NPV	Net Present Value
OPEX	Operational Expenditure
PR	Performance Ratio
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
ROI	Return on Investment
SE1–SE4	Swedish Electricity Price Zones 1 to 4
SEK	Swedish Krona (currency)
STC	Standard Test Conditions
VAT	Value-Added Tax
VPP	Virtual Power Plant
YoY	Year-on-Year



# Contents

<b>List of Acronyms</b>	<b>viii</b>
<b>List of Figures</b>	<b>xiii</b>
<b>List of Tables</b>	<b>xv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	1
1.2 Purpose . . . . .	2
1.3 Limitations . . . . .	3
<b>2 Theory</b>	<b>5</b>
2.1 Residential Solar PV Systems . . . . .	5
2.2 Solar Panels . . . . .	6
2.3 Inverters . . . . .	6
2.4 Battery Energy storage system (BESS) . . . . .	6
2.5 Factors Affecting PV Output in Sweden . . . . .	6
2.5.1 System Losses and Performance Ratio . . . . .	7
2.6 Market Research . . . . .	8
2.6.1 Solar Panels . . . . .	8
2.6.2 Battery Storage . . . . .	8
2.7 Government Incentives and Subsidies . . . . .	8
2.7.1 Swedish Electricity Market Context . . . . .	9
2.8 Economic Analysis of Solar PV and Battery Systems . . . . .	9
2.8.0.0.1 Key Variables . . . . .	10
2.8.0.0.2 Annual Savings . . . . .	10
2.8.0.0.3 Revenue Calculation . . . . .	10
2.8.0.0.4 Payback Period . . . . .	10
2.8.0.0.5 Net Present Value (NPV) . . . . .	10
2.8.0.0.6 Return on Investment (ROI) . . . . .	11
2.9 Energy Management and Control Strategies . . . . .	11
<b>3 Methods</b>	<b>13</b>
3.1 Economic analysis . . . . .	13
3.1.1 Initial Investments . . . . .	13
3.1.2 Electricity Prices . . . . .	13
3.1.3 Electricity Usage and Savings . . . . .	13

3.2	Method: Energy Management and Control Strategies . . . . .	14
3.2.1	System Configurations . . . . .	14
3.2.2	Load and Generation Data . . . . .	14
3.2.3	Electricity Pricing and Feed-In Tariff . . . . .	15
3.2.4	Control Strategies Simulated in MATLAB . . . . .	15
3.2.5	MATLAB Implementation . . . . .	15
<b>4</b>	<b>Results</b>	<b>17</b>
4.1	Economic Evaluation . . . . .	17
4.1.1	System Configuration . . . . .	17
4.1.2	Annual Energy Production . . . . .	18
4.1.3	Economic Analysis of System Configurations . . . . .	19
4.1.3.1	Annual Revenue Breakdown . . . . .	20
4.1.3.2	Net Present Value (NPV) . . . . .	20
4.1.3.3	Payback Period and ROI . . . . .	20
4.2	Energy Management and Control Strategies . . . . .	21
4.2.1	Summary of Annual Revenue . . . . .	21
4.2.1.1	Observations . . . . .	21
<b>5</b>	<b>Discussion</b>	<b>23</b>
5.1	Economic Viability of 5 kW vs 10 kW Systems . . . . .	23
5.2	Impact of Battery Storage on Financial Performance . . . . .	23
5.3	Control Strategies: Rule-Based vs Predictive . . . . .	23
5.4	Sensitivity to Key Parameters . . . . .	24
5.5	Practical Recommendations for Swedish Homeowners . . . . .	24
5.5.1	System Size Should Match Household Consumption . . . . .	24
5.5.2	Batteries Increase Energy Independence but Delay Financial Returns . . . . .	25
5.5.3	Economic Viability Depends on Policy Conditions . . . . .	25
5.5.4	Energy Management Strategies Can Improve Financial Outcomes . . . . .	25
5.5.5	Geographic Location Influences System Performance . . . . .	25
5.6	Limitations and Future Work . . . . .	25
5.7	Sustainability and Ethical Considerations . . . . .	26
<b>6</b>	<b>Conclusion</b>	<b>27</b>
	<b>References</b>	<b>29</b>
<b>A</b>	<b>Appendices</b>	<b>I</b>
A.1	PVGIS Simulation Output for 5 kW System . . . . .	I
A.2	PVGIS Simulation Output for 10 kW System . . . . .	I
A.3	MATLAB Code for Economic Analysis . . . . .	II
A.4	MATLAB Code: Revenue from Control Strategies . . . . .	V

# List of Figures

1.1	Residential solar-battery system with wall-mounted inverter and battery bank.[1] . . . . .	3
2.1	Energy flow in a residential hybrid solar PV system. [2]. . . . .	5
2.2	Average global solar radiation in Sweden in one year. [3]. . . . .	7
2.3	Categories of energy management controller. [4] . . . . .	12
4.1	PVGIS-5 5kw Configuration . . . . .	17
4.2	Monthly solar energy production for a 5 kW system in Gothenburg (kWh) . . . . .	18
4.3	Monthly solar energy production for a 10 kW system in Gothenburg (kWh) . . . . .	19
A.1	PVGIS output for 5 kW fixed-angle solar system in Gothenburg[5] . .	I
A.2	PVGIS output for 10 kW fixed-angle solar system in Gothenburg[5] .	I



# List of Tables

3.1	Monthly average electricity prices in SE3 (Gothenburg) 2024, SEK/kWh (incl. VAT) [6] . . . . .	14
4.1	Annual revenue breakdown for each configuration . . . . .	20
4.2	Net Present Value over 30 years (3% discount rate) . . . . .	20
4.3	Estimated payback period and return on investment . . . . .	20
4.4	Annual revenue by configuration and control strategy . . . . .	21



# 1

## Introduction

### 1.1 Background

Grid Collective is a Swedish Provider of Renewable Energy Solutions that has experienced a significant decline in solar panel adoption within the residential sector throughout 2024. This decline can primarily be attributed to two key factors: persistently low electricity prices throughout the Nordic region and the recent reduction in government subsidies for residential renewable energy installations[3]. In response to these challenges, Grid Collective is actively seeking actionable strategies to enhance the financial attractiveness of combined solar panel and battery systems for Swedish homeowners.

The company has identified several specific challenges that currently limit the value proposition of residential solar systems:

1. **Inefficient energy management:** Most installed systems lack sophisticated control mechanisms to optimize energy flows between production, storage, and consumption.
2. **Underutilized home batteries:** Many customers invest in home battery systems but fail to maximize their economic potential due to suboptimal charge and discharge patterns.
3. **Insufficient integration with EV charging:** Despite the growing adoption of electric vehicles in Sweden, most residential energy systems are not configured to intelligently coordinate EV charging with solar production and battery storage.

### Industry Context

Sweden has experienced a steady increase in residential solar panel installations in the last decade, with the total installed photovoltaic (PV) capacity growth from 2018 to 2023 being 67% in 2023, 49% in 2022, 45% in 2021, 57% in 2020, 66% in 2019, and 59% in 2018 [3]. The steady growth can be attributed to the capital subsidies system [7] and the reduced costs of solar panels and their installation. Similarly, the adoption of home battery storage has increased with the support of the green deduction for batteries [8]. Electric vehicle sales for passenger cars have also increased by 14.4% year-on-year (YoY), with 51.6% of all new passenger cars being plug-in vehicles [9].

However, despite this growth, the financial returns from these investments have been diminishing due to various market and policy shifts:

1. **Shift from Capital Subsidy to Tax Deduction Support:** The Capital Subsidy Program for Solar PV was replaced by a tax deduction scheme for the installation of green technology, narrowing long-term subsidy support.[10]
2. **Low Electricity Prices:** The Nordic electricity market has experienced relatively low average prices in 2023–2024. In 2024, the Nord Pool market had the lowest yearly average price of €36.06/MWh in Europe [11].
3. **Demand Tariffs:** The Swedish Energy Markets Inspectorate (Energimarknadsinspektionen, Ei) introduced a requirement for a demand tariff (*effektavgift*) [12]. In response, many grid operators have implemented or announced plans to adopt demand-based pricing schemes that charge consumers based on their peak power usage rather than solely on total energy consumption.

These developments have created a challenging environment for residential renewable energy investments, but also present opportunities for more sophisticated energy management solutions that can navigate these complexities.

## 1.2 Purpose

The purpose of this thesis is to develop and evaluate control strategies that optimize the interaction between residential solar photovoltaic (PV) systems, home battery storage, and household electricity consumption to maximize the financial value of such systems for Swedish single-family homeowners under 2024 market conditions.

This study addresses the economic challenges facing solar adoption in Sweden, particularly due to reduced subsidies, low spot electricity prices, and the implementation of demand-based tariffs. By simulating energy flows and assessing key economic outcomes, the thesis aims to provide actionable recommendations.

Specifically, the thesis intends to deliver the following:

1. An energy management simulation model, developed in *MATLAB*, that illustrates optimized energy flows between solar production, battery storage, household consumption, and EV charging. The model compares baseline (non-optimized), rule-based, and predictive control strategies, with a focus on adapting to hourly electricity prices and peak demand charges under evolving Swedish tariff structures.
2. A quantitative economic analysis, including calculation of annual savings, net present value (NPV), return on investment (ROI), and payback period for four system configurations (5 kW and 10 kW, with and without battery storage). The analysis reflects real 2024 data on system costs, Nord Pool spot prices, tax deductions, and feed-in tariffs applicable in Sweden.
3. Practical, data-driven recommendations for Swedish homeowners considering investments in solar PV and battery systems, helping them to understand under which conditions such investments are financially viable and how energy management strategies can improve returns.



**Figure 1.1:** Residential solar-battery system with wall-mounted inverter and battery bank.[1]

### 1.3 Limitations

This thesis focuses specifically on residential-scale solar PV and battery systems in the Swedish market context. To maintain an achievable scope, this thesis operates within the following limits:

- The analysis is limited to single-family residences (villas) rather than multi-dwelling buildings or commercial properties.
- The research addresses only grid-connected (hybrid) solar PV systems, with an example installation shown in Figure 1.1.
- Weather and solar irradiance data will be based on conditions in Gothenburg, Sweden.
- The study excludes detailed hardware design considerations such as solar panel manufacturing techniques, mounting solutions, or specific battery chemistries etc.
- The study considers only lithium-ion battery and solar PV technologies that are currently commercially available.
- Data is primarily obtained from available secondary sources, with limited primary data collected personally through case studies.
- The economic analysis including calculations of payback period, NPV, and ROI is conducted based on current electricity pricing, policy instruments (e.g., tax credits), and market conditions in Sweden as of 2024.
- The study takes a microeconomic approach, focusing on the economic viability and performance of solar PV and battery systems from the perspective of individual households. Broader macroeconomic or grid-level impacts (e.g., demand response, grid balancing) are beyond the scope of this thesis.



# 2

## Theory

### 2.1 Residential Solar PV Systems

Residential solar PV systems generate electricity from sunlight and are increasingly adopted in single-family homes to reduce electricity bills and increase energy independence. These systems typically include PV panels, inverters, optional battery energy storage systems (BESS), and interconnections to the electrical grid [13]. In Sweden, most residential installations are grid-connected or hybrid systems combining battery storage with grid access [3].

Residential PV systems fall into three main categories:

- **Grid-connected systems:** The most common type, allowing the household to draw power from and export excess electricity to the utility grid.
- **Off-grid systems:** Operate independently of the utility grid and require significant storage capacity.
- **Hybrid systems:** combine grid connection and battery storage, offering both flexibility and backup power. This thesis focuses specifically on hybrid systems, as they provide a balance between self-sufficiency and grid interaction. The solar power can be used, stored, or exported, as illustrated in Figure 2.1.

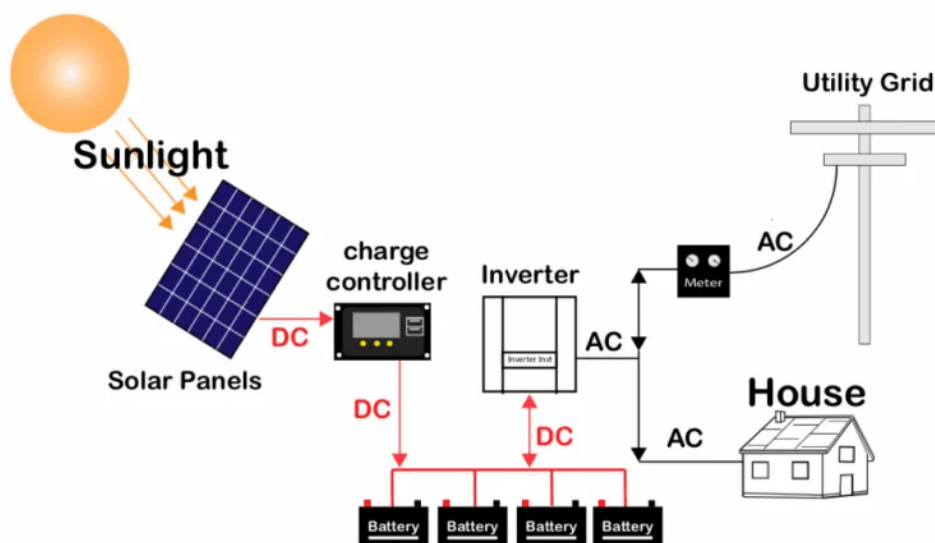


Figure 2.1: Energy flow in a residential hybrid solar PV system. [2].

## 2.2 Solar Panels

Solar PV panels operate on the photovoltaic effect, where sunlight excites electrons in semiconductor materials (usually silicon), generating direct current (DC) electricity. Most consumer-grade solar panels are made from crystalline silicon (c-Si) and have an efficiency between 15% and 22%. These efficiency ratings are measured under standard test conditions (STC), defined as a light intensity of  $1000 \text{ W/m}^2$  and a panel temperature of  $25 \text{ }^\circ\text{C}$ . The performance of solar PV systems depends on multiple factors, including solar irradiation levels, panel orientation and tilt, temperature effects, and system efficiency[14].

## 2.3 Inverters

Inverters serve as the central hub of a solar PV system. They are electrical components that convert the direct current (DC) produced by solar panels into alternating current (AC), which is required for residential appliances and grid compatibility. The choice of inverter significantly influences system performance, monitoring capabilities, and future expansion potential. Some inverters are hybrid models that include integrated battery storage, while others feature maximum power point tracking (MPPT) technology. MPPT is an algorithm-based function that continuously adjusts the electrical operating point of the panels to maximize power output. MPPT optimizers can improve solar system efficiency by 10–30% compared to non-MPPT systems by ensuring that the panels operate at their optimal power point [15].

## 2.4 Battery Energy storage system (BESS)

Battery storage allows excess solar energy to be stored for use during periods of low production or high electricity prices. Lithium-ion batteries dominate the residential market due to their high energy density, long lifespan, and declining cost. For safety and efficiency, installations are typically done indoors, away from direct sunlight and moisture. Battery proximity to the inverter and main electrical panel is also recommended[16].

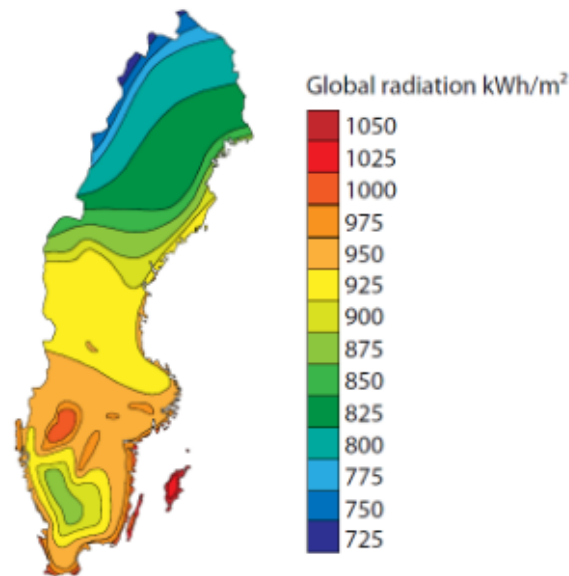
## 2.5 Factors Affecting PV Output in Sweden

Several factors affect the performance of residential PV systems in Sweden, including solar irradiance, geographic location, seasonal variations, temperature effects, system losses, and snow coverage [17]:

- **Solar Irradiance:** Sweden has a moderate solar resource, as shown in Figure 2.2. Annual global solar radiation ranges from approximately  $750$  to  $1100 \text{ kWh/m}^2$ . Southern and coastal regions receive the highest levels of solar energy (e.g., Stockholm receives approximately  $990 \text{ kWh/m}^2/\text{year}$ ).
- **Latitude and Daylight Hours:** Sweden's high latitude causes significant seasonal variation in solar production. Extended daylight hours during sum-

mer increase energy output, while production during winter is minimal, especially in northern regions.

- **Panel Tilt and Orientation:** To maximize solar gain, PV panels in Sweden are typically installed at steeper angles, often close to the local latitude.
- **Temperature Effects:** The efficiency of PV panels decreases with rising temperatures. A typical crystalline silicon panel loses about 0.3 - 0.4% efficiency per degree Celsius above 25 °C [18].
- **Snow Coverage:** Snow accumulation during winter can reduce or block solar output. However, steeper installation angles and natural snow shedding can help minimize long-term losses.



**Figure 2.2:** Average global solar radiation in Sweden in one year. [3].

### 2.5.1 System Losses and Performance Ratio

In addition to environmental factors, a number of system-level losses reduce the actual energy output of PV installations compared to their theoretical potential:

- **Optical losses:** Caused by reflection, dirt (soiling), and partial shading.
- **Thermal losses:** Efficiency drops due to elevated module temperatures.
- **Resistive losses:** Energy losses from wiring and connection resistance.
- **Conversion losses:** Inefficiencies in the inverter during DC-to-AC conversion.
- **System downtime:** Occurs due to maintenance activities or equipment failures.

The combined impact of these losses is represented by the *Performance Ratio* (PR), defined as the ratio of actual energy output to the theoretical maximum under ideal conditions. For well-designed residential systems in Sweden, PR values typically range between 0.70 and 0.85 [19].

## 2.6 Market Research

The Swedish market offers a range of suppliers and retailers for solar panels, battery storage systems, and inverters. Among the available technologies, mono-crystalline solar panels and string inverters are the most commonly used in residential installations in Sweden [3]. These technologies are considered both cost-effective and well-suited to Sweden's geographic and environmental conditions.

### 2.6.1 Solar Panels

As of 2023, the typical price for a standard crystalline silicon module is approximately 3.1 SEK/Wp [3]. Most residential PV systems fall within the smaller size category, particularly installations under 20 kW, which are typical for single-family homes (villas). By the end of 2022, systems under 20 kW accounted for 131,298 installations, representing around 56% of the total residential PV capacity in Sweden [20].

The Swedish Energy Agency (Energimyndigheten) notes that the <20 kW class is "normally mounted on house roofs" [20]. In 2024 alone, 36,500 new small-scale systems (<20 kW) were added, representing a 62% decrease compared to 2023, with a combined capacity of approximately 389 MW [21].

According to the 2023 PVPS survey, residential Building-Applied Photovoltaics (BAPV) systems typically range from 5–10 kW, with installed prices between 11–19 SEK/Wp [3]. A typical villa installation consists of 20–40 panels covering about 30–90 m<sup>2</sup>. For instance, a 5 kW rooftop array covering roughly 30 m<sup>2</sup> is considered suitable for an average household, with a total cost around 92,500 SEK [22]. This cost can be reduced by 20% through the green technology tax deduction.

### 2.6.2 Battery Storage

The battery storage market in Sweden is also growing [3]. A typical 10 kWh home battery system, intended to increase self-consumption of solar energy, costs approximately 40,000 SEK after a 50% tax deduction [23]. This translates to about 3,500–4,500 SEK per kWh of installed capacity (including VAT and incentives). Without the subsidy, the raw cost is nearly double, at around 80,000 SEK. In summary, homeowners looking to install both solar PV and battery storage can expect to invest between 100,000 and 150,000 SEK for a 5–10 kW system paired with a 10 kWh battery [23].

## 2.7 Government Incentives and Subsidies

To support the adoption of residential solar PV systems, Sweden offers several fiscal incentives aimed at reducing upfront investment costs. The primary mechanism is the *grön teknik* (green technology) tax credit, which provides a 20% deduction on the cost of installation work and materials for grid-connected solar panels [10]. This deduction is capped at 50,000 SEK per person per year.

A more substantial 50% tax deduction is available for the installation of energy storage systems, including home batteries and EV chargers, also subject to the same annual cap [10]. These incentives are typically applied directly to the installer’s invoice, functioning similarly to the broader ROT/RUT tax deduction scheme. However, beginning in July 2025, the deduction rate for new solar installations is scheduled to be reduced from 20% to 15% [24].

In addition to upfront incentives, homeowners currently benefit from a feed-in tax credit of 0.6 SEK/kWh for surplus electricity exported to the grid. This applies to up to 30,000 kWh of exported energy per year, translating to a maximum tax credit of approximately 18,000 SEK annually [3]. This “micro-production” credit has been a key driver of residential solar adoption in recent years. However, under the proposed 2024 national budget, this incentive is slated for removal beginning in January 2026 [25].

### 2.7.1 Swedish Electricity Market Context

Sweden’s electricity market operates within the larger Nordic power system, with hourly pricing determined on the Nord Pool spot market. The country is divided into four electricity price zones (SE1 - SE4), and prices vary regionally based on local supply and demand as well as transmission constraints [3].

Residential electricity bills in Sweden typically consist of several cost components:

- **Energy cost:** Based on hourly spot market prices or fixed-rate contracts negotiated with electricity providers.
- **Grid tariffs:** Charged by grid operators and include both fixed fees and, increasingly, variable components based on peak usage.
- **Demand tariff (Effektavgift):** A power-based charge calculated from the user’s maximum load on the grid during a billing period, typically measured in kilowatts (kW) [12].
- **Taxes and levies:** Standard government-imposed charges.
- **Value-added tax (VAT):** Currently set at 25% on electricity and related services.

## 2.8 Economic Analysis of Solar PV and Battery Systems

The economic evaluation of residential PV and battery systems assesses the financial viability of the investment by estimating cost savings, potential revenue, and the time required to recover the initial expenditure. This analysis is essential for determining whether installing a PV system with or without battery storage is economically sustainable for a household.

Residential PV systems reduce reliance on grid electricity by generating power for on-site consumption. Surplus energy that exceeds immediate consumption can be exported to the grid and compensated via a feed-in tariff (FiT) or net metering

mechanism. The total financial benefit consists of both savings from self-consumed energy and income from exported electricity [3].

### 2.8.0.0.1 Key Variables

- $E_{\text{prod}}$  – Annual energy produced by the PV system (kWh/year)
- $E_{\text{cons}}$  – Annual household electricity consumption (kWh/year)
- $E_{\text{self}}$  – Portion of  $E_{\text{prod}}$  directly consumed on-site
- $E_{\text{export}} = E_{\text{prod}} - E_{\text{self}}$  – Surplus energy exported to the grid
- $C_{\text{elec}}$  – Retail electricity price (SEK/kWh)
- $R_{\text{FiT}}$  – Feed-in tariff rate (SEK/kWh)
- $I_{\text{total}}$  – Total system investment cost, including PV, battery, inverter, and installation (SEK)
- $S_{\text{annual}}$  – Annual monetary savings (SEK)

**2.8.0.0.2 Annual Savings** The total annual savings are calculated as:

$$S_{\text{annual}} = E_{\text{self}} \cdot C_{\text{elec}} + E_{\text{export}} \cdot R_{\text{FiT}} \quad (2.1)$$

This equation accounts for both:

- Savings from using self-generated electricity (valued at the retail electricity rate).
- Revenue from excess energy exported to the grid (valued at the feed-in tariff).

**2.8.0.0.3 Revenue Calculation** The annual revenue is computed as:

$$\text{Revenue} = \sum_{i=1}^{12} (\text{Self}_i \cdot P_{\text{spot},i} + \text{Export}_i \cdot R_{\text{FiT}}) \quad (2.2)$$

Where  $P_{\text{spot},i}$  is the spot electricity price in month  $i$ .

**2.8.0.0.4 Payback Period** The payback period, defined as the time needed to recover the initial investment, is given by:

$$\text{Payback Period} = \frac{I_{\text{total}}}{S_{\text{annual}}} \quad [26] \quad (2.3)$$

A shorter payback period typically indicates a more financially attractive investment. This metric does not include maintenance costs, degradation, or inflation.

**2.8.0.0.5 Net Present Value (NPV)** For a more comprehensive analysis, the Net Present Value (NPV) considers the time value of money over the system's operational life  $n$  with a discount rate  $r$ :

$$\text{NPV} = \sum_{t=1}^n \frac{S_{\text{annual}}}{(1+r)^t} - I_{\text{total}} \quad (2.4)$$

Where:

- $r$  is the annual discount rate (typically 3 - 5%)
- $n$  is the system lifetime (typically 25 - 30 years)

A positive NPV indicates that the investment generates more value than it costs over time.

**2.8.0.0.6 Return on Investment (ROI)** ROI expresses profitability as a percentage of the original investment:

$$\text{ROI} = \left( \frac{\text{Net Profit}}{I_{\text{total}}} \right) \times 100 \quad [26] \quad (2.5)$$

Where Net Profit equals total financial benefit minus total cost.

## 2.9 Energy Management and Control Strategies

Energy Management Systems (EMS) coordinate distributed energy resources such as solar PV, battery storage, and controllable loads—to optimize system performance. Control strategies vary in complexity, from simple rule-based logic to advanced predictive optimization as shown in Figure 2.3 [4].

Key approaches include:

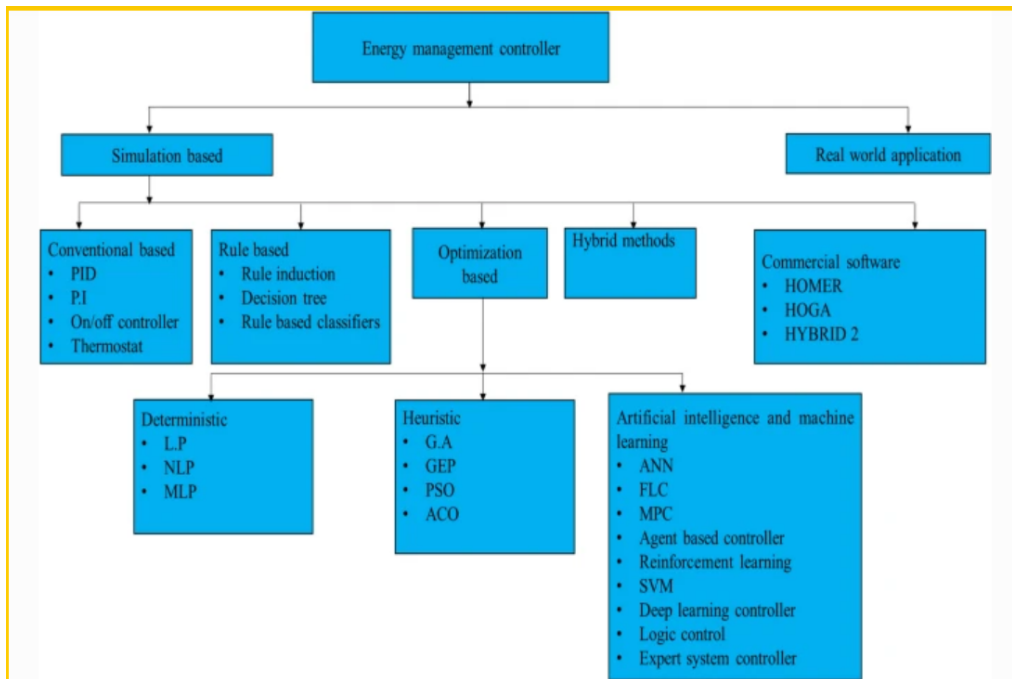
1. **Baseline Operation:** In baseline mode, the system prioritizes solar power for on-site use, charging the battery only after on-site demand is met, and drawing from the grid only when necessary. This mode operates with no responsiveness to market signals or forecasts.
2. **Rule-Based Control:** Rule-based EMS employ heuristic “if–then” rules such as: “If electricity price is low and battery is not full, charge from the grid.” These strategies can reduce peak grid demand and improve self-consumption without complex computations [4].
3. **Predictive (Optimal) Control:** Predictive control uses forecasts—of weather, loads, and prices—to make optimized decisions over a future horizon. Model Predictive Control (MPC), for example, may schedule charging to take advantage of low prices and solar availability while managing load shifts and system constraints. Simulations using MATLAB/Simulink show that MPC-based EMS can significantly outperform fixed schedules in terms of efficiency and reliability [27].

In practice, Swedish EMS implementations often blend forecast-driven optimization with user preferences, striking a balance between cost savings and comfort.

### Real-World EMS Solutions in Sweden

Several Swedish companies have implemented practical Energy Management System (EMS) solutions aligned with the concepts of smart control and virtual power plants (VPP):

- **Tibber (Homevolt):** Tibber is a Nordic energy startup offering the Homevolt battery with integrated EMS capabilities. In Sweden, Tibber’s “Grid Rewards” program enables aggregated Homevolt batteries and EVs to act as a VPP [28]. The system can automatically charge EVs or home batteries during low-price hours on the Nord Pool electricity market, and export energy back to the grid when prices peak. Users must connect an EV or set the system to “optimized for revenue” mode. This setup allows homeowners to reduce energy costs and participate in grid balancing markets [28].



**Figure 2.3:** Categories of energy management controller. [4]

- **CheckWatt:** CheckWatt is a Swedish company specializing in Home Energy Management Systems (HEMS) and VPP platform. Its platform enables real-time monitoring, control, and optimization of distributed energy assets such as solar PV, battery storage, EV chargers, and heat pumps, and other controllable loads—coordinating them in real time via IT systems to function as a single virtual power plant [29]. Through this setup, CheckWatt enables homeowners to optimize their consumption and support grid stability, for instance by discharging batteries or delaying EV charging during times of local grid stress. [29].

# 3

## Methods

The energy output for 5 kW and 10 kW monocrystalline solar PV systems in Gothenburg, Sweden, was simulated using the European Commission’s Photovoltaic Geographical Information System (PVGIS) interactive tool [5], as shown in Appendix A.1 and Appendix A.2. Economic performance metrics—payback period, return on investment (ROI), and net present value (NPV)—were calculated using MATLAB code provided in Appendix A.3 and Appendix A.4.

### 3.1 Economic analysis

#### 3.1.1 Initial Investments

According to the IEA PVPS 2023 survey [3], residential solar PV system prices in Sweden range from 11 to 19 SEK/Wp. Costs vary based on retailer, location, and system configuration. For this analysis, the pre-tax installation cost is estimated at 75,000 SEK for a 5 kW system and 150,000 SEK for a 10 kW system.

The Swedish “Grön teknik” tax credit offers a 20% deduction on eligible installation and equipment costs [10], reducing the net cost to approximately 60,000 SEK and 120,000 SEK for the 5 kW and 10 kW systems, respectively.

Battery Energy Storage Systems (BESS) prices depend on technology and vendor. A 10 kWh battery is estimated at 80,000 SEK before incentives. With the 50% tax deduction for energy storage systems, the effective cost is 40,000 SEK [23].

These values constitute the initial investment inputs for the economic analysis.

#### 3.1.2 Electricity Prices

Electricity pricing for Gothenburg is based on the SE3 price zone in the Nord Pool electricity market. Monthly spot prices for 2024 (including VAT) in SEK/kWh are listed below in Table 3.1:

#### 3.1.3 Electricity Usage and Savings

The household energy consumption is set at 9,000 kWh annually (750 kWh/month), including EV charging but excluding electric heating. Monthly savings are calculated by comparing energy consumption costs with and without solar generation, based on hourly spot pricing.

<b>Jan</b>	<b>Feb</b>	<b>Mar</b>	<b>Apr</b>
1.0037	0.6293	0.7434	0.7039
<b>May</b>	<b>Jun</b>	<b>Jul</b>	<b>Aug</b>
0.2964	0.3408	0.2590	0.1068
<b>Sep</b>	<b>Oct</b>	<b>Nov</b>	<b>Dec</b>
0.2055	0.2872	0.8369	0.7281

**Table 3.1:** Monthly average electricity prices in SE3 (Gothenburg) 2024, SEK/kWh (incl. VAT) [6]

During summer, PV generation exceeds consumption, resulting in surplus electricity. This excess is sold back to the grid under a feed-in tariff of 1.21 SEK/kWh [23], which accounts for tax incentives and average utility compensation. These revenues are included in the total annual savings.

Economic metrics are calculated as follows:

- **Payback Period:** Ratio of initial investment to annual savings.
- **Net Present Value (NPV):** Discounted cash flow over the system lifetime.
- **Return on Investment (ROI):** Percentage return on capital over the project’s lifetime.

## 3.2 Method: Energy Management and Control Strategies

### 3.2.1 System Configurations

Four configurations were modeled to assess the impact of battery integration and control strategy effectiveness:

- 5 kW Solar PV (without battery)
- 5 kW Solar PV + 10 kWh Battery
- 10 kW Solar PV (without battery)
- 10 kW Solar PV + 10 kWh Battery

Each configuration was evaluated for annual energy production, household electricity consumption, and monetary returns.

### 3.2.2 Load and Generation Data

Household electricity consumption was set to 750 kWh per month (totaling 9,000 kWh/year), based on Energimyndigheten data for typical villas without direct electric heating or EV charging.

Monthly solar generation estimates for 5 kW and 10 kW systems were obtained from the PVGIS tool. The 10 kW output was calculated using the same tool which essentially doubles the 5 kW system’s monthly values.

### 3.2.3 Electricity Pricing and Feed-In Tariff

Monthly electricity spot prices for the SE3 region (Gothenburg) were sourced from Nord Pool’s 2024 data and include VAT (see Table 3.1). Surplus solar energy exported to the grid is compensated at a feed-in tariff of 1.21 SEK/kWh [23].

### 3.2.4 Control Strategies Simulated in MATLAB

Two energy management strategies were simulated using a custom MATLAB script shown in A.4:

- **Rule-Based Control:** Charges the battery with up to 30% of available solar production and discharges during high-load periods. Battery efficiency was set at 90%, and capacity was capped at 10 kWh.
- **Predictive (Optimal) Control:** Uses monthly price signals to guide discharge decisions. If spot prices exceed 0.6 SEK/kWh, the battery discharges to reduce costly grid consumption. This simulates a dynamic, price-responsive control approach.

Economic benefit is calculated from:

- **Self-consumption savings:** Avoided cost of grid electricity through on-site solar usage.
- **Feed-in revenue:** Earnings from exported surplus energy.

### 3.2.5 MATLAB Implementation

The models was implemented in MATLAB, with production profiles ( $E_{\text{prod}}$ ), monthly prices ( $C_{\text{elec}}$ ), and investment costs ( $I_{\text{total}}$ ) as inputs. The simulation calculates:

- Annual revenue for each system configuration
- NPV, Payback Period, and ROI over a 30 year system lifetime
- Graphical comparison of financial metrics using bar plots

In the MATLAB codes (see A.3 & A.4), a control strategy (battery or no battery) determines how much PV output is used directly, stored, or exported. With battery integration, up to 30% of excess energy is assumed to be stored and used during higher-priced hours to increase  $E_{\text{self}}$ .

The code is structured to allow scenario analysis under varying assumptions, including electricity price trends and system costs.

The MATLAB script loads the monthly input parameters and loops through each month to simulate energy production, consumption, battery charging/discharging, and control logic. Revenues are calculated and recorded for each scenario. Function definitions appear at the end of the script in accordance with MATLAB scripting practices.



# 4

## Results

### 4.1 Economic Evaluation

To assess the potential solar energy production for a standard Swedish single-family home, simulations were conducted using the PVGIS tool developed by the European Commission's Joint Research Centre [5]. This tool provides location-specific solar irradiation and photovoltaic (PV) output estimates based on historical climate data and system parameters. All simulations assume modules operating under Standard Test Conditions (STC).

#### 4.1.1 System Configuration

A fixed, south-facing PV system was simulated using the parameters detailed in Appendix A.1 and Appendix A.2. These represent typical installations for residential buildings in Sweden, example for 5 kw configuration below.

PVGIS-5 estimates of solar electricity generation:

<b>Provided inputs:</b>		<b>Simulation outputs</b>	
Latitude/Longitude:	57.650,12.010	Slope angle:	42 (opt) °
Horizon:	Calculated	Azimuth angle:	3 (opt) °
Database used:	PVGIS-SARAH3	Yearly PV energy production:	4571.45 kWh
PV technology:	Crystalline silicon	Yearly in-plane irradiation:	1187.67 kWh/m <sup>2</sup>
PV installed:	5 kWp	Year-to-year variability:	171.88 kWh
System loss:	15 %	Changes in output due to:	
		Angle of incidence:	-2.97 %
		Spectral effects:	1.55 %
		Temperature and low irradiance:	-8.09 %
		Total loss:	-23.02 %

**Figure 4.1:** PVGIS-5 5kw Configuration

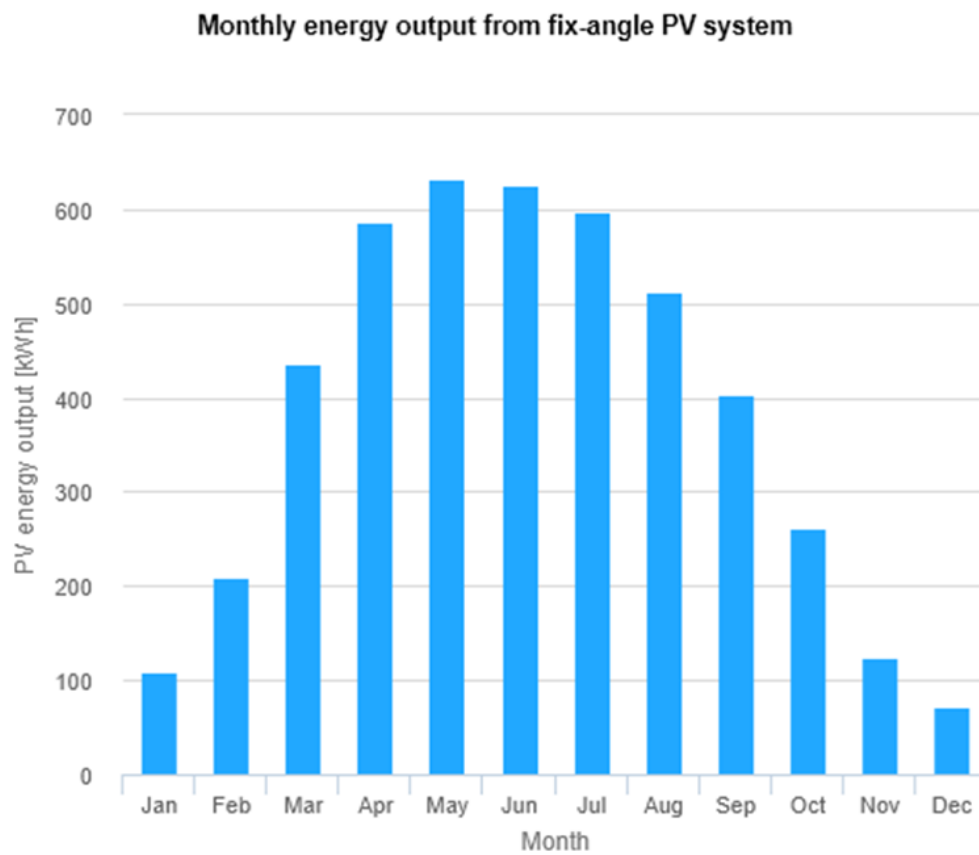
### 4.1.2 Annual Energy Production

PVGIS estimates for monthly electricity production from a 5 kW system in Gothenburg are:

For the 5 kW system:

$$\text{Monthly Production (kWh)} = \{110.0, 209.3, 435.9, 585.6, 633.2, 625.8, 598.4, 512.1, 402.8, 261.1, 124.9, 72.6\} \quad (4.1)$$

**Total Annual Production:** 4571.7 kWh

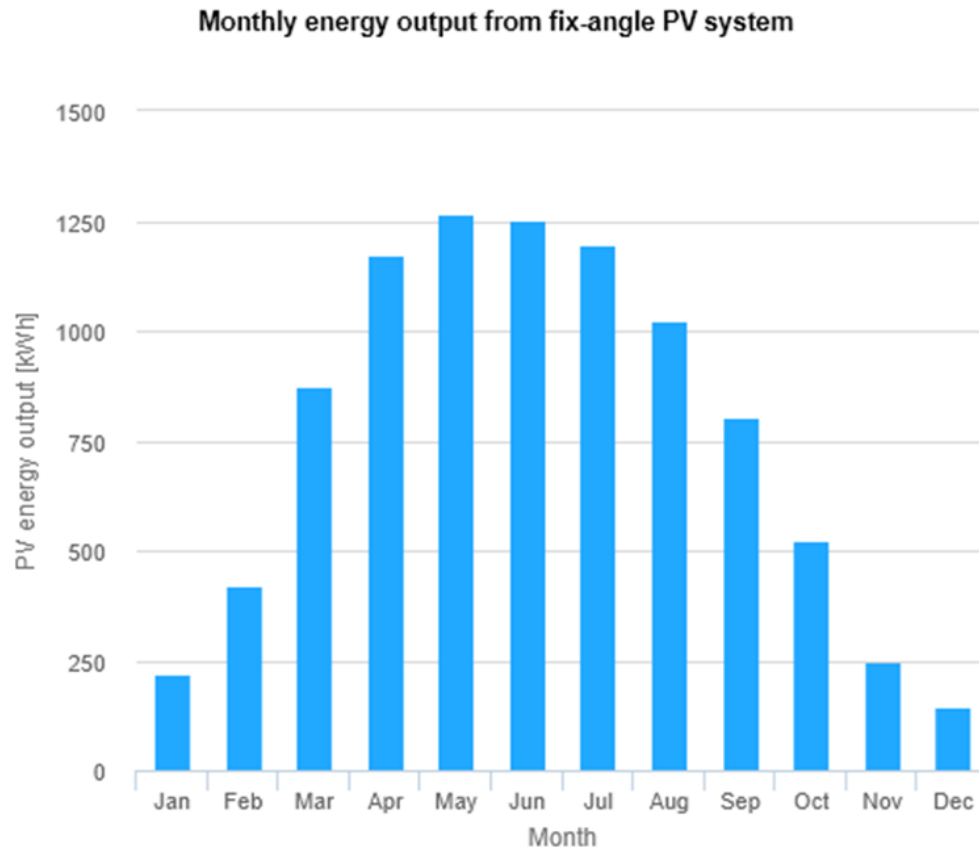


**Figure 4.2:** Monthly solar energy production for a 5 kW system in Gothenburg (kWh)

For the 10 kW system:

$$\text{Monthly Production (kWh)}: \{220.0, 418.5, 871.7, 1171.1, 1266.4, 1251.5, 1196.7, 1024.3, 805.5, 522.1, 249.7, 145.3\} \quad (4.2)$$

**Total Annual Production:** 9142.8 kWh



**Figure 4.3:** Monthly solar energy production for a 10 kW system in Gothenburg (kWh)

### 4.1.3 Economic Analysis of System Configurations

The financial viability of four configurations was evaluated with the code in A.3:

1. 5 kW solar-only
2. 10 kW solar-only
3. 5 kW solar + 10 kWh battery
4. 10 kW solar + 10 kWh battery

The analysis incorporates 2024 Nord Pool electricity prices, tax incentives (*Grön teknik*), a typical household load of 9000 kWh/year, and a feed-in tariff of 1.21 SEK/kWh. The financial assessment considers a 30-year horizon at a 3% discount rate.

#### 4.1.3.1 Annual Revenue Breakdown

Configuration	Total (SEK)	Self-Use Savings	Feed-in Revenue
5 kW (solar-only)	1,904	1,904	0
10 kW (solar-only)	5,769	2,941	2,828
5 kW + Battery	7,262	1,904	5,358
10 kW + Battery	5,751	3,096	2,655

**Table 4.1:** Annual revenue breakdown for each configuration

#### 4.1.3.2 Net Present Value (NPV)

Configuration	NPV (SEK)
5 kW (solar-only)	-22678
10 kW (solar-only)	-6930
5 kW + Battery	+42346
10 kW + Battery	-47273

**Table 4.2:** Net Present Value over 30 years (3% discount rate)

Only the 5 kW + battery system has a positive NPV, making it financially viable under current market assumptions.

#### 4.1.3.3 Payback Period and ROI

Configuration	Payback Period (Years)	ROI (%)
5 kW (solar-only)	99	-4.79%
10 kW (solar-only)	34	44.22%
5 kW + Battery	19	117.87%
10 kW + Battery	61	7.83%

**Table 4.3:** Estimated payback period and return on investment

The 5 kW + battery system offers the shortest payback time and highest return on investment, making it the most economically attractive configuration under current market conditions.

## 4.2 Energy Management and Control Strategies

### 4.2.1 Summary of Annual Revenue

The total annual revenue for each system configuration was calculated by combining savings from self-consumption with income from surplus energy sold to the grid at a feed-in tariff of 1.21 SEK/kWh. Control strategies evaluated include no battery (baseline), rule-based control, and predictive (price-responsive) control. The MATLAB implementation of these strategies is provided in Appendix A.4.

Configuration	Control Strategy	Revenue (SEK/year)
5 kW Solar Only	No Battery	1,904.1
5 kW + Battery (10 kWh)	Rule-Based	1,843.7
5 kW + Battery (10 kWh)	Predictive	1,852.5
10 kW Solar Only	No Battery	5,768.8
10 kW + Battery (10 kWh)	Rule-Based	5,649.2
10 kW + Battery (10 kWh)	Predictive	5,733.2

**Table 4.4:** Annual revenue by configuration and control strategy

#### 4.2.1.1 Observations

- The highest revenue was achieved by the 10 kW solar-only system (5,768.8 SEK/year), closely followed by the same system using predictive control (5,733.2 SEK/year).
- For the 5 kW system, adding a battery slightly reduced annual revenue, regardless of the control strategy. This is likely due to limited surplus energy and minimal benefit from load shifting in smaller systems.
- In both 5 kW and 10 kW systems, predictive control slightly outperformed rule-based control, offering around 1.5% higher revenue in the 10 kW scenario.
- Battery control shows more potential in larger systems, where increased surplus energy and electricity price variability provide better opportunities for optimization.

These results suggest that, under 2024 Swedish market conditions, battery control strategies yield modest financial gains. Unless combined with other goals (e.g., energy independence, backup functionality, or future participation in dynamic pricing schemes), battery integration may not be economically justified purely from a revenue standpoint.



# 5

## Discussion

### 5.1 Economic Viability of 5 kW vs 10 kW Systems

The economic analysis of the simulated systems reveals clear trends in financial performance between the 5 kW and 10 kW solar PV installations, as well as the impact of integrating battery storage. As presented in the results (see Figure 4.3), the 10 kW PV-only system produces approximately twice the annual energy output of the 5 kW system—around 9,143 kWh versus 4,572 kWh. This output scaling translates to roughly double the annual savings in electricity costs under current Swedish tariffs and compensation mechanisms.

The Results illustrate that although the 10 kW PV system achieves a higher NPV and cumulative savings than the 5 kW system, the increase in NPV is not linear. Due to greater excess generation, a larger proportion of energy from the 10 kW system is sold to the grid at lower compensation rates rather than offsetting household consumption. Consequently, diminishing returns appear as system size exceeds the household's consumption needs. This outcome underscores the importance of aligning PV system size with household demand to maximize cost-effectiveness. Although the 10 kW system provides higher total profit over its lifetime, its longer payback period, it shows the lower marginal value of exported electricity at least at its current rate.

### 5.2 Impact of Battery Storage on Financial Performance

Adding battery storage significantly alters financial metrics. Across all configurations, the integration of a 10 kWh battery led to lower NPVs compared to PV-only setups. In some cases, NPVs turned negative, and payback periods extended beyond 18 years. While batteries enhance self-consumption and reduce grid reliance, the associated upfront costs and finite lifespan limit their financial return under current Swedish market conditions.

### 5.3 Control Strategies: Rule-Based vs Predictive

Beyond economic performance, technical evaluation of energy management strategies shows that battery control plays a key role in system efficiency. Three scenarios

were evaluated: no control, rule-based, and predictive control.

Rule-based control—charging the battery when surplus PV is available and discharging during peak usage—significantly increases self-consumption. Predictive control further enhances performance by using forecasts to optimize battery use. In our results, predictive strategies marginally outperformed rule-based methods, with slightly higher annual savings.

Predictive control also improves efficiency by minimizing unnecessary cycling and reserving energy for high-value periods, the incremental gains over rule-based strategies were relatively modest under flat tariffs (1.5% gain).

These results suggest that under current electricity pricing structures in Sweden, and with relatively stable feed-in tariff rates, advanced battery control strategies alone are unlikely to provide a strong economic justification for BESS deployment. Their value may become more prominent in the future with more dynamic pricing models or incentives for grid services participation.

### 5.4 Sensitivity to Key Parameters

The analysis was sensitive to several assumptions:

- **Electricity Prices:** As the cost of grid electricity rises or becomes more variable, the value of self-consumption and optimized control strategies increases.
- **Battery Cost and Incentives:** The “Grön teknik” subsidy (50% rebate for storage systems) played a major role in the feasibility of battery systems. Without it, the economic case for batteries would weaken significantly.
- **System Size and Load Matching:** Smaller systems with high self-consumption ratios (like 5 kW) benefit more from battery integration than larger systems, which tend to overproduce relative to household demand.

### 5.5 Practical Recommendations for Swedish Homeowners

#### 5.5.1 System Size Should Match Household Consumption

- Homeowners are advised to size their PV systems according to their annual electricity demand. For instance, a 5 kW PV system coupled with battery storage aligns well with households consuming between 7,000 and 9,000 kWh per year.
- Oversizing the system (e.g., a 10 kW system in a low-consumption home) can lead to substantial excess generation. This surplus electricity is exported to the grid and compensated at lower feed-in tariffs, thereby reducing the system’s overall profitability.

### 5.5.2 Batteries Increase Energy Independence but Delay Financial Returns

- Battery energy storage systems (BESS) can increase household self-consumption by 20–40%, decreasing dependence on grid imports. However, the additional investment cost associated with batteries typically prolongs the system’s pay-back period.
- Battery integration is most financially viable for households with high evening loads, such as those with EV charging or heat pump heating, and for users who value energy independence.

### 5.5.3 Economic Viability Depends on Policy Conditions

- Current tax incentives, including the 20% “Grön Teknik” deduction for PV systems and 50% for batteries, play a crucial role in improving investment viability. These subsidies are scheduled to be reduced or phased out by 2026. Therefore, installing systems before policy changes take effect is essential to maximize financial benefits.

### 5.5.4 Energy Management Strategies Can Improve Financial Outcomes

- Predictive energy management, which adjusts battery charge/discharge patterns based on hourly electricity price signals, yields slightly higher annual revenues compared to simple rule-based control.
- Although the increase in return on investment (ROI) is modest, predictive strategies are better suited for households with dynamic electricity tariffs and variable daily demand.

### 5.5.5 Geographic Location Influences System Performance

- Solar irradiance in Sweden varies by region. Cities such as Stockholm and Gothenburg receive approximately 950–1000 kWh/m<sup>2</sup>/year, supporting high PV output when panels are optimally tilted and south-facing.
- In contrast, locations in northern Sweden (e.g., Kiruna) may experience up to 20% lower annual yields due to reduced winter sunlight and lower irradiance.

## 5.6 Limitations and Future Work

While this study provides a useful snapshot of system economics under 2024 conditions, several limitations are acknowledged:

- This study assumes that the European PVGIS database is reliable, although its precision was not independently verified beyond minimal validation.

- The simulations used average monthly values for load and production, which may not fully capture the variability and peak dynamics of real-world operation.
- Control strategies were implemented with simplified logic. More advanced techniques, such as real-time price forecasting or AI-based schedulers, may yield improved performance.
- The study did not consider system degradation, maintenance costs, or inverter replacement, which could impact long-term viability.

Future research could explore:

- Real-time data-driven EMS strategies.
- Scenarios under future electricity market reforms (e.g., time-of-use tariffs).

### 5.7 Sustainability and Ethical Considerations

This project supports Sweden's energy transition by promoting residential solar PV adoption, which contributes to emission reductions and improved grid efficiency. It empowers homeowners to make informed, environmentally responsible decisions. From an ethical perspective, it fosters energy autonomy and aligns with national climate objectives.

# 6

## Conclusion

The findings indicate that rooftop PV systems in Sweden are economically viable under current market and policy conditions, especially when system size is appropriately matched to household electricity consumption. Even when integrated with battery storage, these systems can be financially attractive, although the profitability of battery investments remains marginal unless supported by additional incentives or value-added services.

Battery control strategies were found to influence system performance, with predictive (optimal) control offering slight improvements in annual revenue compared to rule-based. However, these gains were modest and did not significantly alter the overall financial outcome. Notably, the transition from a baseline (no control) to controlled battery operation resulted in a small decrease in annual revenue, primarily because of the opportunity cost of storing surplus energy instead of exporting it at favorable feed-in tariff rates. This suggests that while advanced control strategies can improve energy autonomy and grid flexibility, their direct financial benefit remains limited under current conditions.

Policy instruments such as the Grön Teknik tax deduction and the microproduction feed-in credit play a critical role in the financial viability of residential PV and storage systems. Planned reductions or removals of these incentives, such as the phase-out of the 0.6 SEK/kWh feed-in tax credit by 2026 could substantially impact investment attractiveness, particularly for battery-integrated systems. Continued economic viability will likely depend on future adjustments to electricity pricing structures, including dynamic tariffs or capacity-based grid fees.

A comparative scenario using 2022 spot prices revealed a higher revenue potential in all configurations, highlighting the sensitivity of economic returns to fluctuations in the electricity market. For households that prioritize energy independence or resilience, this volatility may serve as a compelling argument in favor of investing in battery storage, despite its limited current payback.



# Bibliography

- [1] Beny Electric, “On-grid vs off-grid solar: Omfattande jämförelse.”  
<https://www.beny.com/sv/on-grid-vs-off-grid-solar-system-all-you-need-to-know/>, Sept. 2021.  
Accessed: 2025-06-07.
- [2] STG Solar FZCO, “Off-grid solar system.”  
<https://stgsolar.ae/off-grid-system/>. Accessed: 2025-06-07.
- [3] IEA-PVPS, “National survey report of pv power applications in sweden 2023: Pvpvs task 1 strategic pv analysis and outreach.”  
<https://iea-pvps.org/wp-content/uploads/2024/09/National-Survey-Report-of-PV-Power-Applications-in-Sweden-2023.pdf>, 2023. Accessed: 2025-06-01.
- [4] M. S. Bakare, A. Abdulkarim, A. N. Shuaibu, *et al.*, “Energy management controllers: strategies, coordination, and applications,” *Energy Informatics*, vol. 7, p. 57, 2024. Accessed: 2025-06-08.
- [5] European Commission, “Jrc photovoltaic geographical information system (pvgis) - european commission,” 2016. Accessed: 2025-06-08.
- [6] Fortum, “Rörligt elpris.”  
<https://www.fortum.com/se/el/elpriser/spotpriser>, 2024. Accessed: 2025-06-09.
- [7] Riksdagen, “Förordning (2009:689) om statligt stöd till solceller.”  
[https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/forordning-2009689-om-statligt-stod-till\\_sfs-2009-689/](https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/forordning-2009689-om-statligt-stod-till_sfs-2009-689/), 2021.  
Accessed: 2025-06-07.
- [8] Svensk Solenergi, “Över 50 000 villabatterier.”  
<https://svensksolenergi.se/over-50-000-villabatterier/>, Aug. 2024.  
Accessed: 2025-06-07.
- [9] European Alternative Fuels Observatory, “Sweden’s ev market in january 2025: 14.4% yoy increase | european alternative fuels observatory.” <https://alternative-fuels-observatory.ec.europa.eu/general-information/news/swedens-ev-market-january-2025-144-yoy-increase>, Feb. 2025.  
Accessed: 2025-06-07.
- [10] Skatteverket, “Grön teknik - privat.”  
<https://www.skatteverket.se/privat/fastigheterochbostad/gronteknik.4.676f4884175c97df4192860.html>. Accessed: 2025-06-07.
- [11] AleaSoft Energy Forecasting, “Analysis year 2024: In 2024 european electricity markets reached their lowest prices since 2021 thanks to renewable

- energy and falling gas prices.” <https://aleasoft.com/fall-european-market-prices-2024-renewable-energy-gas/>, Jan. 2025. Accessed: 2025-06-07.
- [12] Energimarknadsinspektionen (Ei), “Effektavgift.” <https://ei.se/konsument/el/el-natsavgiften-och-el-natsreglering/effektavgift>, Nov. 2022. Accessed: 2025-06-07.
- [13] Sustainable Energy Authority of Ireland (SEAI), “A homeowner’s guide to solar pv.” <https://www.seai.ie/sites/default/files/publications/Homeowners-Guide-To-Solar-PV.pdf>. Accessed: 2025-06-07.
- [14] U. Noor, “Solar panel efficiency vs. temperature.” <https://8msolar.com/solar-panel-efficiency-vs-temperature/>, Dec. 2024. Accessed: 2025-06-08.
- [15] HinenSupport, “What is an mppt inverter? advantages and disadvantages.” <https://www.hinen.com/blogs/energy-storage/what-is-an-mppt-inverter>, June 2024. Accessed: 2025-06-07.
- [16] Vattenfall AB, “Installera solceller.” <https://www.vattenfall.se/solceller/installera-solceller/>. Accessed: 2025-06-08.
- [17] P. Blomqvist and T. Unger, “Teknisk-ekonomisk kostnadsbedömning av solceller i sverige.” <https://www.energimyndigheten.se/globalassets/fornybart/solenergi/ovriga-rapporter/teknisk-ekonomisk-kostnadsbedomning-av-solceller-i-sverige.pdf>, May 2018. Accessed: 2025-06-08.
- [18] RISE – Research Institutes of Sweden, “Solar energy in northern conditions.” <https://www.ri.se/en/solar-energy-in-northern-conditions>. Accessed: 2025-06-08.
- [19] N. H. Reich, B. Mueller, A. Armbruster, W. G. J. H. M. van Sark, K. Kiefer, and C. Reise, “Performance ratio revisited: Is pr>90% realistic?,” *Progress in Photovoltaics: Research and Applications*, vol. 20, pp. 717–726, Jan. 2012.
- [20] Energimyndigheten, “Antalet solcellsanläggningar fortsätter att öka.” <https://www.energimyndigheten.se/nyhetsarkiv/2023/antalet-solcellsanlaggningar-fortsatter-att-oka/>, Dec. 2023. Accessed: 2025-06-08.
- [21] Svensk Solenergi, “Installerad solkraft 2024.” <https://svensksolenergi.se/installerad-solkraft-2024/>, 2025. Accessed: 2025-06-08.
- [22] Energimyndigheten, “Välj en anläggning som passar dina behov.” <https://www.energimyndigheten.se/effektiv-energianvandning/guider/solelportalen/hur-stor-anlaggning-passar-mig/valj-en-anlaggning-som-passar-dina-behov/>, 2025. Accessed: 2025-06-08.
- [23] W. Bergmark, E. Bülow, and S. Hemming, “Priser på solcells batterier.” <https://hemsol.se/solceller/solcells-batteri/pris/>, May 2025. Accessed: 2025-06-08.

- [24] Skatteverket, “Rot- och rut-avdraget: Så fungerar det.”  
<https://www.skatteverket.se/privat/fastigheterochbostad/rotochrutarbete/saharfungerarrotochrutavdraget.4.d5e04db14b6fef2c866097.html#Rotochrutavdragetsstorle>, 2025.  
Accessed: 2025-06-08.
- [25] Regeringen, “Förändrade skattesubventioner för solceller.”  
<https://www.regeringen.se/pressmeddelanden/2024/09/forandrade-skattesubventioner-for-solceller/>, Sept. 2024. Accessed: 2025-06-08.
- [26] I. Campbell, “Everything to know about roi, tco, npv, and payback.”  
<https://nucleusresearch.com/everything-to-know-about-roi-tco-npv-and-payback/>, May 2020.  
Accessed: 2025-06-08.
- [27] N. Nkosi, P. F. L. Roux, G. U. Nnachi, and D. E. Okojie, “Smart energy management in buildings using matlab simulink,” 2021. Accessed: 2025-06-08.
- [28] Tibber, “Grid rewards tibber,” 2025. Accessed: 2025-06-08.
- [29] CheckWatt AB, “Tjänster – checkwatt,” 2025. Accessed: 2025-06-08.



# A

## Appendices

### A.1 PVGIS Simulation Output for 5 kW System

PVGIS-5 estimates of solar electricity generation:

<b>Provided inputs:</b>		<b>Simulation outputs</b>	
Latitude/Longitude:	57.650,12.010	Slope angle:	42 (opt) °
Horizon:	Calculated	Azimuth angle:	3 (opt) °
Database used:	PVGIS-SARAH3	Yearly PV energy production:	4571.45 kWh
PV technology:	Crystalline silicon	Yearly in-plane irradiation:	1187.67 kWh/m <sup>2</sup>
PV installed:	5 kWp	Year-to-year variability:	171.88 kWh
System loss:	15 %	Changes in output due to:	
		Angle of incidence:	-2.97 %
		Spectral effects:	1.55 %
		Temperature and low irradiance:	-8.09 %
		Total loss:	-23.02 %

Figure A.1: PVGIS output for 5 kW fixed-angle solar system in Gothenburg[5]

### A.2 PVGIS Simulation Output for 10 kW System

PVGIS-5 estimates of solar electricity generation:

<b>Provided inputs:</b>		<b>Simulation outputs</b>	
Latitude/Longitude:	57.650,12.010	Slope angle:	42 (opt) °
Horizon:	Calculated	Azimuth angle:	3 (opt) °
Database used:	PVGIS-SARAH3	Yearly PV energy production:	9142.91 kWh
PV technology:	Crystalline silicon	Yearly in-plane irradiation:	1187.67 kWh/m <sup>2</sup>
PV installed:	10 kWp	Year-to-year variability:	343.76 kWh
System loss:	15 %	Changes in output due to:	
		Angle of incidence:	-2.97 %
		Spectral effects:	1.55 %
		Temperature and low irradiance:	-8.09 %
		Total loss:	-23.02 %

Figure A.2: PVGIS output for 10 kW fixed-angle solar system in Gothenburg[5]

## A.3 MATLAB Code for Economic Analysis

**Listing A.3:** MATLAB script for calculating payback period, ROI, and NPV

```
1
2 clc; clear;
3
4 %% INPUT DATA
5 monthly_load = 750; % Monthly electricity usage in kWh
6 annual_load = monthly_load * 12;
7
8 spot_price = [1.0037, 0.6293, 0.7434, 0.7039, 0.2964, 0.3408,
9             ...
10             0.2590, 0.1068, 0.2055, 0.2872, 0.8369,
11             0.7281];
12
13 prod_5kW = [110.0, 209.3, 435.9, 585.6, 633.2, 625.8, ...
14            598.4, 512.1, 402.8, 261.1, 124.9, 72.6];
15
16 prod_10kW = [220.0, 418.5, 871.7, 1171.1, 1266.4, 1251.5,
17            1196.7, ...
18            1024.3, 805.5, 522.1, 249.7, 145.3];
19
20 cost_5kW = 60000;
21 cost_10kW = 120000;
22 battery_cost = 40000;
23 feed_in_tariff = 1.21;
24 discount_rate = 0.03;
25 lifetime = 30;
26
27 %% CALCULATE REVENUES
28 [rev_5, save_5, feed_5] = calc_annual_revenue(prod_5kW,
29         spot_price, monthly_load, feed_in_tariff, false);
30 [rev_10, save_10, feed_10] = calc_annual_revenue(prod_10kW,
31         spot_price, monthly_load, feed_in_tariff, false);
32 [rev_5b, save_5b, feed_5b] = calc_annual_revenue(prod_5kW,
33         spot_price, monthly_load, feed_in_tariff, true);
34 [rev_10b, save_10b, feed_10b] = calc_annual_revenue(prod_10kW,
35         spot_price, monthly_load, feed_in_tariff, true);
36
37 %% NPV & PAYBACK CALCULATIONS
38 npv_5 = calc_npv(cost_5kW, rev_5, discount_rate, lifetime);
39 npv_10 = calc_npv(cost_10kW, rev_10, discount_rate, lifetime)
40 ;
41 npv_5b = calc_npv(cost_5kW + battery_cost, rev_5b,
42         discount_rate, lifetime);
43 npv_10b = calc_npv(cost_10kW + battery_cost, rev_10b,
44         discount_rate, lifetime);
45
46 pb_5 = calc_payback(cost_5kW, rev_5, discount_rate);
```

```

36 pb_10 = calc_payback(cost_10kW, rev_10, discount_rate);
37 pb_5b = calc_payback(cost_5kW + battery_cost, rev_5b,
    discount_rate);
38 pb_10b = calc_payback(cost_10kW + battery_cost, rev_10b,
    discount_rate);
39
40 roi_5 = calc_roi(cost_5kW, rev_5, lifetime);
41 roi_10 = calc_roi(cost_10kW, rev_10, lifetime);
42 roi_5b = calc_roi(cost_5kW + battery_cost, rev_5b, lifetime);
43 roi_10b = calc_roi(cost_10kW + battery_cost, rev_10b,
    lifetime);
44
45 %% DISPLAY RESULTS
46 fprintf('\n--- Economic Results (SEK) ---\n');
47 fprintf('5kW: Annual Rev = %.2f, Savings = %.2f, Feed-in =
    %.2f, NPV = %.2f, Payback = %d years, ROI = %.2f%%\n',
    rev_5, save_5, feed_5, npv_5, pb_5, roi_5);
48 fprintf('10kW: Annual Rev = %.2f, Savings = %.2f, Feed-in =
    %.2f, NPV = %.2f, Payback = %d years, ROI = %.2f%%\n',
    rev_10, save_10, feed_10, npv_10, pb_10, roi_10);
49 fprintf('5kW + Battery: Annual Rev = %.2f, Savings = %.2f,
    Feed-in = %.2f, NPV = %.2f, Payback = %d years, ROI = %.2f
    %%\n', rev_5b, save_5b, feed_5b, npv_5b, pb_5b, roi_5b);
50 fprintf('10kW + Battery: Annual Rev = %.2f, Savings = %.2f,
    Feed-in = %.2f, NPV = %.2f, Payback = %d years, ROI = %.2f
    %%\n', rev_10b, save_10b, feed_10b, npv_10b, pb_10b,
    roi_10b);
51
52 %% PLOT NPV
53 figure;
54 bar([npv_5, npv_5b, npv_10, npv_10b])
55 title('Net Present Value of Solar Configurations')
56 ylabel('NPV (SEK)')
57 set(gca, 'xticklabel', {'5kW', '5kW+B', '10kW', '10kW+B'})
58 grid on
59
60 %% PLOT PAYBACK PERIOD
61 figure;
62 bar([pb_5, pb_5b, pb_10, pb_10b])
63 title('Payback Period of Solar Configurations')
64 ylabel('Years')
65 set(gca, 'xticklabel', {'5kW', '5kW+B', '10kW', '10kW+B'})
66 grid on
67
68 %% PLOT ROI
69 figure;
70 bar([roi_5, roi_5b, roi_10, roi_10b])
71 title('Return on Investment of Solar Configurations')
72 ylabel('ROI (%)')

```

```
73 set(gca, 'xticklabel', {'5kW', '5kW+B', '10kW', '10kW+B'})
74 grid on
75
76 %% FUNCTIONS
77
78 function [total_revenue, self_savings, surplus_income] =
    calc_annual_revenue(prod, spot_price, monthly_load,
    feed_in_tariff, use_batt)
79     total_revenue = 0;
80     self_savings = 0;
81     surplus_income = 0;
82     for i = 1:12
83         production = prod(i);
84         load = monthly_load;
85         if use_batt
86             shiftable = min(production - load, 0.3 *
                production);
87             load = load + shiftable;
88             production = production - shiftable;
89         end
90         self_use = min(production, load);
91         surplus = max(0, production - load);
92         self_savings = self_savings + self_use * spot_price(i
            );
93         surplus_income = surplus_income + surplus *
            feed_in_tariff;
94     end
95     total_revenue = self_savings + surplus_income;
96 end
97
98 function npv = calc_npv(initial_cost, annual_revenue,
    discount_rate, lifetime)
99     npv = -initial_cost;
100     for t = 1:lifetime
101         npv = npv + annual_revenue / ((1 + discount_rate)^t);
102     end
103 end
104
105 function payback = calc_payback(initial_cost, annual_revenue,
    discount_rate)
106     cum_cashflow = 0;
107     for t = 1:100
108         cum_cashflow = cum_cashflow + annual_revenue / ((1 +
            discount_rate)^t);
109         if cum_cashflow >= initial_cost
110             payback = t;
111             return;
112         end
113     end
end
```

```

114     payback = NaN;
115 end
116
117 function roi = calc_roi(initial_cost, annual_revenue,
    lifetime)
118     total_gain = annual_revenue * lifetime;
119     roi = ((total_gain - initial_cost) / initial_cost) * 100;
120 end

```

## A.4 MATLAB Code: Revenue from Control Strategies

**Listing A.4:** MATLAB script for estimating revenue under different control strategies

```

1
2 clc; clear;
3
4 %% INPUT DATA
5 monthly_load = 750; % Monthly electricity usage in kWh
6 annual_load = monthly_load * 12;
7
8 % Spot price for SE3 (2024) in SEK/kWh
9 spot_price = [1.0037, 0.6293, 0.7434, 0.7039, 0.2964, 0.3408,
    ...
10             0.2590, 0.1068, 0.2055, 0.2872, 0.8369,
    0.7281];
11
12 % Monthly solar production (5kW system)
13 prod_5kW = [110.0, 209.3, 435.9, 585.6, 633.2, 625.8, ...
14            598.4, 512.1, 402.8, 261.1, 124.9, 72.6];
15 prod_10kW = [220.0, 418.5, 871.7, 1171.1, 1266.4, 1251.5,
16             1196.7, ...
17             1024.3, 805.5, 522.1, 249.7, 145.3];
18
19 feed_in_tariff = 1.21;
20 battery_capacity = 10; % 10 kWh battery
21 batt_eff = 0.9;
22
23 %% SIMULATE ALL CONFIGURATIONS
24 % 5kW, no battery
25 rev_5 = run_strategy(prod_5kW, false, '', spot_price,
    monthly_load, feed_in_tariff, batt_eff, battery_capacity);
26
27 % 5kW + battery
28 rev_5b_rule = run_strategy(prod_5kW, true, 'rule', spot_price
    , monthly_load, feed_in_tariff, batt_eff, battery_capacity

```

```

);
28 rev_5b_pred = run_strategy(prod_5kW, true, 'predict',
    spot_price, monthly_load, feed_in_tariff, batt_eff,
    battery_capacity);
29
30 % 10kW, no battery
31 rev_10 = run_strategy(prod_10kW, false, '', spot_price,
    monthly_load, feed_in_tariff, batt_eff, battery_capacity);
32
33 % 10kW + battery
34 rev_10b_rule = run_strategy(prod_10kW, true, 'rule',
    spot_price, monthly_load, feed_in_tariff, batt_eff,
    battery_capacity);
35 rev_10b_pred = run_strategy(prod_10kW, true, 'predict',
    spot_price, monthly_load, feed_in_tariff, batt_eff,
    battery_capacity);
36
37 %% DISPLAY RESULTS
38 fprintf('\n---Revenue from Control Strategies (SEK/year)
    ---\n');
39 fprintf('5kW no battery: %.2f\n', rev_5);
40 fprintf('5kW + Battery (Rule): %.2f\n', rev_5b_rule);
41 fprintf('5kW + Battery (Predictive): %.2f\n', rev_5b_pred);
42 fprintf('10kW no battery: %.2f\n', rev_10);
43 fprintf('10kW + Battery (Rule): %.2f\n', rev_10b_rule);
44 fprintf('10kW + Battery (Predictive): %.2f\n', rev_10b_pred);
45
46 %% FUNCTION DEFINITIONS
47 function revenue = run_strategy(prod_kW, battery,
    control_type, spot_price, monthly_load, feed_in_tariff,
    batt_eff, batt_cap)
48     revenue = 0;
49     for i = 1:12
50         prod = prod_kW(i);
51         load = monthly_load;
52
53         if battery
54             if strcmp(control_type, 'rule')
55                 batt_charge = min(0.3 * prod, batt_cap);
56                 batt_charge_eff = batt_charge * batt_eff;
57                 prod = prod - batt_charge;
58                 batt_discharge = min(batt_charge_eff, max(0,
                    load - prod));
59                 load = load - batt_discharge;
60             elseif strcmp(control_type, 'predict')
61                 if spot_price(i) > 0.6
62                     extra_demand = max(0, load - prod);
63                     batt_help = min(batt_cap, extra_demand);
64                     load = load - batt_help;

```

```
65         prod = prod - batt_help / batt_eff;
66     end
67     end
68 end
69
70     self_use = min(prod, load);
71     surplus = max(0, prod - load);
72     revenue = revenue + self_use * spot_price(i) +
73         surplus * feed_in_tariff;
74 end
```

DEPARTMENT OF ELECTRICAL ENGINEERING  
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden

[www.chalmers.se](http://www.chalmers.se)



**CHALMERS**  
UNIVERSITY OF TECHNOLOGY