Master Level Thesis

European Solar Engineering School

No 318, September 2023

The implementation of a solar photovoltaic park with potential energy storage on SSAB's industrial area and its impact on the internal electricity system

Master thesis 30 credits, 2023
Solar Energy Engineering

Author:
Rana Abdelmageed

Supervisors:
Emmanouil Psimopoulos

External Supervisors:
Jennica Simesgården

Examiner:
Ewa Wäckelgård

Course Code: EG4001

Examination date: 20/09/2023

MASTER THESIS

ESES EUROPEAN SOLAR ENGINEERING SCHOOL

SERC Centrum för solenergiforskning Solar Energy Research Center

HÖGSKOLAN DALARNA

Dalarna University
Solar Energy Engineering

Abstract

The global push for increased renewable energy in power production is reshaping how industries approach energy systems. As the urgency to combat climate change grows, industries are integrating alternative power pathways alongside existing systems. This shift is driven by factors such as renewable energy adoption, energy storage advances, decentralization, electrification, circular economy principles, regulatory support, sustainability goals, and technological progress. These changes not only yield economic benefits but also enhance environmental and social impact. Integrating alternative pathways necessitates strategic planning, optimization, and a phased approach for seamless integration. Through these transformations, industries position themselves as sustainability leaders, align with climate goals, and ensure long-term energy security.

The proposed implementation of a photovoltaic (PV) system at SSAB's steel production plant in Borlänge, specifically for forming line 4's electricity needs, will have a positive impact. This integration introduces renewable energy generation, offsetting the load and reducing reliance on the grid during peak hours, potentially leading to lower costs. It aligns with SSAB's environmental goals by curbing emissions, bolsters energy resilience, and aiding peak demand management. However, challenges in grid integration and infrastructure adjustments must be addressed for successful implementation. Overall, this move embodies SSAB's commitment to sustainability and efficient operations.

Through the utilization of simulation tools such as PVsyst and Homer Pro, an extensive study was conducted to investigate diverse scenarios involving combinations of a PV system, hydrogen modules, batteries, and a grid-connected load. The primary aim was to assess the feasibility of these scenarios within the energy system context. By leveraging PVsyst's capabilities for photovoltaic system analysis and Homer Pro's system optimization features, the study comprehensively examines interactions between electricity generation, storage, and consumption. This simulation-driven approach provided valuable insights into the performance dynamics, energy balance, and economic viability of each configuration, aiding in the informed selection of optimal combinations that align with the project's feasibility objectives.

The results obtained suggest that the ideal size for the PV system in this context is 2.7 MW, allowing for an annual energy generation of 2.5 GWh. The electricity output aligns well with the yearly demand of 2.4 GWh for Forming Line 4.

The results from different scenarios offer valuable insights into how integrating renewable energy and incorporating energy storage affect the overall efficiency and cost-effectiveness of the system. Each scenario was assessed in comparison to the base case of grid connection, uncovering a spectrum of LCOE values. It is noteworthy that the highest LCOE, reaching 0.12 €/kWh, was observed when all renewable resources were combined, whereas the lowest LCOE, at 0.059 €/kWh, was achieved with the PV system-only configuration.

Acknowledgment

I want to sincerely thank the people and organizations who contributed significantly to the completion of this thesis. Your guidance, support, and encouragement have been extremely helpful to me throughout my academic career.

First and foremost, I want to express my gratitude to Emmanouil Psimopoulos, who advised my thesis. His knowledge, unwavering commitment, and perceptive criticism have been extremely helpful throughout this project. Simultaneously, his role as the program coordinator for Master Programme in Solar Energy Engineering has a profound impact on my academic experience. His dedication to advancing our program, creating a supportive learning environment, and fostering a sense of community among students has been remarkable.

I am grateful for the opportunity provided by the SSAB company. I am ecstatic to be working with a company that shares my enthusiasm for pushing innovation and sustainability in the energy market.

I must acknowledge my family's constant support and encouragement, especially my mother, siblings, and my Egyptian friends. Their understanding, patience, and support sustained me during the most difficult parts of this academic journey.

Finally, I would like to express my gratitude to the academic community, particularly Emelie Nilsson, for her friendship, talks, and shared knowledge that have improved my academic experience.

Contents

Abbreviations

Abbreviation	Description
AC	Alternative Current
CSP	Concentrated Solar Power
DC	Direct Current
HOMER	Hybrid Optimization of Multiple Energy Resources
LCOE	Levelized Cost of Electricity
MBE	Mean Bias Error
NPC	Net Present Cost
O&M	Operation and Maintenance
PEM	Proton exchange membrane electrolyser
PR	Performance Ratio
PV	Photovoltaic
PVsyst	Photovoltaic system simulation software
SSAB	Svenskt Stål AB

Nomenclature

Symbol	Description	Unit
LCOE	Levelized Cost of Electricity	€/kWh
NPC	Net Present Cost	€
SC	Self-Consumption	%
SF	Solar Fraction	%

1 Introduction

1.1 Background

During the past twenty years, finding renewable energy sources has become humanity's top priority. In order to maximize the benefits of the various energy sources that have never been employed in a highly effective manner, new studies have been launched all over the world [1]. In order to achieve the worldwide renewable energy targets and make the switch from fossil fuels to renewable energy sources, solar energy is crucial. Several nations currently include PV in their energy mix as a result of decreasing costs and expanded production of PV technology [2].

In Sweden, less than 1% of the electricity produced is from solar sources. Production of 100% renewable electricity is the target by 2040. For Sweden to eventually attain negative emissions, there must be no net emissions of greenhouse gases into the atmosphere by 2045 at the latest [3]. One of main types of solar power systems is "grid-tied" or "on-grid" solar system is one in which the PV solar panels or array are electrically connected to the utility or the local mains electricity grid, which feeds electricity power back into the grid. The main advantages of a grid-connected PV system include its simplicity, reasonably low operating and maintenance costs, and decreased electricity bills [4]. Sweden has seen a dramatic increase in the number of grid-connected PV systems over the past four years, with an average annual growth rate of almost 55% [5, 6]. The Swedish government is promptly focusing on the development of renewable energy sources and encouraging all the country's sectors towards it.

SSAB is a multinational steel corporation and one of the world leaders in high-strength steel and related services. SSAB’s goal is to help creating a more durable, lighter, and stronger planet. By 2026, SSAB wants to be the first steel firm in the world to put fossil-free steel on the market. By 2030, SSAB wants to have almost eliminated its own operations' carbon dioxide emissions. Around 8.8 million tons of steel may be produced annually at SSAB's production plants in Sweden, Finland, and the United States [7]. SSAB wants to contribute to the UN 7 global goal of sustainable industry and access to sustainable energy [8, 9]. So, SSAB wants to implement a PV system in the steel production plant of SSAB in Borlänge to satisfy the requirements of forming line 4 and how it will affect the internal electricity supply.

1.2 Aims

The study is aiming to:

- Design a photovoltaic system to meet the electrical load of Forming Line 4 of 2.4 GWh (2022) on the industrial site of SSAB in Borlänge [10].
- Investigate the possibility of adding electrical energy storage or hydrogen storage.
- Conduct an analysis on the economic viability of the system and carry out techno-economic optimization to ascertain the most optimized levelized cost of electricity (LCOE).
- Execute a sensitivity analysis by using Homer Pro software to evaluate a range of key figures or performance metrics to gain insights into how alterations in input parameters will impact the system.

1.3 Method

The following steps present the methodology that the study followed to reach the objectives of the work.

- Literature study.
- Load data analysis prior to the design.

- Sizing of PV system design by using PVsyst software for a PV park in SSAB industrial site and determine the annual production of electricity meeting the yearly electrical load of the forming line 4 and subsequently import the generated AC electricity production data into Homer Pro software.
- Using Google earth software to export the site location dimensions and area measurements.
- Using the online tool "Suncurves" to export the data used for the horizon profile as an imported input used in PVsyst.
- The potential of the energy storage system is performed using Homer Pro software.
- Economic analysis with Homer Pro software.
- Perform a sensitivity analysis with Homer Pro software by considering various key figures or performance metrics. These key figures are crucial for assessing how variations in input parameters affect the behavior and outcomes of the system. Some of the essential key figures to examine during a sensitivity are LCOE and discounted payback.

1.4 Literature study

EVRAZ North America has declared that its steelmaking activities in Pueblo, Colorado, will be powered by solar energy. With its recently unveiled Bighorn solar project, the Pueblo site will reduce emissions and become the first mill in the world to be powered primarily by solar energy. The Pueblo site operates an electric arc furnace that can produce finished steel from recycled ferrous scrap, making it Colorado's largest recycler. Over 7.3 km² of land, the project's 300 MW DC/240 MW AC solar field makes it the largest on-site solar plant in the US that is exclusively used by one client. The 7750000 PV solar panels on the property supply almost all of the plant's annual electrical needs [11].

The Rajamäki, Finland, factory of coatings producer Teknos has solar panels installed for its paint production. One of the company's goals to reduce the use of fossil fuels and fight climate change is to use solar electricity. Up to 2 % of the factory's total energy use will be covered by the new PV system. This implies that solar energy can be used to power the majority of the factory's cooling systems. On the roof, there are about 600 solar PV panels, which each year cover a total capacity of 210 kW and provide 180 MWh of sustainable energy production for the factory's immediate use [12].

The specifics of the various technologies that are covered within the project's scope have been the subject of some research. The main breakthroughs that are evaluated within the scope are PV, hydrogen, and batteries.

The research made by Lindahl, J et al. (2022) [13] examined six large-scale photovoltaic parks that were commissioned in Sweden in 2019 and 2020. The findings underscored the significance of financing conditions and site selection in reducing the levelized cost of energy for utility-scale solar parks constructed without government subsidies in this Scandinavian nation. It was determined that the levelized cost of electricity ranged from 0.027 to 0.049 €/kWh. These PV parks had capacities ranging from 3 to 14 MW and anticipated operational lifespans spanning from 20 to 45 years.

The PV Park with the lowest levelized cost of energy in Sweden, amounting to 0.027 €/kWh, is associated with a plant expected to operate for 45 years. In contrast, the solar park with the highest levelized cost of energy, at 0.049 €/kWh, is projected to have a lifespan of 20 years. Upon comparing the levelized cost of energy values from these six PV parks commissioned between 2019 and 2020 in Sweden with the revenues generated from the spot market and tradable green certificates during the same period, it can be concluded that the profitability of PV parks can be achieved under a merchant PV business model. However, it's important to note that such profitability is not guaranteed and depends on various factors.

Gebrehiwot et al. (2019) [14] examined a hybrid power system that incorporated PV, wind, diesel generation, and batteries to meet the energy needs of a remote village. Their investigation resulted in a levelized cost of electricity of 0.18 €/kWh.

Similarly, *Ghenai et al. (2020)* [15] conducted a techno-economic optimization study for an off-grid solar photovoltaic and hydrogen energy system aimed at satisfying the daily demand of 500 kWh in a desert community. Their analysis yielded a levelized cost of electricity of 0.13 €/kWh.

Furthermore, *Dawood et al. (2020)* [16conducted a comparative analysis of off-grid systems catering to a remote settlement with a daily demand of 2 MWh. They explored various configurations involving PV, batteries, and hydrogen storage. Interestingly, they found that a hybrid energy storage system incorporating both batteries and hydrogen achieved the lowest levelized cost of electricity at 0.29 €/kWh. Importantly, this hybrid system significantly reduced solar photovoltaic curtailment when compared to systems that relied solely on solar photovoltaic and batteries.

A recent study in Norway made by *Viole et al. (2023)* [17] of an optimization model that was employed to design a hybrid power system for an off-grid sustainable telescope, powered by a combination of solar photovoltaic energy, batteries, and hydrogen. This system was tailored to meet an annual energy demand of 7.7 GWh while achieving a levelized cost of electricity at 0.12 €/kWh. The primary energy sources in this cost-effective system are solar photovoltaic arrays combined with batteries, along with the utilization of fuel cells powered by both imported and on-site produced green hydrogen. To ensure reliability, a backup system for diesel generators is also integrated into the setup.

2 Data Analysis

This section will gather data from the subject organization under investigation, SSAB, and assess it to determine the optimal design of PV systems capable of meeting the load profile specifications for Forming Line 4.

2.1 SSAB's industrial area in Borlänge

The project site is in the industrial area of SSAB in Borlänge as shown in Figure.2.1. The site is located at latitude 60°28'N and longitude 15°26'E. The site area contains a lot of different facilities and buildings, and about 40 km of railway [18]. The industrial area owned by SSAB in Borlänge is around 122 hectares in area [19]. According to the data provided by SSAB, there is a significant demand for electricity in the whole industrial site facilities and reached 423 GWh in 2021 [10]. There are 4 forming lines in the industrial site. In the forming lines, steel coils are formed, straightened, and cut into sheets in accordance with the customer's demand.

Figure 2.1. Production facilities on the industrial area of SSAB in Borlänge

Figure 2.2 shows the electricity load for the 4 forming lines according to SSAB data provided for 2021 electricity load. The graph shows the total electricity load for Forming Line 4 which is equal to 2.7 GWh in 2021 and 2.4 GWh in 2022 which is not a significant difference between both years, but it is still the biggest line for the electricity load among all the forming lines [10].

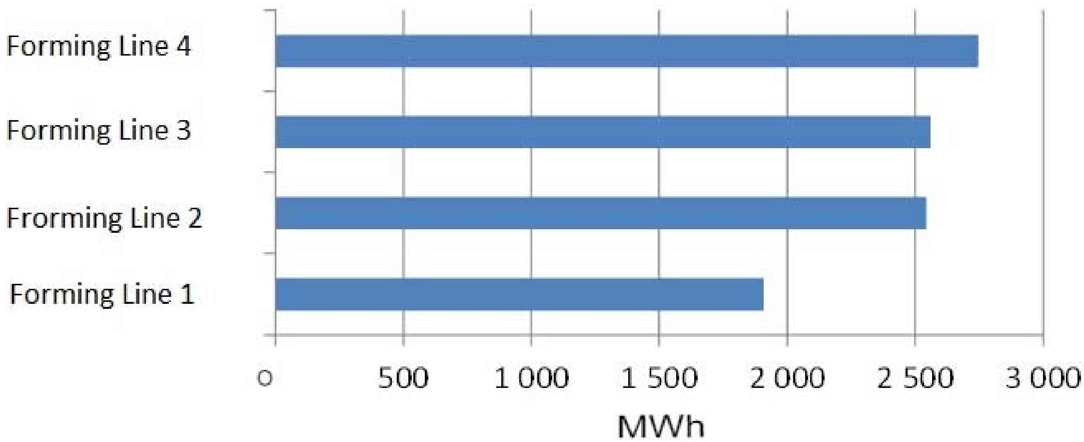

Figure 2.2. Yearly electricity load of the 4 forming lines (Information about FS4, SSAB)

2.2 Forming line 4

The primary emphasis of this study revolves around Forming Line 4 as depicted in Figure 2.3 [10], which involves the steel forming process. A dedicated solar PV system will be constructed to fulfill the electrical requirements of Forming Line 4..

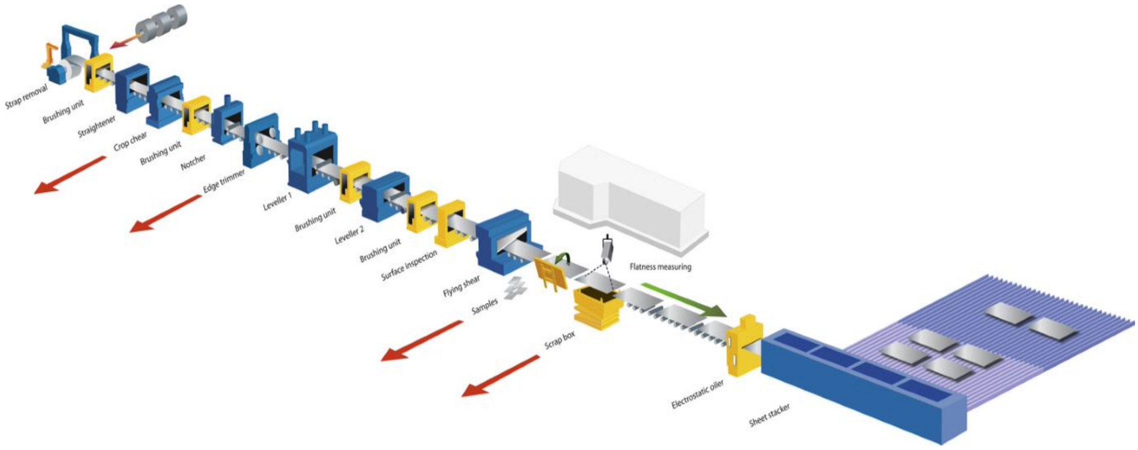

Figure 2.3. Steel forming process of Forming Line 4 (Information about FS4, SSAB)

2.3 Load analysis

The monthly electricity load for Forming Line 4 in 2022 is shown in Figure 2.4, which differs monthly. The daily electricity load in 2021 is shown in Figure 2.5 and the daily electricity load in 2022 is shown in Figure 2.6. It has been noticed the variations throughout the day according to the production capacity of the work and steel forming, so there is no certain peak load at a certain time daily or monthly. The yearly total electricity load of Forming Line 4 is 2.4 GWh which represents 0.65% of the total electricity use in SSAB industrial site in 2022 which is used as the load in this study [10].

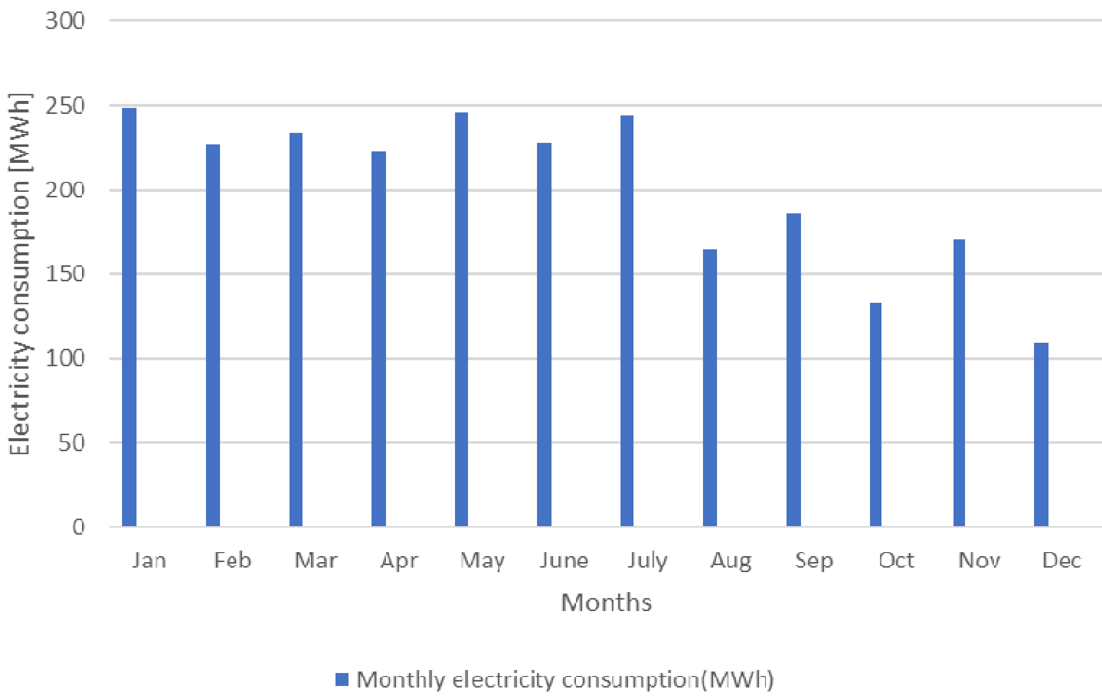

Figure 2.4. Monthly electricity consumption For forming Line 4 in 2022

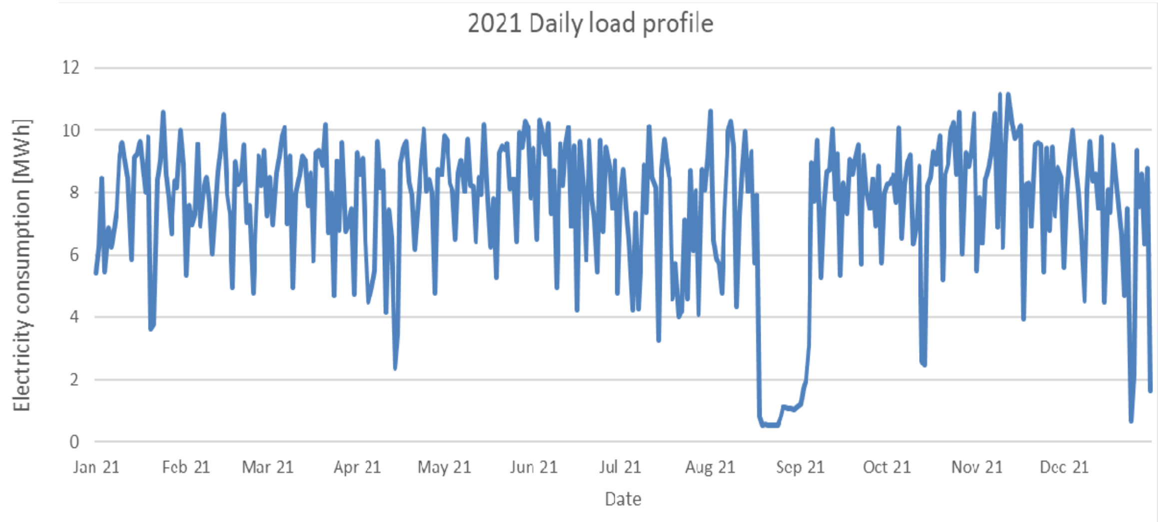

Figure 2.5. Daily electricity consumption for Forming Line 4 in 2021

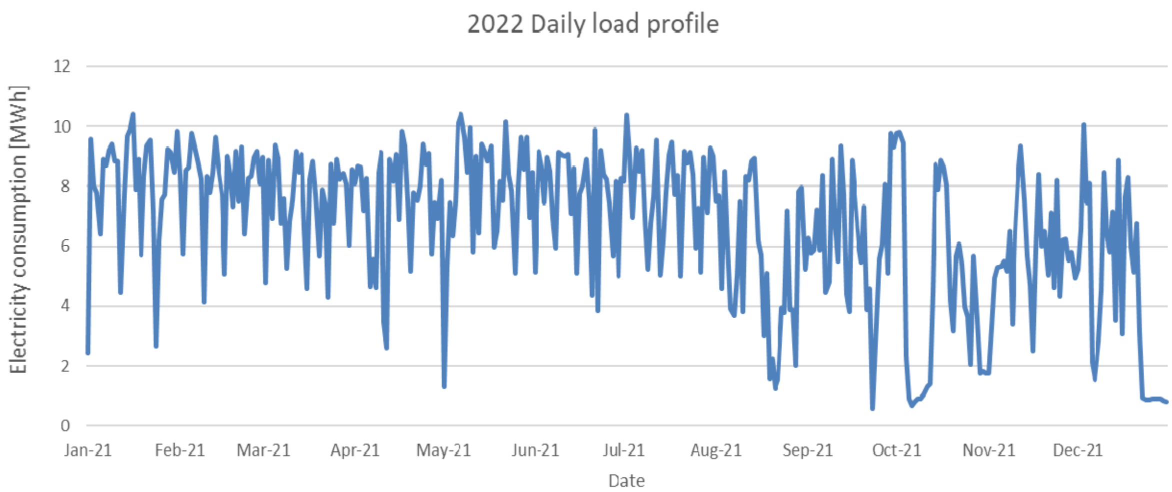

Figure 2.6. Daily electricity consumption for Forming Line 4 in 2022

3 Design and sizing

The key project circumstances, including the project's location and the corresponding solar radiation statistics, as well as the variables that influenced the modeling and the design parameter used in the simulation using the PVsyst simulation program, will be covered in this chapter. The tool selected for conducting the modeling, simulations, and techno-economic optimization is Homer Pro. After introducing the chosen tool, a concise overview of its capabilities is provided, followed by an explanation of all the input parameters necessary to create the model within Homer Pro.

3.1 Meteorology data

One of the key elements to consider when estimating how much electricity can be produced at SSAB's industrial site in Borlänge is the data of solar radiation. The weather information is sourced from PVsyst, which based the specifics on Meteonorm. There are several weather stations in the Meteonorm database. It contains information from numerous diverse international databases regarding global radiation, temperature, humidity, wind, sunshine duration, and rainy days [20]. The global horizontal irradiation for the SSAB industrial location in Borlänge is shown in Figure 3.1, and it reaches 935 kWh/m² annually.

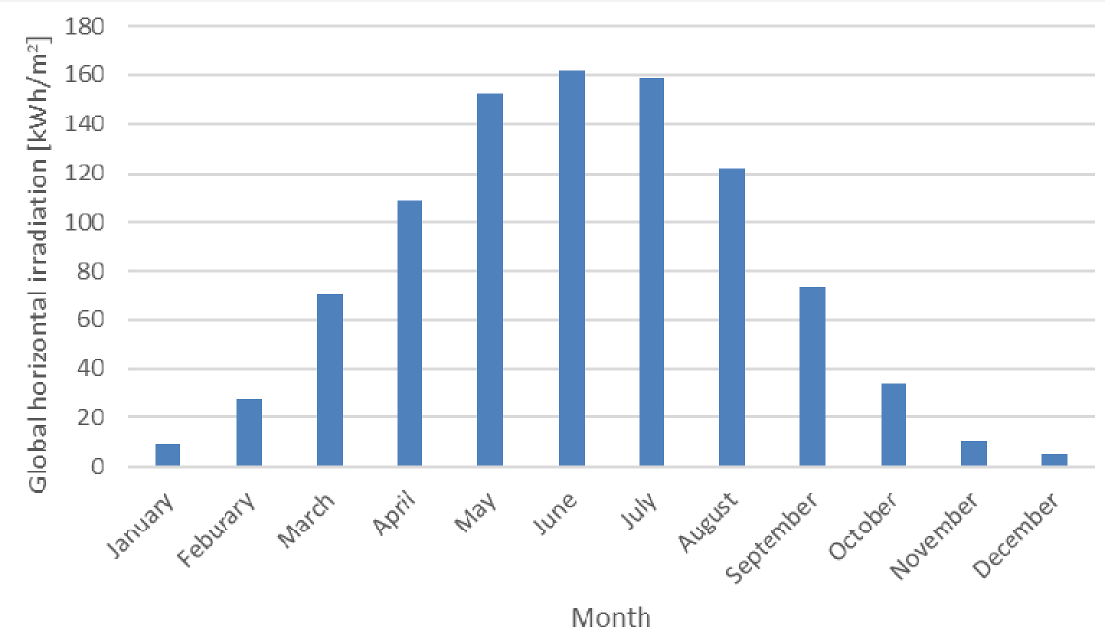

Figure 3.1 Global horizontal irradiation from Pvsyst

3.2 PVsyst

The first simulation software used in the study is PVsyst. It is a software application for studying, calculating the size, and analyzing data on the PV systems. The systems, whether they are stand-alone or connected to the grid, and whether they feature storage or not. As part of its database, which is a popular tool for large-scale and utility-scale solar projects, significant meteorological data and complete PV components are included. It also offers a thorough economic evaluation utilizing real component pricing, supplementary expenses, and investment circumstances, if that is required [21].

With thousands of PV modules, inverters, and batteries available as components data, PVsyst offers an enormous equipment library with accurate information from manufacturer's datasheets to choose the suitable to the project. It is also possible to input data for a particular component specifically for a project.

3.3 Boundary conditions

It takes an in-depth understanding of operating conditions, design parameters, and chosen components to meet the objective of a superior design and obtain the highest output of it with the least losses using such assessments. In the following subsections, some important design parameters will be illustrated like PV array inclination or tilt angle, inter-row spacing, shading effects, and soiling losses.

3.3.1 Tilt angle

The angle of inclination between a PV panel and its mounting ground is known as the tilt angle. The site's location, climate, and land topography all play a role in choosing the best angle. It is an important consideration in the design of PV systems because it impacts the amount of solar radiation that the panel receives and, consequently, its ability to produce energy. In the design of PV systems, choosing the proper tilt angle is important. Lower electricity output could come from the panel not receiving enough solar radiation if the angle is too low. The panel may receive too much solar radiation if the angle is too high, which could result in overheating and deficient performance. The panel's shading is also impacted by the angle, which can also impact its performance. In general terms, the tilt angle should be set to maximize the total solar radiation that the panel receives over the duration of a year.

Stridh [22] assessed the solar park in Västerås, Sweden and used a variety of fixed and tracking methods to study the impact of tilt angle. The author proposed constructing fixed solar arrays in Sweden despite the higher production yield for configurations using solar trackers. Primarily because solar tracking system-related investment, operational, and maintenance costs are much higher. Additionally, it has been noted that fixed systems' land utilization increased significantly due to their ability to produce more energy per unit of space than sun-tracking systems. For Sweden, the optimum inclination for PV panels reported is between 41° and 48° [23].

3.3.2 Inter-row spacing

The inter-row spacing, or pitch is a crucial element in figuring out the ideal tilt angle for a ground-mounted project, particularly for sizable utility-scale PV systems. The optimal tilt may be impacted by inter-row spacing to make up for self-shading losses due to the impacts of self-shading that were previously addressed.

A significant challenge in constructing large-scale PV systems is determining the ideal inter-row spacing and installation tilt for ground-mounted PV systems. Because row-shading has less of an influence when the array is spaced farther apart, this increases annual generated energy. However, it also makes the expenses of land purchase or lease, and wiring expenses get higher. By running multiple simulations at once in different scenarios using PVsyst's "Batch mode" and compiling the results into an Excel sheet. The pitch's impact on the Performance Ratio (PR) was shown by a study of the data from the excel sheet. Due to near-shade losses, the changes are particularly severe at low pitches. The losses are reduced because there is less shadowing as the rows are set farther apart. Due to the need for more space without a discernible improvement in yield, increasing pitch distance causes the LCOE to increase more, increasing the capital investment's cost [24]

3.3.3 Shading losses

Due to the possibility of existence of the terrain or mountains near the location of the PV systems, the shadings from the horizon effect were assessed using an online tool called "Suncurves". In PVsyst, the horizon parameter can import suncurves data. It requires only the selection of the desired location to provide the data, making it simple to use. Figure 3.2 shows the sun path curve with the effect of the horizon that Pvsyst showed depending on the data received from Suncurves [25]

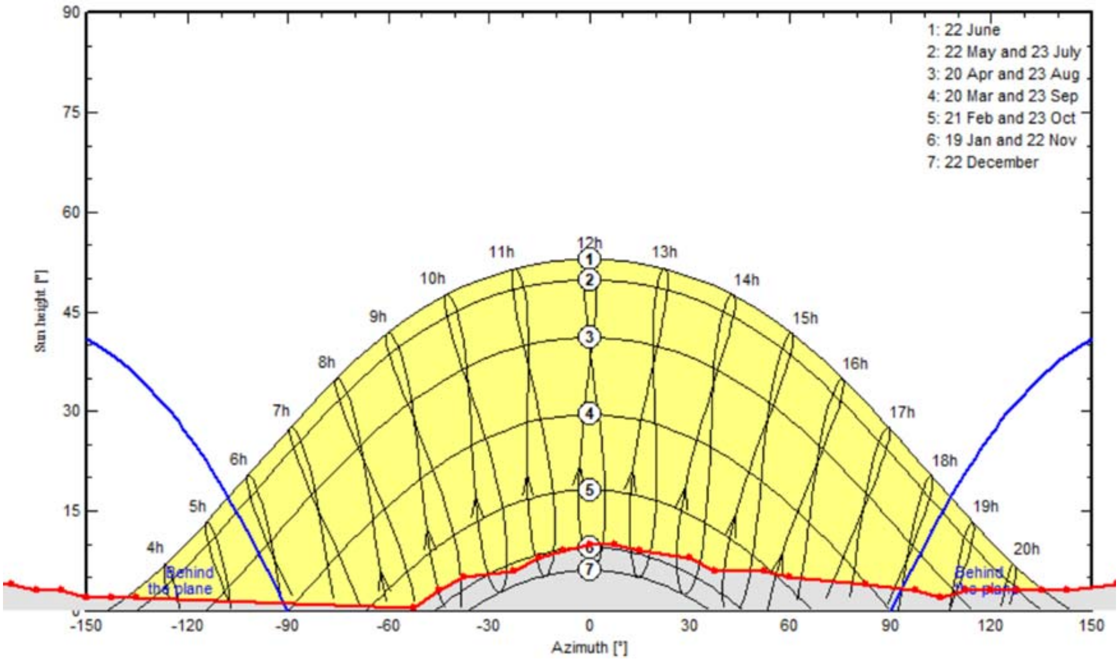

Figure 3.2 Sun-path diagram with horizon effect in Savelgärdet, SSAB Borlänge

3.3.4 Soiling and snow losses

For the annual soiling losses, PVsyst applies a default value of 3.0%. But it will not be too realistic to be considered like that. Another aspect that demands consideration regarding the location of the PV system in Borlänge is the prevalent weather conditions, characterized by anticipated snowfall from mid-October to mid-April [25]. That is why the snow-loss factor must be considered as a parameter when designing. Owing to the absence of a corresponding Swedish standard related to that, there is a city in Norway called Lillehammer which is located at latitude 61°'N like the latitude of Borlänge [26].

It should be noted, yet, that Norway experiences more precipitation than Sweden. Since Borlänge experiences fewer snow days and less snow overall, it stands to reason that soiling losses will be smaller as well [27] and [28]. According to Table 3.1, the average losses would be 4.8%, which is quite higher for Borlänge considering that Lillehammer, a city in Norway's north, receives more snowfall. Because of this, a deviation of the losses needs to be calculated using assumptions.

Table 3.1 Monthly soiling losses at Lillehammer for tilts of 25° to 60°

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Losses	10%	10%	8%	4%	2%	2%	2%	2%	2%	2%	3%	10%

3.4 Homer Pro

Homer (Hybrid Optimization of Multiple Electric Renewables) is a software developed by the National Renewable Energy Laboratory (NREL). Hybrid microgrid systems are frequently modeled using Homer Pro, which gives the option to design both grid-connected and off-grid systems. It enables the simulation of complicated systems by combining heat and power, AC and DC loads, enhanced grid connections, battery and hydrogen storage using a variety of modules [29]. Energy system simulation and optimization are both possible with Homer Pro. Additionally, a variety of sensitivity assessments can be performed utilizing the software [30].

3.4.1. Data inputs for modeling

There is a wide range for the inputs in Homer Pro. Homer requires some data for simulation and optimization such as the location of selection, the load profile of consideration, the components characteristics, technical and economic data. In the following sections, the important modelling inputs will be described.

3.4.2. Grid

Advanced grid module is one of the components included in Homer, which enables the modeling of grid-connected systems. There are several separate ways to define the grid [31]. Real-time rates are used to design the grid for the project. Borlänge is in the bidding area or the electricity price area SE3 of Sweden. The electricity prices considered for modelling are the hourly rate at Nordpool for the bidding area SE3 over the year 2022 as shown in Figure 3.3 [32]. The electricity network charges have been added to the hourly rate according to the charges from Borlänge Energi to be considered as the power price on Homer pro by adding 210 € per year for the connection and 0.033 €/kWh for the electricity transmission [33]. The electricity saleback rate is considered as the hourly rate at Nordpool [34]. No outages are considered in the modeling because it is assumed that the grid in Borlänge is stable. The emissions for the grid of Borlänge were then estimated and added to Homer. The largest portion of output comes from nuclear, then from wind as per Table 3.2 [35].

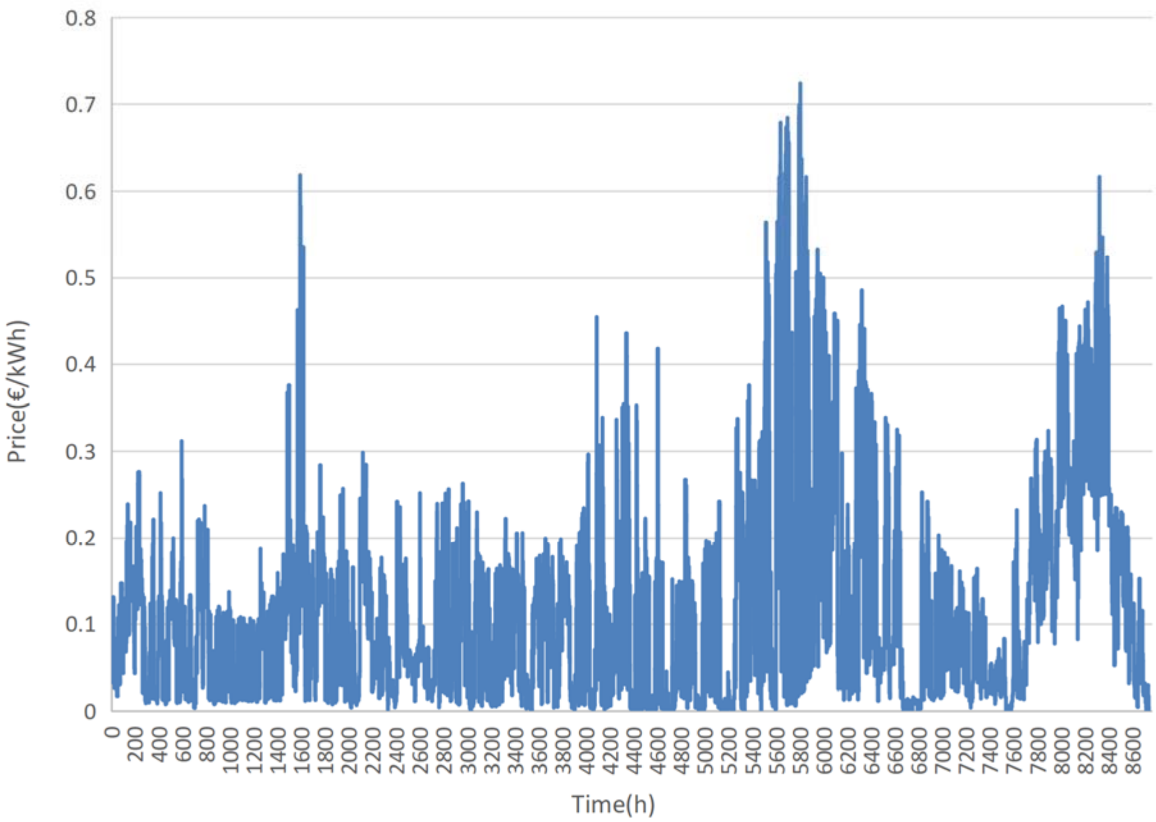

Figure 3.3 Spot electricity price for SE3 in 2022

Table 3.2 Emissions for the electricity produced from grid.

Parameter	***Value***
Carbon Dioxide CO_2 (g/kWh)	24
Sulfur Dioxide SO_2 (g/kWh)	2.7
Nitrogen Oxides NO (g/kWh)	1.3

3.4.3. Load Profile

There are several.csv file layouts that Homer Pro can identify. A file of synthesized data has been created of two column formats of date-time and load (kW) [36]. Homer calculates the average 12-month load profile from the imported data, displays it in the table and graph, and then discards the data from the imported file. Homer also calculates the average 24-hour load profile for the entire year and displays it in a graph. Figure 3.4 displays the daily load profile as it appears in Homer during modeling.

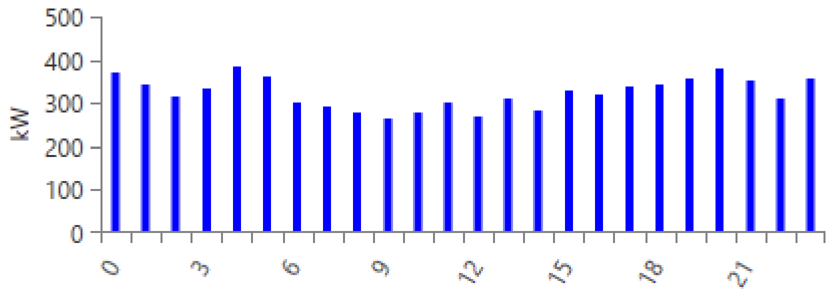

Figure 3.4 Daily profile for the load from Homer pro

3.4.4. Overview of simulations

To be able to investigate and analyse the potential of the energy storage technologies by using Homer pro, there are four different scenarios implemented, and they are stated in section 4.2. The base case in this thesis in all scenarios is the load connected to the grid The control strategy that has been used while using the software of Homer pro is load following. This control method can be explained as follows:

- When the PV output matches the load, the load is met without attempting to charge the batteries. No excess electricity is produced in this instance.
- When the PV output is greater than the load, the excess electricity charges the battery. If the battery is fully charged, the hydrogen will receive the excess electricity.
- When the PV output is insufficient to meet a load, the least expensive option is selected to meet the demand.

In Homer Pro, the impact of excess electricity is assessed across various scenarios, each representing different system configurations and operational strategies. When the energy generation from renewable sources such as solar panels exceed the immediate demand from the connected loads, an excess of electricity is produced. This excess electricity can have several implications based on the chosen scenario:

- Energy storage and self-consumption: In scenarios where energy storage systems like batteries are incorporated, excess electricity can be stored for later use. This enhances self-consumption by optimizing the use of generated energy during periods of low generation or high demand. This approach reduces reliance on the grid and increases the system's ability to provide power during non-generating periods.
- Grid interaction: Excess electricity can be exported to the grid when the system is grid-connected. This scenario might lead to the possibility of earning revenue through feed-in tariffs or other incentive mechanisms, contributing to the financial feasibility of the project. Grid interaction also enhances energy resilience by maintaining a connection to the grid as a backup energy source.
- Economic and financial implications: The handling of excess electricity impacts the financial viability of the system. By comparing scenarios with and without excess electricity management strategies, the financial benefits of energy storage, grid interaction, or curtailment can be evaluated. These considerations influence key financial metrics such as payback period, return on investment, and net present value.

3.4.5. PV

The PV component will be studied using the PVsyst tool because it provides a more comprehensive analysis of PV systems, and the production data will be uploaded to Homer Pro using its PVsyst data importing wizard. The hourly production data extracted from PVsyst has been prepared for importing into Homer Pro. Table 3.3 lists the primary variables considered for the modeling of the PV panels [37].

Table 3.3 Modelling parameters for PV

Parameter	***Value***
Capital cost [€/kW]	800
Replacement cost [€/kW]	718
O&M cost [€/kW/year]	9
Lifetime[years]	25

3.4.6. Converter

The Converter in Homer converts electric power from DC to AC. Homer assumes constant inverter efficiency [38]. The converter's economic features for Homer modelling are shown in Table 3.4

Table 3.4 Modelling parameters for Converter

Parameter	***Value***
Capital cost [€/kW]	273
Replacement cost [€/kW]	273
O&M cost [€/kW/year]	0
Lifetime[years]	15

3.4.7. Battery storage

The battery functions by storing electricity in a chemical state, allowing the stored energy to be recharged and utilized for continuous operation as needed. A battery pack is taken into consideration to store both the excess electricity generated by the PV panels and the grid's power during periods of low or negative prices. When grid prices are higher or when using the energy stored in the battery could result in a lower cost of electricity than using other modes, the energy will be discharged and utilized. Under the library, various battery types are listed. Lithium Ion (Li-ion) battery is the type of batteries selected for the project. It was chosen because it offers a better power density compared to other battery types, a longer lifetime, and quick charge cycle and discharge cycle [39]. From the available advanced storage battery models, a generic 1MWh Li-ion battery was selected for modeling on Homer Pro. The modelling parameters of 1 kWh are described in Table 3.5 [38].

Table 3.5 Modelling parameters for Battery storage

Parameter	***Value***
Type	1kWh Li-ion
Capital cost [€/kW]	500
Replacement cost [€/kW]	500
O&M cost [€/kW/year]	9
Lifetime[years]	15

3.4.8. Electrolyser

The excess electricity generated by the PV panels can also be converted into hydrogen by utilizing an electrolysis process. This process employs an electrolyser, a device that uses electricity to split water into oxygen and hydrogen. There are two main types of commercially used electrolysers: the proton exchange membrane electrolyser (PEM) and the alkaline electrolyser. Both of these electrolysers are employed in the process of water electrolysis to produce hydrogen. The capacity of these electrolyser types can vary depending on technological advancements and specific manufacturer offerings:
PEM Electrolysers are renowned for their rapid response times and suitability for smaller-scale applications, making them an ideal choice for on-site hydrogen production. Typically, PEM electrolysers have ranged from a few kilowatts (kW) to several hundred kilowatts (kW) in capacity. However, recent advancements in PEM technology have enabled some systems to reach the lower megawatt range, potentially exceeding 10 MW or more.
Alkaline electrolysers are generally preferred for larger-scale applications due to their capability to handle higher currents. They are available in a wider range of sizes, spanning from small units at around 100 kW to several megawatts, with the potential to go up to 20 MW or more for specific industrial purposes. PEM electrolysers occupy less space and can quickly adjust their production rate to match intermittent electricity generation, such as that from PV panels. On the other hand, alkaline electrolysers are more cost-effective and have a longer operational lifespan. Consequently, the PEM electrolyser is the preferred choice when coupled with intermittent renewable sources, as it delivers superior performance in such scenarios. To enable connection to the DC side, the electrolyser is AC connected with a rectifier. This configuration provides energy transfer compatibility and efficiency. In practice, the PV panels are not directly linked to the electrolyser. Instead, before being routed to the electrolyser, the PV-generated electricity is converted from DC to AC by the rectifier. The modelling parameters of the electrolyser are described in Table 3.6 [40].

Table 3.6 Modelling parameters for Electrolyser

Parameter	***Value***
Capital cost [€/kW]	1780
Replacement cost [€/kW]	1078
O&M cost [€/kW/year]	18
Lifetime[years]	15
Efficiency [%]	75

3.4.9. Hydrogen tank

The system's hydrogen tanks are used to store the hydrogen generated by the electrolyser. It is assumed that tanks will be used for storage. The dimensions, losses, varieties, and constituents of hydrogen tanks exhibit variability contingent upon their designated purpose and intended usage. Here, the crucial facts for consideration:

- Storage capacity: Hydrogen reservoirs encompass a diverse spectrum of sizes, ranging from compact, portable containers tailored for fuel cell vehicles to sizable tanks designed for industrial or energy storage applications. Storage capacity can fluctuate from a few liters to several thousand liters, or even beyond.
- Losses: -
  1. Permeation losses: Given hydrogen's diminutive molecular size, it can gradually permeate through specific materials. To mitigate this, hydrogen tanks frequently incorporate specialized barriers or liners to thwart permeation.
  2. Boil-off losses: In cryogenic hydrogen storage setups, where hydrogen is maintained at extraordinarily low temperatures, some boil-off losses can occur due to heat seeping into the tank.

- Types:
  i. Compressed hydrogen tanks: These reservoirs store hydrogen gas at elevated pressures, generally within the range of 350 to 700 bar (5,000 to 10,000 psi). They find common usage in fuel cell vehicles and certain industrial applications. These tanks are typically crafted from robust steel or composite materials renowned for their strength.
  ii. Liquid hydrogen tanks: Liquid hydrogen necessitates storage at profoundly low temperatures (-253°C or -423°F). These tanks are deployed in aerospace applications and select industrial settings. They are typically constructed with dual walls and insulation to curtail heat infiltration.
  iii. Metal hydride tanks: These tanks rely on chemical reactions to absorb and release hydrogen. They function under moderate pressures and cater to specialized niches.
  iv. Carbon nanotube tanks: This emerging technology capitalizes on carbon nanotubes for the adsorption and retention of hydrogen. It harbors the potential for substantial storage density.
- Materials:

i. Compressed gas tanks: These containers are predominantly fashioned from high-strength steel or lightweight composite materials. The composite materials frequently involve carbon fibers reinforced with epoxy or similar polymers.
ii. Liquid hydrogen tanks: These vessels are typically composed of materials such as stainless steel, featuring double-walled insulation to sustain low temperatures.
iii. Metal hydride tanks: These tanks employ an array of metal alloys as their storage medium.
iv. Carbon nanotube tanks: The materials employed in carbon nanotube-based storage are under active exploration for their prospective role in hydrogen storage.

It's crucial to underscore that the selection of hydrogen tank type and material hinges upon the precise prerequisites of the given application, encompassing considerations like storage capacity, weight limitations, operational conditions, and safety requisites. The domain of materials science continually fosters innovation in hydrogen storage technologies, striving to enhance efficiency, safety, and cost-effectiveness [41]. The financial factors that were considered when modeling the Homer hydrogen storage tank are shown in Table 3.7 [40].

Table 3.7 Modelling parameters for Hydrogen tank

Parameter	***Value***
Capital cost [€/kW]	390
Replacement cost [€/kW]	390
O&M cost [€/kW/year]	0
Lifetime[years]	25

3.4.10. Economics inputs

The nominal discount rate, inflation rate, and project lifetime are the primary project economic factors that apply to the project. Table 3.8 shows the economic data considered for the Homer Pro simulation [42] [43].

Table 3.8 Modelling parameters for Economics

Parameter	***Value***
Interest rate [%]	3.5
Inflation rate [%]	8.5
Project lifetime [years]	25

3.4.11. Key figures

This section explains the terminologies and formulas utilized and provides a deeper analysis of some of the output variables produced.

3.4.11.1. Levelized Cost of Electricity

Levelized Cost of Electricity (LCOE) serves as a clear benchmark for assessing the cost-effectiveness of various power plants and stands as a commonly employed instrument for evaluating the expenses associated with diverse electricity generation methods. The LCOE definition can be articulated as the real electricity price required to precisely offset the aggregate costs when considering their present value [44].

$$LCOE = \frac{Initial\ investment + (Annual\ costs \cdot n) - Residual\ value}{\sum_{j=1}^{j=n} \frac{First\ year\ yield \cdot (1 - System\ degredation\ rate)^{j-1}}{(1 + Interest\ rate)^{j}}}$$ *Equation 3.1*

Where: j is the years
n is the lifetime of the system

3.4.11.2. Net Present Cost

Net Present Cost (NPC) is the difference between all of the expenses a system faces and all the income it generates throughout its lifetime. The costs included are capital expenses, replacement costs, operation and maintenance costs, fuel prices, charges for pollution, and the cost of using the grid to get power. There are two sources of income are grid sales revenue and salvage value. The cumulative discounted cash flows for each year of the project's life cycle are added to determine the total NPC. It can be calculated by the formulas [45].

$$NPC = \frac{C_{ann,tot}}{CRF(i, N)}$$ *Equation 3.2*

Where: CRF is the capital recovery factor using which the present value of annuity is calculated
N is the project lifetime

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$ *Equation 3.3*

Where: i is the real discount rate

$$i = \frac{i' - f}{1+f}$$ *Equation 3.4*

Where: i' is nominal discount rate
f is the expected inflation rate

3.4.11.3. Solar Fraction

Solar Fraction (SF) is the "Share of solar" likely refers to the proportion or percentage of the total energy demand that is being met by solar energy sources in a given microgrid or energy system configuration. In Homer Pro, there are different input energy sources such as solar panels, wind turbines, generators, and batteries, along with their respective capacities, costs, and efficiencies. The share of solar would indicate how much of the energy consumed by the system is being provided by solar power. This metric is valuable for understanding the level of reliance on solar energy and its contribution to the overall energy mix in the system.

$$SF = \frac{E_{PV}}{E_{Load}}$$ *Equation 3.5*

Where: E_{PV} is the electrical production from PV
E_{Load} is the total electrical load

3.4.11.4. Self-Consumption

Self-consumption (SC) refers to the utilization of electricity generated by a PV solar system within the premises where the system is installed, as opposed to feeding it back into the grid. It represents the portion of the solar electricity produced that is directly used at the site.

$$SC = \frac{E_{PV}}{E_{prod,\,tot}} \qquad \text{Equation 3.6}$$

Where: E_{PV} is the electrical production from PV
$E_{prod,\,tot}$ is the total electricity produced

3.4.11.5. Discounted Payback

Payback is the number of years in which the total cash flow of the difference between the current system and the base case system changes from being negative to being positive. The payback gives an idea of how long it would take to make up the investment cost difference between the current system and the best-case scenario. The point when the discounted cash flow differential line reaches zero is known as the discounted payback.

3.5 Simulation tools uncertainties

PVsyst is a widely used software tool for simulating and analyzing the performance of PV systems. It's designed to model the behavior of solar panels, inverters, and other system components in various environmental conditions. However, like any simulation tool, PVsyst simulations come with inherent uncertainties. Here are some sources of uncertainty in PVsyst simulations:

- Weather data accuracy: PVsyst simulations heavily rely on accurate weather data such as solar irradiance, temperature, wind speed, etc. Uncertainties in these data inputs can lead to deviations between simulated and actual system performance.
- Module and inverter characteristics: The accuracy of the module and inverter specifications used in the simulation can impact the results. These specifications include efficiency, temperature coefficients, and other performance parameters. Variability in manufacturing can introduce uncertainty.
- Shading and obstructions: Accurate shading analysis is critical for PV system performance prediction. If the shading inputs are inaccurate or incomplete, the simulation results may not match real-world performance.
- Model assumptions: PVsyst makes certain assumptions about how components behave under different conditions. If these assumptions don't hold true for a specific system, the simulation results could deviate.
- System configuration: Accurately modeling the system layout, orientation, tilt, and azimuth angle is important. Any discrepancies between the simulated configuration and the actual installation can lead to uncertainties.
- Inverter behavior: Inverter models in PVsyst may not perfectly capture the dynamic behavior of all types of inverters. Inverter efficiency, clipping behavior, and response to varying irradiance can introduce uncertainty.
- Electrical and thermal losses: PVsyst provides detailed information about the losses within a PV system. The software is designed to perform comprehensive simulations of PV systems and offers a breakdown of various types of losses that can affect system performance. Variability in electrical losses due to wiring, connections, and so on, as well as thermal losses due to module temperature .variations, can affect system performance

- Maintenance and degradation: Simulations often assume ideal operating conditions, while in reality, PV systems degrade over time due to factors like soiling, module degradation, and potential faults. These effects are not always perfectly accounted for in simulations.
- Performance models: The accuracy of the underlying models used by PVsyst to predict module behavior under varying conditions contributes to uncertainties. Models might not capture all the complexities of real-world behavior.
- Site-specific factors: Factors such as local weather patterns, altitude, and environmental conditions can vary from the default assumptions in PVsyst, leading to differences between simulated and actual performance.

To minimize uncertainties in PVsyst simulations, it's crucial to input accurate and site-specific data whenever possible. Regularly updating simulations with real-world performance data and validating the results against actual system outputs can also help refine the model and reduce discrepancies. While PVsyst provides valuable insights, it's important to recognize that simulation results are approximations and may not perfectly match real-world outcomes. According to assessments, the PVsyst software can accurately simulate a wide range of diverse grid-connected systems. It has been made an effort to pinpoint the uncertainties associated with measurement and parameter determination as well as those inherent to modeling by independently evaluating each of the algorithms. Finally, it can be said that the simulation's overall results have an accuracy of between 1-2% Mean Bias Error (MBE) accuracy over one year [46].

Homer Pro is a software tool for microgrid and distributed energy system optimization. Similar to PVsyst, Homer Pro simulations also have uncertainties due to various factors:
- Input data accuracy: Homer Pro requires various input data such as load profiles, renewable resource data, equipment specifications, and cost information. Inaccuracies in these inputs can lead to uncertainties in the simulation results.
- Resource variability: Renewable resources like solar irradiance and wind speed can vary over time. The accuracy of historical resource data and the representativeness of the data for the project location can affect simulation outcomes.
- Component characteristics: The performance characteristics and efficiency values of components like solar panels, wind turbines, batteries, and generators can have inherent variability that impacts simulation results.
- Model assumptions: Homer Pro relies on mathematical models to simulate various system components and their interactions. These models are based on assumptions, and deviations from real-world behavior can lead to uncertainties.
- Cost data: Economic data, such as equipment costs, fuel prices, and discount rates, are used in optimization and financial analysis. Variability in these cost inputs can introduce uncertainty in financial metrics.
- Operational strategies: The chosen operational strategy, such as dispatch algorithms and control settings, can influence how the system components are utilized. The effectiveness of these strategies can introduce uncertainty.
- Battery degradation: If batteries are used, Homer Pro models their degradation over time. However, the actual rate of degradation can differ from modeled assumptions.
- Load variability: the load patterns might deviate through the years. So, the load profiles that are used in simulations, lead to differences in system performance.
- Regulatory and grid factors: Regulations, policies, and grid conditions can impact system operation and financial performance. Uncertainties related to these factors can influence simulation results.
- Validation Data: Lack of real-world validation data for specific system configurations and operational scenarios can lead to uncertainties in simulation outcomes.

For system precision in this study, a default relative precision of 0.01 (1%) has been used. This means that the relative system accuracy value, which is fed into Homer Pro as an input, may have a relative deviation of 1% of the range between the minimum and maximum range of each component size. To address uncertainties in Homer Pro simulations, the use accurate and site-specific input data whenever possible, sensitivity analyses can help understand how variations in input parameters affect results.

4 Results

This chapter will cover the results of the simulation studies done using the PVsyst tool and the Homer Pro tool.

4.1 PVsyst Simulation Result

system constructed on the Savelgärdet land area, which had been selected as the solar park's field as shown in Figure 4.1. The orientation is south facing, all the panels are oriented in a fixed position to face south direction with tilt angle of 45°. According to the simulation of this system, it has a capacity of 2.7 MW and 2.5 GWh of electricity is produced yearly, with a specific production rate of 922 kWh/kWp/year and a Performance Ratio of 78%. The annual electricity demand of 2.4 GWh of Forming Line 4 is obtained with the PV electricity production without any storage type added.

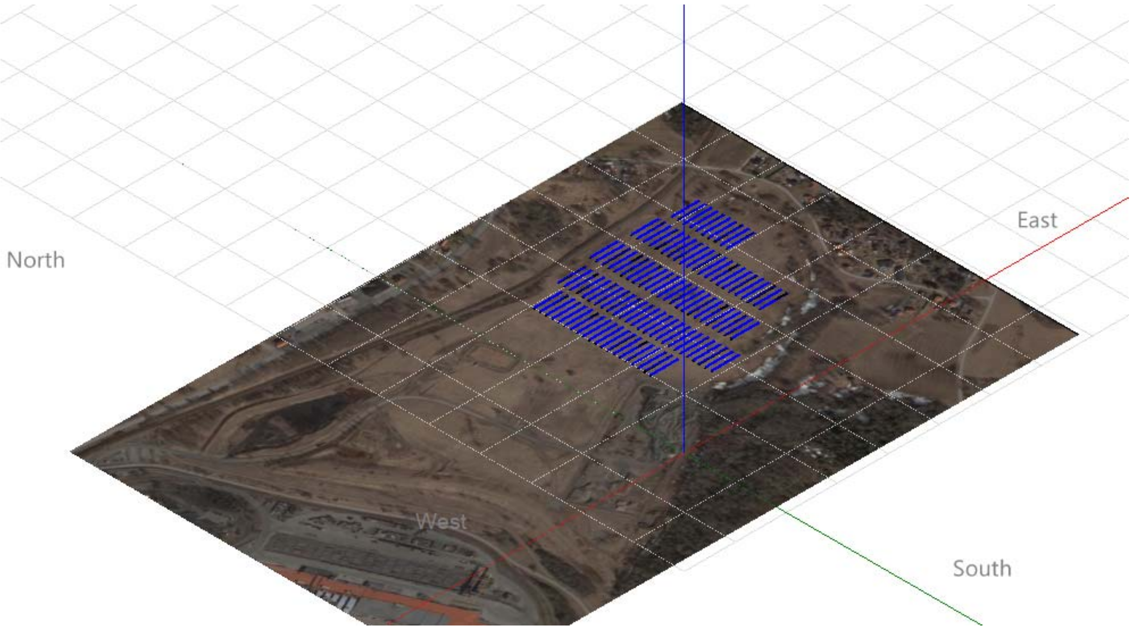

Figure 4.1 Model of PV modules on Savelgärdet field

Figure 4.2 shows the monthly electricity production of the PV system. Figure 4.3 shows the monthly electricity consumption of forming line 4, the monthly electricity production of PV system and the excess electricity. The excess electricity which illustrated in Table 4.1 shows that there is excess electricity during the months of the spring and summer and there is a need of having electricity to be added to cover the consumption of Forming Line 4 during the months of winter and spring.

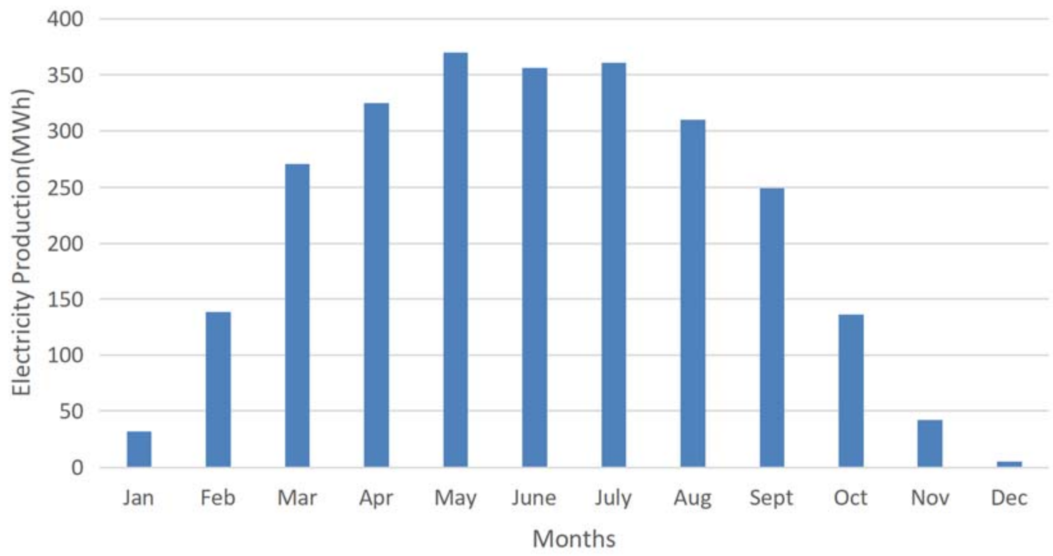

Figure 4.2 Monthly Electricity Production

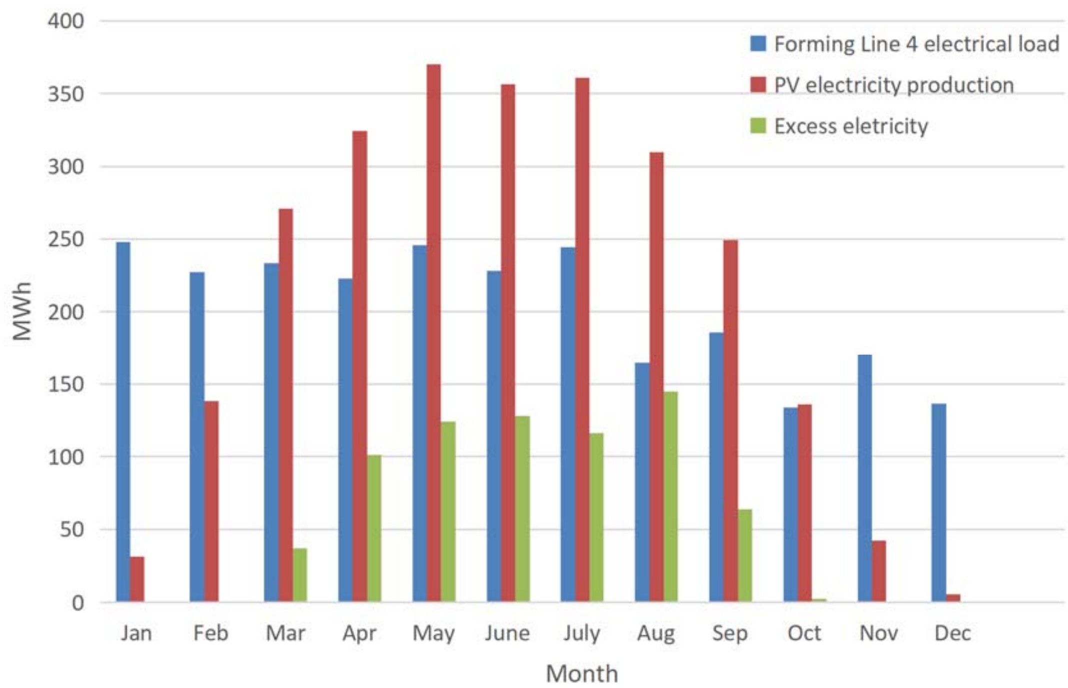

Figure 4.3 The electricity consumption of Forming Line 4, the PV electricity production and the excess electricity.

Table 4.1 Excess electricity values on the months

Month	***Value [MWh]***
Mar	37
Apr	101
May	124
June	128
July	116
Aug	145
Sep	64
Oct	2

The output of the PV production will then serve as an input for Homer Pro. The next step is to investigate the viability of adding electrical energy storage or hydrogen storage with the PV system to utilize the excess electricity generated by the PV system during the months mentioned above.

4.2 Homer Pro Simulation Results

In this section of the study, the simulation results produced for the system for the investigation of techno-economic optimization and feasibility analysis are discussed. The following sections are the feasibility analysis of the different system scenarios.

4.2.1. Base case

In the base case scenario, the electrical load of Forming Line 4 is directly connected to the grid. This configuration represents the current operational setup without any additional electricity production or storage systems integrated. The load requirements of Forming Line 4 are fulfilled solely through the grid connection, implying that the line's power demands are met by the electricity supplied by the utility. For the year 2022, the average electricity price in SE3 was 0.067 €/kWh. This base case serves as a reference point against which alternative scenarios involving energy storage solutions can be compared to assess their impact on system performance, cost savings objectives.

4.2.2. Scenario 1: Base Case and PV

The simulations for Scenario 1 are done to model and assess the viability of a base system with adding PV system as a renewable resource. The modelling specifications for the grid as described before in Section 3.4.2 and the modeling parameters for PV panels are stated in Section 3.4.5. Figure 4.4 shows the system architecture that Homer pro has been accounted for when modeling Secnario1.

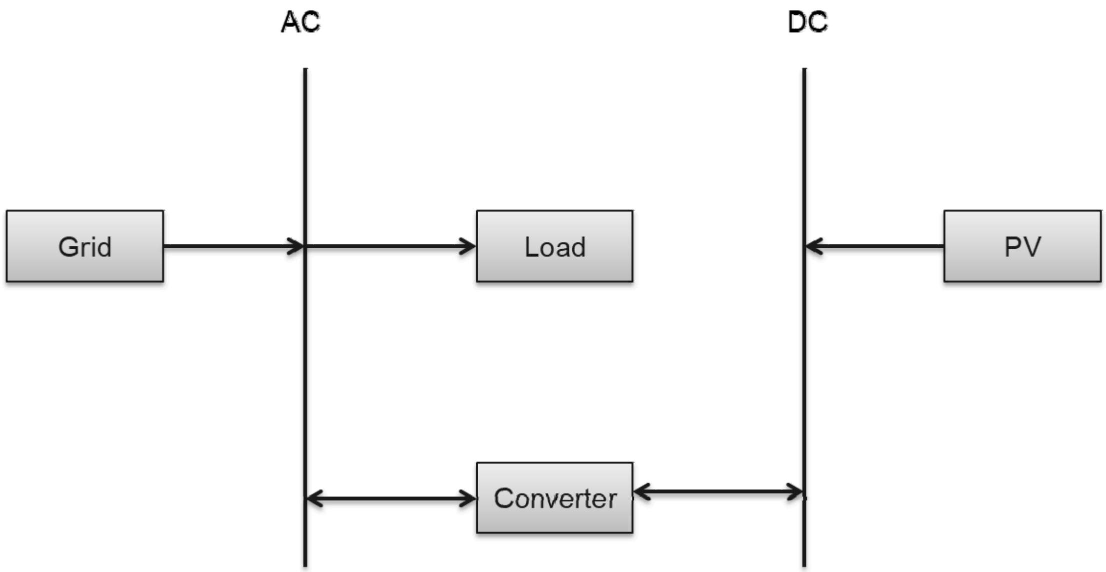

Figure 4.4 Schematic of Scenario 1 on Homer

Table 4.2 shows the size of the components for Scenario 1.

Table 4.2 Size of the components

Parameter	***Scenario 1***
PV [kW]	2715
Converter[kW]	2275

Table 4.3 displays the key findings of Scenario 1.

Table 4.3 Key figures of Scenario 1

Parameter	***Scenario 1***
NPC [M€]	48
LCOE [€/kWh]	0.059
Solar Fraction [%]	31
Self-consumption [%]	29
Discounted Payback [years]	3.8

The simulations demonstrated that the system is feasible when the PV system is added as a renewable energy resource and achieving a lower LCOE of 0.059 €/kWh compared to the system with the base case. It is also achieving 31% of solar fraction and 29% of self-consumption. Besides the discounted payback time of Scenario 1 is 3.8 years.

4.2.3. Scenario 2: Base Case, PV and Battery storage

The simulations for Scenario 2 are done to model and assess the viability of a base system with an additional battery module for energy storage. The modelling specifications for the grid as described before in Section 4.3.2 and the modeling parameters for PV panels are stated in Section 4.3.4. The modelling parameters for the battery module are mentioned in Section 3.4.6. Figure 4.5 shows the system architecture that Homer has been accounted for when modeling Scenario 2.

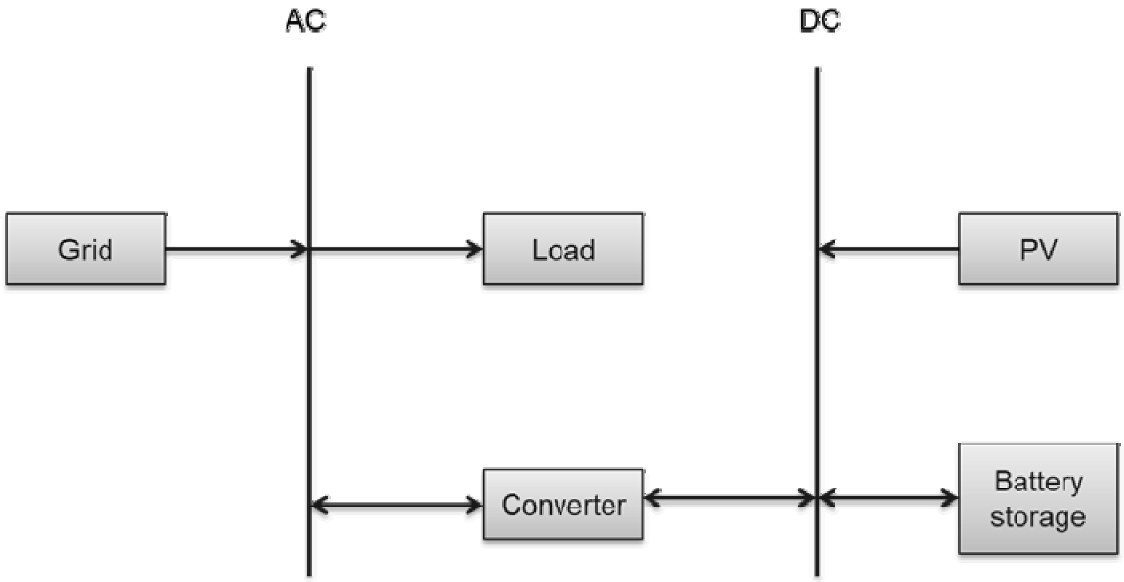

Figure 4.5 Schematic of Scenario 2 on Homer

Table 4.4 shows the size of the components for Scenario 2.

Table 4.4 Sizes of the components

Parameter	***Scenario 2***
PV [kW]	2715
Converter[kW]	2275
Batteries [MWh]	6

Table 4.5 displays the key findings of secnario2.

Table 4.5 Key figures of Scenario 2

Parameter	***Scenario 2***
NPC [M€]	43
LCOE [€/kWh]	0.064
Solar Fraction [%]	61
Self-consumption [%]	65
Discounted Payback [years]	5.6

The simulations demonstrated that the system is feasible when the batteries as a storage energy with the PV panels are added as a renewable energy resource and achieving a lower LCOE of 0.064 €/kWh comparing to the system with the base case. By adding batteries, the solar fraction has increased and achieving 61%. The discounted payback time of Scenario 2 is 5.6 years due to the fact of the lifetime of the batteries which need maintenance and replacement during the lifetime of the project, but it is still good payback in 5.6 years comparing to the 25 years of the project lifetime.

4.2.4. Scenario 3: Base Case, PV and Hydrogen storage

The simulations for Scenario 3 are done to model and assess the viability of a base system with an additional battery module for energy storage. The modelling specifications for the grid as described before in Section 4.3.2 and the modeling parameters for PV panels are stated in Section 4.3.4. The modelling parameters for the hydrogen components are mentioned in Section 3.4.7 and Section 3.4.8. Figure 4.6 shows the system architecture that Homer has been accounted for when modeling Scenario 3.

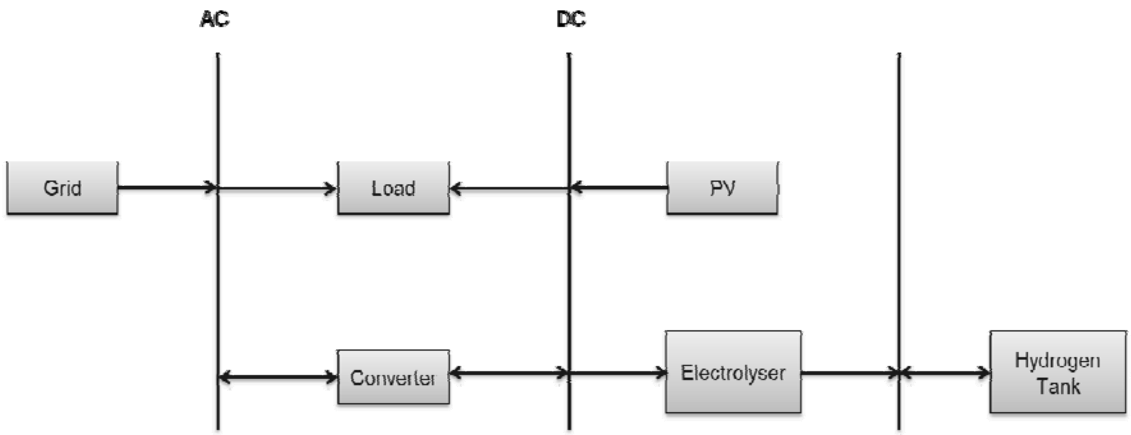

Figure 4.6 Schematic of Scenario 3 on Homer

Table 4.6 shows the size of the components for Scenario 3.

Table 4.6 Size of the components

Parameter	***Scenario 3***
PV [kW]	2715
Converter[kW]	2275
Electrolyser [kW]	1000
Hydrogen tank [kg]	10000

Table 4.7 displays the key findings of Scenario 3.

Table 4.7 Key figures of Scenario 3

Parameter	**Scenario 3**
NPC [M€]	57
LCOE [€/kWh]	0.072
Solar Fraction [%]	63
Self-consumption [%]	75
Discounted Payback [years]	3.1

The simulations demonstrated that the system is feasible when a system with local Hydrogen production is made possible by excess electricity produced by aPV system. The scenario has a higher LCOE of 0.072 €/kWh compared to the system using a storage type of batteries and the system in the base case. By adding the hydrogen storage, the solar fraction has increased and achieving 63% and also the self-consumption has increased to 75%. The discounted payback time of Scenario 3 is 3.1 years which is a good payback period for the investment with the hydrogen.

4.2.5. Scenario 4: Base Case, PV, Battery storage and Hydrogen storage

The simulations for Scenario 4 are done to model and assess the viability of a base system with. The modelling specifications for the grid as described before in Section 3.4.2 and the modeling parameters for PV panels are stated in Section 3.4.5. The modelling parameters for the battery module are mentioned in Section 3.4.6. The modelling parameters for the hydrogen components are mentioned in Section 3.4.7 and Section 3.4.8. Figure 4.6 shows the system architecture that Homer has been accounted for when modeling Scenario 4.

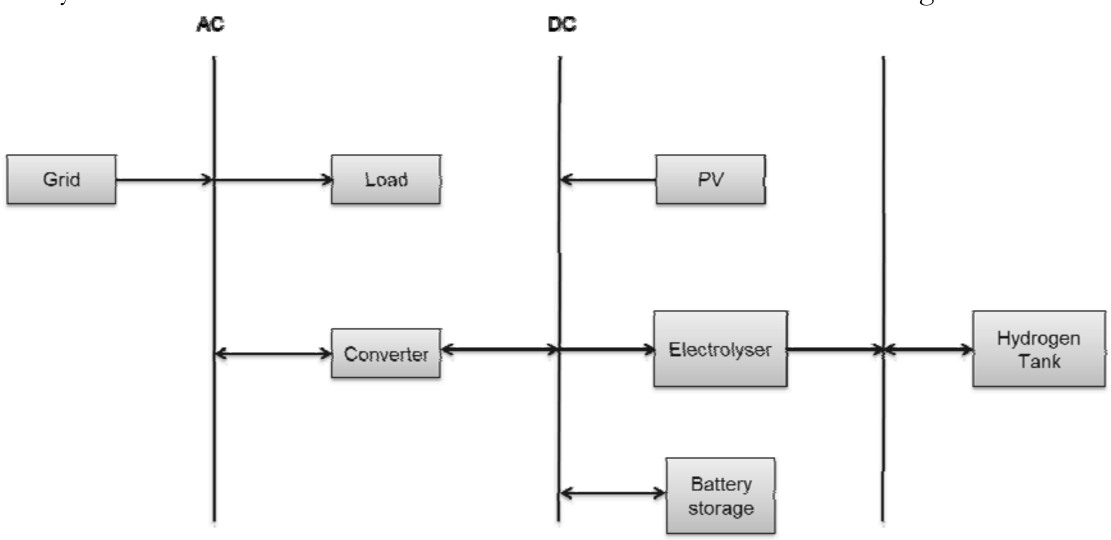

Figure 4.6 Schematic of Scenario 4 on Homer

Table 4.8 shows the size of the components for Scenario 4.

Table 4.8 Sizes of the components

Parameter	**Scenario 4**
PV [kW]	2715 kW
Converter[kW]	2275 kW
Batteries [MWh]	6

Table 4.8 shows the size of the components for Scenario 4 .

Table 4.8 Sizes of the components

Parameter	***Scenario 4***
PV [kW]	2715 kW
Converter[kW]	2275 kW
Batteries [MWh]	6
Electrolyser [kW]	5000
Hydrogen tank [Kg]	50000

Table 4.9 displays the key findings of Scenario 4.

Table 4.9 Key figures of Scenario 4

Parameter	***Scenario 4***
NPC [€M]	86
LCOE [€/kWh]	0.12
Solar Fraction [%]	66
Self-consumption [%]	100
Discounted Payback [years]	5.7

The simulations showed that the system considered complete is not feasible compared to the base system. It has a higher LCOE compared to the base system of 0.12 €/kWh. It is observed that Scenario 4 has the highest payback period compared to all the scenarios with a solar fraction of 66 % and a self-consumption of 100%. So, a comprehensive system with PV solar panels with battery storage and hydrogen storage is achieving the highest LCOE among all the scenarios.

4.2.6. Impact of LCOE with the scenarios

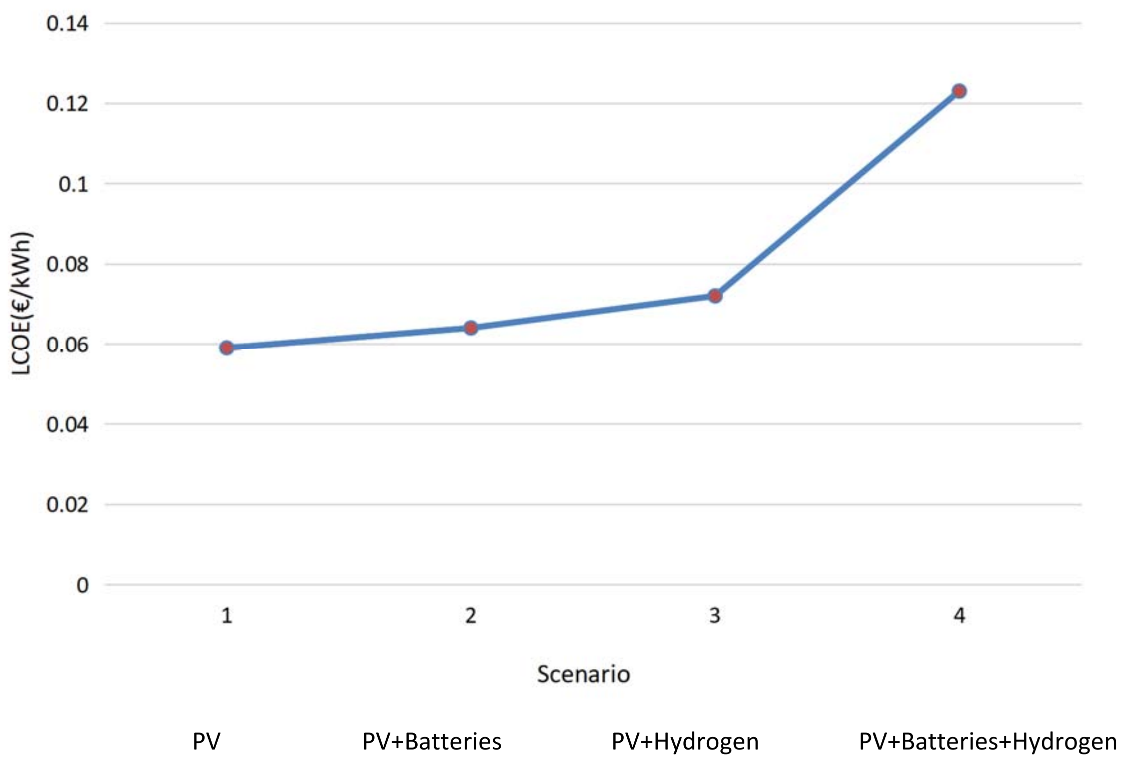

Figure 4.7 LCOE impact with the scenarios

Figure 4.7 shows the results of the scenarios that have been explained above. All the scenarios have been compared to the base case of connecting the system to the grid. It has been observed that by adding the renewable source starting with the PV panels, batteries storage and the hydrogen storage till the complete system of all the renewable resources together, the highest LCOE of 0.12 €/kWh is achieved by the complete system and the lowest LCOE of 0.059 €/kWh is achieved by the system that includes PV panels only.

4.2.7. Impact of excess electricity with the scenarios

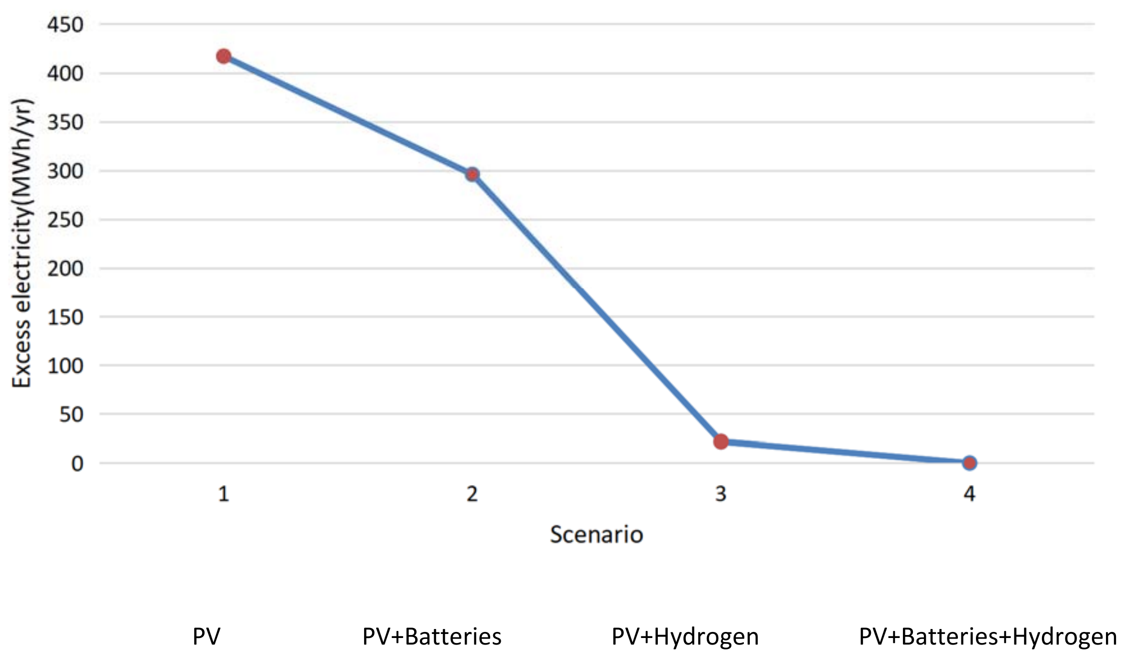

Figure 4.8 Excess electricity impact with the scenarios

Figure 4.8 illustrates the outcomes of excess electricity management across different scenarios. In each scenario, a comparison has been made against the baseline scenario where the system is solely connected to the grid. Notably, the addition of renewable energy sources, beginning with PV panels and then incorporating battery storage and hydrogen storage, culminating in the integration of a comprehensive array of all renewable resources, has resulted in a progressive reduction of excess electricity. This reduction trend is observed to continue until the point of achieving a scenario (Scenario 4) characterized by the absence of any excess electricity.

This observation highlights the effectiveness of gradually augmenting the renewable energy portfolio within the system. By initiating with PV panels and subsequently introducing energy storage solutions like batteries and hydrogen storage, the system has achieved better equilibrium between generation and consumption. The culmination of all the resources in Scenario 4 showcases the ability to harmonize energy generation and consumption to a degree where excess electricity is entirely mitigated ·

The depicted trend underscores the value of incremental renewable integration and underscores the capacity of these technologies to optimize energy management. This reduction in excess electricity holds promising implications for enhanced energy sustainability, reduced reliance on external grids, and improved operational efficiency in .alignment with the system's evolving green energy objectives ·

4.3 Sensitivity analysis

In this section, "Scenario 4" is used to perform a sensitivity analysis on it as it can be called as the complete system as the scenario with the greatest promise among the other scenarios.

4.3.1. Battery size change

The first sensitivity analysis was carried out to determine how the total system's LCOE changes as the size of the Li-ion battery changes. The size of the Li-ion battery was reduced from 6 MWh as the complete scenario to 4 MWh and 2 MWh and for each of these sizes, the system's equivalent LCOE was indicated. Figure 4.9 illustrates how the system's LCOE increases but not very much when the Li-ion battery size decreases.

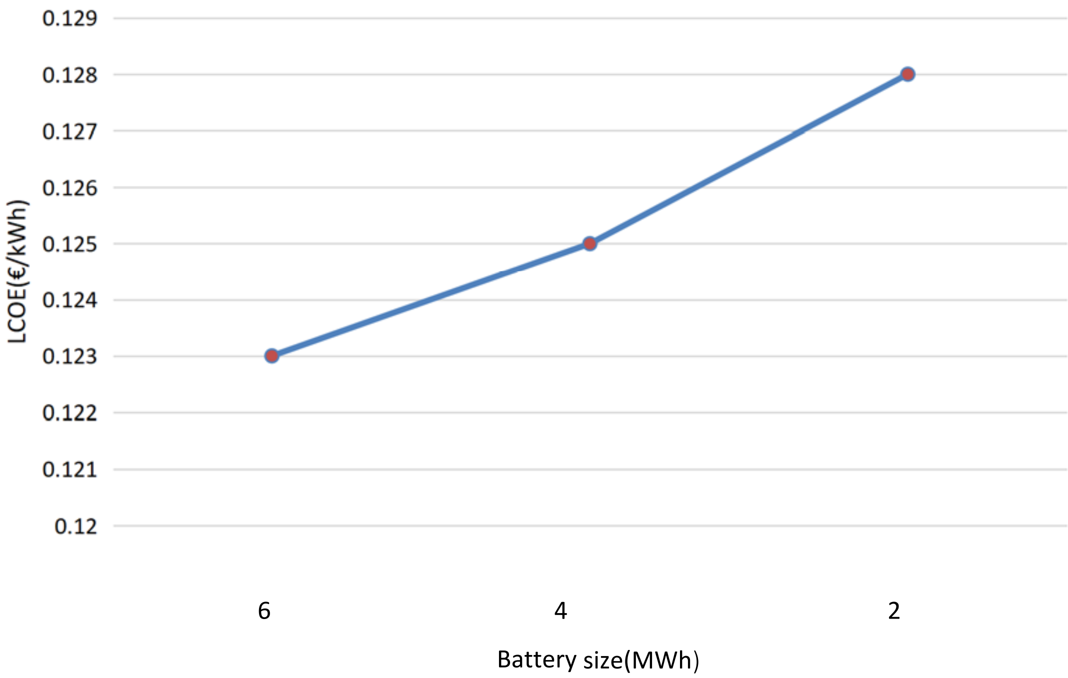

Figure 4.9 Sensitivity analysis of the LCOE with the decrease of size of the Li-ion battery

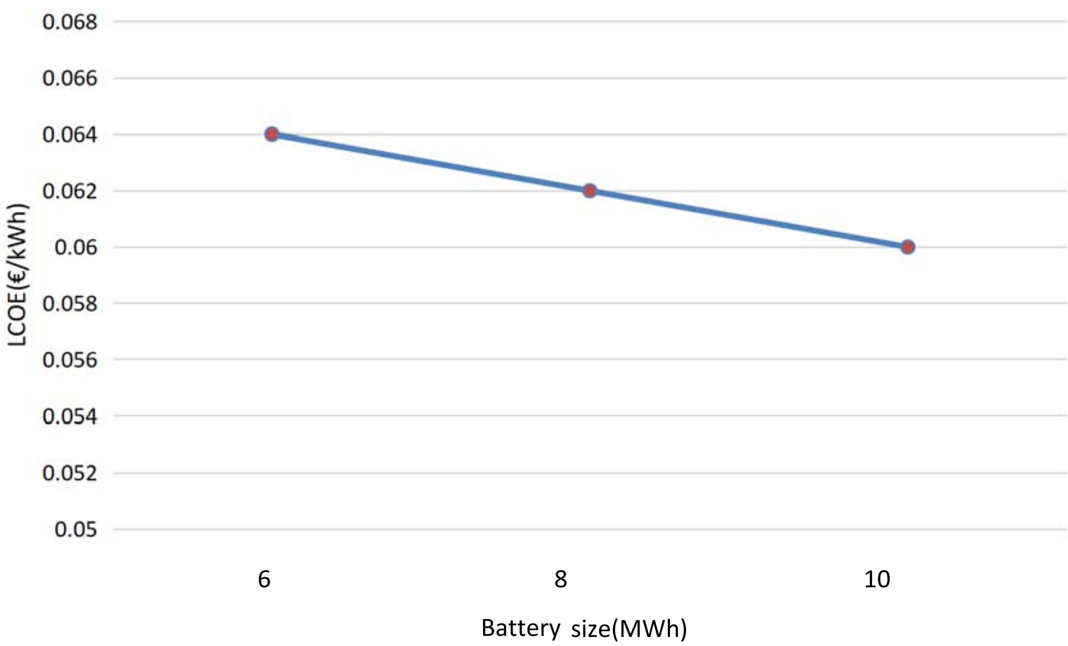

Figure4.10 Sensitivity analysis of the LCOE with the increase of size of the Li-ion battery

While increasing the size of the Li-ion battery from 6 MWh as the complete scenario to 8 MWh and 10 MWh and for each of these sizes, the system's equivalent LCOE was indicated. Figure 4.10 illustrates how the system's LCOE slightly decreases but not very much when the Li-ion battery size increases.

4.3.2. Hydrogen size change

The second sensitivity analysis was carried out to determine how the system's LCOE changes as the size of the hydrogen components change. With the size of the hydrogen components as in the complete system "Scenario 4" the LCOE of 0.12 €/kWh is achieved. While decreasing the size of the hydrogen components from 100% to 75%, 50% and 25% respectively, the LCOE is getting decreased as shown in Figure 4.11. It has been noticed that with the hydrogen components of 100% size, all the excess electricity is stored. But while decreasing the size, the excess electricity is getting increased.

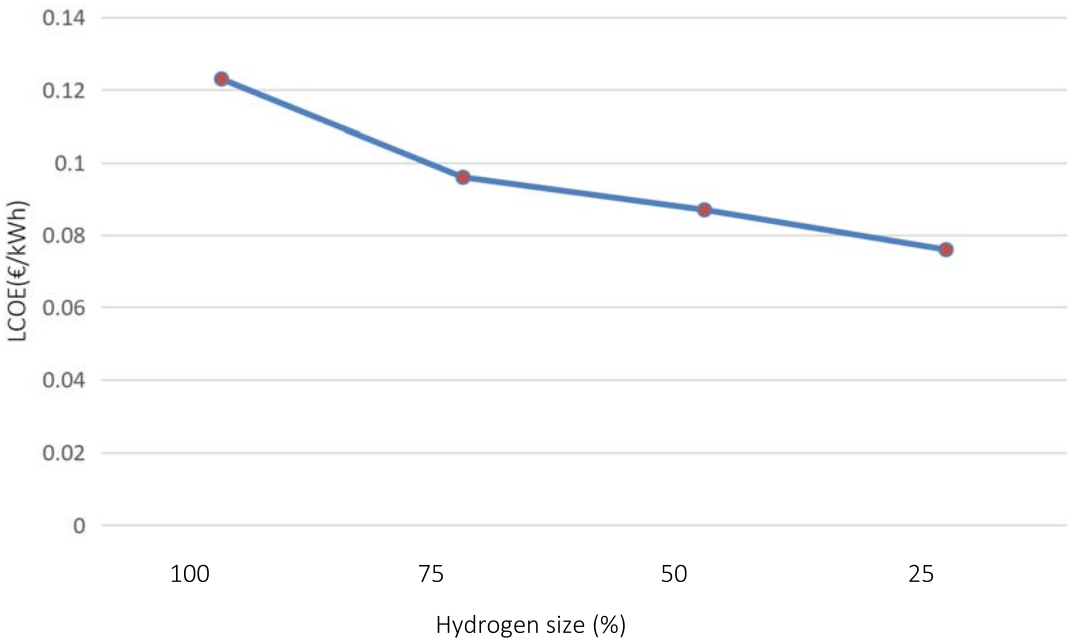

Figure 4.11 Sensitivity analysis of the LCOE with the size of the hydrogen components changes

4.3.3. Battery and Hydrogen costs change

The last sensitivity analysis was carried out to determine how the total system's LCOE changes as the cost of the Li-ion battery and the hydrogen components change. Costs of the battery module and the hydrogen components were reduced by 75%, 50%, and 25% in order to run the sensitivity simulations. Figure 4.11 shows the sensitivity analysis of the LCOE with the storage components costs. As the costs of the battery storage and hydrogen storage are getting reduced, the LCOE for the entire system is getting decreased significantly.

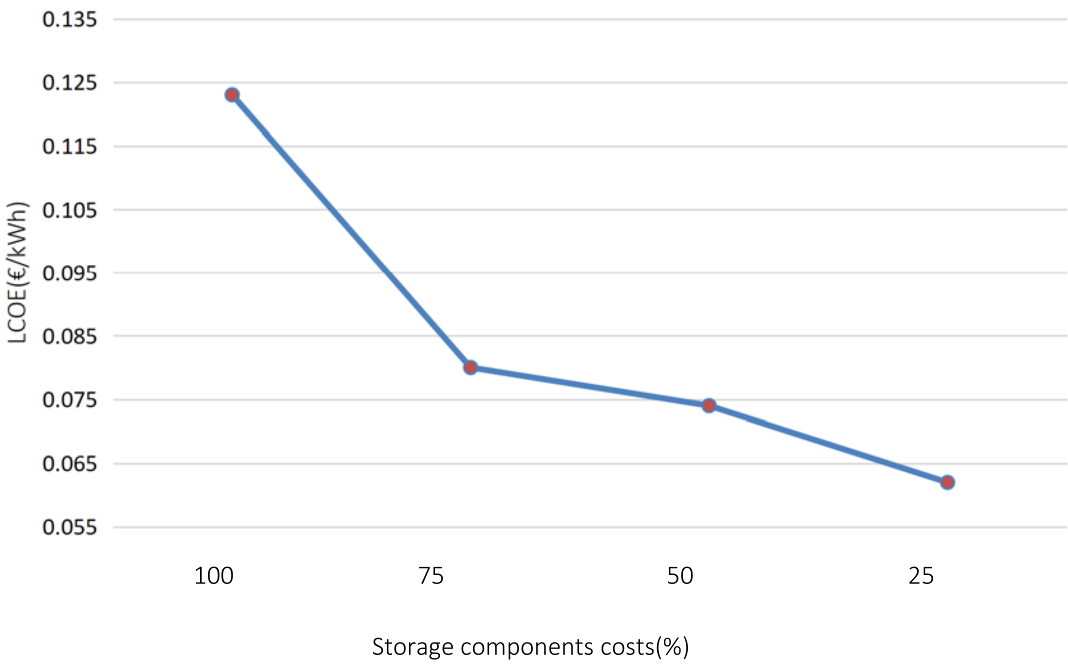

Figure 4.11 Sensitivity analysis of the LCOE with the storage components costs

5 Discussion and conclusion

In the conducted study, the utilization of PVsyst played a pivotal role in simulating a PV system capable of accommodating the electrical load of Forming line 4 situated within the SSAB industrial site in Borlänge. Through this simulation, crucial insights were garnered regarding the PV system's characteristics, capacity, and electricity generation potential. The derived results indicate that the optimal PV system size for this application is 2.7 MW, enabling an annual energy production of 2.5 GWh. The output of electricity satisfactorily matches the annual electricity demand of 2.4 GWh for Forming Line 4.

One noteworthy observation arising from the simulation data is the notable excess of solar electricity production relative to the electrical load between March and October. This excess electricity during these months signifies a pivotal opportunity for incorporating innovative solutions such as hydrogen or electrical energy storage. Leveraging this excess electricity offers the potential to effectively store excess electricity during periods of high solar irradiance, subsequently releasing it during times of higher demand or lower solar availability. This not only enhances the overall energy self-sufficiency of the system but also optimizes energy utilization and resource efficiency.

In essence, the utilization of PVsyst in this study has provided a comprehensive understanding of the optimal PV system parameters and its synchronization with the electrical load of Forming Line 4. The observed excess electricity production during certain months further underscores the feasibility and economic viability of integrating advanced energy storage technologies, thus contributing to a more resilient and sustainable energy solution for the SSAB industrial site.

From the results, the system considered with PV system attains a LCOE of 0.059 €/kWh. While comparing to the LCOE pf six large-scale PV parks that were commissioned in Sweden in 2019 and 2020 which are ranging from 0.027 to 0.049 €/kWh. It is higher due to the interest rates have generally increased since 2021, it is reasonable to predict higher values for 2022 and beyond .Given that 2022 is not a typical year for electricity prices in view of the significant events that occurred over the past few years, using that data as a starting point for this analysis could be seen as a limitation. The economics parameters such as the inflation rate and the interest rate from the year 2022 can also considered as limitation. Changing the values for these parameters can lead to different results. Also, choosing the components used in the different scenarios and the costs for them according to the previous searchers can be considered as limitations for the study.

The outcomes of the various scenarios provide valuable insights into the impact of renewable energy integration and energy storage on the overall performance and cost-effectiveness of the system. Each scenario was compared against the base case of grid connection, revealing a range of LCOE values. Notably, the highest LCOE of 0.12 €/kWh was observed when all renewable resources were combined, while the lowest LCOE of 0.059 €/kWh was achieved with the PV system-only configuration.

Self-consumption can be accomplished using a combination of hydrogen storage, batteries, and photovoltaic electricity generation, according to the previous studies of the hybrid energy systems revealing a range of LCOE values from the lowest of 0.12 €/kWh to the highest of 0.29 €/kWh even these studies have been done based on different inputs and settings of the inflation rate or interest rate. While the result from the complete system is achieving a 0.12 €/kWh value of the LCOE. So, the system would incur higher costs when compared to a grid-connected load or the system with the PV system-only configuration.

Regarding excess electricity management, the scenarios were analyzed in terms of their ability to mitigate excess energy generation. The trend observed was that, progressively, the integration of renewable resources and storage systems led to a reduction in excess electricity production, culminating in Scenario 4 where no excess electricity remained. Incorporating sensitivity analyses further enriched the understanding of these results. When varying the size of the Li-ion battery, the LCOE showed a moderate increase with decreasing battery size. A similar pattern emerged in sensitivity analyses involving hydrogen components, with excess electricity storage linked to hydrogen storage size. Additionally, altering the costs of battery and hydrogen components revealed that reducing these costs by varying percentages of 75%, 50%, and 25% led to substantial decreases in overall system costs and LCOE.

These findings collectively underscore the intricate relationship between system configuration, costs, and performance. The integration of renewable resources and energy storage not only leads to reduced LCOE but also effectively manages excess electricity, enhancing system sustainability. Sensitivity analyses highlight the sensitivity of these outcomes to parameters like battery size and cost, demonstrating the flexibility and adaptability of the system's economics to changing conditions. Ultimately, this comprehensive study offers insights into the optimization of renewable-integrated systems and provides valuable guidance for informed decision-making in the transition towards sustainable energy solutions.

Delving deeper into the significance of these findings, the study underscores the concept of energy resilience and adaptability. The varying LCOE values across scenarios emphasize that there's no one-size-fits-all solution in renewable energy integration. Instead, the optimization process involves a delicate interweaving of technologies, capacities, and cost structures. The dichotomy between the higher LCOE observed in the combined renewable resource scenario and the lower LCOE with PV panels alone accentuates the need to carefully balance the benefits of diversified energy sources against the potential complexity and costs associated with multifaceted systems.

The insights gained from excess electricity management resonate beyond the confines of the study itself. As the world continues its transition to cleaner energy, excess electricity management becomes a strategic imperative. The observation of a gradual reduction in excess electricity until complete elimination in Scenario 4 underscores the adaptability of renewable-integrated systems. This adaptability extends beyond isolated scenarios, reflecting the potential of such systems to harmonize with grid dynamics, demand fluctuations, and evolving energy policies.

The sensitivity analysis, meanwhile, illuminates the nuanced interactions between system parameters. As Li-ion battery size decreases and hydrogen components vary, the marginal changes in LCOE signify the delicate equilibrium between energy supply, storage, and utilization. This understanding is vital for engineers, policymakers, and stakeholders who must navigate the intricate trade-offs that define real-world energy systems.

Furthermore, the exploration of cost sensitivity highlights the role of economics in shaping the renewable energy landscape. The observed reduction in storage costs and overall system LCOE through incremental cost reductions underscores the interconnected nature of technology advancement, cost efficiency, and energy affordability. This dynamic mirrors the broader trends seen in the renewable energy sector as it continues to mature and become more economically competitive. One of the most significant challenges of the complete system is the high cost of all the main technologies, such as hydrogen storage and battery storage which can be observed in the results of the discounted payback time as getting increased by adding a storage system. Incorporating energy storage solutions brings several additional advantages, potentially offering economic benefits, making the full system implementation a valuable secondary power source after considering firstly the viability of the PV system-only configuration.

In conclusion, this study transcends the realm of simulations, providing a holistic perspective on the complexities of renewable energy integration and storage. By unveiling the multifaceted impacts of various scenarios and their interactions, the study extends its relevance beyond academia, offering actionable insights for those steering the energy transition. As the world navigates toward a sustainable energy future, the study stands as a testament to the interdisciplinary collaboration required to harmonize technological innovation, economic feasibility, and environmental stewardship.

6 Future work

First and foremost, it is important to note that the results presented here are based on a single-year load profile, and they may vary in different years. These findings offer a broad overview of the trend, but it's essential to investigate results using data from other years in future research.

Furthermore, it is worth mentioning that electricity prices in southern Sweden (specifically in SE3 and SE4) saw a significant increase in 2022, with daily and hourly peak prices notably higher than before. The electricity prices used in our modeling for this study were derived from the hourly rates at Nordpool for the SE3 bidding area throughout the year 2022. These rates do not represent the precise electricity prices of the company under study. Therefore, the accurate utilizing of the company specific electricity prices would lead to different results, yielding more realistic outcomes. Besides, the using of different values of the economic parameters such as the interest rate and the inflation rate can be investigated.

By looking to future scenarios with an increased share of renewable energy sources, it is important to recognize that energy storage could play a role in providing grid support services. These services were not within the scope of this project but could offer numerous additional economic benefits. Exploring these aspects further could significantly impact the technical optimization of the system and the LCOE for the energy generated.

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Appendix A
Summary of the thesis for the examiner

Throughout the thesis work, it has been coming across quite a few unexpected challenges. The complex scope of the study was a major element in the longer schedule. The project scope initially proved itself to be more complex than anticipated, especially in the areas of data collecting and analysis. As a result, in order to address these unexpected obstacles, the research methods had to be adjusted, resulting in an extension of the project timetable. It is critical to emphasize that, despite these problems, the devotion to the thesis was steadfast, and determined efforts to overcome these issues. The active advice from the supervisor (Emmanouil Psimopoulos) made the required changes to the research strategy, streamlining the data collection procedure and refining the analysis approaches.