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Feasibility Assessment of a Proposed Solar Power Farm

Stora Enso Sweden Case Study

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Preface

The authors would like to thank Abolfazl Hayati and Stora Enso for providing the opportunity to perform this case study, Mattias Gustafsson and Björn Karlsson for their time, commitment, and support during the whole project. Additional thanks go to Arne Berglund at Vattenfall and Oscar Öhrman Svensk Solenergi, for providing valuable knowledge, to Conny Johansson at Stora Enso for contributing with information regarding the company and its interaction with the grid, and to Victor Hernando Uriarte for providing Winsun PV climate data and its validation.

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Abstract

This study investigates the economic and practical potential of a 50 MWp solar farm aimed at providing electricity for a factory owned by Stora Enso in Skutskär, Sweden. By connecting the solar farm towards electricity consumption, there is an opportunity for the factory to drastically reduce its share of purchased electricity, which is of greater economic value than selling electricity, while still selling any surplus electricity to the grid. Using the simulation software PVsyst and Winsun PV, and climate data from the University of Gävle, the solar farm's electricity production is modeled and matched against the factory's electricity purchases of 2023 on an hourly basis. The results of the study show that the solar farm's conditions for connection towards consumption are very good, as it is very likely that the case will be classified as a non-concession-bound network. Depending on different cost scenarios, the cost of the solar farm in the form of levelized cost of electricity is calculated to range from 45.4 - 97.0 öre/kWh. The value of a saved kWh is calculated to be about 10 öre more than a sold kWh. The weighted value of a kWh produced by the solar farm regardless of whether it is sold or used to reduce consumption is calculated to be 50.32 - 52.64 öre. This means that even though the price difference between a saved and a sold kWh is significant, it is unlikely that the solar farm will be profitable in the current situation since the weighted value of produced electricity is only marginally higher than the cost of the best possible scenario. Since there is an obvious economic potential in reducing purchased electricity rather than selling it, the question of connecting a solar farm for consumption is still important, and the strategy has potential to become profitable in the future, should fees, interest rates, and benefits change favorably.

Keywords: PV, LCOE, PVsyst, Winsun PV, solar farm, conserve electricity, simulation, Sweden

Sammanfattning

Denna studie undersöker den ekonomiska och praktiska potentialen hos en 50 MWp solcellspark vars syfte är att tillhandahålla el för en fabrik ägd av Stora Enso i Skutskär, Sverige. Genom att koppla parken mot reducering av elkonsumtion finns det möjlighet för fabriken att drastiskt minska sin andel köpta el, vilket har större ekonomiskt värde än att sälja el, och dessutom sälja eventuellt elöverskott till nätet. Med hjälp av simuleringsprogrammen PVsyst och Winsun PV, och klimatdata från Högskolan i Gävle, modelleras solcellsparkens elproduktion och matchas mot fabrikens elköp under 2023 på timbasis. Resultatet visar att solcellsparkens förutsättningar att kopplas direkt mot konsumtion är mycket goda då det är mycket troligt att fallet klassas som ett icke koncessionspliktigt nät. Beroende på olika kostnadsscenarion beräknas solparkens kostnad i form av levelized cost of electricity till ett spann av 45.4 – 97.0 öre/kWh. Värdet för en sparad kWh beräknas till ca 10 öre mer än en såld kWh. Det viktade värdet av en kWh producerad av solparken oavsett om den säljs eller används till att reducera konsumtion beräknas till 50.32 – 52.64 öre. Detta betyder att även fast prisskillnaden mellan en sparad och en såld kWh är signifikant så är det inte troligt att solcellsparken kommer vara i dagens läge eftersom det viktade värdet på producerad el endast är marginellt högre än kostnaden för det bästa möjliga scenariot. Eftersom det finns uppenbar ekonomisk potential i att spara el framför att sälja, så är frågan att koppla en solcellspark mot konsumtion intressant, och strategin har potential att bli lönsam i framtiden om avgifter, räntor, och kompensationer skulle förändras förmånligt.

Nyckelord: PV, LCOE, PVsyst, Winsun PV, solcellspark, spara el, simulering, Sverige

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Abbreviations

A – Annual

CAPEX – Capital expenditures

Dg – Degradation rate

EIFS – Energimarknadsinspektionens föreskrifter

ETS – Emission trading system

HiG – Högskolan i Gävle

IAM – Incidence Angle Modifier

IKN – Icke koncessionspliktiga nät

kWh – Kilo watt hours

LCOE – Levelized cost of electricity

MPP – Maximum power point

MPPT – Maximum power point tracker

MSEK – Million Swedish krona

MWh – Mega watt hours

N – Lifetime

O&M$_f$ – Fixed operation and maintenance

O&M$_v$ – Variable operation and maintenance

PPM – Power park module

PV – Photovoltaic

ReInv – Reinvestment

ResC – Residual cost

RFG – Requirements for Generators

SEK – Swedish krona

STC – Standard test conditions

TMY – Typical Meteorological Year

WACC$_r$ – (Real) weighted average cost of capital

WAV – Weighted average value

Wp – Watt peak

Y$_0$ – Annual Yield

Nomenclature

Centralized solar power production – Refers to large scale solar farms supplying electricity to the grid.

Decentralized solar power production – Smaller scale solar electricity production, usually produced and used on site.

Local grid - The local grid can be compared to small roads of the electricity network which transport the electricity the last bit to households and other end users of 0.4–20 kV.

Regional grid - The regional grid can be compared to the country roads of the electricity grid that transport electricity from the main grid to the local grids over medium-long distances at voltage levels of 30–150 kV.

Transmission grid - The transmission grid can be compared to the highways of the electricity network that transport large amounts of electricity over long distances at high voltage levels of 220-400 kV. Sometimes known as “Stamnät” in Swedish.

1 Introduction

There is a growing trend for industries today to reduce their electricity consumption and their emissions, both due to reducing their energy costs and to conform to the growing demand of reducing carbon emissions from both national goals and regulations in the EU. The current EU climate targets are to successively reduce greenhouse gas (GHG) emissions each year, in order to achieve net-zero emissions by 2050 (*Climate Strategies & Targets - European Commission*, 2024). The Swedish national targets are somewhat stricter, aiming for net-zero emissions by the year 2045. (*Sveriges klimatmål och klimatpolitiska ramverk*, 2024)

There are a vast number of strategies that can be employed in order to work towards these goals. To name a few, companies can invest in environmentally sustainable infrastructure, such as carbon capture technology, engage in afforestation efforts, purchase guaranteed fossil-free electricity from their utility providers or, alternatively, generate their own electricity through renewable sources. The latter option has gained considerable traction over the past two decades. According to Sánchez-Pantoja et al. (2018), the self-production of electricity has seen a significant increase, with photovoltaic (PV) modules now being commonly installed on residential homes, apartment buildings, and industrial facilities across Sweden. Given that the sun is the largest available source of renewable energy, PV systems are a valuable asset in the work towards a sustainable and fossil free future (Psiloglou et al., 2020).

Unfortunately, the economic potential of PV-systems are dubious, having historically relied much upon subsidies to be economically viable but over the last decade these subsidies have seen dramatical reductions (Lindahl et al., 2022). However, in recent years, basically all costs related to PV-systems have dropped dramatically, which has made PV-technology economically competitive in more regions across the world. On the global market, centralized PV-systems stands for 63% of the total installed capacity. In Sweden however, the vast majority of installed PV-capacity is made up of decentralized systems. While the private homeowner can benefit from subsidies, industries area no longer able to, therefore, PV-systems have not been seen as a major candidate for future commercial electricity production in Sweden. (Lindahl et al., 2022)

In a report from 2018, the Swedish national transmission operator, Svenska Kraftnät, estimated that in 2040, PV will contribute to only 4% of the annual electricity production in a 100% renewable scenario (Brunge et al., 2019). The estimates from the latest report by Svenska Kraftnät from 2024 are somewhat higher. Depending on the scenario, in 2035, the PV contribution will be around 2-3,5% and in 2045 it will be around 4,8-6,4% (Nycander et al., 2024). Although the difference is not dramatical, this might be a sign that PV technology will contribute with a larger share of the total energy production in Sweden than what was previously thought. For comparison, the 2025 estimate from the same report is at 2% and is independent of scenarios. It should also be mentioned that the total production is estimated to increase from 191 TWh in 2025 to 233-342 TWh, depending on scenario. So, while the increase is only a few percentage points compared to the total electricity production, relatively, the PV production is estimated to be 3-5 times higher than today. Future predictions vary heavily depending on the source. Another short-term prediction by the Swedish Energy Agency, estimates that the PV contribution to the total Swedish electricity production will rise from around 1,2% in 2022 to around 4,6% in 2027. (*Kortsiktiga prognoser*, 2024)

Traditionally, solar farms generate electricity which is immediately delivered to the grid and sold to the utility company at a relatively low price. However, when a company consume electricity, it is purchased at a higher rate, since sold electricity excludes various taxes and fees. This method undermines the economic value of PV-produced electricity. A more advantageous strategy could involve utilizing the generated electricity directly on-site, with any surplus then being sold to the grid. Such a method could significantly decrease the necessity to purchase energy from the grid, which may lead to considerable savings of electricity tax and fees costs. This strategy could also yield a few other benefits such as reducing the peak power usage for the industry, which would further reduce electricity costs.

This case study explores the economic and practical potential of connecting a 50MWp solar farm towards direct consumption of a factory located in Skutskär, Sweden, and owned by Stora Enso. The study is based on annual electricity data provided by Stora Enso, and climate data measured for Gävle 2023 provided by the University of Gävle. The PV simulation software PVsyst and Winsun PV are used to analyze the potential electricity production of the solar farm.

First a brief review of the current state of the art of PV technology is conducted, followed by an investigation regarding theoretical aspects such as shading, environmental impacts of a solar farm, and regulatory requirements. Secondly the details of the methods are explained, such as inputs and data used for the simulations. This chapter also covers used formulas and details about cost assumptions. Thirdly the results are presented, which consist of an analysis of different mounting configurations followed by an economic evaluation and an analysis of the connection possibilities.

1.1 Purpose

The focus of this master's thesis is to conduct a feasibility study of a solar farm project proposed by Stora Enso, whether it is economically viable, and examine the possibility to connect towards their own electricity consumption. In order to determine if the solar farm is economically viable, it is of the utmost importance to calculate monetary difference between a sold and a conserved kWh of PV-produced electricity. The study should also include research about the effectiveness of different mounting configurations for the solar farm.

1.2 Research questions

The main questions that the study aims to answer are:

- Is it feasible to build a solar farm at the suggested location and connect it towards the industry's own consumption?
- Is the solar farm in this case study economically viable?

1.3 Delimitations

The data collected in this study is bound to both specific geographic locations as well as the year 2023. The weather data was collected at Gävle University during 2023.The electricity consumption data was collected during 2023 for the facility Skutskärs Bruk. This means that while this study generalizes this data, the exact hours when electricity production and consumption occur will be different for other years.

Since the case study is based in Sweden, the legal aspects of the project will be limited to Swedish laws and regulations. Fees and regulations may differ in different municipalities and with different local grid owners, which means that the exact procedures and costs may differ depending on the location in Sweden. However, this difference is not expected to be dramatic.

Since it is Impossible to know exactly how the area will look at time of a contingent future construction, the shading of potential nearby objects will not be accounted for. It is assumed that these losses will be minimal since the area consists of forest and the company owns the surrounding land and therefore could cut down trees in the surrounding area. The inclusion of shading along the edges would also make the result more complicated to scale for use in other areas of different sizes.

Effects from wind are not considered, except what PVsyst automatically applies to the simulation. The reason for this is both that the effect can be considered as negligible, and that we do not have access to any wind data for that specific location during 2023.

Snow accumulation poses a significant challenge for PV-simulations in Nordic regions. However, due to the limitations of PVsyst in simulating snow-related effects, this issue will not be examined in depth. The impact of snow-related effects on the final results are assumed to be negligible since the irradiation during these months is very low.

One analysis that needs to be made in order to connect the solar farm to the grid is impact on the electricity quality of the grid (Bagge, 2015). However, the grid quality analysis was deemed to not be significant to the results of this study, and it is therefore omitted entirely from this paper.

Since the measured climate data file was deemed invalid by PVsyst, a different simulation software, Winsun PV, was used to simulate PV-production with the Gävle 2023 climate data.

The electricity cost is taken from 2023 hourly data, but additional fees are estimated and derived from the latest regulations that took effect in 2024. For this reason, the cost of electricity will not completely match the scenario of 2023. However, it will make the results more up to date and meaningful. Although the results are based on assumptions and simulations with varying degrees of accuracy, it was decided to keep the number of disclosed figures high in order to best preserve the generated data in case it will be utilized by future analyses by the company.

This study will rely on a number of simulated scenarios that were found to yield the most promising combinations of electricity production and ground coverage by our assessment. A full optimization of the land usage depends on many different parameters such as shading angle, tilt, azimuth, ground coverage choice of material, choice of subcontractors and is a very complex problem (Stridh, 2016). It is probably even impossible at this moment, since some data such as exact boundaries of the area has yet to be determined.

2 Background

A large Swedish industry is looking at the possibility of investing in a solar farm. Although PV-technology is known to have mediocre economic potential, the prices are constantly decreasing, which is why an up-to-date economic analysis is relevant. There is also the somewhat unique ability of connecting the solar farm towards the industry's consumption since it will be located close to the facility. This might further increase the economic potential of such an investment. Although the specific location has already been assessed, the study will attempt to generalize results as much as possible, so that they will be applicable to similar scenarios and areas.

2.1 Site information

2.1.1 Stora Enso

Stora Enso was established in 1998 as a result of the merging of the Finnish company Enso Oyj and the Swedish company Stora Kopparbergs Bergslags Aktiebolag (STORA). (*Stora Enso, Vår historia*, 2024)

STORA's operations can be traced back to 1288 and have historically involved mining and refining of various materials. As fuel is an important part of mining activities, the forest industry has always been an important part of the company's operations. In the 1970s, STORA sold its mining operations to fully focus on forestry and pulp production. Enso can be traced back to 1872 when the steam driven lumbermill W.Gutzeit & Co was established in Kotka, Finland. Over the years this company acquired and merged with various other companies, such as Enso Träsliperi AB in 1912 and Veitsiluoto in 1996, which is when the company changed its name to Enso Oyj. Today Stora Enso's refers to itself as the Renewable Materials Company and produces a wide range of products/solutions mostly from wood. These products in many cases aim to be a sustainable alternative to products based on non-renewable materials. (*Om Stora Enso*, 2024)

The Stora Enso-group includes over 40 facilities worldwide, most of which are located in Europe, but facilities do exist on every continent. The total number of employees is around 21 000 and the total revenue for 2022 was 11.7 billion EUR. (*Stora Enso Locations*, 2024)

The factory which is part of the case investigated in this report, is already somewhat self-sufficient regarding electricity. It is equipped with both 10 MWp wind turbines and a 50 MWp back-pressure turbine.

2.1.2 Pre analysis of the location

Prior to the start of this research, an initial assessment of various potential sites owned by Stora Enso was conducted by Sweco grid experts. Figure 1 illustrates the diverse locations in the vicinity of Skutskär and Älvkarleby, identified as having potential for the establishment of a solar power farm. These areas have been analyzed, filtered out, and subsequently ranked depending on the different criteria. According to Swedish legislation, there are some criteria which would render an area completely impossible as location for a solar farm. These are known as "hard stops", and include criteria such as Armed forces has interest of said land, area of importance on land, Built-up areas withing 100 m, single residential houses within 100 m, defined as a Nature conservation area, Natura 2000 Habitat directive (or similar) by Swedish Nature Conservation Agency etc. Except these hard stops, there are also some, less strict criteria, known as "soft stops", which may render an area less suitable for a solar farm. These include, but not limited to, areas classed as *Archaeological sites* by the Swedish National heritage board and areas that the County Administrative Boards view as *Landscapes with high ecological value.*

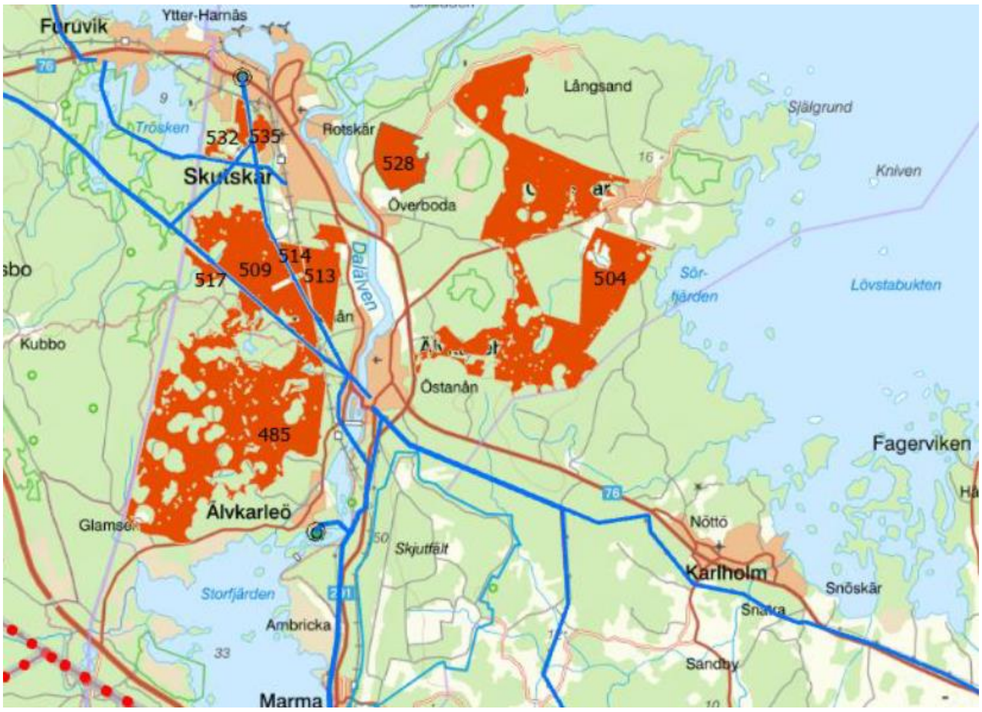


FIGURE 1 INITIAL AREAS INVESTIGATED

In addition to hard and soft stops, Sweco also identified some additional criteria which should be avoided for the area to have strong potential as a location for a solar farm. The area should preferably *not be;* further than 1 km from a regional substation, be included electricity bidding areas SE1 & SE2, be smaller than 20 ha, or have a slope higher than 2.5°.

Following the completion of the filtering process, two primary locations emerged as the most promising candidates for further consideration: areas 532 and 535 shown in Figure 1. A detailed view of these areas is provided in Figure 2, illustrating their proximity to one another. Combined, these sites encompass an approximate total area of 67 hectares, and are located in electricity bidding area SE3.

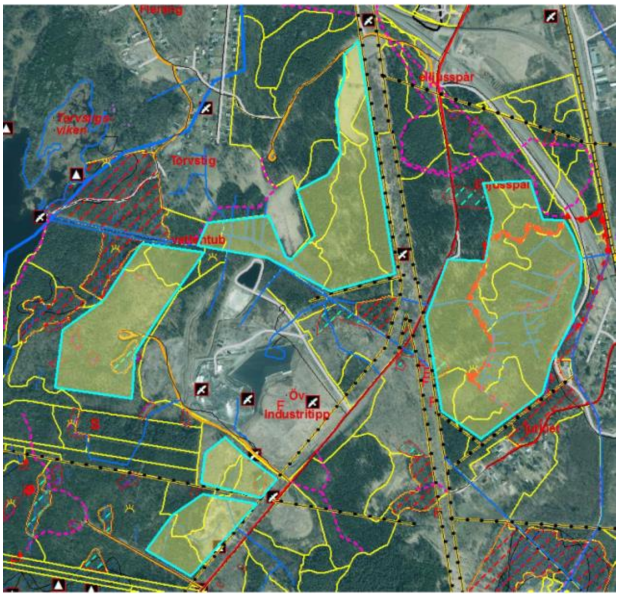


FIGURE 2 AREAS USED IN THE CASE STUDY

2.2 Technical background

2.2.1 PV modules

PV modules has the ability to convert solar energy into electrical energy. This works by having cell constructed by thin layer of a semiconductor, and electrical contacts on either side. When sunlight of a certain energy level hits the surface an electric field is created, which produces an electric potential between the contacts. Since the contacts are connected to an external circuit, an electric current will flow as long as there is sunlight irradiating on the surface of the cell. A higher potential can then be created by connecting several cells in a series. (Abel & Elmroth, 2007) A PV module is made up of a number of these cell-series, and several modules make an PV array, as seen in Figure 3. (Irwanto, 2009)

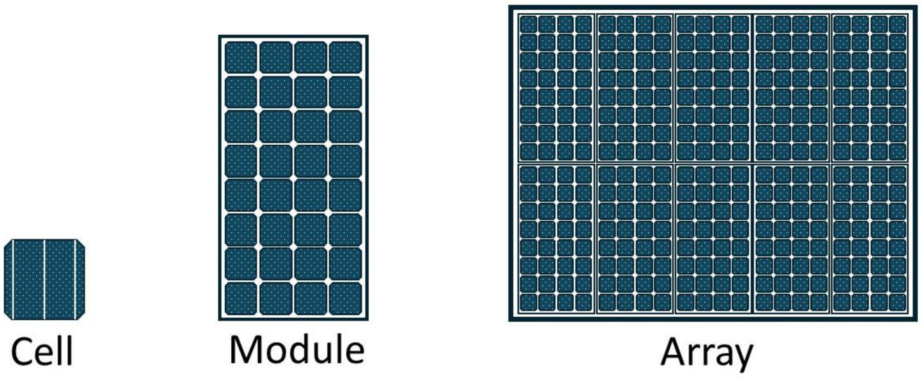


FIGURE 3 PV PANEL ARRANGEMENTS

The advantages of PV modules as an energy source are many and keep increasing with time. Some of its key advantages include; direct conversion of solar radiation to electricity, simple to install due to no moving parts, low maintenance cost, high reliability, and high power to weight ratio. However, there are still some limiting factors of PV panels, e.g. dependent on the cycles of the day, and therefore need an energy storage (battery or hydrogen) in order to provide electricity when there is no sunlight. (Singh, 2013)

2.2.2 By-pass diodes and hot spotting

A series of solar cells' electrical current production is limited to the cell in the series that produces the least amount of current. This means that if a single cell is shaded i.e., has zero electrical current production, the entire series will have zero production. A single PV-module usually consists of several series of cells that are separated by by-pass diodes. As seen in Figure 4 the by-pass diodes have the function to allow electric current to "pass by" a series of cells that has very low or zero current production. This means in practicality that if a single cell has zero current production, the electric current production of around 1/3 of the entire module will be shut down, but series of cells not connected to the shaded series will be unaffected. Although most modules have three by-pass diodes, the exact wiring of the cells and diodes varies with different models, which means that shading will impact the modules in slightly different ways and can allow for different strategies on how to place modules to best avoid shading losses. (Bengtsson et al., 2017)

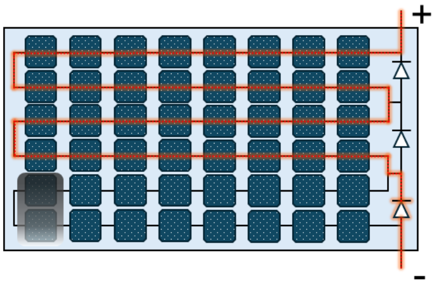


FIGURE 4 FUNCTION OF A BY-PASS DIODE

Hot spotting in solar cells refers to the occurrence of localized overheating in certain areas of a solar panel. This phenomenon typically happens when some cells in a solar panel are shaded or damaged, causing a reduction in their electrical output. As a result, the current produced by the unshaded or undamaged cells flows through the weaker cells, which cannot handle the excess current. This leads to an increase in temperature in the affected cells, creating hotspots. According to Kim & Krein (2015) by-pass diodes are used as the main method to prevent hot spotting in PV panels. These diodes are connected in parallel with the solar cells or groups of cells, allowing the current to bypass the shaded or damaged cells, thus reducing the risk of overheating. Additionally, regular maintenance and monitoring of solar panels can help identify and address potential causes of hotspots, such as debris or shading that may cover parts of the panel.

2.2.3 Maximum power point trackers

Simply put, An MPPT is an electronic device that regulates resistance in order to manipulate the voltage and electric current of solar cells or modules to maximize their power output. MPPTs are built into basically every inverter available today and usually operates on module-string level (Bengtsson et al., 2017). While there also exist versions that operate on single modules known as power optimizers, these have been shown to not be economically viable under Swedish condition (Stridh, 2016). Power optimizers also only have a function if the system is unevenly shaded PV systems (Bengtsson et al., 2017).

2.2.4 Bifacial PV module

The definition of a bifacial PV module is that it has the ability to absorb irradiation from both the front- and the backside of the panel. When comparing a mono-facial panel to a bifacial, with the same design and orientation, the additional delivered energy is known as bifacial gain. This gain can be quite significant, up to 5-30% in certain situations, without any noteworthy increase in manufacturing costs. However, in larger systems, such as a solar farm, this gain has shown to be between 3-10% (Braga et al., 2023).

According to Kopecek & Libal (2021) it has been easy for most companies to switch their manufacturing from a regular mono-panel since the main difference is the material of choice for the backside of the panel. A mono-panel is often constructed with simple aluminum on the backside since this is a relatively cheap and sturdy material. By incorporating glass on both sides of the panel, a bifacial PV panel is achieved. Since glass is a more durable material, this choice of material also allows manufacturers to increase the warranty time for their products, which acts as a further encouragement for producing bi-facial PV panels. The bi-facial modules gained traction and started dominating the market in 2016, and since then the price, compared to a mono-panel, have now stabilized on a very similar level (Kopecek & Libal, 2021).

A study by Kopecek & Libal, (2018) revealed that rooftop bifacial PV systems could achieve bifacial gains of 15%, while optimally mounted bifacial PV systems operating in ideal conditions could attain annual bifacial gains of 30% with fixed-tilt systems. For single axis tracking systems at the utility scale, bifacial gains could surpass 40%. The research also indicated that the energy yield from vertically mounted bifacial PV systems could be on par with fixed-tilt mono-facial systems in regions with higher latitudes, underscoring the potential for dual land use, such as in agrivoltaics applications. However, in practice, the real bi-facial gain for a large ground mounted fixed tilt installation is between 3-10% (Braga et al., 2023).

When simulating a PV system equipped with bi-facial modules, the complexity of the calculations increases drastically due to the rear irradiance. However, because of the higher potential financial return from said PV modules, a lot of efforts have been made, by both commercial software providers and academic institutions, to accurately simulate the irradiance reaching the rear side of the module. (Kopecek & Libal, 2021)

According to Stein et al., (2021) there are some complications regarding the power rating of bifacial PV panels. It is common practice for manufacturers to specify the power rating of photovoltaic modules based on the Standard Test Conditions (STC) output of the front side, occasionally incorporating an estimated contribution from the rear side. However, there are no established reference conditions for determining the rated output power of bifacial photovoltaic modules. Furthermore, there are no standardized requirements for reflecting the bifacial characteristics on the module's nameplate or within the manufacturer's datasheet.

2.2.5 Half-cut circuit design

Shading of solar panels halts its ability to generate power, with even minimal shading leading to substantial reductions in the projected energy production. According to Klasen et al., (2022), this is one reason for testing new layouts when developing new solar cell technologies.

Several kinds of innovations for PV systems have been developed just in the last few years, one example of this is the half-cell module, also known as half-cut, or twin module. This layout of the circuit differs from the traditional way by dividing the module into two pieces, and letting two series of cells share one by-pass diode. This provides a number of advantages compared to a standard module. However, it also comes with some disadvantages, such as a more complicated manufacturing process. (Joshi et al., 2019)

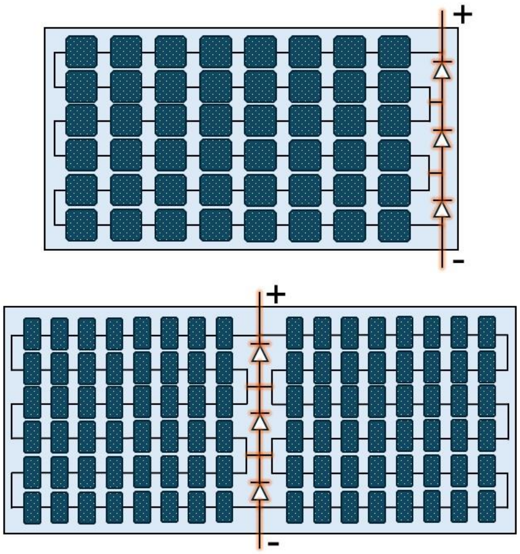


Figure 5 Active by-pass diodes in half-cut vs standard PV circuit design

The half-cut design is essentially a modification of a standard module. Ismail et al., (2023) explains that the efficiency of the solar panel is improved by basically cutting each individual cell in half, and thereby doubling the number of individual cells, as well as changing the shape of the cells from squares to rectangles. This design inherently reduces the current that each cell needs to handle by half, which in turn reduces resistive losses and makes the panel less susceptible to the effects of shading. Additionally, Sykes (2024) states that the cells in a half-cut panel are also wired in a unique way compared to a standard panel, which further mitigates the effects of shading on power production. As shown in Figure 5, the standard panel has 3 series of strings with cells with one by-pass diode for each string, while a half-cut panel has doubled the amount of cells, and is wired both series, and each string has a parallel string which shares the same by-pass diode. This parallel wiring method allows a larger part of the panel to continue operating during partial shading since it has two different maximum power points (MPP). However, only under very specific conditions, and combined with an inverter capable of multiple maximum power point tracking (MPPT). (Sykes, 2024)

Figure 6 shows the current through both a standard and a half-cut solar panel during 100% irradiation. In this scenario, both panels are able to deliver at maximum power output, and there is no clear benefit of one design over the other.

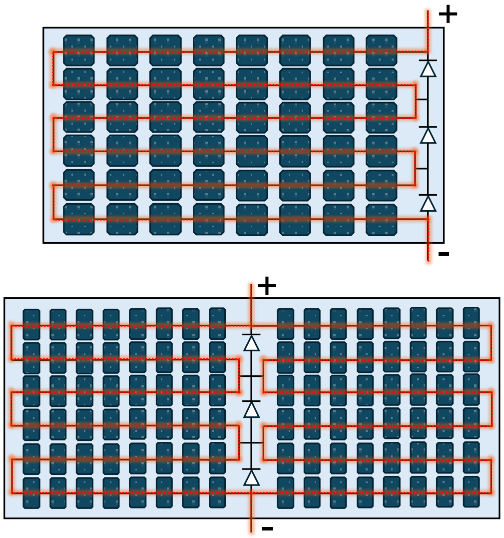


Figure 6 Inactive by-pass diodes in half-cut vs standard PV circuit design

Figure 7 shows a scenario using an inverter without MPPT, where one section of the panels is shaded, and the effects on the path of the current due to said shade. As illustrated, there is not much of a difference between the two panels, rather the effect of the shading has the same effect on both panels. Due to the shading, both the standard panel, and the half-cut panel will now be able to deliver two thirds of the maximum power output. This is due to the by-pass diode being activated in order to protect the shaded cells from hot-spotting. This results in both of the parallel series of cells being deactivated in favor of the by-pass diode, and therefore there is not any major advantage for the half-cut panel in this specific scenario. (GSES, 2021)

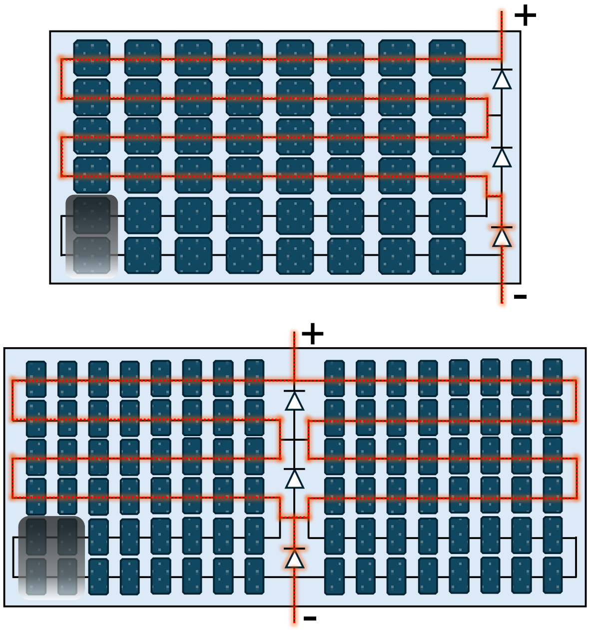


Figure 7 Half-cut vs standard PV during shading

If the solar panel is combined with an inverted capable of handling both the voltage and current characteristics in an efficient way, this allows for a more efficient handling of partial shading of the solar panel. If the inverter is equipped with multiple power point tracking (MPPT) channels it is possible to lower the current and raise the voltage across each cell, and in that way allow the current to take the path through only unshaded side of the parallel circuit, as illustrated in Figure 8. Here there are two available maximum power points (MPPs). The first MPP occurs at the standard current, and standard voltage, which also unlocks by-pass diode for the shaded string. The second MPP occurs at a lower current, and a higher voltage. This allows the current to flow through the other half of the shaded string, instead of through the by-pass diode. Figure 9 illustrates an example of the two different MPPs, and the difference in output power from the same PV module, during the same shading scenario. During the first MPP, there is only current going through one third of the PV module, which results in an output of 108 W. While utilizing the second MPP, at a lower current, the total output amounts to 180 W.

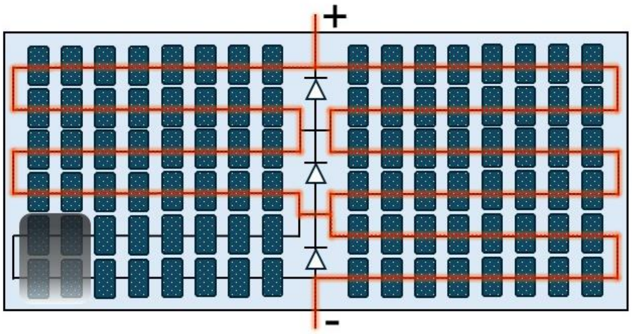


Figure 8 Half-cut PV during partial shading combined with a MPPT

Figure 9 Multiple MPPs effect on power output (GSES, 2021)

Half-cut solar panels offer superior performance under shaded conditions compared to standard panels, primarily due to their cell design and unique wiring configurations. While they do not require specific inverters for normal operation, an inverter which can handle MPPT can improve system performance during certain shading situations (GSES, 2021). Figure 10 shows the power and I-V curves for both a standard cell and a half-cut cell during the shading scenario illustrated in Figure 9. Since the standard cell is not capable of utilizing more than one MPP, the maximum output in this scenario is no more than 108 W, while the half-cut cell is able to operate at a lower current due to the nature of the cells being cut in half. By using an inverter with an MPPT it is possible to lower the current which in turn unlocks a larger part of the PV module, resulting in in a higher voltage, and subsequently an overall higher power output (GSES, 2021). However, the inverter controls the MPP of an entire string of modules at the same time, which means that this would only be relevant if a majority of the modules in a string had the same shading conditions. In a large system such as a solar farm, this is very unlikely. According to a study of a solar farm in Scotland, the gain from utilizing half-cut cells was only 1.4% higher, and was therefore not a recommended choice out of economic reasons (Chiodetti et al., 2019).

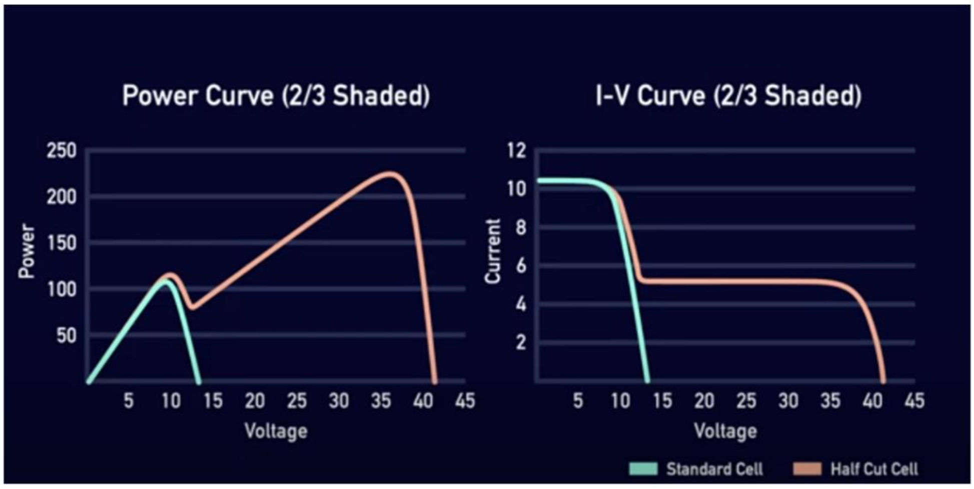


FIGURE 10 POWER AND I-V CURVES (GSES, 2021)

In summary, the main advantage with a half cut solar panel, is according to Joshi et al., (2019) that it is possible to provide the same amount of current as in a standard cell, but with reduced resistance. This results in a slightly increased efficiency and reduced power losses.

2.2.6 Solar tracking PV-systems

Tracking PV-systems consists of modules that follow the movement of the sun across the sky each day in order to maximize electricity production. They are referred to as either 1-axis tracking, which adjusts the tilt of the modules or 2-axis tracking which adjusts both the tilt and the azimuth.

A Swedish study showed that while 2-axis tracking yields 31-40% more energy compared to fixed systems, they also use significantly more land area, making the energy yield per unit area less effective. This combined with the increased investment and maintenance costs of tracking systems makes them economically inferior to fixed systems in Sweden at this time. Regarding 1-axis tracking systems, the data quality was lower as there were problems with the datalogger. But the results show that 1-axis tracking yields roughly 20% more energy than fixed systems. However, since the particular tracking model used in the study have nearly identical cost to the 2-axis tracking model, they could not be justified economically under Swedish conditions. The author does point out that in southern regions in the US, 1-axis tracking is used with success, since there exist cheaper models, and they are more effective in those regions. (Stridh, 2016)

2.2.7 Mounting configurations, tilt, and orientation

Because of the nature of the bifacial PV panel, which is to collect irradiance from both sides of the panel, this results in many different possible configurations. For example, it is now more possible to mount PV panels completely vertically (like a fence), utilizing both sides of the panel equally. This will result in a very small footprint from the PV panels themselves and allows for other endeavors to take place in between the rows of panels. Because of the small footprint, this setup is very common for agrivoltaics, where both farming and livestock can be kept on the same area as a solar farm.

Figure 11 illustrates three different mounting configurations for bifacial solar panels. Vertical Configuration (Left Side): This setup features a solar panel mounted vertically, standing perpendicular to the ground. It captures direct irradiance from the sun that strikes the panel from above, as well as reflected irradiance that bounces off the ground and hits the lower portion of the panel. This configuration might be used in applications where space is limited or for specific functional purposes, such as integrating with a wall or fence.

Horizontal Configuration (Middle): Here, the solar panel is mounted horizontally or near-horizontal to the ground. It receives direct irradiance from above and also captures reflected irradiance from the ground. This configuration is common for rooftop installations, such as on flat roofs or carports, where the panel can double as a shelter while generating power.

Slanted Configuration (Right Side): The solar panel in this configuration is tilted at an angle. It benefits from direct irradiance hitting the panel at an oblique angle and reflected irradiance from the ground. This slanted position is typical for ground-mounted solar arrays and is designed to optimize the angle of incidence for the sun's rays, improving energy capture over the course of the day.

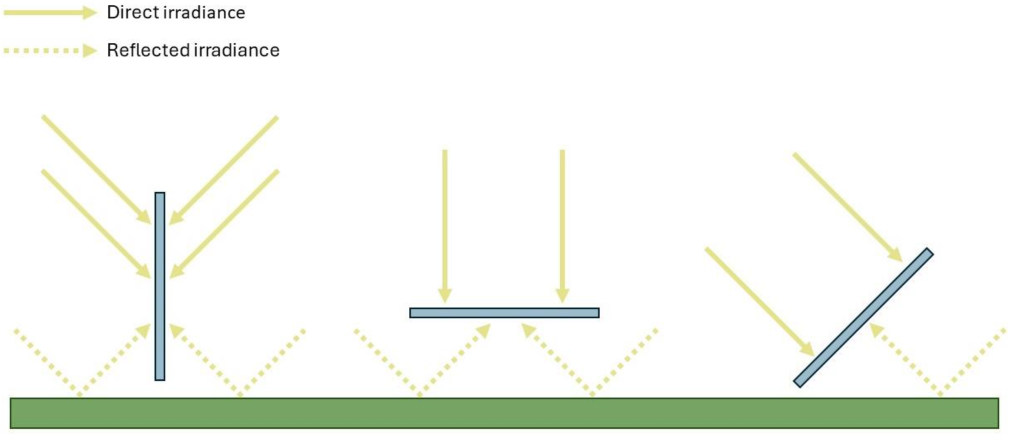


FIGURE 11 MOUNTING CONFIGURATIONS

Each configuration is designed to maximize the amount of solar energy in different scenarios, by taking advantage of both the direct sunlight and the additional light reflected from the ground, which can contribute to the overall energy yield of the solar panels. The choice of configuration depends on various factors, including geographic location, climate, intended use, and the physical constraints of the installation site.

Figure 11 illustrates the three general concepts for mounting configurations. The conventional slanted setup is akin to the standard mono-facial slanted mounting, allowing for up to a 30% bifacial gain from light reflected off the ground beneath the panels. This setup is commonly employed in the same manner as mono-facial photovoltaic (PV) systems, but it can also take advantage of varying albedo enhancements through the use of different ground cover materials positioned under the panels. The remaining configurations, horizontal and vertical, are primarily adopted to facilitate the simultaneous use of land for other purposes. The horizontal or near-horizontal arrangement is particularly advantageous for capitalizing on rooftop spaces to generate electricity locally, such as integrating additional power generation into carports for electric vehicle charging stations. Vertical setups are being explored for their potential in agrivoltaics systems, where agriculture and PV generation are combined (Campana et al., 2024).

According to (Wang et al., 2015) it has been demonstrated that, in some parts of the world, it is possible to increase the energy output of bifacial modules using a higher elevated mounting position. This elevation reduces the shaded area on the ground beneath the modules, thereby boosting the amount of light reaching the backside of the panels. In contrast, at higher latitudes, such as in Nordic regions, a lower mounting height may be adequate due to the sun's lower angle of elevation. Another critical factor for bifacial systems is the spacing between rows. A single-row layout is ideal as it eliminates shading between rows. In multi-row configurations, the impact of shading between rows is contingent on the spacing; wider distances between rows generally reduce the effects of this shading (Wang et al., 2015).

There are several different ways to anchor solar modules to the ground. According to a study by Björnsson et al., (2022) where the authors investigated the technical design of existing solar farms in Sweden during 2021, piling was by far the most common anchoring method (80%), but there was also anchoring with ground screws (one facility), ground screw with ballast (one facility), only ballast (one facility), and the only solar farm with sun-tracking modules was placed on a concrete slab. The highest annual yield from unshaded solar panels is achieved when the panels are angled towards the south with an inclination that depends on where in the country you are, about 40 degrees in southern Sweden and about 45 degrees in northern Sweden. 90% of the studied facilities are oriented to the south, two are mounted in an east-west direction, and one facility was sun-tracking. In the same study, the results showed that two-thirds of facilities have solar modules at a minimum height above the ground of 75 cm or more, while the remaining one third have solar panels at a minimum height of less than 75 cm.

A study conducted by Stridh, (2016) compared the differences of three different solar farm setups using PVGIS. Two of the setups (Arneby and Arvika) were based on real solar farms in Sweden. The third setup was based on data from several procurement documents, from which the author deducted that an 18° shading angle a and 30° tilt is a common standard used for Swedish PV-systems. The simulations all used Stockholm as the location. The PV-system used in each simulation consisted of 10 rows with portrait-oriented modules. The results are shown in Table 1.

TABLE 1 COMPARISON BETWEEN DIFFERENT MOUNTING CONFIGURATIONS WITH PVGIS. (STRIDH, 2016)

	Arvika	***Arneby***	***Procurements***
Tilt [deg]	45	30	30
Shading angle [deg]	9.87	12	18
Yield/installed p. [kWh/kWp, yr]	977	953	919
Yield/area [GWh/m2,yr]	0.32	0.46	0.59
Ground coverage [%]	21	31	41

By comparing the data in Table 1, it becomes apparent that with less production-efficient tilt angles, and shading angles, the specific yield only decreases by a few percent, while the increase in yield per area and relative ground coverage is substantially larger, in the range of roughly 20% per percentage lost in yield. Though it should be noted that the Arvika and Arneby solar farms have a rather weak setup in terms of ground coverage. Comparing the Arneby and Arvika results, with Arvika being more optimized towards electricity yield, the yield is only 2.5% higher for Arvika, while the yield per ha is 44% more with the Arneby setup. By comparing Arneby with the setups found in various procurements that use a higher shading angle, Arneby has 3.7% higher yield, but the procurement setups have 28% more yield per ha. From this data, it can be concluded that a slightly more efficient setup towards energy yield comes at a high cost of land usage. For the optimal layout of a solar farm, both parameters need to be considered. Of note is that the common Swedish setup of 30° tilt and 18° shading angle seems to be a very strong setup both in terms of efficient yield per module and for a high ground coverage.

2.2.8 Dirt, soiling and snow

Soiling losses include all types of surface contaminations such as dirt, dust, bird droppings, pollen etc. Soiling depends on both the location and climate and the effects decreases exponentially with elevation. (Sayyah et al., 2014)

Dust and dirt can cause significant problems to PV power production due to shading, however, these problems are in general not very significant in Sweden. Natural rain acts as a cleaning procedure for the modules. Both flow speed and amount of rain hitting the modules is affected by the tilt of the module. (Bengtsson et al., 2017)

According to a study by Pedersen et al., (2016) rain effectively cleans most dust and dirt at 45° tilt modules in Norway. However, Bengtsson et al., (2017) found that the maximum cleaning effect is achieved at around 30° tilt in Sweden. It should also be noted that bird droppings can be especially troublesome for PV-modules, since they are not effectively washed off by natural rain. It is therefore recommended to occasionally clean the modules manually. (Lindahl et al., 2022)

Snow can also be described as a type of soiling loss. In a small study, the author examined the potential economic benefits of cleaning modules from snow and dust in three European cities: Murcia, Spain, Munich, Germany, and Helsinki, Finland. Since Helsinki's coordinates (lat 60.2, long 24.9) are similar to Skutskär, snow and soiling conditions can be assumed to be similar. The study states that a clear statement could not be made for Helsinki since there is a lack of data on soiling losses in Nordic countries, but it nevertheless concluded that it is probably not economically beneficial to clean modules of dirt. Similarly, it is unlikely that there is any value of removing snow, since the costs to do so would be similar to cleaning dirt and the snow fall occurs quite often during winter periods, meaning that snow removal would have to be performed regularly, thus increasing costs. (Stridh, 2012)

Even though 30° tilt will benefit from more efficient cleaning during rain (Bengtsson et al., 2017), higher tilts will benefit from less snow coverage (Stridh, 2016). However, the issue of snow is not considered a significant problem for PV-systems in Sweden since the solar irradiation during these months is very low (Bengtsson et al., 2017).

2.2.9 Solar panel degradation

PV-modules are subject to an annual degradation rate due to wear and tear of the electrical components. A study that evaluated nearly 2000 measured degradation rates the last 40 years on both systems and individual models found that the median yearly degradation of module power was 0.5% per year. Note that this is worldwide and not tied to any specific location. (Jordan & Kurtz, 2013)

For PV-modules in Sweden however, the degradation rate seems to be lower. In the evaluations of degradation rates of two PV-systems in Sweden, one being active for 25 years with 20 modules, and one for 20 years, with 70 modules, the degradation rate was found to be lower than expected. For both these systems, one module was detected to be defective and working far less efficiently than the rest. But for the remaining modules, only 2% lower power output was measured for both systems. This value was also within the range of measurement accuracy, so it could not be verified that any degradation had occurred at all. As a comparison, a degradation rate of 0.4% will result in around 8% less power output after 20 years and 10% after 25 years. (Stridh, 2016), (Palmblad, 2009)

The oldest grid-connected PV system in Sweden has been working fine for 35 years (Wallnér, 2019). Although some of the auxiliary equipment have been replaced from time to time, such as the inverter in 2015 due to the old one malfunctioning and some wiring in 2014 due to water damage. To evaluate the degradation of this system scientifically, it would need to be demounted and transported to a lab, but due to the equipment being so old, many of its parts would probably not survive demounting, transporting and remounting, so an in-depth performance test on this system will not be made. However, a simplified evaluation was made at the location by a technician in 2017, who deemed that the degradation even after 35 years was close to zero. (Wallnér, 2019)

It seems that degradation under Swedish conditions is less than the 0.5% / year that is the international median. Bengt suggests that this may have to do with the cool Swedish climate. (Stridh, 2016)

2.2.10 Annual variation of solar irradiation

Although the yearly insolation in Sweden varies each year, the variation is relatively small. Roughly speaking, it varies around +/- 10% of the long-time mean value for both solar hours and global irradiation, meaning that a year with high insolation has +10% and a year with low insolation has -10% compared to the mean value. The most important factor for this variation is cloudiness, which in Sweden is often very similar over large areas. One interesting trend observed in the report over the years 1985-2005, is that sunshine hours and global insolation is currently rising each year, by 0.7% and 0.4% on average respectively per year. (SMHI, 2007)

2.2.11 Technical design and location factors

The cost of purchasing/leasing land as well as proximity to the power grid seem to be of the greatest importance according to Björnsson et al., (2022). Legal aspects, such as consideration of natural values and arable land, were not as commonly mentioned, and otherwise, the choice of location and design seemed to be governed by relatively diverse aspects, which did not reveal any particular pattern. However, according to the results of the survey by Björnsson et al., (2022), there has been a shift towards pre-emptively excluding areas that risk longer processing times due to high natural values.

2.3 Theoretical background

2.3.1 Shading angle, pitch, and ground coverage

Around half of the yearly solar irradiation in Sweden is diffuse, but this varies greatly with season and time of day. On a sunny day, the direct irradiation can be as high as 90% of the global irradiation.

Since shading mostly impacts direct irradiation and the vast majority of the direct irradiation in Sweden occurs during daytime and during the summer months, the shading aspects of the PV-system should be designed towards summer and daytime conditions (Bengtsson et al., 2017).

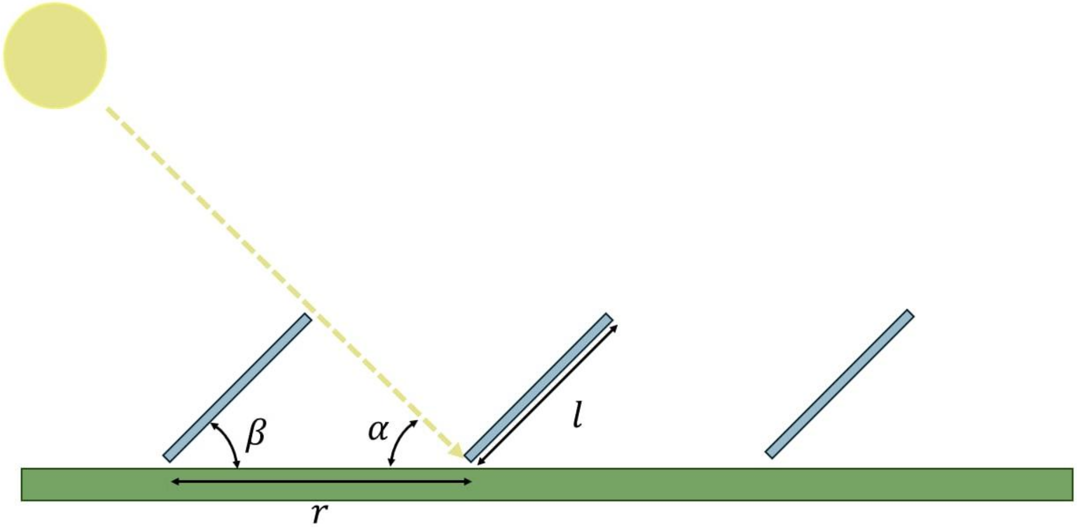


FIGURE 12: SHADING ANGLE VISUALIZATION

The shadows that module rows will cast on the row behind is dependent on a few parameters such as module length, solar height and module tilt. This row-to-row shading is referred to as mutual shading in PVsyst. The angle α as seen in Figure 12 is known as shading angle, shading limit or profile angle, and is defined as the minimum solar height for which no mutual shading occurs. Since row distance varies with module length and tilt, shading angle is the main parameter used to describe the mounting configurations and the mutual shading conditions of a solar farm. There is no universal standard for acceptable shading angle in Sweden, but it is usually set to 18° for newer solar farms (Stridh, 2016) which is in line with the PVsyst recommendations of keeping it below 20°. (*Project Design > Plane Orientation > Shed Optimization*, 2024)

The formula for calculating the row distance (known as pitch in PVsyst) where no shading will occur for a given minimum solar height is shown in Equation 1. (Bengtsson et al., 2017)

EQUATION 1

$$r = l \cdot \left(\cos(\beta) + \frac{\sin(\beta)}{\tan(\alpha)} \right)$$

Where:

r = row distance or pitch
β = module tilt
α = solar height where no shading occurs (shading angle)
l = module length

Another important aspect of a larger PV-system is the ground coverage. It is the ratio between the PV-module length and the pitch and is used to describe how effectively a PV-system utilizes the area it covers or how tightly the modules are spaced. As the pitch increases, both the mutual shading and the ground coverage decreases, so a system with low ground coverage will be more effective per module since there is less shading between them, but such a system will also provide a lower electricity yield per unit of land area. Ground coverage vs pitch is an optimization problem and depends on how much area is available and the desired wattage of the system. (Tonita et al., 2023)

If the total module area of the PV system is divided by the ground coverage, the result will be the theoretical minimum land usage of the system, i.e., land usage for PV-modules only, excluding any supporting equipment or buildings. It should be mentioned that for each specific area, the conditions will vary slightly for how to best utilize the available land. Depending on factors such as parts of the area need to be used for roads, the buildings of the solar farm, cables etc. There is also usually a fenced clear area around the perimeter of a solar farm. The practical maximum Wp that is possible to install in an area can be estimated to be 10-20% lower than the theoretical maximum. (Stridh, 2016)

2.3.2 Shading from nearby objects

A rule of thumb regarding the solar modules distance to shading objects (such as trees) is to not place any solar modules within a distance of 3 times the height difference to the shading object within a zone of +/- 30° north of the shading object, which can be seen in Figure 13.

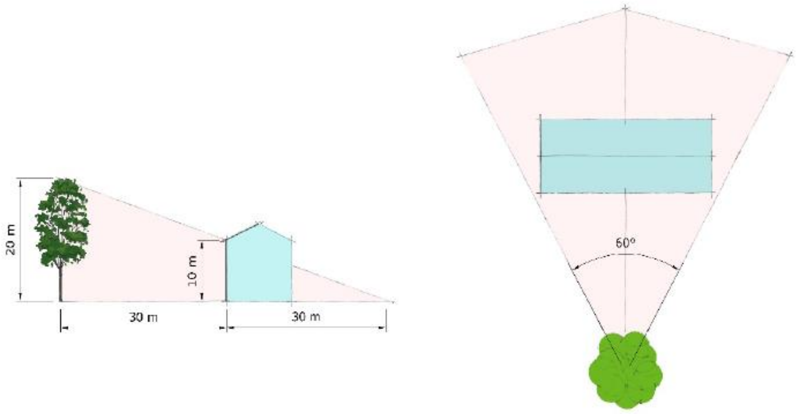


Figure 13 Shading from nearby objects (Bengtsson et al., 2017)

This rule of thumb is based on the shading angle of the object. If the distance to a shading object is 3 times the height difference, the minimum shading angle will be 18°, if the distance is 4 times the shading angle is 14° and for 2 times it is 27°. (Bengtsson et al., 2017)

2.3.3 Environmental effects from production of solar panels

As the global shift towards renewable energy intensifies, the development of solar power farms has emerged as a strong contender for achieving sustainable energy goals. However, this expansion of renewable energy infrastructure, such as solar farms, demands a careful analysis of its effects to minimize the environmental impact. This section discusses the different potential environmental consequences associated with setting up a solar power farm in the forests of northern Europe, as well as the possible strategies that are available (for Stora Enso) to minimize these consequences.

Photovoltaic (PV) systems are widely recognized as a promising source of clean and sustainable energy. However, a recent study by Tawalbeh et al. (2021) underscores the importance of addressing environmental challenges associated with these systems throughout their lifecycle, from manufacturing to disposal.

While PV systems contribute to clean energy production, their manufacturing process raises concerns due to the use of hazardous materials, water pollution, and air emissions. Tawalbeh et al., (2021) suggests practical solutions to mitigate negative environmental effects. Optimized design, the development of novel materials, minimizing the use of hazardous substances, promoting recycling practices, and carefully selecting installation sites emerge as key strategies to enhance the sustainability of PV systems. However, when comparing the carbon footprint of PV systems to burning oil there is a substantial difference. With emissions ranging from 19 - 28 g CO2-eq/kWh, compared to 742 g CO2-eq/kWh from oil, silicone PV modules demonstrate a noteworthy environmental advantage over traditional energy sources (Tawalbeh et al., 2021).

2.3.4 Effects on wildlife and habitats

The integration of a solar farm within a landscape, such as a forest, raises concerns about its potential impact on local wildlife ecosystems, e.g. removing existing trees and vegetation which acts as protection for some animals. According to Chock et al., (2021) the land used for solar panels and associated infrastructure can disrupt established habitats, and affect the flora and fauna that inhabit the area negatively. Furthermore, the installation and operation of solar farms may introduce new sources of noise and light, which can have implications for wildlife behavior, migration patterns, and reproduction. It is therefore important to consider these ecological dynamics, and to identify potential risks to biodiversity and propose mitigation measures to safeguard the local fauna, and if possible, try to improve the circumstances. Oscar Öhrman, Head of technology at Svensk Solenergi, argues that it is important to consider measures which promote biodiversity. He also states that during the planning phase of a solar park, one can do a great deal of good for the local environment with fairly modest means. (O. Öhrman, personal communication, 27 February 2024)

2.3.5 Impact on landscape and visual considerations

Beyond the immediate environmental implications, the establishment of a solar farm may also have an impact on different geographical interests, such as existing recreational areas, running and walking trails, and other outdoor activities. The transformation of a forested landscape into an array of solar panels introduces aesthetic changes, that may be met with varying degrees of acceptance from the local community (SVT Nyheter, 2023). In recent years, there has been a notable increase in the installation of solar energy systems in rural regions, as well as urban (Sánchez-Pantoja et al., 2018). The visual impact of a solar power farm not only affects its closest neighbors, it also influences the character of the landscape and may alter any potential scenic value of the area. Understanding how these alterations may be perceived by local residents, outdoor enthusiasts, or those foraging for mushrooms, is crucial for minimizing potential conflicts.

2.3.6 PVsyst and Winsun PV

PVsyst is the industry standard within the field of PV simulation, and is designed to be used by both architects, engineers, and researchers (Yadav et al., 2015). This has a user-friendly interface and allows the user to both access a large database of metrological data, but also import other data collected by the user or a third party. According to a study conducted by (Kumar et al., 2017), in which an analysis was performed in order to assess the performance of a photovoltaic system PVsyst, the results generated are highly reliable.

Winsun PV is a PV-simulation software aimed mostly for the simulation of roof-installed PV-systems. It was developed by the researchers Björn O. Karlsson and Bengt Perers. Winsun PV is simple to use, it is a Microsoft Excel file that only requires a few user inputs. Therefore, the software does not consider some of the more advanced losses such as row-to-row shading. Winsun PV can both retrieve climate data automatically from a built-in database, and use custom measured climate data.

When using measured climate data, Winsun has shown to generate results that are very close to measured electricity production of PV-systems in Gävle. Figure 14 and Figure 15 shows a comparison of the measured electricity production of a PV-system (green) installed at the University of Gävle, and results from a Winsun PV simulation (blue) of the same system that uses measured irradiation data from 2023 and 2022. (Hernando Uriarte, 2024)

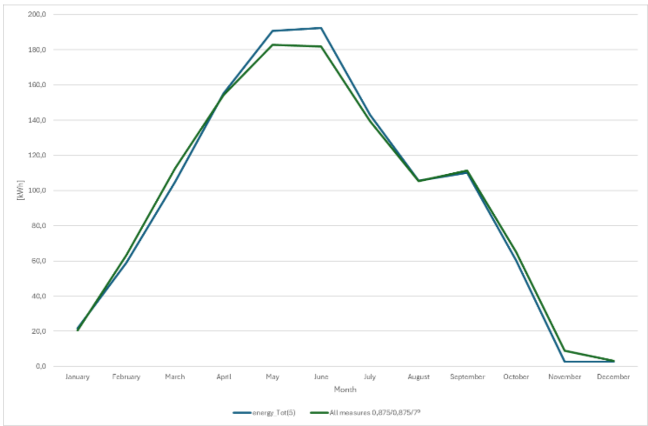


Figure 14 Winsun PV results compared to measurments 1 (Hernando Uriarte, 2024)

Figure 15: Winsun PV results compared to measurements 2 (Hernando Uriarte, 2024)

2.3.7 Perez as a solar radiation model

When using simulation software such as PVsyst for assessing the available solar energy at a specific location, there are several different solar irradiance models one can choose from. According to Loutzenhiser et al., (2007), a few of the more commonly used models include Klucher, Hay-Davis, Muneer, and Perez. The last example was used for the simulations performed in this research.

The Perez model for irradiance is a sophisticated mathematical framework developed by Dr. Richard Perez, which has significantly advanced the field of solar energy by enabling more accurate predictions of solar irradiance on tilted surfaces, such as solar panels. This model is particularly renowned for its ability to decompose the sky's diffuse irradiance into three primary components: isotropic, circumsolar, and horizon brightness (Perez et al., 1990). These components are quantified using a set of empirical coefficients that dynamically adjust based on various inputs such as the solar zenith angle, the angle of incidence, and the diffuse horizontal irradiance. This model has also been described as one of the more computationally intensive models, but which also provides a more detailed analysis compared to other models (Loutzenhiser et al., 2007)

Originally developed to enhance the accuracy of solar irradiance models on tilted planes, the Perez model utilizes Typical Meteorological Year (TMY) data to calculate irradiance, which is crucial for assessing the solar potential of specific locations (Staff, 2017).

The model's robustness and versatility have led to its integration into numerous solar energy simulation software and tools, aiding solar designers and engineers in optimizing the configuration and expected output of solar installations. This capability is essential for integrating photovoltaic (PV) systems into the power grid, as it allows for better prediction and management of solar energy production, thereby enhancing the reliability and efficiency of solar power systems (Staff, 2017). Perez also claims that to make a good economical assessment of an energy system, it is essential to be able to predict exactly how much energy a system is going to produce. An accurate modelling of the weather can therefore influence the decision making substantially. (Staff, 2017)

The Perez model's ability to accurately simulate and predict solar irradiance across various conditions and orientations makes it an important part in the planning and optimization of solar energy system, including solar farms.

2.3.8 Levelized cost of electricity

According to Aldersey-Williams & Rubert, (2019) levelized cost of electricity (LCOE) is a widespread method used for calculating and comparing the cost of electricity generated over an electricity generating facility's entire lifetime.

LCOE is expressed in cost / unit of produced electricity over the lifetime, such as €/MWh. This cost is then usually compared either with LCOE calculations for other electricity generators to determine the cheapest alternative, or with the current electricity price to determine if the project would be economically profitable to undertake. (Lindahl et al., 2022)

LCOE is often the preferred method used for calculating the cost of a project and is widely used in academics and by stakeholders, according to Aldersey-Williams & Rubert, (2019). It is, however, very sensitive to fluctuating future fuel costs and to the chosen discount rate and it is thus important to use the method correctly. It should also be pointed out LCOE is strictly a monetary evaluation, so no value is given to emissions, health hazards, amount or conveniency of produced electricity or other similar aspects. (Lindahl et al., 2022)

While there exist many different variations on the LCOE formula, the one used in this study is a slightly simplified version applicable to solar farms as shown below and in Equation 2. Since this study concerns a Swedish project, costs will be expressed in SEK. (Lindahl et al., 2022)

$$LCOE = \frac{CAPEX_0 + \sum_{t=1}^{N} \left[\frac{O\&M_f + O\&M_v * Y_0 * (1 - Dg)^t}{(1 + WACC_r)^t} \right] + \frac{ReInv_1}{(1 + WACC_r)^{x1}} + \frac{ReInv_2}{(1 + WACC_r)^{x2}} + \frac{ResC}{(1 + WACC_r)^N}}{\sum_{t=1}^{N} \left[\frac{Y_0 * (1 - Dg)^t}{(1 + WACC_r)^t} \right]}$$

Where $CAPEX_0$ is the initial capital investment in SEK, N is the lifetime of the project in years, $O\&M_f$ is the fixed operation and maintenance costs in the year t, expressed in SEK, $O\&M_v$ is the variable operation and maintenance cost in the year t, expressed in SEK, Y_0 is the annual electricity production during the first year or production before degradation has occurred expressed in MWh, Dg is the annual degradation factor expressed in a decimal number, $ReInv_1$ is the first reinvestment in year x_1 needed to reach the expected lifetime, expressed in SEK, $ReInv_2$ is the second reinvestment in the year x_2 needed to reach the expected lifetime, expressed in SEK, ResC is the residual cost at the end of the projects lifetime, expressed in SEK and $WACC_r$ is the real weighted average cost of capital per annum expressed in a decimal number. (Lindahl et al., 2022)

The main difference between this version and other more general versions is the exclusion of fuel costs, since PV technology uses no fuel, and the addition of a degradation rate since the effectiveness of PV technology degrades by around 0.2% every year. Another term that is not always present in the LCOE formula but is included here in the solar farm version is the reinvestment terms, since this is always needed in order to reach the full lifetime potential of all components of a solar farm.

The way LCOE is designed is that some of the costs are subject to a discount rate, meaning that costs are increased or decreased or both increased and decreased, depending on the type of cost and in what year the cost takes place. The discount rate can be considered as an annual return on the money spent. This means that money spent today is worth more than money that will be spent in the future, since costs that occur today are money that could have been used as an investment which would generate income and this income could in turn be invested again.

Explanations of the terms

$CAPEX_0$ is the capital investment required in year 0. This is the single largest cost for a solar farm and includes everything required to actually establish the solar farm, and mainly consists of contractor, material and permit costs. This cost is lifted out of the $\sum$ summation since it is rare for solar farms to require more than a single year to build, and hence the cost does not need to be split up over several years. (Lindahl et al., 2022)

$O\&M_f$ is the fixed annual operation and maintenance costs. These are known costs such as administrative costs, insurance costs, land leasing costs, property tax, production monitoring costs, fixed grid fees, electrical maintenance and site maintenance. These costs may vary depending on how the ownership of the solar farm and the maintenance of it is handled, it also depends on local and current grid fees. (Lindahl et al., 2022) Although CAPEX is the single largest part of the total investment, Lindahl et al., explains that the $O\&M_f$ has a larger impact on the final LCOE value, since it is a recurring cost. Because of this, it is therefore important to keep this at a minimum level.

$O\&M_v$ is the variable annual operation and maintenance costs. These are costs that are dependent on the amount of electricity that is produced, which for a solar farm in Sweden are electricity trading and balance responsibility costs. In the reference study, this term also includes a compensation fee that the owners are granted by the grid operator (a negative cost) per MWh fed into the grid. This compensation is because a local electricity production will help to reduce transmission losses. It is important to omit this compensation from the cost formula if it is included in the revenue calculations. (Lindahl et al., 2022)

Y_0 is the annual yield, or electricity production in year 0, or the first year. Depending on the calculation, it might be important to take into account here that PV-modules have an expected degradation rate of around 1% in the first year, after which it reduces to around 0.2-0.4%. For PVsyst, the documentation states that this effect is not very well researched and can vary with module type and even for module to module within the same type. The first-year loss is therefore not included by default in PVsyst simulations. (*Project Design > Array and System Losses > LID Loss*, 2024)

Dg is the annual degradation rate that PV-modules are subject to. It is important to input this as a decimal number and not as the percentage that it is referred to on the module's datasheet, so 0.4% should be inputted as 0.004.

ReInv are the major investments in the year x that are needed for the solar farm to reach its expected lifetime. These terms mainly concern inverter replacements, since currently, these have an expected lifetime of around 10-15 years while a solar farm usually is expected to operate for 30-40 years. There can be any number of reinvestment terms, but for a solar farm and depending on the expected lifetime of specific cases, the usual number is 1-2 major reinvestments. (Lindahl et al., 2022)

ResC is the residual costs, or costs for decommissioning the solar farm at the end of its lifetime. Although the data for residual costs of solar farms is scarce, since few, if any have yet been demolished, this cost is expected to be low. There is also scrapping value of the electrical wires, and the added value of the grid access to the land. Stakeholders usually expect the residual cost in combination with the added values to even out and set this cost to 0. (Lindahl et al., 2022)

$WACC_r$ is the real weighted average cost of capital, and can also be used in place of discount rate. It represents the cost for a company to put resources into a project, since resources could otherwise be invested elsewhere with profit. It can also be thought of as the minimum return that an investment must yield in order to be profitable. (Rodríguez, 2024)

The WACC is a crucial figure when companies are considering investments, and no less so in LCOE calculations. How WACC is calculated is a whole new topic on its own, and will only be touched upon briefly here, since this study utilized a WACC that was already calculated by the company. In short, there are many variations on the WACC and it can depend on many factors, such as bank interest rates, inflation, tax rates etc. Two factors that are always included are cost of equity and cost of debt. These rates are then weighted and added together to form a single figure known as WACC.

In the formula, the $WACC_r$ is used in several places and represents the added value of interest upon interest for a number of years represented by the power factor. In the ReInv and ResC terms, the $WACC_r$ represents a decrease of the costs, since these costs will be made in the future, and thus the capital that will be used for these costs can be the subject of interest rates for a number of years. In the O&M term, the meaning of $WACC_r$ is the same as mentioned before, except that it is dependent on the year t which in turn is the summation index. The effect of this is that with each increasing year, the annual O&M costs will be subject to an increasing WACC each year, therefore the O&M costs will decrease more each year. In the summation in the denominator, the $WACC_r$ accounts for the added discount rate during the entire lifetime and will then increase all costs by this amount. The effect of WACC at this place is that after all costs have been adjusted and decreased according to in which year they will take place, the remaining present-day value of the costs will be subject to interest rate and would therefore increase in value with each year.

Lastly, in the summation in the main denominator, Y_0 * (1-Dg) represents the total amount of electricity produced over the entire lifetime of the project, with an increasingly higher degradation included. This part simply divides all the costs by the total amount of electricity, since LCOE represents the cost per unit of produced electricity. (Lindahl et al., 2022)

2.4 Permits, certificates, and regulatory requirements

Receiving the correct permits, certificates, filing the relevant applications can be seen as a daunting task. However, a study by Björnsson et al., (2022) suggests that none of the respondents who took part in the study faced any major obstacles in the permitting processes of their solar farms. A large-scale solar panel installation often means that the natural environment is significantly altered, which requires consultation. Anyone planning to build a solar farm always needs to contact the municipality's building permit department (Kommunens bygglovsavdelning) and the County Administrative Board (Länsstyrelsen).

2.4.1 Permits required for solar a solar farm

According to the Swedish energy agency, when establishing a standalone solar farm, the municipality's building permit department needs to be contacted. Even if the farm is planned outside a detailed development plan area, which generally does not require a building permit, the municipality should always be informed. Depending on the size and design of the facility, a building permit may be required even outside areas that are exempt from building permits and without area regulations. (*Tillstånd för solcellspark*, 2024)

Ground mounted solar panels do not require a building permit as long as they are not installed in a zoning area. This is an area in which the municipality regulates how land and water are to be used and what the buildings should look like, and specifies what can and cannot be performed in terms of construction activities, according to the definition made by Boverket (*Detaljplanering*, 2022). However, building permits are required for transformer stations and technical sheds connected to ground-mounted solar panels (*Tillstånd för solcellspark*, 2024).

Solar installations on structures that are higher than 3 meters may also require a building permit. The Land and Environment Court of Appeal ruled in a case from 2021 that solar panels installed on a high ground structure required a building permit. The structure in the case had a minimum height of 3 meters and was therefore considered a space where people could stay. For this reason, the structure was counted as a building and required a building permit. (*Bygglov för solceller 2024*, 2024)

Today, solar farms do not require a building permit as long as they are located outside a zoning area. However, a notification to the County Administrative Board is required. The County Administrative Board then makes sure that protected areas, areas with species protection, and sites of historical interest, are not affected by the solar farm, through a consultation. (*Bygglov för solceller 2024*, 2024)

2.4.2 Notification of Consultation

Large-scale solar panel installations are, according to the Swedish energy agency, generally considered a structure which significantly alters the natural environment. For this reason, the County Administrative Board (Länsstyrelsen) needs to be notified by anyone who wants to install ground mounted solar panels. The County Administrative Board then reviews and assesses whether the facility will violate laws, such as the protection of farmland (skydd av jordbruksmark). In the consultation, concerned parties, such as neighbors and the County Administrative Board, have the opportunity to express their opinions about the solar farm. Even if the land is not classified as an environmentally protected area, a meeting for consultation may still be necessary. It is the County Administrative Board that assesses whether the environment is at risk of being altered or damaged, and if consultation is required for the solar farm. (*Tillstånd för solcellspark*, 2024)

Anyone who is planning to build a large-scale solar panel installation is responsible for providing complete documentation for the consultation, which describes the impact of the solar farm on the surrounding environment. Once the consultation is completed, the County Administrative Board decides whether the solar farm is allowed to be built, if precautionary measures are required, or if the operation should be prohibited. The County Administrative Boards in Sweden have produced material to support anyone who plan to install ground mounted solar panels, e.g. a checklist regarding relevant information needed prior to a consultation, which can be seen below.

Checklist for Consultation (*Tillstånd för solcellspark*, 2024):

- What are the conditions at the site?
- Are exemptions and permits needed?
- Does the project involve a solar panel installation on farmland?
- How will the natural environment be affected, for example, animals and plants?
- How will the cultural environment be affected?
- Are there national interests that are affected?
- Are there municipal plans that are affected?
- How will outdoor life be affected?
- Are there maps with layout sketches and dimensions, as well as photos of the site from different directions?
- How will the land in the facility be managed?
- Is an environmental impact assessment required?

2.4.3 Application for Voluntary Environmental Permit

According to the Swedish energy agency, anyone who is planning to install ground mounted solar panels can also choose to apply for a voluntary environmental permit (SE: Frivilligt miljötillstånd) for the solar farm. In that case, the County Administrative Board prepares the application. This preparation may include a consultation, as described above, and it may also require an assessment regarding the potential environmental impact. (*Tillstånd för solcellspark*, 2024) This is not always mandatory, since a solar farm normally is not considered an environmentally hazardous facility and therefore does not require a permit, however one must always consult with the County Administrative Board beforehand (*Prövning av miljöfarlig verksamhet*, 2024). The reason why it might be necessary to apply for a permit is, according to the County Administrative Board, that installing solar panels on natural land is an action that "can significantly change the natural environment," as stated in the Environmental Code. Even though they do not produce emissions, noise, or require transportation during their operational period, they do require space in the landscape and can thus affect existing activities and interests such as natural and cultural environments, agricultural land, and outdoor activities (*Solceller på mark*, 2024).

The decision regarding the application for permit is made by the Environmental Permitting Board (Miljöprövningsdelegationen), which is an independent section of the County Administrative Board. The Environmental Code is central to the assessment, and a balance is struck against other general interests. Permits granted are time-limited and come with conditions, as described in the decision. Stakeholders, such as the owner of the solar farm, can appeal the Environmental Permitting Board's decision to the Land and Environment Court (mark- och miljödomstolen).(*Tillstånd för solcellspark*, 2024)

2.4.4 Connecting to the grid

According to the Swedish law Ellag (1997:857) chapter 4, paragraph 1: The holder of a network concession is obligated to connect an electrical installation to the grid under objective, non-discriminatory, and otherwise reasonable conditions, if the owner of the electrical installation requests that it be connected. However, according to chapter 3 paragraph 2: Deviations from the obligation according to Section 1 may be made if:

1. there is a lack of available capacity and there are no possibilities to increase the capacity in a way that is economically justified without reinforcing the grid, or
2. other unique circumstances.

Depending on the size of the power production, a solar farm will fall into different categories, which involve different levels of requirement. These categories have been established on an EU level, and is defined in the regulation called Requirements for Generators (RfG), and has been enforced in Sweden since May 2016 (*Requirements for Grid Connection of Generators (RfG) 2016/631*, 2016). Requirements may also differ depending on how power the is generated. One approach could be synchronous power generating and another could be power park modules (PPM). Synchronous power generating modules refer to synchronous generators (conventional generators), e.g. generators used in hydro power or nuclear power plants. (*Requirements for Grid Connection of Generators (RfG) 2016/631*, 2016)

Examples of PPM include wind and solar power, which typically consists of several connected power-generating units, forming one economic unit with a common connection point (Gehlhaar et al., 2016). Which units that should be included in a power park module, and thus form the combined capacity of which it will be assessed, is made in consultation with Vattenfall Eldistribution (or whatever network who has network concession). In a case such as this, the requirements are formulated and verified for the overall PPM, with all units included. A power production facility can consist of one or more PPMs (*Guide till Anslutningsförfarandet Av Kraftparksmoduler till Distributionssystemet - Vattenfall*, n.d.). According to the published regulation Requirements for Generators (RfG) and Swedish Energy Markets Inspectorate regulations, EIFS 2018:2, power generating modules are classified into four different type classes from type A to type D, depending on their maximum continuous power and connection voltage, as shown in Table 2. (*Föreskrift EIFS 2018:2*, 2018)

The process for the connection procedure is based on the threshold category which can be seen in Table 2. Power generating modules of type B, C & D have certain requirements for a connection procedure. These requirements are verified through collaboration between the owner of the power generating module and the grid owner. (*Guide För Anslutning Av Kraftproduktionsmodul till Överföringssystemet - Från Anslutningsavtal till Slutligt Driftsmeddelande*, 2021)

Technical requirements also vary between the different types of power generating modules (synchronous power generating module compared to power park module) and type class, where type A has the lowest technical capability, and type D has the highest technical capability.

Table 2 Classification of power generating modules (*Guide För Anslutning Av Kraftproduktionsmodul till Överföringssystemet - Från Anslutningsavtal till Slutligt Driftsmeddelande*, 2021)

Threshold for:	***Type A***	***Type B***	***Type C***	***Type D***
Maximum continuous power	≥ 0.8 kW	≥ 1.5 MW	≥ 10 MW	≥ 30 MW
	and	and	and	or
Connection voltage	< 110 kV	< 110 kV	< 110 kV	≥ 110 kV

For the case studied in this thesis, the landowner (Stora Enso) aims to produce around 50 MW minimum, which means that this project will be classed as a type D.

After an agreement for connection to the grid has been reached, the process of connecting to the grid can be initiated. In RfG Section III (called "*Förfarande för driftsmeddelande för anslutning*" in Swedish) it is regulated which operational notifications should be used and what the specific requirements are for each operational notification. According to RfG Articles 33 & 37, four different operational notifications should be used for type D power production modules. Figure 16 illustrates a flow chart that outlines the process for connecting a facility to the grid. It is structured into four main parts, each representing a sequential stage in the connection process. (*Requirements for Grid Connection of Generators (RfG) 2016/631*, 2016)

The process for connecting a PPM to the grid begins with the establishment of a connection agreement between the module owner and grid owner. This agreement outlines the specific requirements for the power production module, which are used in its design and verified throughout the connection process. These requirements may be modified or supplemented during the first part of the process through mutual agreement between the grid owner and the module owner. (*Guide För Anslutning Av Kraftproduktionsmodul till Överföringssystemet - Från Anslutningsavtal till Slutligt Driftsmeddelande*, 2021)

Part 1: Report facility data

Before energizing the power production module's internal electrical network and auxiliary power, a notification of energization must be issued. This notification, required under RfG Article 34, grants the module owner the right to energize their internal network and auxiliary equipment using the specified grid connection. This notification is issued by the grid owner once all requirements are met, including inspections, documentation checks, and relay protection testing, which must be completed at least two months before the planned energization date.

Following this, the process moves to trial operation, where the theoretical validation of the module's requirements is conducted. A temporary operation notice allows the module owner to operate the module and generate power for a limited period, typically up to 24 months, with possible extensions if significant compliance progress is made. This phase includes providing detailed technical data, equipment certifications, and simulation models to verify static and dynamic performance, which are crucial for compliance testing and model validation.

Part 2: Theoretical requirement fulfillment

This phase involves ongoing trial operation where the module's performance is tested according to the compliance plan. A final operation notice is issued by the grid owner once all testing and validation requirements are met, allowing the module to operate indefinitely. This includes providing an updated compliance report based on validated simulation models and actual test data.

Throughout the module's operational life, the module owner must notify the grid owner of any technical changes that might affect compliance. Regular compliance testing and simulations are required to ensure ongoing adherence to standards, with the specifics of these tests negotiated between the grid owner and the module owner.

Part 3: Compliance testing & model validation

In this phase, the power production module undergoes trial operation where compliance testing is conducted according to the current test plan. The compliance testing aims to verify performance that can be validated through testing and to obtain measurement results for the validation of the simulation model and updating of installation data and technical details. According to RfG Article 36, a final operation notice grants the module owner the right to operate the facility indefinitely using the grid connection. This final notice is issued by the grid owner once the following requirements are met: a compliance test report based on the executed test plan, updated and validated simulation models, and an updated compliance simulation report performed with these models. Additionally, actual measured values during the compliance testing must be provided in an updated Annex 2 – installation data type C & D. The module owner must also provide an updated specified declaration of compliance to the grid owner, affirming full compliance with the requirements.

Part 4: Recurring verification

In this final step, it is verified that the power production module meets all applicable requirements in RfG and EIFS 2018:2, and a final operation notice has been issued. As the module is in commercial and ongoing operation, the module owner is responsible for notifying the grid owner in advance of any planned changes to the module's technical capabilities that could affect its compliance with the applicable requirements. Any operational incidents or faults in the power production module that affect its compliance must also be reported to the grid owner. The responsible system operator has the duty to assess compliance throughout the module's lifetime. Consequently, the grid owner has the right to request that the module owner conduct recurring compliance tests and simulations to verify compliance. The need for recurring testing may vary between power production modules and will be regulated separately between the grid owner and the module owner.

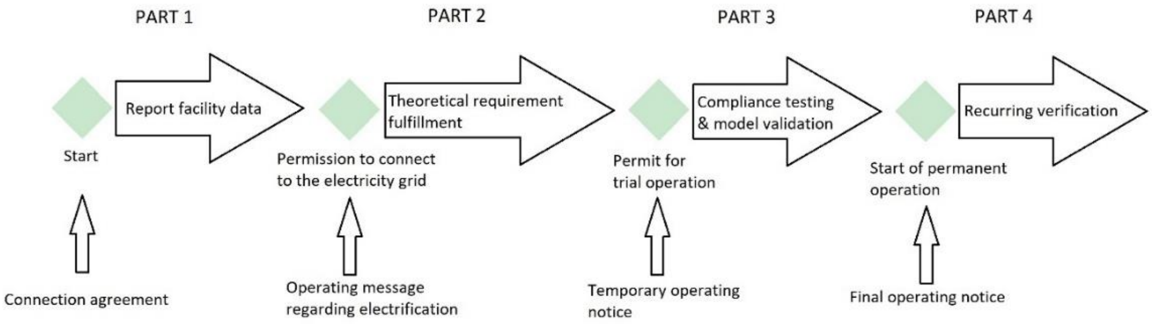


Figure 16 Process and operational notifications for grid connection (*Guide För Anslutning Av Kraftproduktionsmodul till Överföringssystemet - Från Anslutningsavtal till Slutligt Driftsmeddelande*, 2021)

2.4.5 Connection towards consumption

According to Arne Berglund, manager at Vattenfall Eldistribution AB, there are no legal obstacles that would prevent a company from connecting a solar farm directly to their facility and primarily use the electricity for their local needs. As long as the total yearly production does not exceed the total used electricity, and the solar farm only reduces their total electricity purchase, the company is allowed to connect any number of solar modules. Arne makes a comparison to how the rules are made for a private customer, and how they have the same rules. In a situation where a company becomes net producers, they must make arrangements with either an electricity trader or balance responsible, regarding how the sale should be conducted. (A. Berglund, personal communication, 22 March 2024)

According to company officials, if the solar farm can be legally connected to the facility for consumption, it will also automatically be able to transfer electricity to the grid, since such a connection already exists for the facility.

In order to build the high voltage power lines which are required for the solar farm, grid concession (SE: nätkoncession) is required. Grid concession is a type of permit that allows the holder to build and connect high voltage power lines with various limitations and within certain areas (*Koncessioner*, 2020). Note that even the standard 230 V power outlets used in Swedish homes are considered high voltage (*Ny som koncessionsinnehavare*, 2020).

There are a few different types of grid concessions, but the type that is relevant to this case is grid concession for line (SE: nätkoncession för linje) which mainly applies to power lines connected to the regional or national grids (*Nätkoncession för linje*, 2021). Since company officials specifically stated that they will not be connecting the solar farm to the local grid it is mostly regulations at the regional level that will be of interest.

The application for grid concession is a process which requires the applicant submit a vast array of documents, such as environmental impact assessments and technical specifications to the Swedish Energy Market Inspectorate (SE: Energimarknadsinspektionen), a government authority that handles various energy related issues (*Uppdrag och styrning*, 2020).

However, grid concession is not always required, because of the IKN-regulation or non-concession bound grids (SE: icke koncessionspliktiga nät, IKN) (*IKN - förordningen*, 2023). To determine if a case fulfills the requirements for IKN is a process that is unique to every case and depends on many aspects which will be explored further later in this paper. Simplified, there are three basic criteria that every case has to follow in order to be exempt from the grid concession requirement (*Interna nät och de tre kriterierna*, 2023):

1. Internal grid. The power line or transmission grid must be internal. An internal grid is used for transmission of electricity for the owner's account.
2. Not too widespread. The power line or electric grid cannot be too widespread.
3. Well-defined area. The area where the power line or electric grid is established must be well defined.

Since these criteria attempt to cover all situations, and not only solar farms, their exact implications are a bit confusing and intentionally broadly defined.

The enclosed company site is already under the IKN-regulation, but this area is far too small to contain a solar farm anywhere near the capacity of 50 MW.

The question is if the solar farm can be built outside the enclosed area, and the connection issues still would fall under the IKN-regulation. While it may be possible to attain a grid concession for the solar farm, the application process is time consuming, costly and is likely to delay the establishment of the solar farm. For this specific transformer station, there is also a complicated situation regarding ownership and who has legal rights or obligations and so on. According to company officials, the situation is currently under investigation by the grid owner. This unusual situation would undoubtedly complicate the grid concession permit even further, so it is much preferred to work under IKN conditions. Furthermore, there are other various problems that will be avoided if the solar farm qualifies for IKN, such as requiring various permissions from the grid owner.

2.4.6 The value of electricity and power tariffs

The hourly price for electricity changes constantly according to the so called "spot price" on the electricity market. Since there are different fees, taxes, and subsidies depending on if one is purchasing or selling electricity, the value of 1 kWh might be higher if saved (or avoid purchasing) compared to a sold. According to a decision by The Swedish Energy Markets Inspectorate, states in EIFS 2022:1, that by January 1, 2027, all electricity companies in Sweden are required to adopt a new pricing model that includes a power tariff. This model will potentially lower electricity network costs for consumers who distribute their electricity usage throughout the day or shift it to off-peak times and increase costs for those who consume large amounts of electricity simultaneously. Power tariffs are designed to ensure that the electricity network is used as efficiently as possible. With pricing based on power usage, electricity consumers are encouraged to spread out their electricity consumption to avoid peak loads that can cause problems in the electrical system. Typically, electricity usage is high during the morning and evening, and low during late evening, night, and early morning. A more even load on the electricity network has several advantages, including allowing more people to use the existing network and generally contributing to lower network costs and lower electricity prices. (*Effekttariffer*, 2023)

The power tariff is part of the network tariff, which is the fee charged by the electricity network company for transmitting electricity. This network tariff typically consists of a fixed part and one or more variable parts. The power tariff specifically relates to the variable part of the charge, which is based on the amount of electricity consumed hour by hour. Furthermore, the power charge will be calculated based on each customer's individual usage and the overall load on the electricity network. It will also be time-differentiated, meaning the charge will vary at different times to reflect the fluctuating load on the network. However, this time differentiation is not currently mandatory but will be required starting from January 1, 2027.(*Effekttariffer (effektavgift)*, 2022)

There are different tariffs depending on if a company is connected to the local or regional grid. Regional tariffs depend on what part of Sweden a user is located, which company owns the grid, and the connection voltage. The different levels for southern and middle Sweden, for the regional grid owner Ellevio, during 2024 can be seen in Table 3. For this case study, L130 is the relevant level.

Table 3 Regional power tariffs (ELLEVIO, 2024)

Power tariff regional	*T130*	*L130*	*T130T40*	*T40*	*L40*	*130T10*	*40T10*	
Connection voltage	132	132	33-55	33-55	33-55	6-24	6-24	*kV*
Fixed electricity grid fee	36	36	36	36	24	-	-	*TSEK/yr*
Compartment fee	300	130	75	75	75	38	38	*TSEK/yr, compartment*
Annual power (agreed upon)	112	222	197	307	405	374	504	*SEK/kW,year*
Overdraft annual effect	18.7	37.0	32.8	51.2	67.5	62.3	84.0	*SEK/kW, week*
Variable grid charge, fixed	0.74	1.35	0.79	1.40	2.02	1.40	2.07	*Öre/kWh*
Variable grid charge, spot price	0.13	0.39	0.15	0.41	0.68	0.41	0.70	*% of spot price*

Additionally, Ellevio also provides an input tariff, which includes fees for production and input to the grid. The fees for 2024 can be seen Table 4. For this case study, INL130 is the relevant level. (*Elnätspriser Inmatningsabbonemang*, 2024)

Table 4 Input tariff (ELNÄTSPRISER INMATNINGSABBONEMANG, 2024)

Input tariff	*INT130*	*INT130T40*	*INL130*	*INL40X*	*INT40*	*IN130T10*	*INL40*	*IN40T10*	
Fixed electricity grid fee	36	24	36	24	36	8.5	24	8.5	*TSEK/year*
Metering fee	36	16	36	16	16	8	16	8	*TSEK/year*
Metering fee customer owns transformer	15	8	15	8	8	4.5	8	4.5	*TSEK/year*
Distance-dependent annual power fee	0	0	0.38	0.38	0.38	0.38	0.76	0.76	*SEK/(kW*km), year*
Annual power fee	12	24	12	12	24	24	24	36	*SEK/kW, year*
Over transferring fee	2	4	2	2	4	4	4	6	*SEK/kW, week*

2.4.7 Tradable green certificates, subsidies, and EU emission trading

The major systems applied in Sweden to promote renewable energy production are tradable green certificates (Swedish: Elcertifikat), subsidies, and the EU emission trading system.(Lindahl et al., 2022)

Tradable green certificates are a Swedish system that grants certificates to renewable energy producers. These certificates can then be sold for a market price which as of February 2024, was 5.2 SEK / MWh. (*Elcertifikat*, 2024)

Electricity producers and intensive electricity consumers are required to fulfill a yearly quota of their produced or consumed electricity (*För dig som kvotpliktig*, 2023). The quota for consumer year 2023 was 25.1% and is expected to increase by 2-3 percentage points per year, to peak at 38.3% in 2029 (*Kvotplikt och elcertifikat | Fortum*, 2024). The quota will then decrease by around 2 percentage points per year until the system is taken out of place in 2035. The specifics of the quota system are subject to change, for example, the exact figures for the years 2024-2035 are yet to be settled (*Kvotnivåer*, 2023).

It is important to point out that the quota requirements do not account for the source of the consumed electricity. A renewable energy producer will still be subject to the quota, but they may receive certificates which they can then use themselves (*Deklaration av kvotplikt*, 2024).

Another very important aspect of the tradable certificates system is that production facilities constructed after 2021 will not be granted any certificates (*Elcertifikatsystemet*, 2023). In conclusion, the Swedish tradable certificate system will likely have little to zero impact on the revenue from the 50 MWp solar farm studied in this paper.

According to Lindahl et al., (2022) subsidies were introduced in 2005 for all investors of PV technology. However, it was mostly removed by the end of 2020 and as of 2024 subsidies for PV-systems are only granted to private individuals (*Stöd som du kan få vid investering*, 2024).

The EU emission trading system (ETS) is a system built on a principle called the polluter pays, which in effect means that companies pay for their GHG emissions. ETS governs the emissions of a few different GHGs, mainly CO_2 by putting a limit on the total allowed emissions in the EU (*Utsläppshandel*, 2024). It concerns energy producers and larger industries, who combined is estimated to contribute to around 40% of the EUs total GHG emissions. The allowed emission limit is reduced every year, with the current goals being to have 55% less net emissions in 2030 compared to 1990, and to be emission neutral in 2050.(*What Is the EU ETS?*, 2024)

The emissions are governed by allowances, that companies either buy on an auction market, or receive for free. For the current period 2021-2030, 57% of the allowances will be auctioned and 43% will be allocated free of charge. The free allowances are allocated by different national authorities, which in Sweden is the Environmental Protection Agency (SE: Naturvårdsverket). The free allowances are allocated to facilities based on 1) the scale of their emissions, 2) their emission-efficiency, and 3) the risk of the company moving their business outside of the EU, and thus harming the EU economy (this mostly concerns industrial production). This means that the more emission-friendly a facility is, and the more likely that it could move its operations outside of the EU, the more free allowances it will be granted relative to their total emissions. (*Så fördelas utsläppsrätter*, 2024)

ETS mainly concerns emissions from production and consumed heat, and not consumed electricity. (*Ansöka Om Gratis Tilldelning*, 2024) It is therefore unlikely that a solar farm would benefit a facility by reducing emissions that the ETS is concerned about. However, the criteria of being emission-efficient could be affected, which means that a solar farm might grant the facility extra emission allowances, which in turn would save the company money since they would need to buy fewer allowances. The average price of emission allowances was around 83 €/ton CO_2 and around 79 €/ton CO_2 in 2022. (*Statistik och uppföljning*, 2024)

How much extra revenue this would add for a solar farm is impossible to say without delving deep into the facilities emissions, and its possibilities of being granted free allowances, which are outside the scope of this paper. But the prices on allowances are rising, and are expected to rise even further, due to the future inclusion of more categories of polluters and the constant reduction of the emission limit. (*EU*, 2024)

3 Method

The electricity yield and optimization details will be evaluated through running various scenarios in the PV-simulation software PVsyst (*PVsyst – Photovoltaic Software*, 2024) and the software Winsun PV. Since Stora Enso is a large, multinational company, there is much information that is sensitive and confidential, even to the company's own employees. Because of this, the economic evaluation will be based on the aforementioned simulations, electricity market prices and other cost analyses.

The study utilizes an earlier screening of suitable locations done by Sweco which forms a basis for the location issues. Some of the location issues and most of the connection issues will be based on legal documents and both documentation and interviews with various grid owners, industry experts and government authorities.

3.1 Case study

For a project with a natural setting, such as the specific area/location investigated in this project, the case study method is an appropriate approach. This methodology is known for its effectiveness in delving into both singular and comparative analyses of cases (Denscombe, 2010, p. 64). Recognized for its comprehensive investigative capabilities, the case study method is supported by "six sources of evidence." These include the systematic collection of data through documents, interviews, direct observations, participant-observations, and the examination of physical artefacts (Yin, 1994, p. 53, 63, 78). A broad and diverse base of evidence is important for the reliability of the project, especially in the context of renewable energy projects, where environmental, technical, and social dimensions intersect. By using this method, our research gains a robust framework for investigation, significantly enhancing the depth of our findings in the early stages of the solar farm project.

3.2 Data collection

3.2.1 Weather and climate data

Two different kinds of climate data have been used in this case study. Simulations performed using the software PVsyst allows the use of numerous meteorological data sources (*Meteo Data Source – PVsyst*, 2024). This includes data from a "Meteo database", such as Meteonorm and NASA-SSE. For simulations with PVsyst performed in this case study, Meteonorm 7.1 was utilized.

Additionally, climate data has also been collected locally at the University of Gävle, which is located 15 km from the site in Skutskär. Data was collected using pyranometers of the model CMP 10 (*CMP10 Class A Pyranometer - Kipp & Zonen*, 2024). These are connected for continuous measurement of global and diffuse radiation against a horizontal surface as well as radiation at a 45-degree tilt, which can be seen in Figure 17. This set-up has been collecting measurements during the entirety of 2023 which has later been compiled by Hernando Uriarte, (2024), who also provided the data used in the climate file and utilized for simulations performed with Winsun PV.

FIGURE 17 PYRANOMETER SET-UP

3.2.2 Interviews

Finding information about the legal requirements for connecting a solar farm to the power grid was challenging. This was mainly because there are few well-known examples of companies that have successfully done this. As a result, interviewing people who work in the industry became the most effective way to gather the necessary information. According to Lo Iacono et al., (2016) the common conception is that in-person methods for collecting data through interviews is the superior way to collect in-depth and reliable data. However, a study by (Dahlin, 2021) argues that electronic research, such as interviews via email, has become more trustworthy in recent years, and since the COVID-19 pandemic, it has become a more common way for gather data.

To collect information, email was used to send out questionnaires to various companies and experts in the field. This required us to ask clear and direct questions in a consistent manner. However, one of the biggest hurdles was getting people to respond. Since most people we contacted were not obligated to reply, they only did so if they wanted to. To encourage participation, we explained the purpose of our study, promised to keep their information confidential, and allowed them to answer in their own time. This approach often led to more detailed responses.

Two questionnaires were used, the first one was sent to people working in the solar farm industry, and the second one was sent to grid owning companies. The questionnaires were designed as following:

Questionnaire 1:

1. What model of solar panel and inverter would you recommend in a Nordic climate such as in Gävle?
2. Is there any significant difference in tilt, orientation, and row spacing between different parts of Sweden?
3. Is there anything else we should consider for a solar farm project?

Questionnaire 2:

1. Is there anything directly preventing a solar farm being connected directly to the regional grid?
2. What requirements/limits apply to how much power you are allowed to connect?

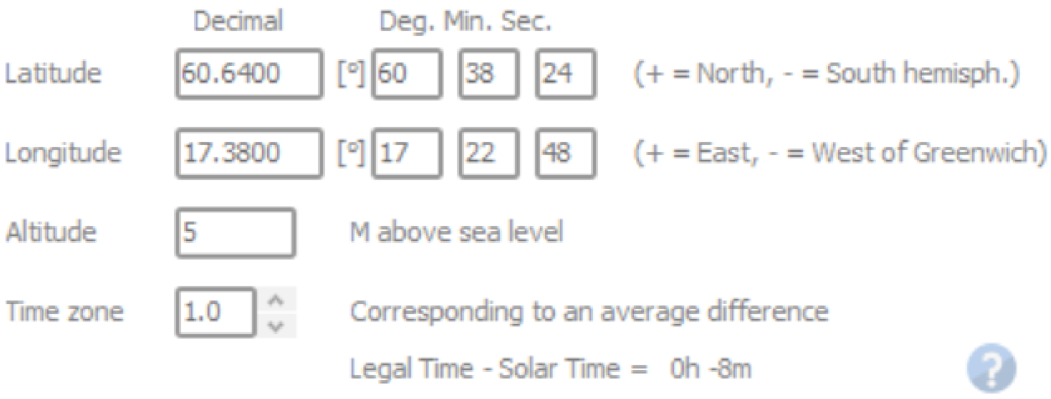
Email interviews are affordable, compared to traveling, and enable one to reach people across different geographical locations. It also allows for an easy way to organize the responses and analyze them for common themes. However, this method has its downsides, such as lower response rates and the absence of body language, which can sometimes cause misunderstandings (Amri et al., 2021). It's also crucial to consider ethical issues like privacy and cultural sensitivity to ensure the research is conducted respectfully and responsibly.

3.3 PVsyst input

PVsyst is an advanced software which allows the user to change a vast array of inputs. However, the software recommends basic users to leave the majority of these inputs at the default values. Inputs and variables which are not mentioned in this chapter, have been left at their default values.

Geographical location / site file

The site file was generated using the built-in function in PVsyst where the user selects location from an interactive world map. The location of the facility in Skutskär generated the coordinates shown in Figure 18.



	Decimal		Deg.	Min.	Sec.	
Latitude	60.6400	[°]	60	38	24	(+ = North, - = South hemisph.)
Longitude	17.3800	[°]	17	22	48	(+ = East, - = West of Greenwich)
Altitude	5	M above sea level				
Time zone	1.0	Corresponding to an average difference Legal Time - Solar Time = 0h -8m				

FIGURE 18: GEOGRAPHICAL LOCATION INPUT IN PVSYST.

These site data are then used by PVsyst to collect climate data from Meteonorm from which PVsyst generates a synthetic hourly climate data file. Note that the measured climate data file was not accepted by PVsyst and was therefore not used in combination with this software.

Tilt angle

Various different tilts were tested, based on literature reviews and interviews with experts in the field. The most efficient tilt according to PVsyst was 30°. This tilt was therefore used in the economic evaluations.

Pitch and shading angle

The pitch needed for each system setup and shading angle was calculated using Equation 1. The different shading angles that were used were 10°, 18°, 21°, 28°, with 18° giving the most desirable results, and was therefore chosen for the economic analysis.

Azimuth angle

According to literature, a zero-degree azimuth angle (facing directly towards the south) has been proven to provide the highest annual specific yield (kWh / installed kWp) and it is by far the most common angle used in the northern hemisphere. (Killinger et al., 2018) For this reason are all the simulations in this study performed using a 0° azimuth angle.

Solar module and inverter data

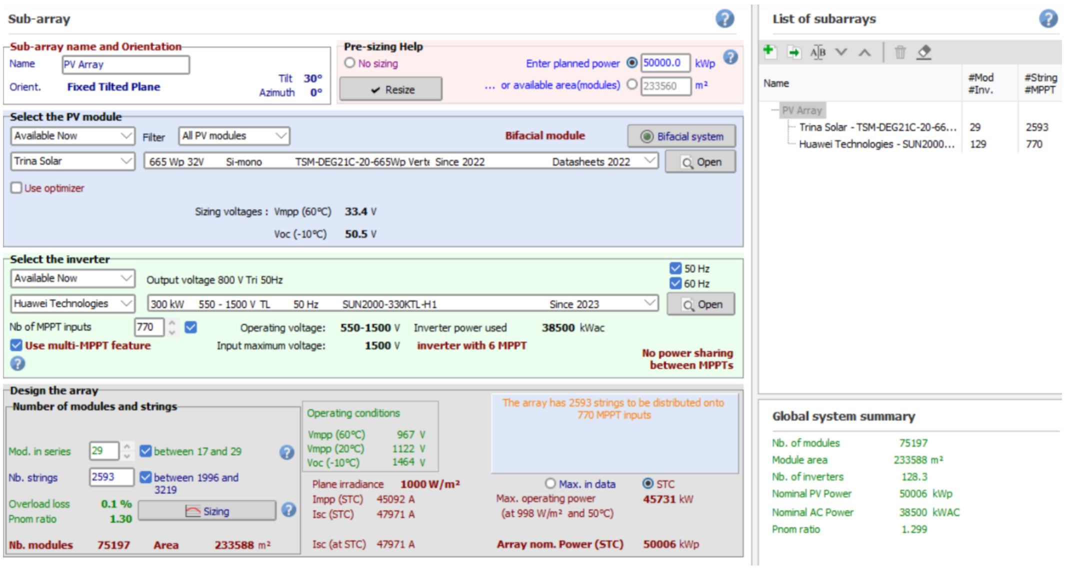
The module type used was TSM-DEG21C.20 Vertex bifacial dual glass monocrystalline 665 Wp manufactured by Trina Solar (Trina Solar, 2022). Originally, the most suitable module was found to be TSM-NEG21C.20 Vertex N Bifacial dual glass 695 Wp (Trina Solar, 2023), however this version was not available in the PVsyst database, which is why the 665 Wp type was used instead. Both of these modules measure 2.384 x 1.303 m. This means that the length of the module is 2.384m in portrait orientation and 1.303m in landscape orientation.

The inverter type used was SUN2000-330KTL-H1 300 kW 550-1500V with 6 MPPTs manufactured by Huawei Technologies (Solar Huawei, 2023).

Both module and inverter types used in the simulations were based on interviews with stakeholders of other solar farms, and experts in the field. The rules of thumb are that modules should have as high wattage as possible and an inverter size of around 300 kW will result in a moderate number of inverters. It is desirable not to have too many inverters since it is more expensive, but at the same time having too few can result in large losses in case of malfunctions. Another aspect to consider is to buy products from trustworthy manufacturers, which according to the interviews, both Trina Solar and Huawei are.

System setup

The system was set-up simply by entering the planned power of 50 MWp, using Perez as the transposition model, and using the auto-sizing feature to let the software calculate the number of modules per string, number of strings, number of inverters etc. The details of the system setup are shown in Figure 19. This setup was used for all simulations.



Sub-array

Sub-array name and Orientation

Name: PV Array

Orient.: **Fixed Tilted Plane** Tilt **30°** Azimuth **0°**

Pre-sizing Help

○ No sizing

Enter planned power ● 50000.0 kWp

… or available area(modules) ○ 233560 m²

Select the PV module

Available Now | Filter: All PV modules | **Bifacial module** | ● Bifacial system

Trina Solar | 665 Wp 32V Si-mono TSM-DEG21C-20-665Wp Vert Since 2022 Datasheets 2022

☐ Use optimizer

Sizing voltages : Vmpp (60°C) **33.4** V

Voc (-10°C) **50.5** V

Select the inverter

Available Now | Output voltage 800 V Tri 50Hz | ☑ 50 Hz ☑ 60 Hz

Huawei Technologies | 300 kW 550 - 1500 V TL 50 Hz SUN2000-330KTL-H1 Since 2023

Nb of MPPT inputs 770 ☑ Operating voltage: **550-1500** V Inverter power used **38500** kWac

☑ **Use multi-MPPT feature** Input maximum voltage: **1500** V **inverter with 6 MPPT**

No power sharing between MPPTs

Design the array

Number of modules and strings

Mod. in series 29 ☑ between 17 and 29

Nb. strings 2593 ☑ between 1996 and 3219

Overload loss 0.1 %

Pnom ratio 1.30

Nb. modules **75197** **Area** **233588** m²

Operating conditions

Vmpp (60°C) 967 V

Vmpp (20°C) 1122 V

Voc (-10°C) 1464 V

Plane irradiance **1000 W/m²**

Impp (STC) 45092 A

Isc (STC) 47971 A

Isc (at STC) 47971 A

The array has 2593 strings to be distributed onto 770 MPPT inputs

○ Max. in data ● STC

Max. operating power (at 998 W/m² and 50°C) **45731** kW

Array nom. Power (STC) **50006** kWp

List of subarrays

Name	#Mod #Inv.	#String #MPPT
PV Array		
Trina Solar - TSM-DEG21C-20-66…	29	2593
Huawei Technologies - SUN2000…	129	770

Global system summary

Nb. of modules	75197
Module area	233588 m²
Nb. of inverters	128.3
Nominal PV Power	50006 kWp
Nominal AC Power	38500 kWAC
Pnom ratio	1.299

FIGURE 19: SYSTEM SETUP FOR PVSYST.

Horizon shading

The horizon height was set to a uniform 10°. This is the default for Sweden used by Winsun PV, and it is an accurate figure for sub-urban areas in central Sweden according Diogo Cabral, PV-systems researcher at HiG (D. Cabral, personal communication, 10 March 2024). The horizon height and its impact on the sun paths of Skutskär according to PVsyst is shown in Figure 20

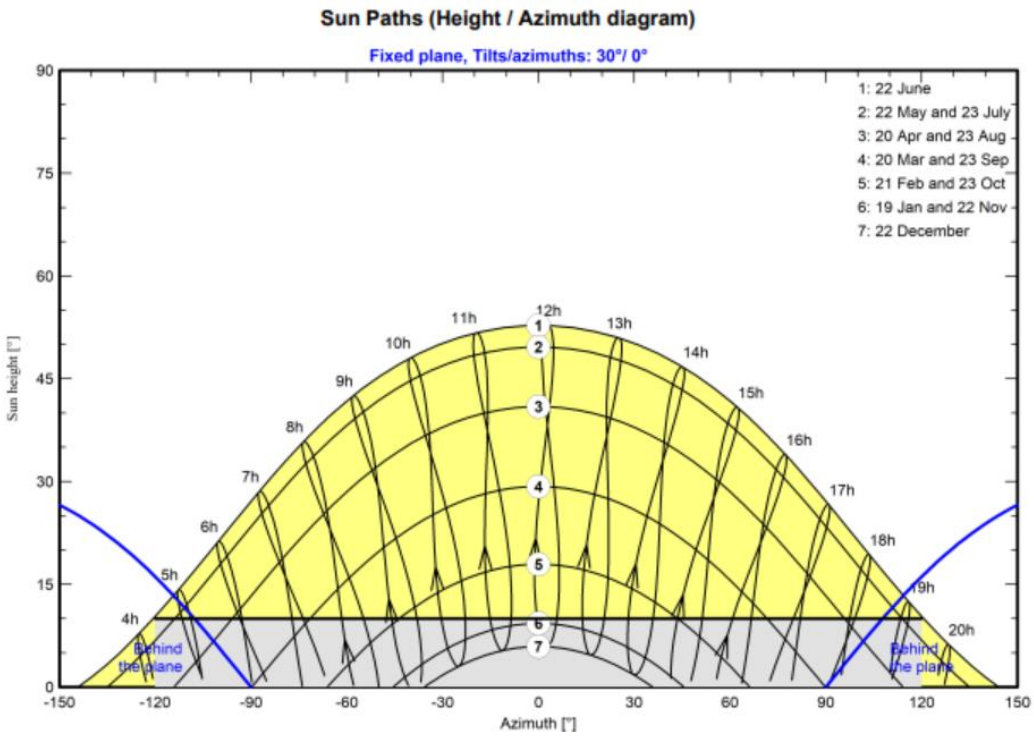
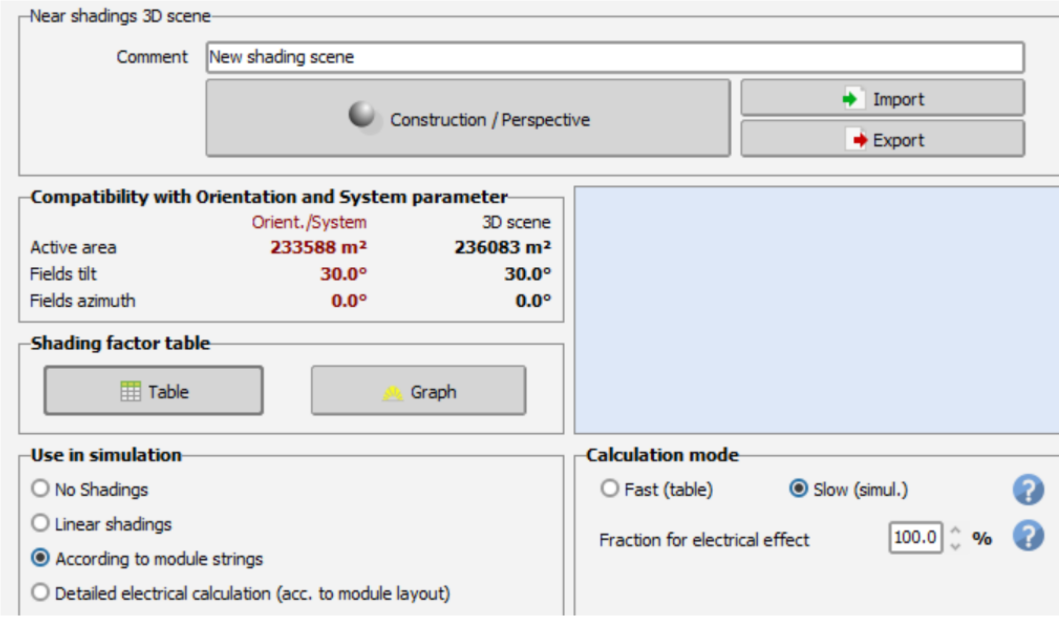


FIGURE 20: SUN PATHS AND HORIZON USED IN PVSYST

Shading scene setup

The near shadings settings used were according to module strings, and slow simulation as shown in Figure 21. As far as we know, these are the most advanced shading settings available for a system of this size, since a detailed electrical calculation cannot be chosen for a system larger than 5 MWp.



Comment: New shading scene

Compatibility with Orientation and System parameter

	Orient./System	3D scene
Active area	**233588 m²**	**236083 m²**
Fields tilt	**30.0°**	**30.0°**
Fields azimuth	**0.0°**	**0.0°**

Use in simulation

○ No Shadings
○ Linear shadings
● According to module strings
○ Detailed electrical calculation (acc. to module layout)

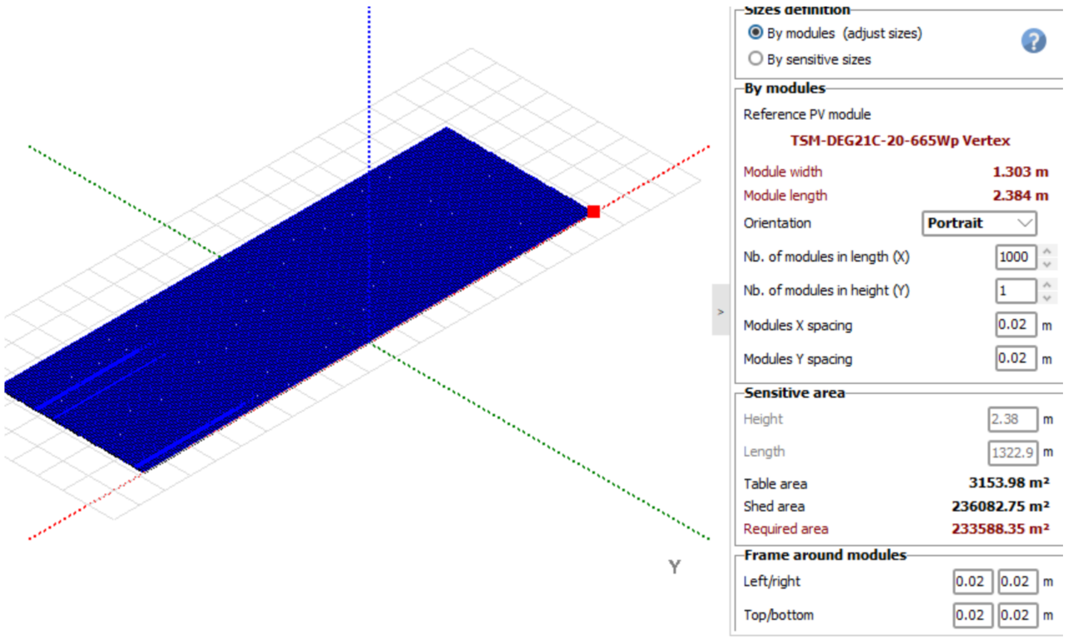
Calculation mode

○ Fast (table) ● Slow (simul.)

Fraction for electrical effect 100.0 %

FIGURE 21 NEAR SHADINGS SETTINGS

The shading scene was constructed as a simple rectangle as shown in Figure 22. The exact number of rows was simplified to 76, each consisting of 1000 modules. This meant that the shading system consisted of 76 000 modules instead of the 75 192 specified in the system inputs. However, this detail only affects shading and tests showed that slight changes in row and module numbers had virtually no impact on the final results. It should be noted that for some of the setups, the shading scene changed somewhat, since it is dependent on module orientation and pitch. But all simulations used the simple 76x1000 rectangle setup.



Sizes definition
● By modules (adjust sizes)
○ By sensitive sizes

By modules
Reference PV module
TSM-DEG21C-20-665Wp Vertex

Module width	1.303 m
Module length	2.384 m
Orientation	Portrait
Nb. of modules in length (X)	1000
Nb. of modules in height (Y)	1
Modules X spacing	0.02 m
Modules Y spacing	0.02 m

Sensitive area

Height	2.38 m
Length	1322.9 m
Table area	3153.98 m²
Shed area	236082.75 m²
Required area	233588.35 m²

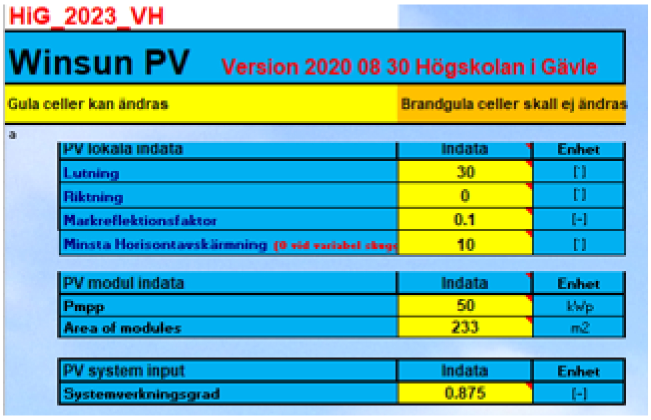
Frame around modules

Left/right	0.02	0.02 m
Top/bottom	0.02	0.02 m

FIGURE 22: SHADING SCENE SETUP IN PVSYST.

3.4 Winsun PV input

The inputs used in Winsun PV are shown in Figure 23. These inputs, such as the tilt of the modules, were carried over from the best performing PVsyst scenario and used for the Winsun PV simulation as well. The software expects kW as input, but if 50 000 kW is used, some of the text boxes will not display output correctly. Therefore, some inputs were adjusted in the software towards the expected kW, but the end-results will be the same as if it was in MW. The module area was set to 233, which was taken from the PVsyst calculated total area of 233 588 m^2, but adjusted for kWp. The measured weather data from the University of Gävle was used as climate data input for the simulation.



HiG_2023_VH

Winsun PV Version 2020 08 30 Högskolan i Gävle

Gula celler kan ändras | Brandgula celler skall ej ändras

PV lokala indata	Indata	Enhet
Lutning	30	[°]
Riktning	0	[°]
Markreflektionsfaktor	0.1	[-]
Minsta Horisontavskärmning (0 vid variabel skugg	10	[°]

PV modul indata	Indata	Enhet
Pmpp	50	kWp
Area of modules	233	m2

PV system input	Indata	Enhet
Systemverkningsgrad	0.875	[-]

FIGURE 23: WINSUN PV INPUTS.

One difference between Winsun PV and PVsyst is that Winsun PV does not consider mutual shadings, it does however consider horizon shadings, which makes up the majority of all shading losses. The mutual shading losses will not be considered in the Winsun PV results.

3.5 Calculations

3.5.1 LCOE

The formula used to calculate LCOE for solar farms is shown in Equation 2.

Equation 2

$$LCOE = \frac{CAPEX_0 + \sum_{t=1}^{N}\left[\frac{O\&M_f + O\&M_v * Y_0 * (1-Dg)^t}{(1+WACC_r)^t}\right] + \frac{ReInv_1}{(1+WACC_r)^{x1}} + \frac{ReInv_2}{(1+WACC_r)^{x2}} + \frac{ResC}{(1+WACC_r)^N}}{\sum_{t=1}^{N}\left[\frac{Y_0 * (1-Dg)^t}{(1+WACC_r)^t}\right]}$$

Where $CAPEX_0$ is the initial capital investment in SEK, N is the lifetime of the project in years, $O\&M_f$ is the fixed operation and maintenance costs in the year t, expressed in SEK, $O\&M_v$ is the variable operation and maintenance cost in the year t, expressed in SEK, Y_0 is the annual electricity production during the first year or production before degradation has occurred expressed in MWh, Dg is the annual degradation factor expressed in a decimal number, $ReInv_1$ is the first reinvestment in year x_1 needed to reach the expected lifetime, expressed in SEK, $ReInv_2$ is the second reinvestment in the year x_2 needed to reach the expected lifetime, expressed in SEK, ResC is the residual cost at the end of the projects lifetime, expressed in SEK and $WACC_r$ is the real weighted average cost of capital per annum expressed in a decimal number. (Lindahl et al., 2022)

For a more in-depth explanation, see 2.3.8.

3.5.2 Spot price, saved, purchased, and sold electricity

The total cost of electricity excluding taxes and fees was calculated by multiplying every individually purchased kWh with the corresponding price for one kWh at that specific time. A similar calculation was performed for the generated electricity from the simulated solar farm. Both PVsyst and Winsun PV provide data which corresponds to the amount of kWh generated each hour for 1 year, or 8760 hours, in total. This data was then combined with the purchased kWh and the spot price for 2023, then subsequently compiled to achieve the total value (excluding taxes and fees) of the electricity generated with the simulated solar farm. The spot price for electricity for SE3 during 2023 was provided by Mattias Gustavsson at the University of Gävle, and the data regarding purchased electricity was provided by Abolfazl Hayati at Stora Enso.

Since taxes and fees are constant for any single kWh, i.e., not dependent on the time of day, these could be calculated by simply multiplying them with the total kWh, purchased and generated respectively, for 2023. In order to accurately allocate various fees, taxes, and subsidies the entire financial gain from the solar farm is calculated as a reduction of the facility's current annual electricity cost, and not as revenue.

3.5.3 Average values of electricity and Weighted average value

The average values of conserved, sold and produced electricity for this particular PV-system with the SE3 spot prices over the entire year of 2023 was calculated with the following method: The amount of electricity that was either produced, conserved or sold for every hour was multiplied with the corresponding spot price during that hour. Then these costs are summed up and divided by the total amount of the respective type of electricity.

The weighted average value (WAV) for a PV-produced kWh for this particular system calculated using Equation 3.

EQUATION 3

$$WAV = \frac{E_s}{E_{tot}} * (P_{as} + Fee_s) + \frac{E_c}{E_{tot}} * \left(P_{ac} + Fee_p\right)$$

Where:

E_s is the amount of electricity sold during the year in kWh, E_{tot} is the total amount of produced electricity during the year in kWh, P_{as} is the average price of sold PV electricity for that year in öre/kWh, Fee_s is all the additional fees and taxes added to sold electricity in öre/kWh, E_c is the amount of conserved electricity due to the PV-production for that year in kWh and Fee_p is all the additional fees and taxes added to purchased electricity. This gives an average value of a kWh of electricity including all taxes and fees, regardless of when it is produced or if it was sold to the grid or used by the industry itself.

3.5.4 Cost Assumptions

Several assumptions have been made regarding the LCOE in this project. Since an in-depth economic analysis will require insight into the economic details of the company, the costs in this feasibility study will be based on assumptions and averages based on data from other solar farm projects. This data comes from 1) Lindahl et al., (2022) who provides real cost data for six solar farms in Sweden, built between 2019-2020, and 2) An investment analysis document regarding a solar farm that was provided by the company. Note that cost data provided by Lindahl et al., (2022) is anonymized by dividing the costs of each scenario with the MWp of that specific solar farm. This has no impact on the final LCOE result. Table 6 shows an overview of the all the various cost items presented by Lindahl et al., (2022), which makes up the basis of assumptions for the LCOE calculations in this case study. Table 5 shows the various sub costs which makes up the total CAPEX costs.

Table 5 Detailed CAPEX costs (Lindahl et al., 2022)

All units [€/MWp]	***Project 1***	***Project 2***	***Project 3***	***Project 4***	***Project 5***	***Project 6***	***Average***
Total labor cost	247 489	100 433	-	-	113 323	164 693	156 485
Total component and material costs	389 821	559 052	-	-	429 683	475 156	463 428
Total cost for subcontractors	637 310	659 484	744 154	562 617	543 006	639 850	631 070
Grid connection costs	23 650	44 274	9 615	23 840	19 538	56 662	29 596
Land costs	0	0	0	0	40 705	0	6 784
Owner costs	1 953	0	22 321	63 573	0	15 739	17 264
Total CAPEXo	**662 912**	**703 758**	**776 091**	**650 030**	**603 250**	**712 251**	**684 715**

TABLE 6 LCOE DATA (LINDAHL ET AL., 2022)

	Project 1	***Project 2***	***Project 3***	***Project 4***	***Project 5***	***Project 6***	***Average***
Lifetime [years]	20	45	30	40	30	30	33
Annual yield [MWh/MWp/a]	910.1	927.6	1 018.2	975.0	1 012.1	970.0	968.8
Annual degradation [%]	0.3	0.1	0.3	0.2	0.4	0.2	0.27
CAPEX [€/MWp]	662 912	703 758	776 091	650 030	603 250	712 251	684 715
Yearly fixed operation and maintenance cost [€/MWp/a]	4 546	11 277	11 576	9 182	4 201	8 908	8 282
Variable operation and maintenance cost [V/MWh]	0.95	-0.83	-1.04	0.08	-1.89	1.79	-0.16
First major reinvestments [€/MWp]	15 188	88 071	51 510	27 813	73 269	75 549	55 233
Year after commissioning for the first major reinvestment [year]	15	25	15	15	15	15	16.7
Second major reinvestment [€/MWp]	-	-	-	11 920	-	-	11 920
Year after commissioning for the second major reinvestment [year]	-	-	-	30	-	-	30
Residual cost [€/MWp]	10 849	0	0	0	0	0	1 808
Nominal weighted average cost of capital per annum [%]	3.10	0.75	2.18	6.50	3.97	4.00	3.42
Real weighted average cost of capital per annum [%]	1.07	-1.23	0.17	4.41	1.93	1.96	1.39
Annual inflation [%]	2	2	2	2	2	2	2
Levelized cost of electricity [€/MWh]	**49.39**	**27.37**	**39.95**	**47.65**	**32.93**	**47.43**	**40.79**

Note that more detailed information regarding the costs is provided by Lindahl et al., (2022) and used in the assumptions in this case study.

Costs for three different scenarios were calculated: A *harsh* conditions scenario where variables were set to the worst expected, but still within realistic limits, a *moderate* conditions scenario where variables were set to mostly averages, and a *lenient* conditions scenario, where variables were set to the best possible but still realistic values.

Six different costs have been calculated for each of the three scenarios, with different WACCs (4%, 5.7%, and 6.5%), and O&Mv set to zero. This was done upon request from company officials to analyze different interest rates, since the WACC is subject to change with time. The calculations were performed with annual specific yield generated from both PVsyst and Winsun PV.

Scenario 1 – Harsh conditions.

Lifetime – 30 years. Since the PV-modules guarantee a 30-year power warranty, this was deemed to be the lowest possible expected lifetime of the solar farm. (Trina Solar, 2023)

Degradation rate – 0.4%. This is provided by the PV-modules datasheet.

WACC – 4.0% and 5.7% and 6.5%. These three rates were calculated for all scenarios.

Fixed operation & maintenance (O&Mf) – 11576 €/MW$_p$ & year. For the harsh scenario, the highest cost among the available data was chosen.

Variable operation & maintenance (O&Mv) – 2.9 €/MWh. Based on the highest balance and trading costs from the data. Any grid compensation is excluded in this scenario, so this is strictly a cost.

First major reinvestment – 75549 €/MW$_p$ after 15 years. Since the expected lifetime of inverters is around 15 years, this cost was based on the highest reinvestment cost among the data that occurred after 15 years.

Second major reinvestment – none. Since the lifetime in this scenario is only 30 years, no second reinvestment is needed.

Residual costs – none. The residual costs and demolition costs are expected to balance out as explained by Lindahl et al., (2022)

CAPEX:

Total costs for subcontractors – 639850 €/MW$_p$. This is the median subcontractors cost in the data. Since this item includes costs for ground preparation and the land at the site is deemed to have excellent conditions for a solar farm this cost will probably not be on the high end even in a harsh scenario.

Grid connection costs – 9615 MW$_p$. This cost was set to the lowest among the data, since it is very likely that the solar farm will fall under the IKN-regulation, these costs should be drastically lower than the norm.

Land costs – none. Since the company already owns the land, there will be no added land costs.

Owner costs – 63573 €/MW$_p$. The highest cost among the owner costs' data was chosen for this scenario. Owner costs include preliminary permit processes, project management, and site investigations.

These costs summed up to a total CAPEX of 713038 €/MW$_p$.

Scenario 2 – moderate conditions

Lifetime – 40 years. Since there is evidence of degradation being lower in Sweden and solar farms surviving longer, it is reasonable to assume a longer lifetime than the documented warranty of the modules. (Stridh, 2016) & (Wallnér, 2019)

Degradation rate – 0.2%. Although the datasheet gives a degradation rate of 0.4% per year (Trina Solar, 2023), evidence suggests that the degradation rate is lower in cold climates. (Stridh, 2016) & (Wallnér, 2019)

WACC – 4.0% and 5.7% and 6.5%. These three rates were calculated for all scenarios.

Fixed operation & maintenance (O&Mf) – 8282 €/MW$_p$ & year. For the moderate scenario, the average cost was chosen.

Variable operation &maintenance (O&Mv) – 1.9 €/MWh. Based on the average of balance and trading cost from the data. Any grid compensation is excluded in this scenario, so this is strictly a cost.

First major reinvestment – 27813 €/MW$_p$ after 15 years. The reinvestment costs were based on the data from the solar farm with an expected lifetime of 40 years and requiring two reinvestments.

Second major reinvestment – 11920€/MW$_p$ after 30 years. Based on the specific case as explained above.

Residual costs – none. The residual costs and demolition costs are expected to balance out as explained by Lindahl et al., (2022)

CAPEX:

Total costs for subcontractors – 639850 €/MW$_p$. This is the median subcontractors cost in the data. Since this item includes costs for ground preparation and the land at the site is deemed to have excellent conditions for a solar farm this cost will probably not be on the high end.

Grid connection costs – 9615 MW$_p$. This cost was set to the lowest among the data, since it is very likely that the solar farm will fall under the IKN-regulation, these costs should be drastically lower than the norm.

Land costs – none. Since the company already owns the land, there will be no added land costs.

Owner costs – 17264 €/MW$_p$. The average cost among the owner costs' data was chosen for this scenario. Owner costs include preliminary permit processes, project management, and site investigations.

These costs summed up to a total CAPEX of 666729 €/MW$_p$.

Scenario 3 – Lenient conditions

Lifetime – 40 years. Since there is evidence of degradation being lower in Sweden and solar farms surviving longer, it is reasonable to assume a longer lifetime than the documented warranty of the modules (Stridh, 2016) & (Wallnér, 2019). It is also reasonable to assume a longer lifetime than 40 years, but since this has quite a large impact on the final LCOE value, and it might not be interesting for a company to calculate costs for such long-term projects, it was decided to leave this figure at 40 years.

Degradation rate – 0.2%. Although the datasheet gives a degradation rate of 0.4% per year (Trina Solar, 2023), evidence suggests that the degradation rate is lower in cold climates. (Stridh, 2016) & (Wallnér, 2019)

WACC – 4.0% and 5.7% and 6.5%. These three rates were calculated for all scenarios.

Fixed operation & maintenance (O&Mf) – 8282 €/MW$_p$ & year. For the lenient scenario, the average cost was chosen. Since the variations in the data is a result of some of the solar farm owners will handle the maintenance themselves, they did not include these costs in their data. Since this would not eliminate the need for maintenance, and it will still function as a form of a cost, the average operation and maintenance cost was considered to be the most realistic even in a lenient scenario.

Variable operation & maintenance (O&Mv) – 0.9 €/MWh. Based on the lowest of balance and trading cost from the data. Any grid compensation is excluded in this scenario, so this is strictly a cost.

First major reinvestment – 27813 €/MW$_p$ after 15 years. The reinvestment costs were based on the data from the solar farm with an expected lifetime of 40 years and requiring two reinvestments.

Second major reinvestment – 11920€/MW$_p$ after 30 years. Based on the specific case as explained above.

Residual costs – none. The residual costs and demolition costs are expected to balance out as explained by Lindahl et al., (2022)

CAPEX:

Total costs for subcontractors – 543006 €/MW$_p$. Since this item includes costs for ground preparation and the land at the site is deemed to have excellent conditions for a solar farm this cost was set to the lowest among the data in this scenario.

Grid connection costs – 9615 MW$_p$. This cost was set to the lowest among the data, since it is very likely that the solar farm will fall under the IKN-regulation, these costs should be drastically lower than the norm.

Land costs – none. Since the company already owns the land, there will be no added land costs.

Owner costs – 1953 €/MW$_p$. The Lowest cost among the owner costs' data was chosen for this scenario. Owner costs include preliminary permit processes, project management, and site investigations.

These costs summed up to a total CAPEX of 554574 €/MW$_p$.

3.6 Data analysis

3.6.1 Microsoft Excel

Microsoft Excel is a rather powerful software for data analysis, due to its comprehensive set of tools features available which simplifies and speeds up the process of analyzing and interpreting data. Excel was used to process all of the numerical data, as well as creating the corresponding graphs, tables and diagrams.

4 Results

4.1 Regulatory issues

The legal aspects concerning establishing a solar farm are many. Oscar Öhrman, from the industry association Svensk Solenergi, points out that the most demanding, challenging, aspect of constructing a solar farm involves achieving a grid connection for a reasonable cost. (O. Öhrman, personal communication, 27 February 2024)

4.1.1 Zoning area

Solar farms typically do not require a building permit when constructed outside designated zoning areas (SE: Detaljplanerat område) (*Tillstånd för solcellspark*, 2024). Figure 24 A) outlines these zoning areas with black and pink lines, while Figure 24 B) identifies potential sites for future solar farms, highlighted in pink and brown. A comparison of these two maps reveals no overlap between the designated zoning areas and the potential sites for solar farms, leading to the conclusion that building permits are not necessary for the solar panels themselves. However, upon closer inspection, it is observed that both the factory and the transformer station fall within a zoning area. Consequently, any additional equipment required for this project may need a building permit if it is to be situated within the zoning boundaries.

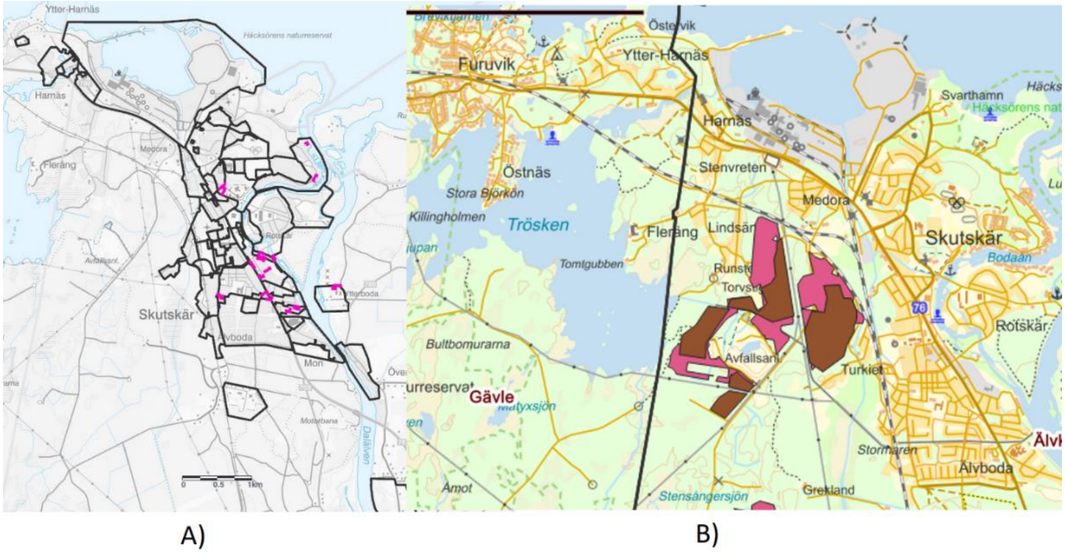


Figure 24 Zoning areas compared to potential solar farm areas (Gävle kommun, 2024)

4.1.2 Connecting towards electricity consumption

Since the 50 MW solar farm in its entirety will likely consist of a few separated but interconnected smaller PV-systems (sections), the connection issues can be divided into two parts: connection between the different sections, and connection from the solar farm to the regional transformer station. The regulation documentation “undantagen i IKN-förordningen” (5 - 22 c §§) (*Undantagen i IKN-förordningen*, 2023) refers to a specific solar farm application for guidance. In the official decision (*Bindande besked om undantag från kravet på nätkoncession Ärendenummer—2022-101635*, 2023) the applicant EEW Sweden 1 AB plans on building a solar farm consisting of two sections that are located around 500 meter apart from each other. The application for exception to grid concession concerned both internal transmission lines between the two sections and a 2 150m long power line connecting the solar farm to the regional grid station see Figure 25.

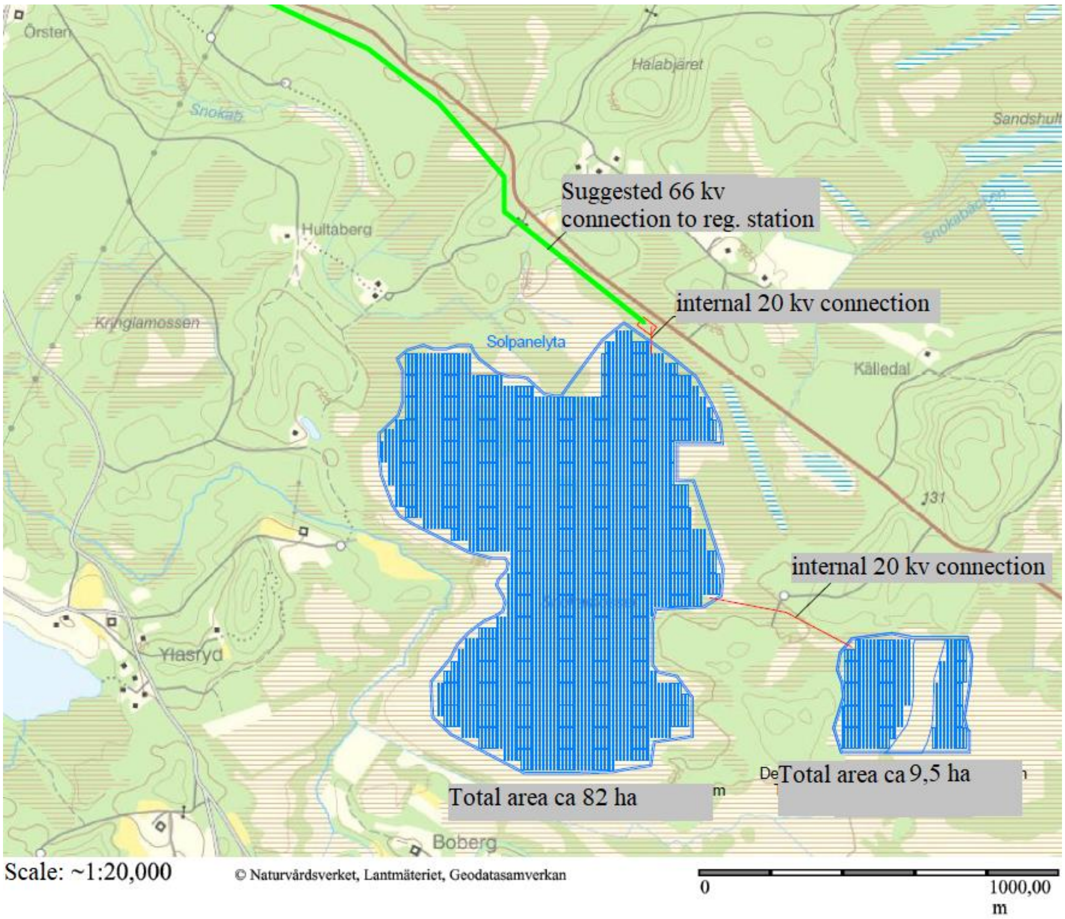


FIGURE 25 AREA OVERVIEW OF A PROPOSED SOLAR FARM

According to the decision, the internal lines between the solar farm sections (red lines in Figure 25) were approved while the power line to the transformer station (green line in Figure 25) was not.

In this case, the current owner of the grid opposes that the proposed solar farm should fall under the IKN-regulation. In their statement, they claim that for wind power, 1 200 meter long power lines have been accepted. But wind power needs to be located far away from residential areas since they create noise and shading. They then argue that since this case concerns a solar farm, which does not need to be distanced from communities or buildings, and the planned power line is longer than the accepted custom for wind power, it should not be granted exception for grid concession.

In the official decision (*Bindande besked om undantag från kravet på nätkoncession Ärendenummer—2022-101635*, 2023) by the Swedish Energy Markets Inspectorate, the transmission line between the sections was judged to fall under the IKN-regulation. However, the planned power line to the regional grid station was deemed not to. The basis for the decision was that the sectional transmission line is shorter than the width of the larger of the two sections and there is no infrastructure or similar activity in the area, which would make it difficult to define the area. Therefore, the transmission grid within the solar farm is within a defined area and falls under the IKN-regulation. For the transmission line to the regional grid station, it is longer than the width of the solar farm, therefore it cannot be considered short. In addition, this transmission line is not within the defined area of the solar farm which makes it unclear where the boundary between the transmission grid and other land is. Therefore, the transmission line to the regional substation is denied IKN privileges.

In another solar farm case from 2021 (*Bindande besked om undantag från kravet på nätkoncession Ärendenummer—2020-103085*, 2021), all connection issues were decided to fall under the IKN-regulation. This case was referred to by the Swedish Energy Markets Inspectorate as the first official decision made by them regarding the impact of the IKN-regulation on solar farms. In that case, the applicant Svedberga PV AB applied for exception to grid concession for a transmission grid within the solar farm PV Svedberga, "with up to five connection lines to the transformer station". The power lines to the transformer station will be about 650m long. The number of power lines to the transformer station depends on final connection voltage, 36 or 145 kV. The power lines will cross a few properties and a small road before it reaches the transformer station which is located on its own property. Neither of the two existing holders of grid concession in the area had any objections against the application. (*Ledningsnät i solcellspark med anslutningsledningar undantas från kravet på nätkoncession*, 2021)

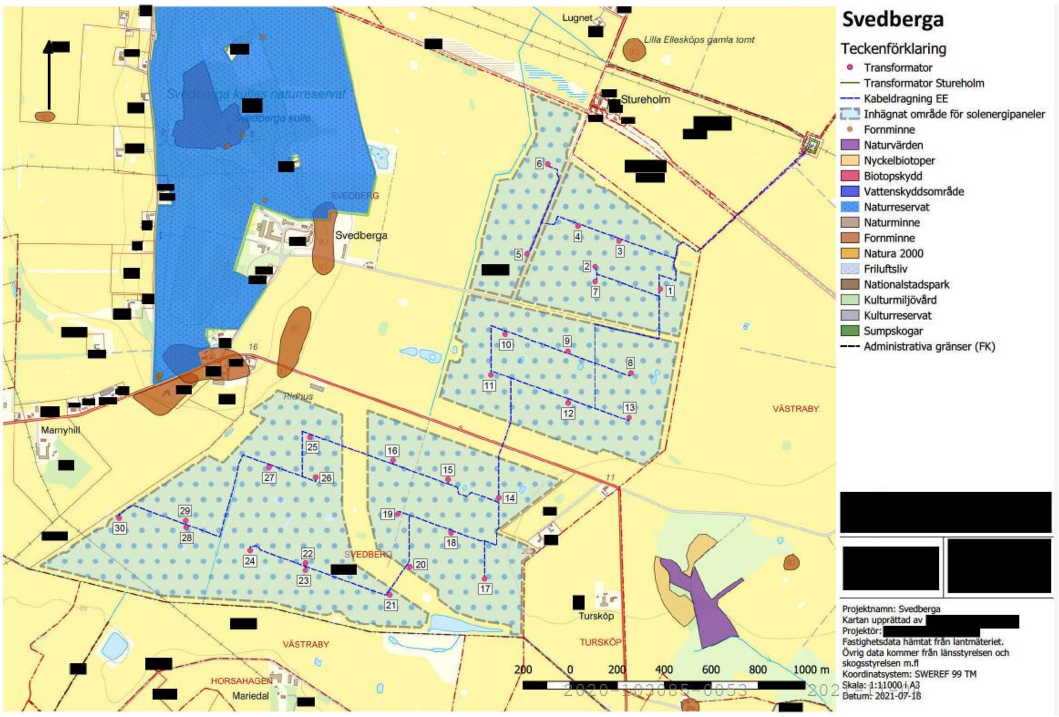


FIGURE 26 AREA OVERVIEW OF PROJECT SVEDBERGA (*LEDNINGSNÄT I SOLCELLSPARK MED ANSLUTNINGSLEDNINGAR UNDANTAS FRÅN KRAVET PÅ NÄTKONCESSION*, 2021)

In Figure 26 the green dotted areas are where the solar farm will be located. The transmission grid to the transformer station is designed to exclusively transfer the produced electricity, and only the applicant will be operating within the solar farm area. The solar farm will consist of five fenced areas with a total area of around 235 ha. The length of the area is around 2 km in the north-south direction and 3 km in the east-west direction. There will be 30 sections each with transformer, internal grid and so on. The total number of inverters will be approximately 600.

In this case the Swedish Energy Markets Inspectorate deemed that the area is well-defined, and the solar farm can be seen as one functional unit. Even though the transmission grid will be located near buildings, it is judged to not interfere with the buildings. The internal grid will transfer produced electricity to the grid owned by one of the area concession holders, and the grid is therefore deemed as internal.

It should be mentioned that since this is the first official decision of this kind in Sweden, there are mostly arguments on how to interpret the different rulings when compared to other power production, and not much in regards of exact rulings of measurements and distances.

In both the aforementioned cases, the reports mentions that environmental issues were handled in consultation with the local county administrations (SE: Länsstyrelsen).

From the results of these two official decisions, we can derive a few guidelines that all solar farms should abide by, in order to be exempt from the requirement of grid concession:

1. The power lines that connect the solar farm to the transformer station should be as short as possible and they should never be longer than the width of the solar farm.

The power lines that connect the solar farm to the transformer station “cannot be too long”. The only definite answer to what “too long” means can be found in the first case mention in this chapter (*Bindande besked om undantag från kravet på nätkoncession Ärendenummer—2022-101635*, 2023), were the permission was denied due to the transmission line being longer than the width of the solar farm.

2. The transmission lines that connect the different sections of the solar farm should not be longer than the width of the largest section and the solar farm cannot be too widespread.

Regarding the internal transmission lines that connect the different sections of the solar farm, the ruling is a bit more lenient. The official decisions rulings are that transmission lines for the internal grid should not be longer than the width of the largest section. This ruling is enough to allow for any roads between the sections, and even allows for some spreading of the sections’ locations. It must, however, also abide by the ruling of being within a well-defined area and not too widespread. While the official decisions clearly show that there are no objections towards connecting two or three nearby sections that are somewhat rectangular in shape, there may be problems for a solar farm that consists of five to six smaller sections of various irregular shapes like the proposed solar farm in our case.

3. The solar farm should not interfere with nearby buildings, be too close to existing power lines, nor should it disturb activity in the nearby area.

If there are buildings or residents in the nearby area does not seem to have any large impact on the decisions. The important aspect here is that the solar farm does not disturb any nearby residents or industries. The area should not experience excessive activity. If the location is frequently used, perhaps for outdoor recreation, it would not be suitable for establishing high voltage power lines.

The only definition of being too close to existing power lines is mentioned in the first case (*Bindande besked om undantag från kravet på nätkoncession Ärendenummer—2022-101635*, 2023), where the applicants power lines were scheduled to be positioned right next to existing power lines, which was not accepted. This rule seems to exist more to prevent the creation of a confusing "spider web" of power lines and to demand that caution is taken and power lines should have reasonable distance to other existing power lines.

4.1.2.1 Applying the guidelines to the case

For the solar farm to be exempt from the requirement of grid concession, it needs to abide by the three guidelines defined earlier in this paper.

The first thing which needs to be established is the definition of width, which is mentioned several times in both cases discussed in the preceding chapter. In Figure 27 and Figure 28 assessments are made of how the different widths likely would be defined for the proposed area in this case study.

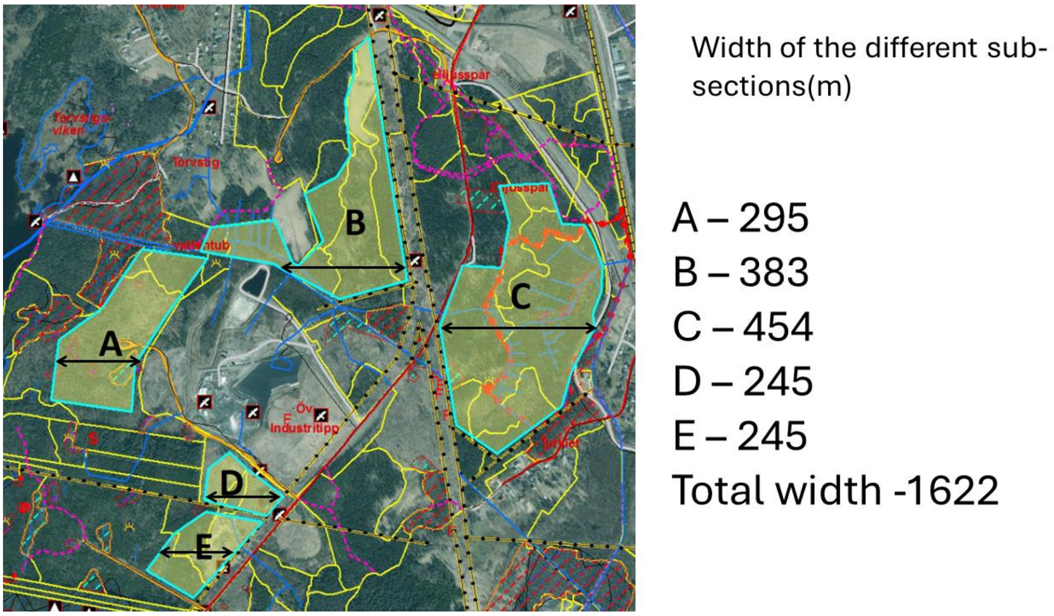
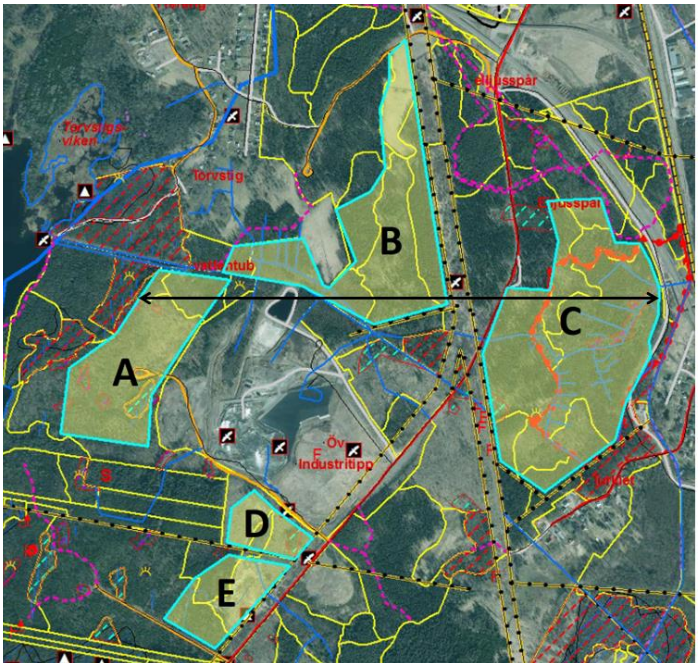


Figure 27 Width of the different sub sections (Data provided by *Lantmäteriet - Min Karta*, 2024)



Width across the whole farm 1550 m

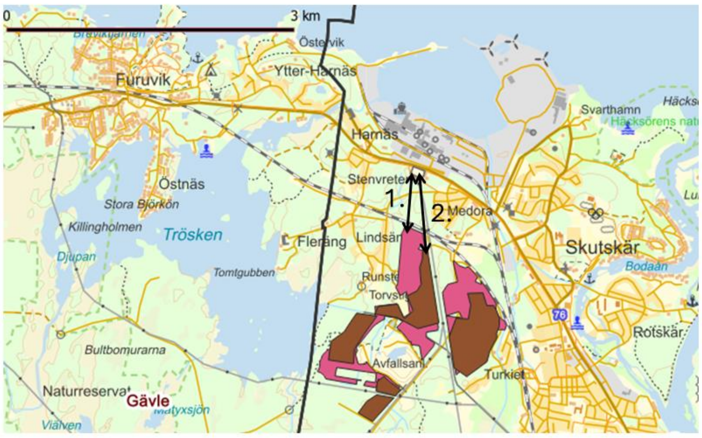
FIGURE 28 TOTAL WIDTH ACROSS THE SUGGESTED AREA (DATA PROVIDED BY *LANTMÄTERIET* - *MIN KARTA*, 2024)

It should be noted that this is something that will be assessed by government officials, which is a unique process for every case. Which means that the exact distances could be judged differently. However, the assessment made in this case study is an honest appreciation of the area's width, and the difference would not be substantial if the assessment is done in any other reasonable way. These definitions of the width will be used when applying the guidelines to the case.

Guidelines

1. The power lines that connect the solar farm to the transformer station should be as short as possible and they should never be longer than the width of the solar farm.

In our opinion, however the width of the entire solar farm is defined, it is clearly wider than the distance to the transformer station. Even if the solar farm would be judged harshly due to its many irregular shapes, there should be no question of whether the power lines to the transformer station is shorter than the width of the entire solar farm. There is also a possible layer of extra safety. Since the land owned by the company extends beyond the highly ranked solar farm area, it is probably possible to have the connection point even closer to the transformer station, even if that extended area contains few or no solar panels as shown in Figure 29.



Distance between solar farm and regional sub station

1. Extended area – 800 m
2. Solar farm area – 600 m

FIGURE 29 DISTANCE BETWEEN SOLAR FARM AND REGIONAL SUB-STATION (DATA PROVIDED BY *LANTMÄTERIET - MIN KARTA*, 2024)

2. The transmission lines that connect the different sections of the solar farm should not be longer than the width of the largest section and the solar farm cannot be too widespread.

The internal transmission lines are also clearly shorter than the width of the largest section. The potential problem with this rule lies in the widespread part. It is possible that the two smaller sections (D and E) could cause the solar farm to be seen as too widespread.

3. The solar farm should not interfere with nearby buildings, be too close to existing power lines, nor should it disturb activity in the nearby area.

The only buildings that are nearby are a handful of residential ones located around 100m from area C. The area in the middle is a landfill area that does not have much activity, nor should any potential activity be disturbed by the solar farm since connecting roads remain untouched. Since the areas exclusively consist of unkempt forest with a few roads the only activities that take place here would be occasional ones such as walking dogs, which are not sufficient to prevent the construction of a solar farm. The one potential problem with this rule is being too close to existing power lines. However, this problem is probably already solved in the screening process, as one of the criteria specifically concerned proximity to power lines.

4.2 Simulated mounting configuration scenarios

Table 7 presents the results from simulations of various configurations for a 50 MWp system using PVsyst. A total of ten different scenarios have been simulated, each featuring unique combinations of shading angles, module tilts, and orientations. These simulations yielded diverse outcomes in terms of ground coverage, specific system production, and performance ratios.

According to Stridh (2016), the most commonly used configuration in Sweden involves a portrait orientation with a shading angle of 18 degrees and a tilt of 30 degrees. This configuration, employed in our Scenario 2, achieved one of the highest specific system productions at 886. The only scenario that outperformed this was

Scenario 1, with a specific system production of 896, which uses a shading angle of 10 degrees. However, Scenario 1 has a significantly lower ground coverage of 27%, compared to 41.6% in Scenario 2. This indicates that while Scenario 1 generates more electricity per module on average, it requires more space due to the lower shading angle, which increases the pitch or distance between rows. Given that Scenario 1 occupies nearly twice the space for only a slight increase in power production, Scenario 2 is deemed the most efficient option for our purposes.

Scenario 8, which mirrors Scenario 2 but switches the module orientation from portrait to landscape, showed a marginal increase in specific system production to 887 from 886. This suggests a slight efficiency improvement with the landscape orientation. However, the difference very small, and since the recommendation from PVsyst is to use half-cut modules in portrait, this small increase could be a result of an anomaly in the software. (*Twin Half-Cut Cells and Shadings*, 2024)

For this reason, the result from scenario 8 is deemed to be unreliable, and therefore neglected in favor of scenario 2. Scenario 10 shows that the effects of bifacial modules are small or nothing when simulated using PVsyst.

Scenario 11 shows the result from simulations performed using Winsun PV, and the climate data from Gävle 2023. Winsun PV does not consider mutual shading, therefore there are no settings for row distance or shading angle, which means that there is no way to calculate the ground coverage of the simulated project. The reason for the higher specific production in this scenario is that measured irradiation data is higher than the data provided by the Meteonorm database used in PVsyst.

Note that the MWp/Ha in Table 7 does not account for any roads, clear perimeters surrounding the farm, or other required sub-systems. It is purely the area occupied by the modules.

Table 7 Generated results from PVsyst and WINSUN

Scenario	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Orientation	Portrait	Portrait	Portrait	Portrait	Portrait	Portrait	Portrait	Landscape	Landscape	Portrait (No bifacial)	WINSUN (No orientation input)
Shading angle [Degrees]	10	18	21	28	18	18	18	18	28	18	No mutual shading
Tilt [Degrees]	30	30	30	30	40	25	35	30	30	30	30
Ground coverage [%]	27	41.6	45.8	55.4	36.5	45.3	38.7	41.6	55.4	41.6	-
Specific production [kWh/kWp/a]	896	886	878	851	879	881	885	887	857	886	987
Performance ratio	0.834	0.824	0.817	0.792	0.805	0.833	0.815	0.825	0.797	0.824	0.820
Power per area [MWp/Ha]	0.58	0.89	0.98	1.19	0.78	0.97	0.83	0.89	1.19	0.89	-

The scenarios which were chosen to be used in the economic evaluation were scenario 2, PVsyst simulation with shading angle 18° and tilt 30°, and scenario 11, Winsun PV simulation. Scenario 2 was chosen because it had the most promising combination of specific production and ground coverage. Additionally, according to Bengtsson et al., (2017) a tilt of 30° will achieve the maximum cleaning effect from rain in Sweden. Scenario 2 is also one of the most common configurations used for Swedish PV-systems (Stridh, 2016). Scenario 11, which included the same configurations using Winsun PV, was chosen because it was based on the measured climate data provided by the University of Gävle.

The monthly irradiation and production results are shown in Table 8 and Table 9 for PVsyst and Winsun PV respectively. The software reports the result slightly differently, hence the difference between the tables. The incident irradiation is approximately 16% higher in the simulation performed using Winsun PV, compared to PVsyst. Winsun PV also has a 7% higher total production.

TABLE 8 MONTHLY IRRADIATION & PRODUCTION RESULTS FROM PVSYST, SCENARIO 2

	Global Horizontal irradiation [kWh/m²]	***Horizontal diffuse irradiation [kWh/m²]***	***Global incident in collector plane [kWh/m²]***	***Effective global, correction for IAM shadings [kWh/m²]***	***Total production [MWh]***
January	7.4	5.4	17.3	4.7	170
February	19.4	13.7	31.5	24.6	1049
March	62.4	33.6	92.8	84.8	4109
April	114.5	43.3	146.2	138.5	6442
May	149.6	75.7	161.9	151.9	6951
June	161.2	82.6	166.8	156.5	7061
July	161.3	76.2	172.9	162.8	7283
August	106.3	55.9	119.9	112.6	5032
September	69.8	35.8	93.7	87.2	3987
October	30.5	18.8	48.7	42.2	1885
November	7.9	6.0	13.9	7.3	2572
December	3.7	2.8	9.1	1.8	559
Total	894.0	449.6	1074.7	975	44283

Table 9 Monthly irradiation and production results from Winsun PV, scenario 11

	Global incident in collector plane, Unshaded irradiance [kWh/m2]	***Global incident in collector plane, Shaded irradiance [kWh/m2]***	***Unshaded PV energy [MWh]***	***Shaded PV energy [MWh]***
January	23.2	9.5	990	406
February	60.4	47.6	2510	2015
March	109.7	104.2	4500	4341
April	158.8	157.4	6392	6363
May	207.8	207.8	8078	8078
June	215.2	215.2	8228	8228
July	162.2	162.7	6252	6271
August	116.7	116.7	4571	4571
September	115.1	112.7	4510	4449
October	63.1	57.5	2560	2368
November	9.3	60	403	261
December	8.0	3.3	372	146
Total	1249.6	1200.5	49366	47496

Figure 30 shows the detailed total losses from the PVsyst simulation in scenario 2, illustrated as a Sankey diagram. Losses due to horizon shadings amount to approximately 6%, this loss is also included in the result from Winsun PV, while the other smaller shading losses are not.

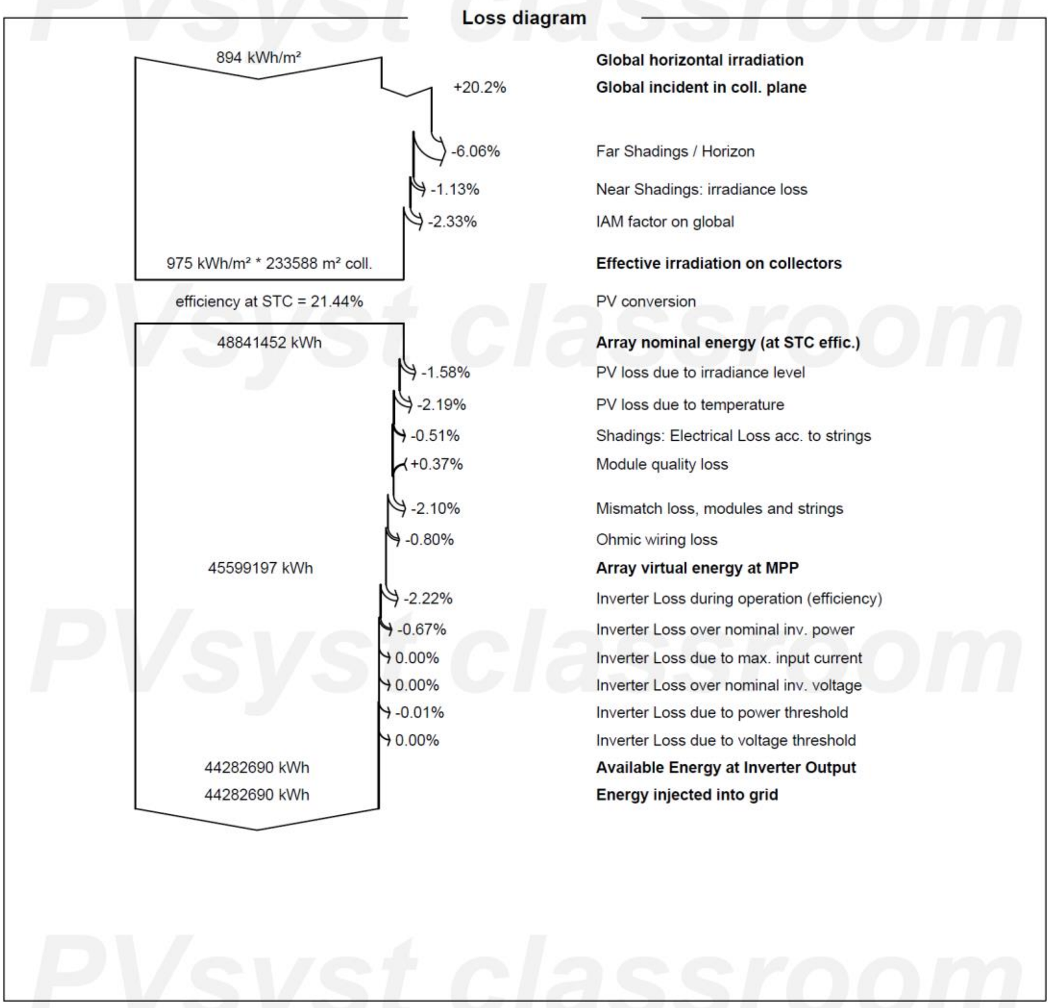


FIGURE 30 DETAILED LOSSES FROM PVSYST SCENARIO 2

4.3 Economic evaluation

4.3.1 Electricity usage for the facility 2023

Several key observations can be noted from the data provided by Stora Enso. Firstly, the electricity produced by the facility is high, while the electricity output to the grid is relatively low, indicating efficient electricity use and high self-sufficiency. The facility roughly produces 80% of its total electricity consumption today. However, since the purchased electricity of the facility still is substantial, there is potential to utilize a large solar farm.

An overview of the purchased, sold, and produced electricity from both wind and the back-pressure turbine can be seen in Figure 31.

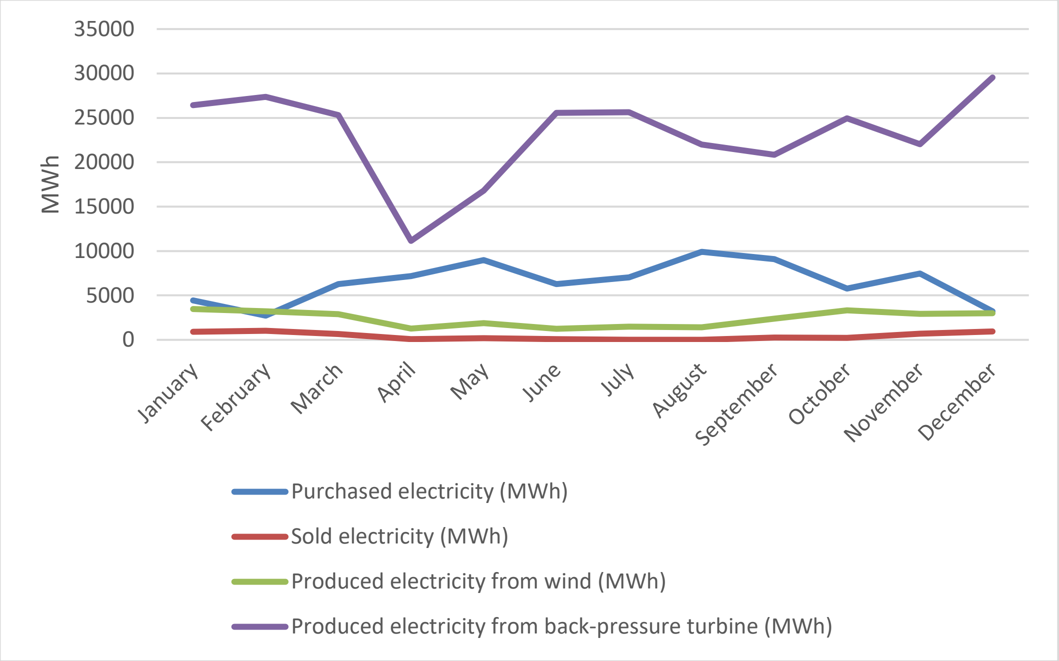


Figure 31 Overview of purchased, sold, and produced electricity 2023

Figure 31 illustrates the bought purchased electricity in blue, and the sold electricity in red. The amount of electricity sold is relatively small compared to the overall total usage.

The electricity generated by the wind turbines at Stora Enso changes dramatically over the course of one year. As seen in Figure 32, the amount of electricity generated in the spring and summer months (April – august) is roughly half compared to the autumn and winter months.

Figure 32 displays the electricity production from wind at the site, highlighting a significant increase during the winter months, peaking in January and reaching its lowest in June. This seasonal pattern suggests that integrating a solar farm, which produces most electricity in the summer, would effectively complement the wind turbines' output. Figure 32 shows electricity generated from the wind turbines compared to electricity from a simulated 50 MWp solar farm. This graph further illustrates this synergy, showing that as wind power generation decreases starting in March, solar power generation begins to rise. This simultaneous shift demonstrates a highly complementary relationship between the two energy sources, ensuring a more consistent electricity supply throughout the year.

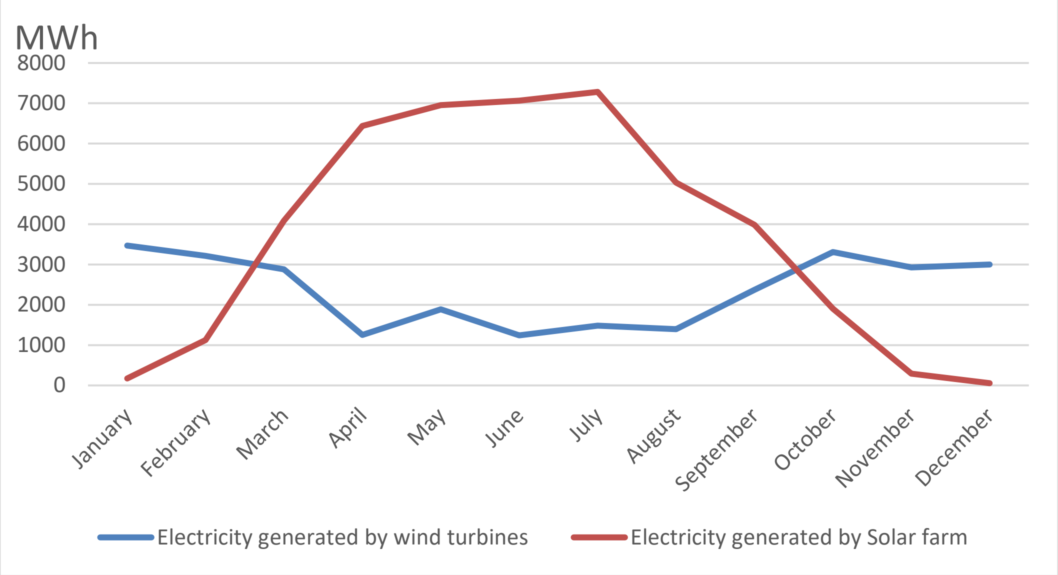


Figure 32 Electricity from wind vs solar 2023

The data also highlights seasonal variations in electricity procurement. Specifically, as seen in Table 10, the purchased electricity peaks in August, with the highest consumption recorded on August 23, between 5:00 PM and 6:00 PM, reaching 47.5 MW. Throughout the months from April to September, the electricity purchased fluctuates between 6 200 MWh/month and 10 000 MWh/month, which can be seen in Figure 31.

Table 10 Electricity usage

	July [MWh]	*August [MWh]*	*Total [GWh/year]*	*GWh/month*	*Power [MW]*
Back-pressure turbine	25 637	21 998	277.5	23	50
Sold	8	20	5	0.4	
Wind turbines	1 484	1 398	28.4	2.4	10
Purchased	7 025	9 912	78.3	6.5	50

4.3.2 Annual yield from a 50 MWp solar farm using PVsyst

Figure 33 illustrates produced electricity by the hour, starting at midnight January 1st, with results generated with PVsyst. The graph clearly shows that most of the electricity is generated during the summer months.

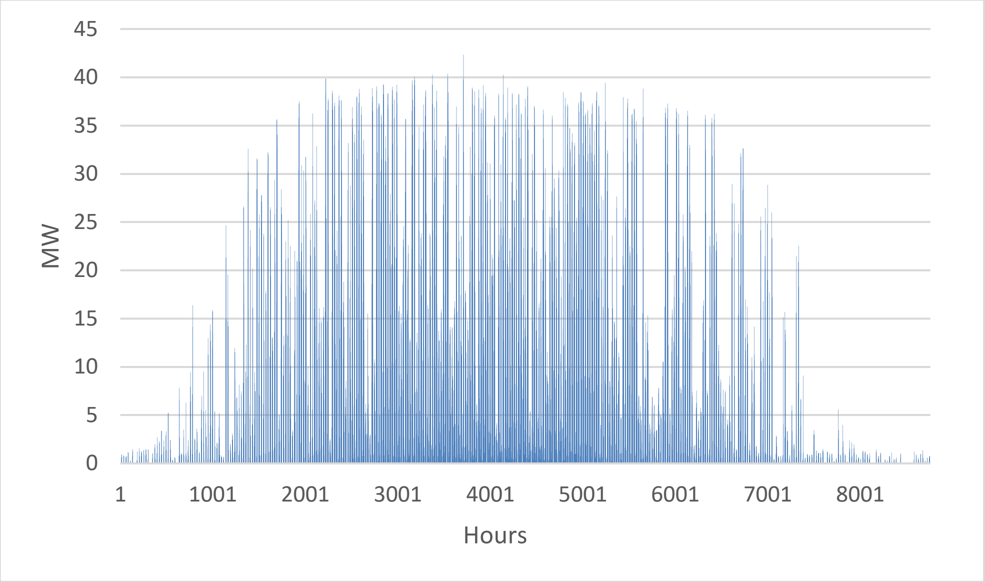


Figure 33 Produced electricity from a 50 MWp solar farm using PVsyst

Using the purchased electricity data provided by Stora Enso, and the results generated in PVsyst, the two datasets were combined. Figure 34 illustrates both purchased and produced electricity overlayed on top of each other.

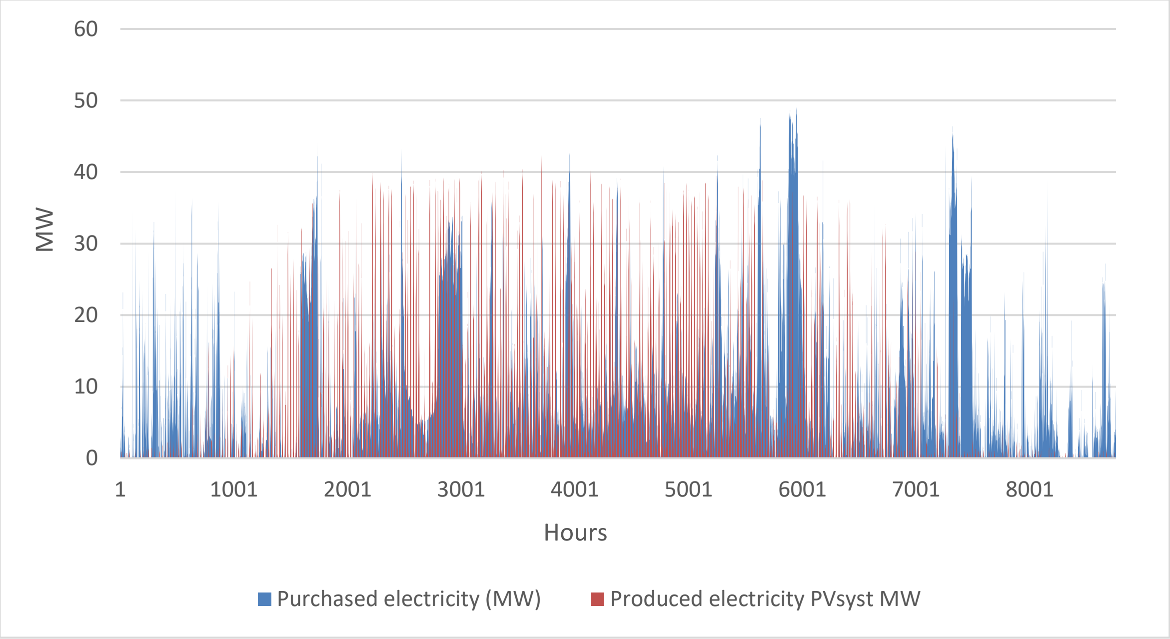


Figure 34 Purchased and produced electricity PVsyst

By subtracting the produced electricity from the purchased electricity for each individual hour for the entire year of 2023, the impact the solar farm would have on purchased electricity was calculated. The amount of purchased and sold electricity can be seen in Figure 35, where the negative values representing sold.

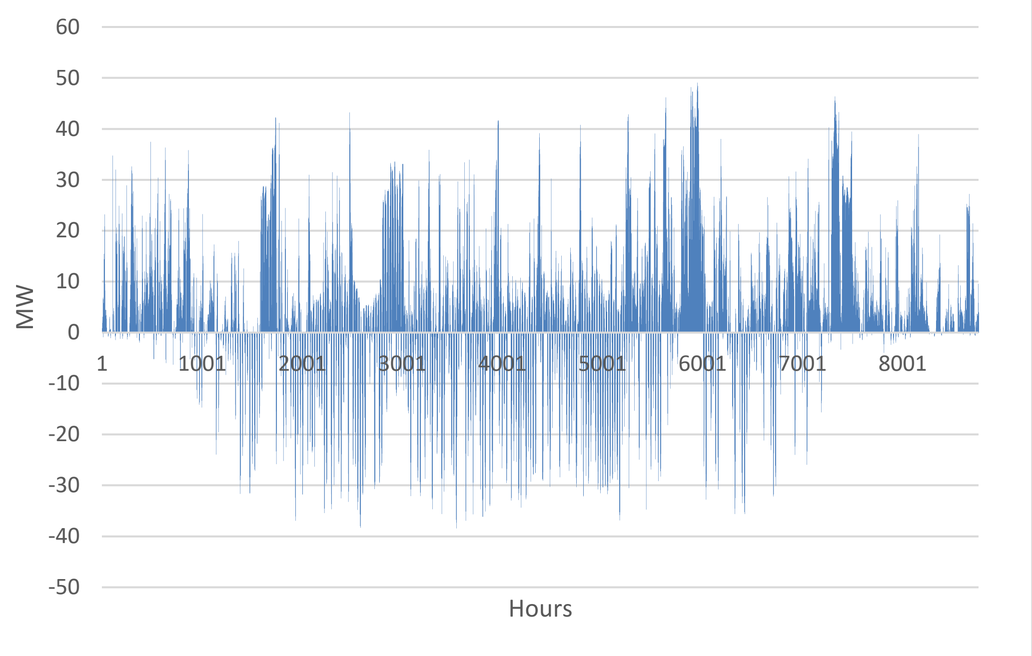


FIGURE 35 PURCHASED AND SOLD ELECTRICITY (MW) PVSYST

A monthly overview of sold, purchased, produced, and conserved electricity can be seen in Figure 36. The columns are stacked on each other, which means that the total height of the conserved electricity and purchased with PV represents the total amount of used electricity for the factory for each specific month.

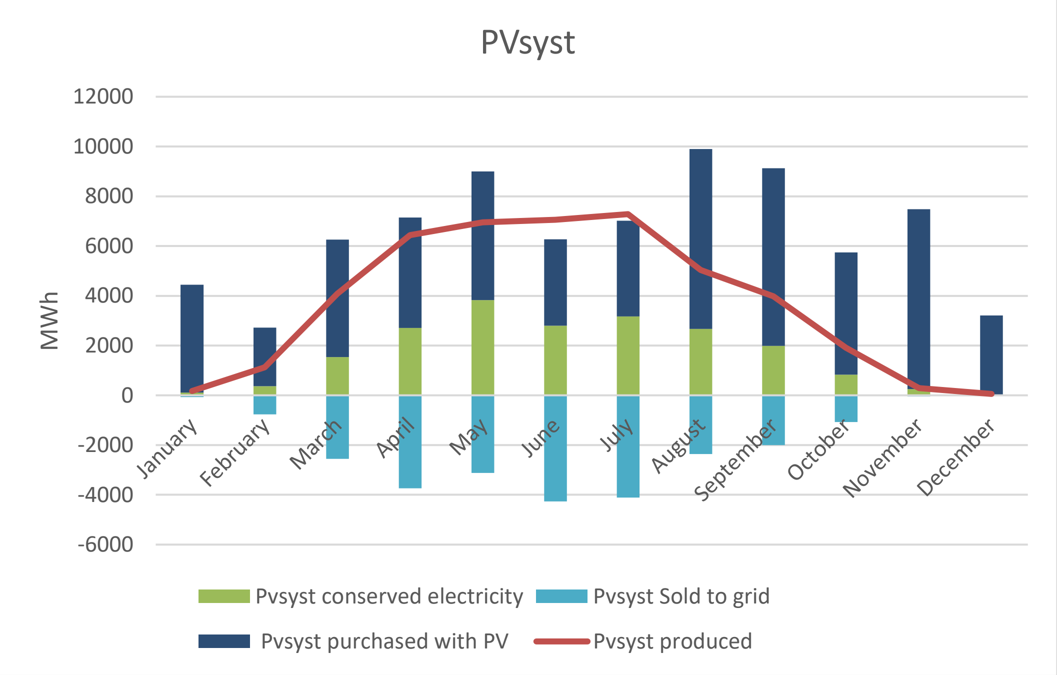


FIGURE 36 MONTHLY ELECTRICITY OVERVIEW PVSYST

A summary of the overall impact of the solar farm, simulated with PVsyst, during one year of production is shown in Figure 37. The total generated electricity from the solar farm amounts to 44395 MWh, of which 24114 MWh was sold and 20281 MWh was used.

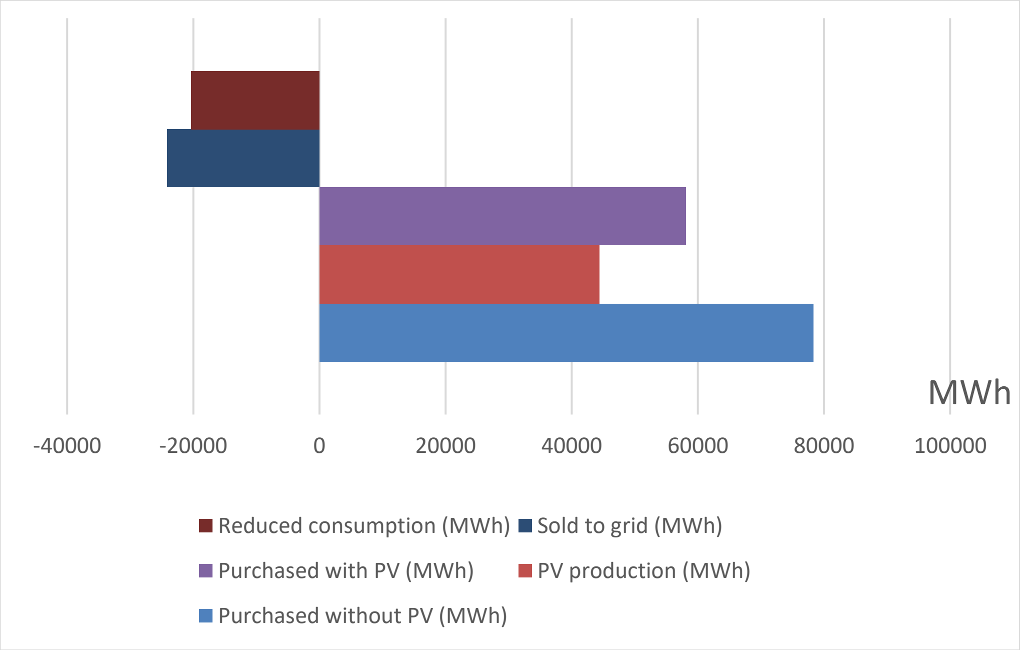


Figure 37 Purchased, produced, sold and reduced MW PVsyst

The hourly data of produced, purchased, and sold MWh combined with the spot price of electricity per hour, gives the total monetary value of each category (excluding taxes and fees), which can be seen in Figure 38. The total cost of electricity both with and without the solar farm, the revenue from selling electricity to the grid, and the total cost of electricity during the year 2023, after said revenue has been subtracted. The total cost of electricity with a solar farm is half that of the original cost.

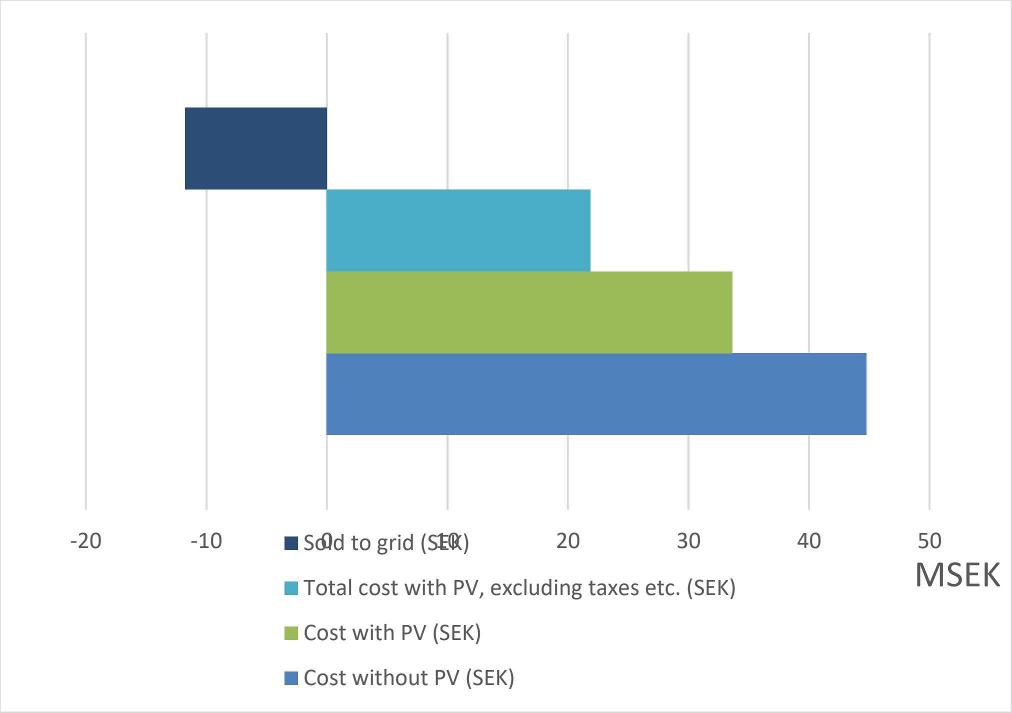


Figure 38 TOTAL COST of ELECTRICITY WITH AND WITHOUT PV using PVsyst (excluding taxes and fees)

4.3.3 Annual yield from a 50 MWp solar farm using Winsun PV

The electricity generated from a 50 MWp solar farm using Winsun PV, and the climate data from 2023 is shown in Figure 39.

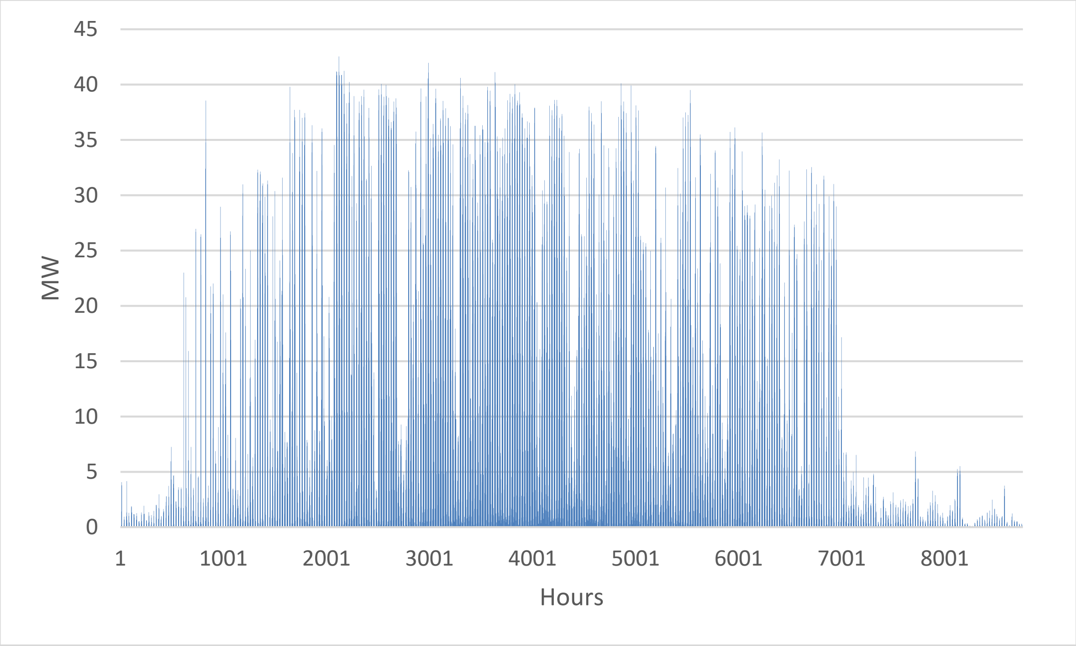


Figure 39 PRODUCED ELECTRICITY FROM A 50 MWP SOLAR FARM USING Winsun PV

The results from Winsun PV are combined with the purchased electricity data in Figure 40. Although the annual yield is higher when using Winsun PV and the climate data from 2023, the yearly pattern is similar to the one generated with PVsyst.

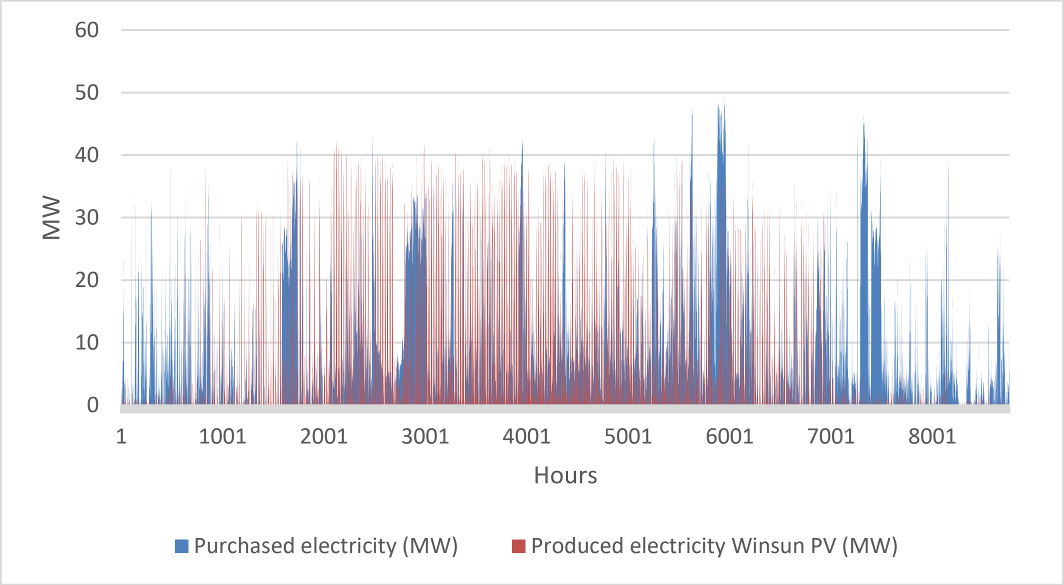


FIGURE 40 PUCRHCASED AND PRODUCED ELECTRICITY WINSUN PV

Subtracting the produced electricity simulated with the climate data from 2023, from the purchased electricity produces the graph shown in Figure 41. The main difference between the results from PVsyst and Winsun PV, is an increase in sold electricity in the results from Winsun PV.

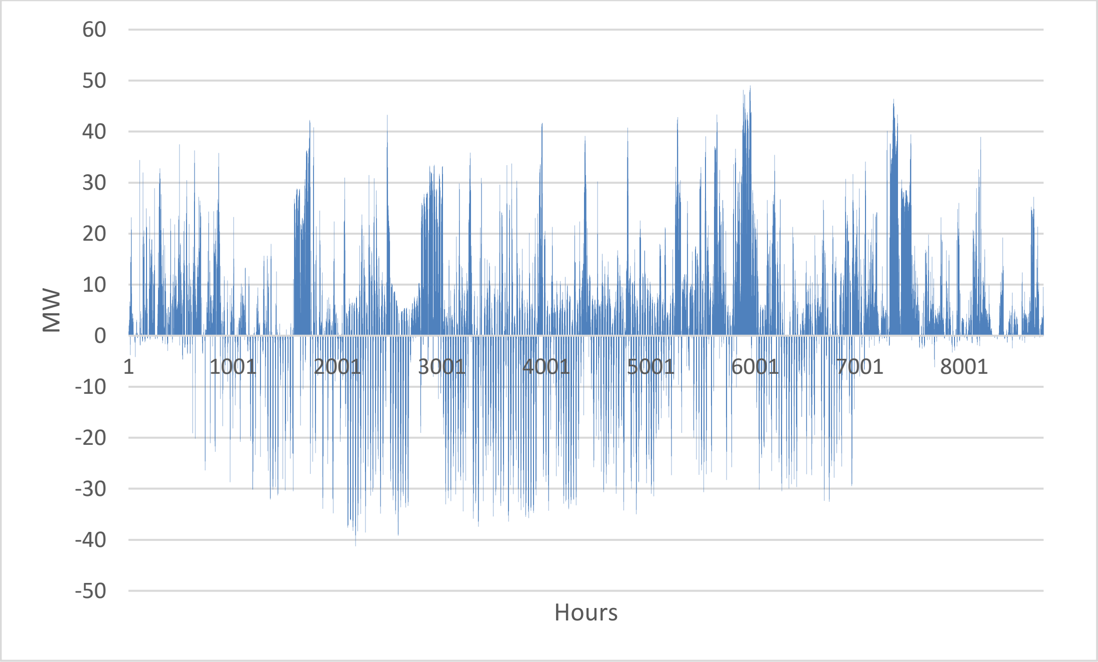


FIGURE 41 PURCHASED AND SOLD ELECTRICITY (MW) WINSUN PV

A monthly overview of sold, purchased, produced, and conserved electricity can be seen in Figure 42. The columns are stacked on each other, which means that the total height of the conserved electricity and purchased with PV represents the total amount of used electricity for the factory for each specific month.

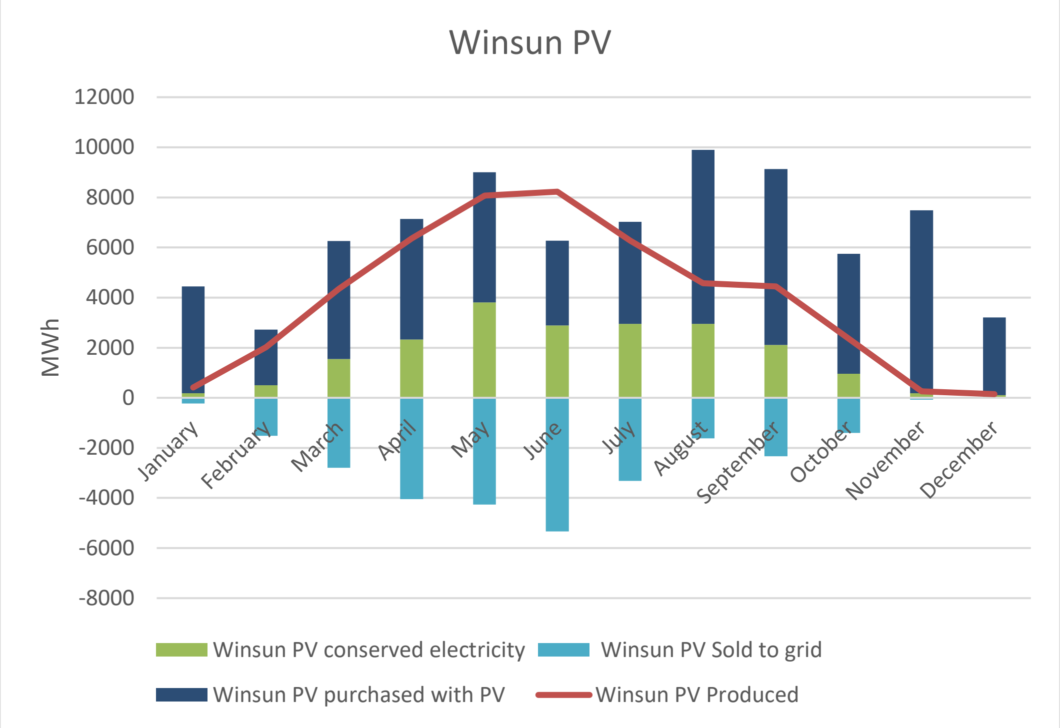


FIGURE 42 MONTHLY ELECTRICITY OVERVIEW WINSUN PV

Figure 43 illustrates the total amount MWh produced, purchased, and sold with and without installed PV, during the entire duration of 2023, using climate data from the same year, with Winsun PV.

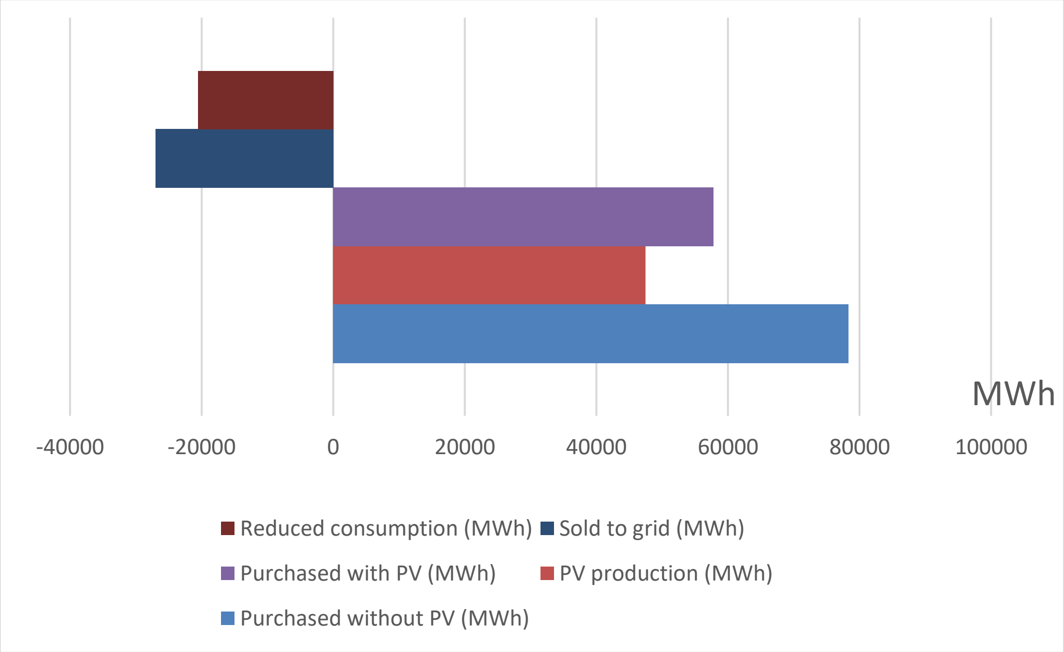


FIGURE 43 PURCHASED, PRODUCED, SOLD AND REDUCED MW WINSUN PV

When simulating with Winsun PV, the total cost of electricity (excluding taxes and fees) with installed PV during 2023, is less than half of the total cost without PV, which can be seen in Figure 44 along with other raw cost details.

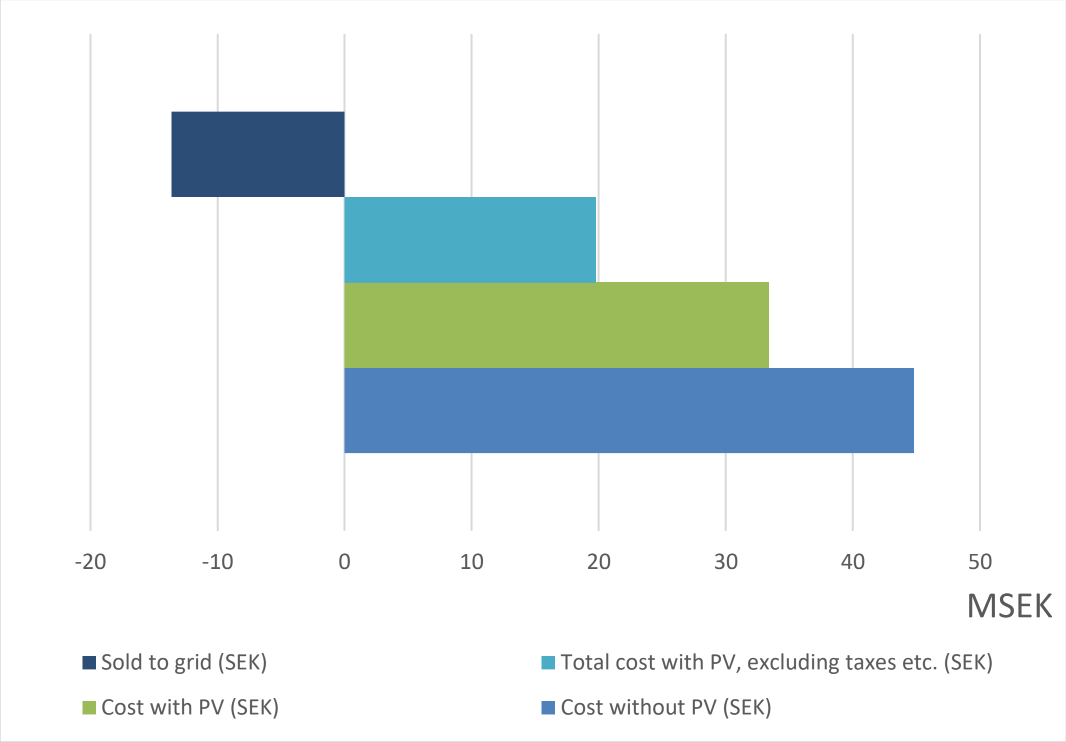


Figure 44 TOTAL COST of ELECTRICITY WITH AND WITHOUT PV using Winsun PV (excluding taxes and fees)

4.3.4 Comparison between PVsyst and Winsun PV results

The generated results and calculated results, excluding taxes and fees, from both PVsyst and Winsun PV are compiled in Table 11. The total PV electricity production is 7% higher with Winsun PV and the climate data from 2023. The higher PV production results in a 2.13 MSEK lower cost of electricity.

Table 11 Comparison between PVsyst and Winsun PV reslults (excluding taxes and fees)

Comparison between PVsyst and Winsun PV	***Pvsyst***	***Winsun PV***	***Difference***
Purchased without PV (MWh)	78337	78337	0
Solar production (MWh)	44396	47496	-3101
Purchased with PV (MWh)	58056	57826	230
Sold to grid (MWh)	-24115	-26985	2871
Reduced consumption (MWh)	-20281	-20511	230
Cost without PV (MSEK)	44.77	44.77	0
Conserved in MSEK	-11.12	-11.40	0.28
Sold in MSEK	-11.76	-13.61	1.85
Total cost with PV, excluding taxes etc. (MSEK)	**21.89**	**19.76**	**2.13**

4.3.5 LCOE

The results generated from simulations in PVsyst showed that the specific production, or annual yield, from a solar farm located in Skutskär amounts to 886 MWh/MWp/a. Using this as the base of our calculations, and the assumptions explained on page 51 in chapter 3.5.1, several different calculations of LCOE was performed using Equation 2. Data presented in Table 12 shows three different scenarios, called Harsh, Moderate, and Lenient.

Table 12 LCOE results from PVsyst simulation in €

Scenario from PVsyst simulation	***No. 1 (Harsh)***	***No. 2 (Moderate)***	***No. 3 (Lenient)***
Annual Yield (MWh/MWp/a)	886	886	886
Total CAPEX (€/MWp)	713038	666729	554574
Lifetime (Years)	30	40	40
Degradation (%)	0.4	0.2	0.2
Fixed operation and maintenance (€/MWp/a)	11277	8282	8282
variable operation and maintenance (€/MWp)	2.9	1.9	0.9
reinvestment no 1 (€/MWp)	75549	27813	27813
reinvestment no. 1 (years after investment)	15	15	15
reinvestment no 2 (€/MWp)	0	11920	11920
reinvestment no. 2 (years after investment)	0	30	30
Residual cost at end of life	0	0	0
LCOE 5,7% WACC (€/MWh)	**78.20**	**62.03**	**52.71**
LCOE 6,5% WACC (€/MWh)	**83.30**	**67.10**	**56.92**
LCOE 4% WACC (€/MWh)	**68.09**	**51.87**	**44.27**
LCOE 5,7% WACC and O&Mv = 0 (€/MWh)	**75.30**	**60.13**	**51.81**
LCOE 6,5% WACC and O&Mv = 0 (€/MWh)	**80.33**	**65.20**	**56.02**
LCOE 4% WACC and O&Mv = 0 (€/MWh)	**65.19**	**49.97**	**43.37**
CAPEX IN DETAIL			
Tot costs for subcontractors (€/MWp)	639850	639850	543006
Grid connection costs (€/MWp)	9615	9615	9615
Land costs (€/MWp)	0	0	0
Owner costs (€/MWp)	63573	17264	1953
Total CAPEX (€/MWp)	713038	666729	554574

The same results converted into SEK (with a conversion rate of 1€ = 11.66 SEK on 15-05-2024) can be seen in Table 13.

Table 13 LCOE results from PVsyst simulation in SEK

Scenario from Pvsyst simulation	***No. 1 (Harsh)***	***No. 2 (moderate)***	***No. 3 (Lenient)***
Annual Yield (MWh/MWp/a)	886	886	886
Total CAPEX (MSEK/MWp)	8.3	7.8	6.5
Lifetime (Years)	30	40	40
Degradation (%)	0.4	0.2	0.2
Fixed operation and maintenance (SEK/MWp/a)	131490	96568	96568
variable operation and maintenance (SEK/MWp)	34	22	10
reinvestment no 1 (SEK/MWp)	880901	324300	324300
reinvestment no 1 years after investment	15	15	15
reinvestment no 2 (SEK/MWp)	0	138987	138987
reinvestment no 2 years after investment	0	30	30
Residual cost at end of life	0	0	0
LCOE 5,7% WACC (SEK/MWh)	**912**	**723**	**615**
LCOE 6,5% WACC (SEK/MWh)	**970**	**782**	**664**
LCOE 4% WACC (SEK/MWh)	**794**	**605**	**516**
LCOE 5,7% WACC O&Mv = 0 (SEK/MWh)	**878**	**701**	**604**
LCOE 6,5% WACC and O&Mv = 0 (SEK/MWh)	**937**	**760**	**653**
LCOE 4% WACC and O&Mv = 0 (SEK/MWh)	**760**	**583**	**506**
CAPEX IN DETAIL			
Tot costs for subcontractors (SEK/MWp)	7460651	7460651	6331450
Grid connection costs (SEK/MWp)	112111	112111	112111
Land costs (SEK/MWp)	0	0	0
Owner costs (SEK/MWp)	741261	201298	22772
Total CAPEX (SEK/MWp)	8314023	7774060	6466333

Simulations using Winsun PV, which utilizes climate data collected on HiG campus, resulted in a higher annual yield of 987 MWh/MWp/a. This is a difference of 101 MWh/MWp/a, which is a substantial amount. This difference also has a big impact on the LCOE, with the values being approximately 10% lower across the board. Table 14 shows the LCOE calculations using the annual yield generated using Winsun PV.

Table 14 LCOE RESULTS FROM Winsun PV SIMULATION in €

Scenario from Winsun PV simulation	*No. 1 (Harsh)*	*No. 2 (Moderate)*	*No. 3 (Lenient)*
Annual Yield (MWh/MWp/a)	987	987	987
Total CAPEX (€/MWp)	713038	666729	554574
Lifetime (Years)	30	40	40
Degradation (%)	0.4	0.2	0.2
Fixed operation and maintenance (€/MWp/a)	11277	8282	8282
variable operation and maintenance (€/MWp)	2.9	1.9	0.9
reinvestment no 1 (€/MWp)	75549	27813	27813
reinvestment no. 1 (years after investment)	15	15	15
reinvestment no 2 (€/MWp)	0	11920	11920
reinvestment no. 2 (years after investment)	0	30	30
Residual cost at end of life	0	0	0
LCOE 5,7% WACC (€/MWh)	**70.50**	**55.88**	**47.41**
LCOE 6,5% WACC (€/MWh)	**75.01**	**60.43**	**51.19**
LCOE 4% WACC (€/MWh)	**61.42**	**46.75**	**39.84**
LCOE 5,7% WACC and O&Mv = 0 (€/MWh)	**67.60**	**53.98**	**46.51**
LCOE 6,5% WACC and O&Mv = 0 (€/MWh)	**72.11**	**58.53**	**50.29**
LCOE 4% WACC and O&Mv = 0 (€/MWh)	**58.52**	**44.86**	**38.94**
CAPEX IN DETAIL			
Tot costs for subcontractors (€/MWp)	639850	639850	543006
Grid connection costs (€/MWp)	9615	9615	9615
Land costs (€/MWp)	0	0	0
Owner costs (€/MWp)	63573	17264	1953
Total CAPEX (€/MWp)	713038	666729	554574

The same results converted into SEK (with a conversion rate of 1€ = 11.66 SEK on 15-05-2024) can be seen in Table 15.

Table 15 LCOE results from Winsun PV simulation in SEK

Scenario from WINSUN simulation	***No. 1 (Harsh)***	***No. 2 (Moderate)***	***No. 3 (Lenient)***
Annual Yield (MWh/MWp/a)	987	987	987
Total CAPEX (MSEK/MWp)	8.3	7.8	6.5
Lifetime (Years)	30	40	40
Degradation (%)	0.4	0.2	0.2
Fixed operation and maintenance (SEK/MWp/a)	131490	96568	96568
variable operation and maintenance (SEK/MWp)	34	22	10
reinvestment no 1 (SEK/MWp)	880901	324300	324300
reinvestment no 1 years after investment	15	15	15
reinvestment no 2 (SEK/MWp)	0	138987	138987
reinvestment no 2 years after investment	0	30	30
Residual cost at end of life	0	0	0
LCOE 5,7% WACC (SEK/MWh)	822	652	553
LCOE 6,5% WACC (SEK/MWh)	**875**	**705**	**597**
LCOE 4% WACC (SEK/MWh)	**716**	**545**	**464**
LCOE 5,7% WACC and O&Mv = 0 (SEK/MWh)	788	629	542
LCOE 6,5% WACC and O&Mv = 0 (SEK/MWh)	**841**	**682**	**586**
LCOE 4% WACC and O&Mv = 0 (SEK/MWh)	**682**	**523**	**454**
CAPEX IN DETAIL			
Tot costs for subcontractors (SEK/MWp)	7460651	7460651	6331450
Grid connection costs (SEK/MWp)	112111	112111	112111
Land costs (SEK/MWp)	0	0	0
Owner costs (SEK/MWp)	741261	201298	22772
Total CAPEX (SEK/MWp)	8314023	7774060	6466333

Depending on scenario, the LCOE ranges from 506 – 970 SEK/MWh for PVsyst and 454 – 875 SEK/MWh for Winsun PV. This translates to 50.6 – 97.0 öre/kWh for PVsyst and 45.4 – 87.5 öre/kWh for Winsun PV. Note that the figures that include O&M$_v$ should only be used for comparisons if all electricity is expected to be injected into the grid, since they include balance & trading costs. For the economic evaluation in this paper, where conserved and sold electricity will have separate values, it is the O&M$_v$ = 0 scenarios that are relevant since the balance and trading costs will be applied to sold electricity only.

4.3.6 The value of PV-electricity

There was not enough information available from the regional grid company, Ellevio, to explain how the power tariff is determined. However, simulations show that the peak wattage was only reduced in 5 months, and only slightly by 0.3 – 1.5 MW. This is unlikely to affect the power tariff. Other regional grid owners, such as Vattenfall, usually base this cost on a few hours that had the highest wattage delivered over the entire year (Vattenfall, 2024). For this reason, we assume that the power tariff is unaffected by the solar farm.

4.3.6.1 Purchased/conserved electricity

Private persons pay an electricity certificate fee of a few öre/kWh of purchased electricity, however intensive electricity using companies are exempt from this fee, since they instead have to buy electricity certificates. This means that the facility studied in this paper does not pay this fee for their purchased electricity. (*Registrering som elintensiv industri*, 2024)

Although the energy tax for electricity in 2024 is 42.8 öre/kWh (VAT excluded), industrial manufacturing processes are eligible for a tax refund, which in effect reduces the energy tax to 0.6 öre/kWh (Skatteverket, 2024). However, since this tax is applied to all consumed energy, it will still be paid if the electricity is produced by the user themselves, therefore it cannot be included in the value of conserved electricity (*Skattepliktig el | Rättslig vägledning | Skatteverket*, 2024) & (*Lag (1994*, 2024). In addition, a corporation does not pay the 25% VAT, or sales tax that a private person pays for the electricity (skatteverket, 2024).

The transfer fee that applies to the facility is 1.35 öre/kWh, according to the level L130, which can be seen in Table 3 on page 40. The total cost estimation for purchased electricity is spot price + transfer fee or spot price + 1.35 öre/kWh.

4.3.6.2 Sold electricity

For the case investigated in this report, transfer fees for sold electricity will not apply. According to the current grid owner Ellevio, there are no transfer fees associated with injecting electricity into the grid.

For sold electricity, producers have to pay balance & trading fees. These fees used in the calculations were taken from the highest and lowest examples by Lindahl et al., (2022), which are 1.05 and 3.38 öre/kWh respectively. The energy tax of 0.6 öre/kWh is not applied to sold electricity (*500 kW energiskatt på el*, 2024).

Swedish electricity producers are able to profit from a compensation called “grid benefit” (SE: nätnytta). This is a revenue that is paid by the grid owner to electricity producers for every kWh fed into the grid. The size of the fee varies in the range of 2-16 öre/kWh depending on grid owner. This fee is meant to promote local production and it is required by law to be paid by the grid owner. (*Nätnytta och ersättningar – Hedemora Energi*, 2024) & (*Nätnytta*, 2022)

However, the law only covers so-called micro producers, which are facilities of sizes 43.5 kW and less. (*Mikroproduktion av el*, 2021)

This means that this fee is not paid out to solar farms by standard, but it is sometimes negotiated between the solar farm owner and the grid owner to pay some amount of this fee, usually a 2-3 öre/kWh since local electricity production can be beneficial for the grid owner (Lindahl et al., 2022). However, company officials stated that it is unlikely that this particular solar farm will receive this compensation. For this reason, grid benefit will not be included in the calculations of this case study.

None of the other fees regarding sold electricity have any direct impact on the price of electricity, they are all various fixed fees which are included in the LCOE. The total estimated price for sold electricity was spot price + balance & trading costs which equals spot price + 1.05 or 3.38 öre/kWh.

4.3.6.3 Weighted average value of electricity including taxes and fees

Four different electricity cost scenarios were deemed as the most interesting to examine. The scenarios were based on the best performing PVsyst setup or Winsun PV in combination with the high balance & trading costs of 3.38 öre/kWh or the low balance & trading costs of 1.05 öre/kWh.

The average value of sold and conserved electricity is shown in Table 16, along with the WAVs for each of the four scenarios, calculated with Equation 3.

Table 16 Average values of PV-produced electricity

	PVsyst				***Winsun PV***				
	Without tax & fees	1.05 B&T	3.38 B&T	Transfer fee	Without tax & fees	1.05 B&T	3.38 B&T	Transfer fee	
Sold	48.78	47.73	45.40	-	50.44	49.39	47.06	-	Öre/kWh
Conserved	54.81	-	-	56.16	55.57	-	-	56.92	Öre/kWh
Average	51.54	-	-	-	52.65	-	-	-	Öre/kWh
	1.05 B&T + transfer fee + energy tax		3.38 B&T + transfer fee + energy tax		1.05 B&T + transfer fee + energy tax		3.38 B&T + transfer fee + energy tax		
WAV	51.58		50.32		52.64		51.32		Öre/kWh

When compared to PVsyst, Winsun PV produces more than 3000 additional MWh per year, but the amount of conserved electricity is only about 200 MWh higher than PVsyst. The biggest difference between the two software simulations is that Winsun PV has a higher amount of sold electricity. This should result in the WAV being lower for Winsun PV, but the calculations show the opposite. This probably means that Winsun PV produces electricity during hours with a higher spot price on average, compared to PVsyst. The difference between the scenarios and software is relatively small, with only a 2.32 öre/kWh difference between the best and worst scenario.

To compare the difference in value between a sold and a conserved kWh, the values from both software and both high and low balance and trading costs were compiled into price ranges as shown in Table 17.

TABLE 17 SUMMARIZED VALUES OF A SOLD AND CONSERVED KWH

Summarized value of a sold kwh	***Summarized value of a conserved kwh***
Average value 48.78 – 50.44	Average value 54.81 – 55.57
Balance and trading -3.38 – -1.05	Transfer fee +1.35
Total 45.40 – 49.39	Total 56.16 – 56.92

The value difference between a conserved and a sold kWh of PV-electricity is significant, with a conserved kWh being worth approximately 10 öre more than a sold kWh, on average.

4.3.6.4 Comparison with LCOE

Since balance and trading costs are included in the electricity price, the LCOE, which should be compared with WAV, must not include balance and trading costs.

The LCOE values from Table 13 and Table 15 expressed in öre/kWh, ranges from 50.3 – 93.6 and 45.4 – 84.1 öre/kWh for the results from PVsyst and Winsun PV respectively. With the best WAV being 52.64 öre/kWh, it is unlikely that the solar farm will be economically viable. The WAV only barely exceeds the LCOE if all the best scenarios coincide. This is unlikely since the best LCOE values are based on a scenario which is probably too good to be realistic. When compared to the moderate costs scenario LCOE of 70.1 for PVsyst or 62.9 for Winsun PV it is obvious that the WAV is too low for the solar farm to be profitable.

Although the best WAV of 52.64 öre/kWh is barely economically viable when compared to the LCOE, it should be noted that the electricity prices fluctuate every year, which would increase the WAV. For example, 2022 being a high-cost-year, it had an average price 164 öre/kWh with fees excluded (M. Sjöberg, personal communication, 20 February 2024).

Energiforsk have calculated LCOE for new facilities and estimated an LCOE between 53 – 107 öre/kWh in 2014 (Nohlgren et al., 2014) and 93 öre/kWh in 2021 (Elmqvist, 2021). These costs are in line with the LCOE calculations in this study.

The LCOE of the six solar farms studied by Lindahl et al., (2022) was calculated to be 32-58 öre/kWh. The reason for the low LCOE, is partly due to the low WACC of below 2% for all six solar farms.

4.3.6.5 Impact of taxes and fees

Using the estimated taxes and fees, four different annual electricity cost scenarios were calculated. The scenarios were based on the best performing PVsyst setup and Winsun PV in combination with the high and low balance & trading costs of 3.38 and 1.05 öre/kWh, these scenarios were then averaged out in order to present only one scenario for the both software. These averaged scenarios and the difference between them are shown in Table 18.

TABLE 18 ANNUAL COSTS OF THE FOUR MOST RELEVANT SCENARIOS.

Costs in MSEK	*PVsyst average*	*Winsun average*	*Difference*
Total cost without PV including taxes & fees	46.30	46.30	-
Total value of sold electricity including fees	11.23	13.01	1.78
Total value of conserved electricity including fees	11.09	11.37	0.28
Final annual cost of electricity	23.98	21.92	2.06
Total savings from PV	**22.32**	**24.38**	**2.06**

The difference in value of sold electricity is 1.78 million SEK, which is significant. The difference in value of conserved electricity is smaller, at 0.28 MSEK in favor of Winsun PV. This is because Winsun PV only has a 1% higher amount of conserved energy, although the total production is roughly 7% higher. According to these calculations, PVsyst saves the company approximately 22.3 MSEK during 2023. The corresponding figure for Winsun PV amounts to 24.4 MSEK, which is roughly half of the facility's electricity cost. The difference between the two software amounts to approximately 2 MSEK, which is roughly 10% of the entire yield, a significant figure. Please note that the calculations in this chapter only include variable taxes & fees, while the fixed taxes & fees are included in LCOE calculations.

5 Discussion

5.1 Method discussion

5.1.1 Simulations and climate data

Scenario 10 in Table 7 shows that there is little to no difference between bi-facial and standard PV modules when simulating using PVsyst, while several studies suggests that the effects from bi-facial should be an increased power production of between 3 – 10 %. This indicates that the results generated in this report may be undervalued, with regards to the effect from bi-facial PV modules. During the simulations, we also noticed that PVsyst seems to ignore the effects of twin half-cut cells and orientation of the modules. Our theory is that the specific wiring and layout of diodes are not taken into account at all by PVsyst, which makes some of the complex settings of PVsyst redundant.

Regarding results generated with Winsun PV, no shading has been taken into account. We know from PVsyst that around 1.13% irradiance is lost due to shading. However, we excluded these losses due to the losses being so small that they made no noticeable difference in calculations and the final result. Therefore, we decided not to interfere with the generated data.

Neither PVsyst nor Winsun PV accounts for the effects of snow. However, the irradiation during winter is negligible in Sweden which makes the issue of snow of little significance. Additionally, snow having a high albedo would increase the reflected irradiation on the backside of the bi-facial modules. We believe that this increased albedo from snow would cancel out snow coverage.

The result when simulating with PVsyst showed that the best and most reliable results was achieved using scenario 2 in Table 7 which had a tilt of 30 and a shading angle of 18. These numbers agree with the theory of Stridh (2016), which claims that this is the most commonly used set up in Sweden. Winsun PV suggests that a tilt of 45 is the optimal angle for Gävle, and since the results from Winsun PV agrees with the measurements from HiG, it makes the results from PVsyst somewhat questionable.

One of the simulations was made with Meteonorm climate data, and the other with actual measurements taken at the university of Gävle. There is a substantial difference between the results depending on which climate data is used. It seems like the Metenorm climate data underestimates the irradiation in Gävle, which is why we believe the results from Winsun PV to be more accurate.

Considering that the difference between the two simulations is quite substantial, even though they should represent the same area, it may be interesting to do simulations with climate data measured in Skutskär. The current data originates from the University of Gävle, approximately 15 kilometers away from the intended site of the solar farm. While this distance might appear minimal, the notable variance in the simulation outcomes presented in this report strongly suggests the need for a new simulation that incorporates climate data from the actual location proposed for the solar farm.

5.1.2 Weighted average value

The WAV is based on the average spot price of PV electricity production in 2023. Since electricity prices fluctuate every year, one could include the average price of more than one year, or even predict future average prices, to increase the reliability of the WAV.

5.2 Result discussion

5.2.1 Mitigate the spikes in electricity use

Upon analyzing the electricity consumption of the factory and comparing it with the output from the solar farm, it is evident that significant spikes in electricity usage persist even after accounting for the solar power contribution. These spikes, which represent the peak electricity demand, are not mitigated by the solar farm. One reason for this may be because they seem to occur at night, when electricity prices are lowest. The factory appears to exploit these lower rates. One strategy to reduce these spikes would be to shift energy-intensive operations to daytime hours when solar production is at its peak, thus significantly decreasing the need to purchase additional electricity. This could result in lower peak effects and might help to reduce the cost of fees and taxes related to the maximum power peaks. However, this would require further and more detailed analysis of the operating hours of the facility.

5.2.2 Wind and solar complement each other

The observations regarding the energy consumption and production patterns at the facility highlight the potential benefits of integrating solar farm electricity production. Given that wind turbine output peaks during the winter months and solar energy production reaches its peak in the summer, there is a clear opportunity to optimize energy usage by aligning it with these seasonal variations. This complementary energy production strategy could enhance the overall efficiency and sustainability of the facility's operations, as well as reduce the total cost of electricity.

5.2.3 LCOE

The results of our literature review indicate that the lifetime of a solar farm far exceeds the expected 30 years warranty which is commonly used in LCOE. The exact lifetime is not known.

The lifetime of a solar farm has a large impact on the LCOE. In this study we have used 30 and 40 years, but it is probably more accurate that the lifetime of a solar farm in Sweden is upwards of 50 or even 60 years. By using these figures, the LCOE would be improved significantly. However, an investment spanning such an extremely long time period is probably not interesting for a company to consider. For this reason, it is probably more reasonable to keep the lifetime expectancy at 30 years.

WACC also has a massive impact on the LCOE, which is to be expected. It might be profitable to wait until the WACC is lower, however this would also impact the cost profile of other projects which still would not make the solar farm a solid project to undertake.

It might also be more accurate to use a more advanced calculation formula instead of the LCOE. Since for a project with such a lengthy lifetime, it is not realistic to assume a constant WACC. To the authors' knowledge however, the LCOE formula is the most widely used to estimate costs for all types of power plants and it is particularly common to compare the LCOE of solar farms.

5.2.4 Guidelines regarding connection towards consumption

In order to comply with the IKN regulations, it would be safest to keep the transmission line between the transformer station and the solar farm as short as possible. Since the company owns more land in the extended areas surrounding the solar farm, it may be possible to have a connection point outside of the solar farm area, while being on their own property. However, it is still important to keep in mind that the solar farm cannot be too widespread.

On the topic of widespread and width, our assessment is that is best to keep a solar farm as square shaped and compressed as possible. For this reason, it might be better to make the intended area more uniform by excluding the two smallest southern sections D and E.

Other than these smaller details, there is nothing that should prevent the solar farm from falling under the IKN regulation.

5.2.5 Economic evaluations

With an LCOE of 45 – 97 öre/kWh, and the highest WAV being 52.64 öre/kWh, the situation requires the best scenarios to coincide for the project to be profitable. While this is unlikely, it is in no way impossible, since the best scenarios have been constructed from what we believe to be very good, but reasonable current conditions. It is even entirely possible to, under the right conditions, achieve an LCOE below 45 öre/kWh.

Part of the electricity consumption that is not linked to production is still subject to the full taxes which are much higher than taxes for the production part. This electricity is used for things such as storage units, external facilities, dining hall etc. However, this fully taxed electricity consumption is well below 5% of the total according to company experts. It may be the case that the electricity production of the solar farm could reduce this fully taxed part which would mean extra benefits in the revenue, but unfortunately there is insufficient data today to account for this in the calculations. It is however unlikely that this would have a large impact on the economics of the solar farm, since it such a small part of the total electricity consumption and it may require different connection setups since the voltage is a lot lower for these support units than for industrial production machinery.

The solar farm is unlikely to be economically viable due to the LCOE being too high, and the WAV being too low. The main factors for the WAV being low include small fees and taxes on purchased electricity, fees on sold electricity, and the lack of grid benefit compensation. Individually, these factors have a low impact on the WAV. However, collectively they contribute to a situation where it is neither particularly attractive to conserve electricity nor sell PV electricity. A conserved kWh is, according to the result, worth around 10 öre more than a sold. This is quite significant since this is a difference of more than 20%. If the amount of conserved electricity could be increased, i.e., adjust the use of high power towards sunlight hours, it could increase the value of the yield from the solar farm significantly. The WAV is also heavily dependent on the average price of PV electricity for a specific year. Using data from other years will most definitely have a big impact on the result. We believe that 2023 had a fairly average electricity spot price, although this is unconfirmed.

The module type which was preliminary chosen for the solar farm in this study had a Wp of 695W. However, the modules used in PVsyst simulations had a Wp of 665 W. This difference which the 695W module would have on the results would be slightly reduced shading due to less modules being required for a 50 MWp solar farm. It would also reduce the CAPEX part of LCOE, since more powerful modules generally are cheaper per Watt. It would also reduce the area of the solar farm, and subsequently increase the MWp/Ha. Winsun PV does not allow the user to choose specific modules, but using a more powerful module would reduce the module-area input which affects the efficiency of the system. This means that the effects of a more powerful PV module would be similar in both PVsyst and Winsun PV.

Since connection issues have been identified as one the most expensive and time-consuming aspects of a solar farm project, falling under the IKN regulations would probably reduce costs, time, and effort required for the project, which might make a solar farm slightly more economically attractive. Since the first solar farm to fall under the IKN regulations was commissioned in 2021, the current data regarding how big of a difference IKN has on connection costs is scarce.

Emission trading, electricity certificates, and subsidies currently have a limited impact on the profitability of the solar farm. However, this might change in the future since the rates and rules for these systems are constantly changing.

5.2.6 System inputs/PV mounting configurations

The most reasonable configuration simulated in this case study has been identified as approximately 30° tilt, 18° shading angle. This gives a good combination of ground coverage and specific production. Increasing the shading angle slightly towards 21, as in scenario 3 in Table 7, could also be a very reasonable option since it increases ground coverage with only a slight reduction in specific production. The results also show that a lower shading angle, such as 10 in scenario 1, gives heavily reduced ground coverage, and should therefore be avoided. Similarly, a much higher shading angle, such as 28 in scenario 4, results in an increase in ground coverage, but the decline in specific production is too large for the system to be viable. Since PVsyst simplifies shading calculations a higher shading angle would probably have an even higher detrimental effect in reality.

6 Conclusions

Even though our cost calculations are based on assumptions, and probably include some inaccuracies, we are still confident that the results are accurate enough to give an answer to the questions:

-Is it feasible to build a solar farm at the suggested location and connect it towards the industry's own consumption?

The short answer to this question is yes. However, the more detailed answer is; Yes, but the advantages from connecting the solar farm directly towards consumption may not be enough to make it an attractive investment. It is however, with the current conditions, highly likely that establishing a solar farm at the intended location would fall under the IKN regulation, which is a major advantage.

-Is the solar farm in this case study economically viable?

In short, no, it is not economically viable. A more detailed answer is not with the current rate of WACC, taxes and fees. Although the difference in value between conserved and sold electricity is significant, the strategy of connecting the solar farm towards consumption is still probably not enough to make it viable under current conditions. Additional beneficial conditions such as lower WACC, lower fees, and grid benefit compensation, could change the situation in favor for the solar farm. For that reason, we encourage the company to further investigate this project, since a few more positive conditions could tip the scales in favor of the solar farm.

6.1 Future work

6.1.1 Energy storage

In order to increase the potential of the solar farm, it might be interesting to look at some kind of energy storage, such as batteries or hydrogen. Integrating a battery storage system with the solar farm might affect the results of this study in more than one way. For example, this would enable the factory to lower its peak power consumption during nighttime hours. Currently, it is purely coincidental if the factory's hours of highest power consumption align with peak solar irradiance. Implementing battery storage would help minimize the "maximum power peaks" which are visible in Figure 34 Purchased and produced electricity PVsyst). Batteries could also eliminate the need to sell excess energy back to the grid, thereby conserving electricity, maximizing savings, and enhancing the utilization of onsite solar power production.

6.1.2 Local climate data

If Stora Enso is seriously planning on going forward with the project of establishing a large-scale solar farm in the area outside Skutskär, they should install measuring equipment to create local climate data on site of the proposed solar farm. This would enable an even more accurate and reliable simulation. The authors have received word from the university of Gävle, indicating that they are interested in undertaking this task.

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