



Linnæus University

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Degree Project

System perspective of rooftop solar PVs in the Swedish industry sector

A case study of GEHAB in Småland



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Summary

To reduce climate change effects, countries are trying to replace fossil fuels with renewable energy sources. In the electricity sector, in Sweden, the goal is to have a completely renewable electricity system by the year 2040. Therefore, nuclear power and the last fossil fuels have to be phased out from the Swedish electricity mix until then. This demands a large contribution from the locally available energy sources of solar and wind power. Currently, there is a great opportunity to work towards this goal by investing in rooftop solar power and at the same time reduce the electricity bill and get additional revenue from the electricity that is sold to the national grid.

GEHAB is a company that is located in Alvesta, in the southern region of Småland, Sweden. They have a strong interest in improving their environmental impact and their current plan is to invest in rooftop solar energy. This thesis investigates the potential and effects of such an investment in the company. The system analysis is based on the simulation tool EnergyPLAN. Four different scenarios are considered, including i.) Calculating the largest possible installation at the site; ii.) Focusing on finding the most cost-optimal size of the solar installation, based on the parameter of Levelized Cost Of Energy (LCOE); iii.) Investigating the cost-optimal size if a battery installation is added; iv.) Describing a net-zero electricity consumption setting, which tries to find the current issues with reaching that scenario. Besides these scenarios, a sensitivity analysis investigates how different factors influence the LCOE of the different investments. The avoided CO₂ emissions caused by such installations are also calculated.

The company used 927 000 kWh of electricity in 2021, which costed them 902 000 SEK, based on Nordpool market prices. The electricity was mostly used during normal working hours on the weekdays, which favours solar electricity production.

The maximum production scenario showed that the largest PV installation at the company was 335 kW_p. However, this was not the most cost-optimal size. Instead, a 215 kW_p installation would have the lowest LCOE, at -366 SEK/MWh, when the avoided costs are included. The discounted payback time of such an investment was found to be 11.3 years. The battery scenario resulted in an LCOE of 273 SEK/MWh, which means that the investment would not pay back within its lifetime. Finally, the net-zero electricity consumption scenario found that currently, the largest issue to reach this scenario is that there is a regulation that limits solar installations to 500 kW_p to avoid an energy tax.

A tax deduction for the sold electricity was found to be the reason for the cost-optimal size not being the largest installation. The deduction has an annual cap of 30.0 MWh and PV installations that caused larger amounts of electricity to be sold resulted in a higher LCOE. The battery scenario showed that it is currently not a good investment due to the large investment costs and the lower cost saving. However, in the future, this investment might become more relevant since the cost of batteries is decreasing rapidly. As a result, the recommendation to GEHAB is to invest in a 215 kW_p PV installation. However, if the goal is to produce as much electricity as possible, the largest installation also has a relatively good payback time and would save energy costs as well.

Abstract

To reach the Swedish goal of reaching a completely fossil-free electricity sector by the year 2040, there is a need for an increased rate of installed renewable electricity sources. Companies have the opportunity to work towards this goal by investing in solar power technologies, which results in a lowered electricity bill, and an additional revenue when electricity is sold to the grid. As a result, the investment usually pays back within a reasonable timeframe.

GEHAB is a company located that is located in Alvesta, Sweden, and they are interested in investing in rooftop solar power. This thesis investigates the potential and effects of such an investment at the company through energy simulations. This is done through four different scenarios, which aim at finding the largest possible installation, the most cost-optimal installation, according to the Levelized Cost Of Energy (LCOE), the impact of an added battery installation and finding the current issues with becoming a net-zero consumer of electricity. Finally, a sensitivity analysis was made to investigate how different factors impacted the LCOE.

The results showed that the most cost-optimal size for the company to invest in was a 215 kW_p installation, which is smaller than the maximum possible size of 335 kW_p that can be installed on the rooftop. Such an installation would have an LCOE of -366 SEK/MWh when the avoided costs are included. The discounted payback time of that investment was 11.3 years. The involvement of batteries showed that they would lead to a higher LCOE and for the largest possible solar installation size, including a battery, means that it would not pay back within the lifetime of the PVs. Finally, the net-zero electricity consumption scenario found that currently, the largest issue to reach this scenario is that there is a regulation that limits solar installations to 500 kW_p to avoid an energy tax.

Keywords: Cost-efficient energy solutions, Photovoltaic power, Solar PV, Electricity storage, Lithium-ion battery, Emission reduction, energy simulations, EnergyPLAN

Preface

This report is a thesis project for the two-year master's program Sustainable Energy Processes and Systems at the Linnaeus University in Växjö. The thesis was performed during the spring semester of 2022.

First, I would like to thank my supervisor Truong Nguyen, who has been giving me valuable information and suggestions during the project, which has been a great help to me during this period.

I would also like to thank GEHAB, and especially Monica Sundell, for allowing me to work with them. They have also made the research possible by supporting me with a lot of the data that has been used for this thesis.

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1. Introduction

1.1. Background

The temperature on the globe is increasing, which has raised growing concerns for our future climate [1], [2]. Since before the industrial revolution, the average temperature has increased by about 1 °C, and keeps rising. This is caused by an increased amount of greenhouse gases in the earth's atmosphere, which are released when fossil fuels are being used as an energy source. To avoid changes to the climate that are irreversible, the Paris Agreement was signed in 2015 by 196 countries, which states that the global average temperature should not increase by 2.0 °C and should preferably stay below 1.5 °C [1], [2]. To reach this goal, net-zero carbon sources must replace fossil fuels shortly. Renewable energy sources are good options for such energy sources.

The Swedish electricity system is, unlike the global system, almost completely fossil-free [3]. The electricity is instead produced mainly by hydro and nuclear power, which provide about 40 % of the electricity each [4], [5]. Thermal power is also an important electricity source, which is partly fuelled by fossil fuels and provides about 10 % of the electricity. The installed capacity of wind power is increasing rapidly and has now reached 12 % of the produced electricity. This leaves the last source of electricity on the grid, solar energy, which currently provides less than 1 % (0.7 TWh in 2019 [4]) of the electricity [4], [5].

The Swedish energy and environmental goals are aimed to make Sweden a net-zero emitter until the year 2045, with a sub-goal of reaching 63 % lower emissions (compared to 1990) until 2030 [6]. In addition to this goal, the government has also established a goal to have a fully renewable electricity system by 2040, which means that nuclear power and the last fossil fuels have to be phased out by then [7], [8]. At the same time, the electricity demand is assumed to increase in the near future.

The Swedish electricity system is divided into four different regions, which represent the variations in demand and supply throughout the country [9], [10]. In the north of Sweden, most of the hydropower is installed, while the population is much lower, which has led to a common oversupply of electricity. In the south of Sweden, all of the nuclear power is located but there is still often an undersupply of electricity due to a larger population. The four electricity areas are trying to reflect these differences by implementing different electricity prices, to show the cost of delivering it from the north to the south. The different electricity areas, their electricity supply and demand, and their average electricity price in 2021 can be seen in Figure 1 [11]. The electricity market is also shared with Sweden's neighbouring countries through Nordpool which provides the current spot price in each region [9], [10]. The shared market ensures that when there is an over- or undersupply of electricity in an area it can be imported or exported between countries as well.

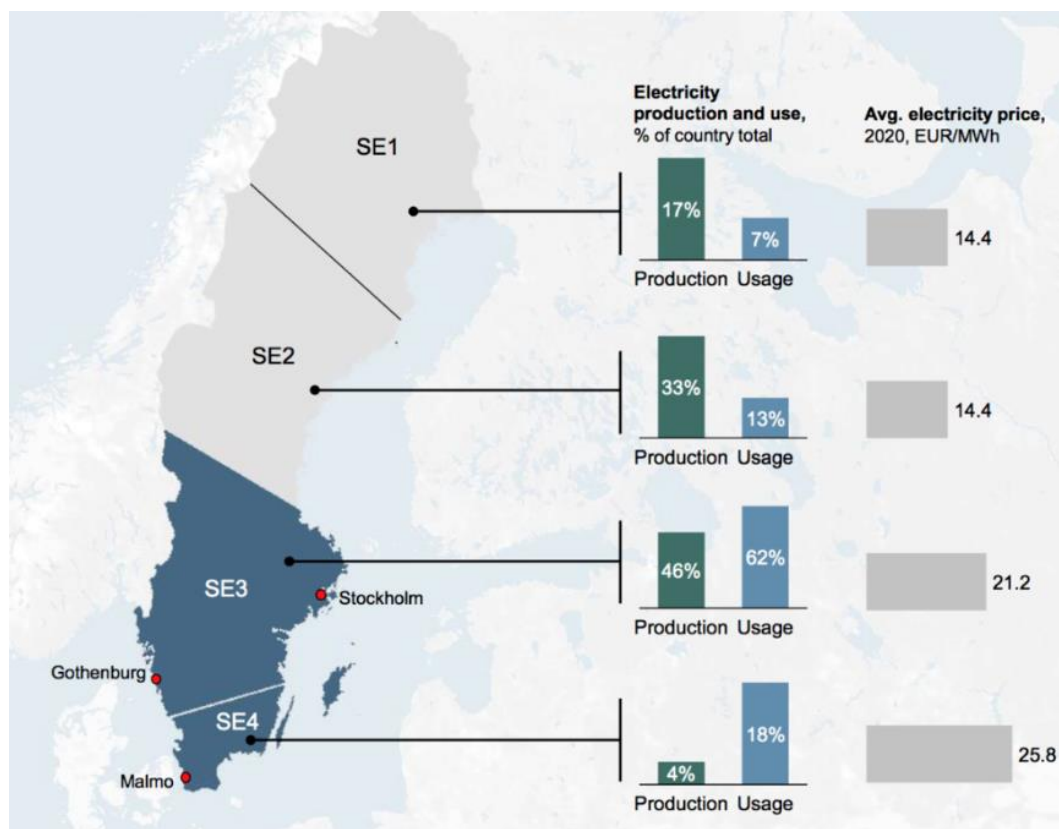


Figure 1: A map of the Swedish electricity areas. It also shows the oversupply in the north and the undersupply in the south, which results in a higher price in the south. [11]

In addition to the varying prices within the country, there are also price fluctuations, both daily and seasonal [12], [13]. This is due to the variation of demand and supply during these time periods. In Figure 2 [12], an example of fluctuating electricity prices can be seen throughout the day. The fluctuating price can be explained by the variation of electricity demand throughout a normal day. In the morning, many start using electricity when they wake up and proceed to morning routines, then, during the day the electricity price decreases when many are at work. Then it usually increases again in the evening when most people get home, and finally, it decreases again during the night [12], [13]. This shows the relationship that the electricity price has with the demand.

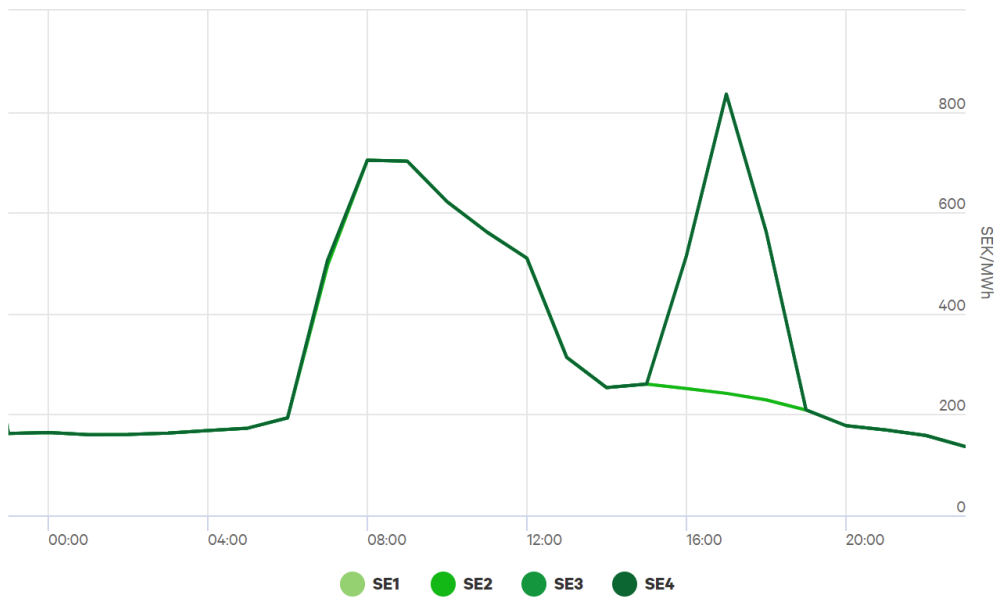


Figure 2: The figure shows a daily price fluctuation for the different electricity areas in Sweden (27th January 2022). The electricity price for SE1 and SE2 are the same throughout the day and the same is true for SE3 and SE4. [12]

The seasonal price variations are due to the varying weather patterns throughout the year [14]. During the winter, due to the cold weather, the need for heat and electricity is usually the highest and during the summer it is at its lowest, which is reflected in the cost, as can be seen in Figure 3 [12]. The varying weather during the year also impact the available energy from some of the renewable energy sources such as wind and solar energy and also the water reservoirs for hydropower, which impacts the prices during the year [14]. The electricity price in the later parts of 2021 was at an all-time high but it can still be seen that the price was higher in January and February than during the spring and some of the summer that year [13]. The high electricity prices have continued into early 2022 as well, due to the current uncertainty of fossil fuel imports in Europe and low water reserves [15].

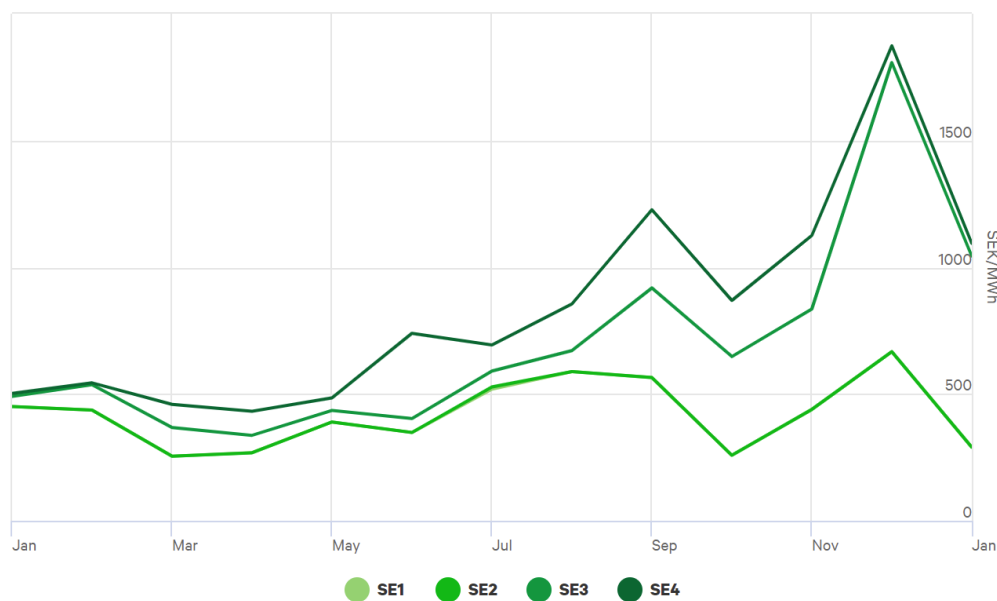


Figure 3: The figure shows seasonal price fluctuations for the different electricity areas in Sweden (January 2021 - January 2022). The average electricity price for SE1 and SE2 are the same throughout the year. [12]

To cover the need for renewable electricity, intermittent resources of solar and wind power are expected to increase greatly to cover the increasing electricity demand and the decrease in nuclear power [7], [8]. According to studies made by The Swedish Energy Agency [7] and Svenska Kraftnät [8], solar power is expected to produce about 8–11 TWh of electricity in 2050 but could reach double that amount in some scenarios according to Svenska Kraftnät's study. At the same time, wind power is also expected to increase considerably [8]. However, if wind and solar power keep increasing, our electricity supply will become all the more dependent on the weather. This could affect the electricity market since there will more often be an over- or undersupply of electricity. This is described in the study made by Svenska Kraftnät, which showed that the difference in electricity price between the cheapest and most expensive will increase. The amount of time the electricity will be more expensive or cheap will also increase [8]. In addition, The Swedish Energy Agency's study also showed that the electricity price will increase in general as well, which is explained by the increasing demand for electricity [7]. This is particularly clear in their scenarios where the electrification of society was assumed to be at a higher rate.

One renewable energy source that is often discussed is solar energy, which is an energy source that is abundant on earth and could theoretically cover all our electricity consumption [16], [17]. However, in reality, it is not that easy. The efficiency of current technologies to convert solar energy to useful electricity is quite low and, therefore, it requires huge areas to produce a large amount of electricity if land area is used. Though, rooftop installations are an appealing option due to the available roof area. This allows companies and homeowners to produce their own electricity without the need for large areas for solar panels. However, technologies based on solar energy are weather dependent, which means that electricity cannot always be produced when there is a demand for it [16], [17]. To solve this issue, electricity storage has gotten increased awareness, since it allows for an overproduction of electricity that can be stored when the sun shines, which can then be used when the electricity production is not sufficient to cover the demand. Although there are some relevant issues, the technology is assumed to be an important energy source in future electricity systems [16], [17]. The investment cost also keeps decreasing, which has made it a relevant investment for homeowners and companies to reduce their electricity bills.

In line with the national targets, many municipalities have adopted strategies toward a carbon-neutral future. Alvesta municipality is located in electricity area SE4, in the southern region of Småland, Sweden. Their energy and climate goals are influenced by the national goals. The main goal is to accomplish carbon neutrality by 2045, and after that achieve negative emissions [18]. Until 2030 the emissions should be reduced to 1.90 tonnes CO_{2-e}/capita, from the 2.95 tonnes in 2018. The progress in reducing their carbon emissions in different sectors since 1990 can be seen in Figure 4 [18]. To achieve this goal, targets to decrease energy consumption, produce more renewable energy, and increase the amount of fossil-free transport vehicles in the municipality have been set. One of the renewable energy targets is to increase the amount of renewable electricity to 450 GWh in 2030, from the 1.9 GWh of solar power and 0.4 GWh of hydropower in 2019. It is projected that 300 GWh will come from wind power by 2022 when a new wind power park will be completed, which is a large step toward that goal [18].

Emissions from different sectors in Alvesta Municipality (tonne CO₂-e/capita)

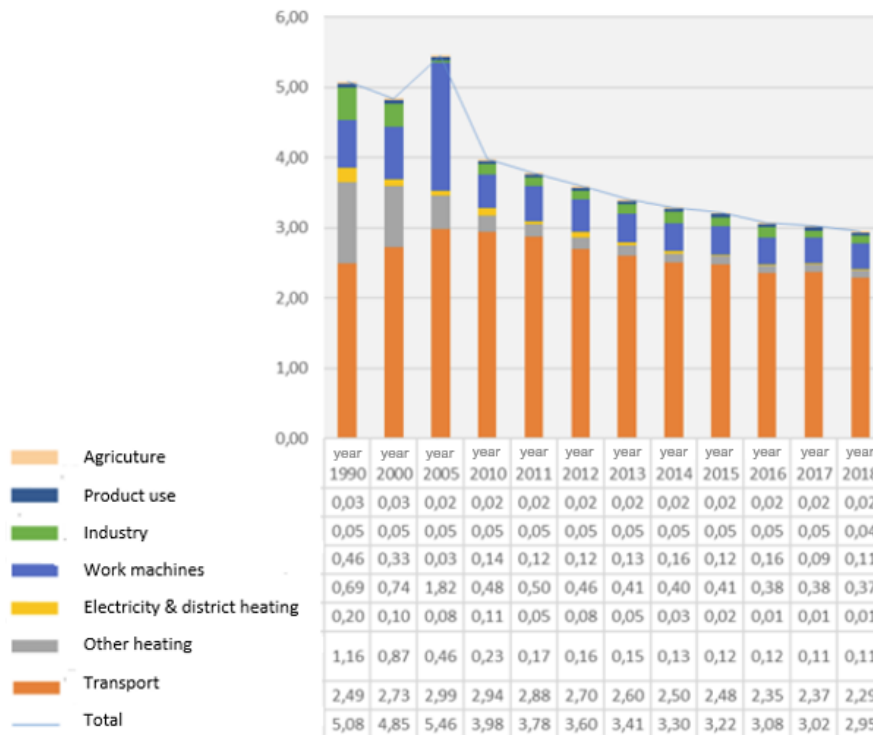


Figure 4: Emissions from different sectors in Alvesta municipality 1990-2018. [18]

To reach these goals, industries have the opportunity to invest in solar power and install them on the rooftops of their buildings. By doing this, a share of their electricity consumption can be replaced by solar power, which results in lower electricity bills. In addition, when the installation produces more electricity than what is being used, the extra electricity can be sold to the grid, which generates an additional income. As a result, solar power investments usually pay back long before they reach their end-of-life. This means that after it has been paid back, the additional electricity it produces leads to a profit for the company. Another option is to also install storage that can store the extra electricity until it is needed so that even less has to be purchased. This could also allow for self-sufficiency in electricity. In addition to the lowered energy costs, solar power also reduces the carbon emissions in the industry since solar power produces no carbon emissions when converting solar radiation to electricity.

GEHAB is a company that is located in Alvesta municipality, and they have set their aim to become more environmentally friendly. They have a strong interest in improving their environmental impact and have a long-time goal of becoming self-sufficient in energy. A few years ago, they planned to invest in a 121 kW_p rooftop solar installation but the plans had to be cancelled since the rooftop could not support the weight without being strengthened. However, today they can install solar panels on another rooftop. Therefore, this master thesis will study what the most cost-optimal solar installation would be for the company GEHAB if an installation on that rooftop were to be made. It will also investigate if electricity storage would increase the self-use of the produced solar electricity and how large the solar installation has to be for the company to become a net-zero electricity consumer.

1.2. Aim and objectives

The purpose of this thesis is to investigate the potential and effects of installing a solar PV system at one of the properties that are owned by the company GEHAB. This is to figure out the optimal share of self-produced electricity for their electricity demand. The project will also investigate if battery storage would allow for a higher share of self-used solar electricity. These options will be presented with an estimated cost to be able to suggest which option is the best from an economic perspective. The resulting avoided CO₂ emissions from the investments will also be investigated.

Specifically, several research questions are to be addressed, including:

- What is the maximum share of electricity that can be covered by the available rooftop area at the company GEHAB?
- What is the most cost-optimal option for a solar panel installation at the company?
- If battery storage would increase the self-use of the produced solar electricity and how such an installation would change the cost of the solar investment?
- If the proposed size of the solar panel installation would allow the company to become a net-zero consumer of electricity or what the required size of the installation would have to be in order to reach that?
- What are the avoided CO₂ emissions from these different installations?

1.3. Limitations

This thesis is based on multiple assumptions. The data used for the simulations are from 2021 and have been assumed to be the same for every year during the solar installation's lifetime. In addition, changes in the future have not been accounted for, such as changes in weather and solar radiation, the electricity price, or the future price of reinvestments in inverters and batteries. The policies in act have also been assumed to remain unchanged during the project's life span. Also, the degradation of the solar PVs and the electricity storage has not been accounted for.

Currently, the company has a fixed price on electricity, but that contract will soon run out. Therefore, the electricity cost will be assumed to be varying according to the Nordpool spot prices, which is not including taxes and profits that an electricity supplier would charge. Some suppliers also grant an additional income when selling solar energy, which has not been accounted for either. If a new contract for a fixed price on electricity would be signed, the economic calculations would have to be changed to stay relevant.

In the electricity storage scenario, some further optimisations might be possible regarding the rate at which they get charged and discharged. Some losses that could occur in the batteries when they heat up or store electricity for a long time have not been accounted for. Also, since the electricity price does not include the additional costs that the electricity supplier would charge, the reason to use the produced solar

electricity at the company is reduced. In addition, the calculations for the avoided CO₂ emissions do not include an environmental reason to use the produced electricity at the company.

2. Theory

Important information on the technical background of the thesis will be described in this section as well as relevant calculations and equations that was used for the simulations.

2.1 Technologies of solar photovoltaic systems

The first commercial PV cells were used in 1954 and were first only used on a very small scale since the efficiency was just a few per cent and the cost was too high [19]. However, with the energy crisis in the 70s, as well as the current climate crisis, the interest in electricity produced from a clean and renewable energy source has increased over time. Therefore, large technological advancements in different solar technologies have been made throughout the years [19], [20]. This has resulted in a much higher efficiency today. The highest achieved efficiencies are over 40 % [20]. However, the more common crystalline solar cells that are commercially available also have a much higher efficiency today and can often reach more than 20 % [21]. In Figure 5 [20], the cell efficiency improvements for different solar technologies since 1976 can be seen.

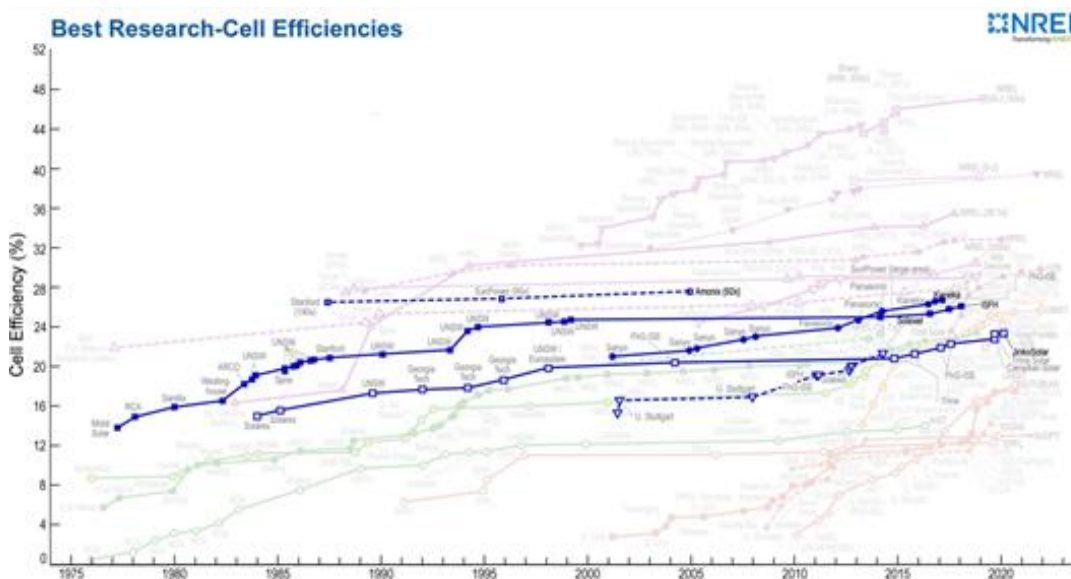


Figure 5: The best research-cell efficiencies for different solar technologies since 1976. The blue graphs represent crystalline technologies, which are focused on in this thesis. [20]

Even though PVs that were installed 20-25 years ago are reaching their end-of-life [22], newly constructed installations are expected to have a technical lifetime of 35 years. Between 2015 and 2020, the technical lifetime of PV installations increased by about five years [23]. This shows how quickly technological advancements are made for solar power.

There are different types of solar PV panels, where monocrystalline and polycrystalline are among the most commonly used, but thin-film PVs are also a technology that is used commercially [23]. In the following sub-sections, these different types of PVs will be described.

2.1.1. Polycrystalline photovoltaics

Polycrystalline PV panels are created from silicone that is melted and then cooled down in a rectangular shape [21], [23]. Through this process, multiple crystal patterns are created in the material and result in a blue coloured PV cell, which can be seen to the left in Figure 6 [21]. This pattern has a lower conversion efficiency than PVs that are monocrystalline. However, the processes used for polycrystalline PVs are less energy-intensive and the final product is cheaper than monocrystalline PVs. Due to their lower cost, polycrystalline PVs are more commonly used when the investment cost has to be kept low or when the area is not a limiting factor, so the efficiency does not have to be as high [21], [23]. Therefore, this option will not be considered further in this investigation.

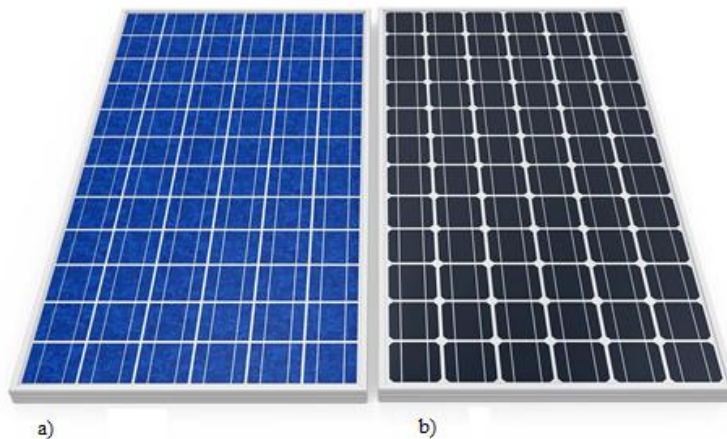


Figure 6: a) A polycrystalline PV panel, which has a blue colour. The cells consist of multiple crystalline structures. b) A monocrystalline PV panel, which has a black colour. Each cell consists of only one crystalline pattern. [21]

2.1.2. Monocrystalline photovoltaics

Monocrystalline PV panels consist of almost completely pure silicone that is produced through purifying processes [23], [21]. When the silicone is complete it is in the shape of a cylinder and consists of a single silicon crystal. Then it is cut into rectangular shapes since circular shapes would leave large empty spaces in the panels. The final PV cells have a darker colour than the polycrystalline cells and can almost appear black, which can be seen to the right in Figure 6 [21]. The production method is quite energy-intensive and leaves large losses of the material, which also leads to it being a more expensive type of PV [23], [21]. However, it leads to more efficient solar cells. Due to the higher efficiency, but also higher price, they often result in similar costs as polycrystalline PVs when two installations that have the same electricity output are compared. Due to the higher efficiency, it does, however, require less space to reach the same output. Additionally, monocrystalline PV panels function better when the

panels heat up from solar radiation [23], [21]. Since the limit of the solar installation in this thesis is the rooftop area, the technology that will be further investigated in this thesis are monocrystalline PVs.

2.1.3. Thin-film photovoltaics

Thin-film PVs work similarly to crystalline PV technologies but also consist of other materials, like cadmium or copper [24], [25]. However, the thin-film PVs use much thinner layers, making them much lighter and more flexible, which is shown in Figure 7 [25]. Therefore, they also use less silicone and are cheaper to produce. The drawback, however, is that some include toxic metals, and that commercially available thin-film PVs only reach about 6–12 % efficiency, depending on the materials used [24], [25]. Due to their low efficiency, they are mostly used for companies or commercial buildings since they usually have larger available areas than residential buildings [25]. As mentioned in the last sub-section, in this thesis the rooftop area is limited, which makes this choice worse than the crystalline technologies.



Figure 7: The flexibility of thin-film PV panels is demonstrated. [25]

2.2. Efficiency of a solar photovoltaic system

The theoretical output of a PV panel is calculated through the following equation [26], [27]:

$$P_{theoretical} = P_{peak} * \frac{G}{1000} \quad [1]$$

where:

$P_{theoretical}$: Theoretical power given by the panels [W]

P_{peak} : Peak power of the panels [W]

G : Solar irradiance [W/m^2]

Though the peak output of a PV panel is usually stated as the STC (standard test conditions), where the module's temperature is 25 °C, the solar irradiation is 1000 W/m^2 , and the angle of incidence is optimal [28]. In reality, however, the solar radiation is varying throughout the year and in Sweden, it rarely reaches radiation levels as high as that. When the panel is used in reality, it will usually not be as

efficient. Therefore, in this thesis, three of the largest impacts on the electrical output of a solar panel will be accounted for and will be described in detail below.

2.2.1. Effects of the panel temperature

One of the important impacts on the actual efficiency of a PV panel is its temperature [29], [30]. The temperature of a panel impacts multiple factors, such as the open-circuit voltage, and current, as well as the maximum power output. The maximum power output decreases when the temperature of the panel increases and is usually at around $-0.44 \text{ \%}/^{\circ}\text{C}$, compared to the STC tests at $25 \text{ }^{\circ}\text{C}$. This means that when the outside temperature is high and there is a lot of solar radiation, the efficiency of the panels will decrease. However, in colder climates, such as in Sweden, the temperature of the panels will often be below $25 \text{ }^{\circ}\text{C}$, which results in increased efficiency, compared to the STC. To calculate the temperature factor, the following equations were used [29], [30]:

$$T_{module} = T_{ambient} + \left(\frac{NOCT-20}{80} \right) * \frac{G}{10} \quad [2]$$

$$K_T = 1 - \beta * (T_{module} - 25) \quad [3]$$

where:

T_{module} : The current temperature of the module [$^{\circ}\text{C}$]

$T_{ambient}$: The current air temperature [$^{\circ}\text{C}$]

NOCT: The temperature used for the nominal operating cell temperature [$^{\circ}\text{C}$]

G: Solar irradiance [W/m^2]

K_T : The temperature correction factor [%]

β : Temperature coefficient [$\text{\%/}^{\circ}\text{C}$]

2.2.2. Effects of the angle of incidence

The angle of incidence (θ) is the angle between the solar radiation and the normal to the surface of the solar panel [26], [27], [31], as seen in Figure 8. The larger this angle is, the more solar radiation will be reflected away from the PV cell, which results in less energy that can be converted into electricity. Also, when the angle is larger than 90° the radiation does not reach the cells at all. This angle depends on multiple different factors and can be calculated through the following equation [26], [27], [31]:

$$\cos(\theta) = \cos(\delta) \sin(\omega) \sin(\beta) \sin(\gamma) + \cos(\delta) \cos(\omega) \sin(\lambda) \sin(\beta) \cos(\gamma) - \sin(\delta) \cos(\lambda) \sin(\beta) \cos(\gamma) + \cos(\delta) \cos(\omega) \cos(\lambda) \cos(\beta) + \sin(\delta) \sin(\lambda) \cos(\beta) \quad [4]$$

where:

θ : Angle of incidence [$^{\circ}$]

δ : Declination [$^{\circ}$]

λ : Latitude [$^{\circ}$]

γ : Azimuth [$^{\circ}$]

ω : Hour angle [$^{\circ}$]

β : Tilt [$^{\circ}$]

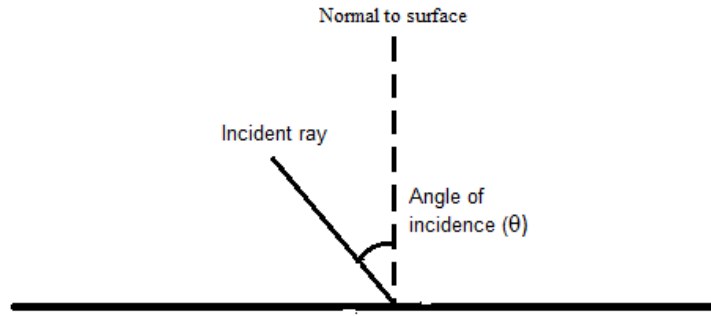


Figure 8: The angle of incidence is shown.

The declination (δ) is the angle between the earth's equator and the sun and varies during the year [26], [27], [31]. This angle is a result of the earth being tilted at a 23.5° angle, as can be seen in Figure 9 [32]. It is this tilt that also causes the varying seasons on earth. Therefore, the solar radiation reaches the earth at an angle between 23.5° and -23.5° during a year. The highest angle is during the summer solstice and the lowest during the winter solstice. The two times the angle is 0° during a year are the spring and fall equinox. Since the angle varies daily throughout the year, it can be calculated according to equation 5 [26], [27], [31]:

$$\delta = 23.45 * \sin \left(\frac{360 * (284 + d)}{365} \right) \quad [5]$$

where:

d: Day of the year in the Gregorian calendar

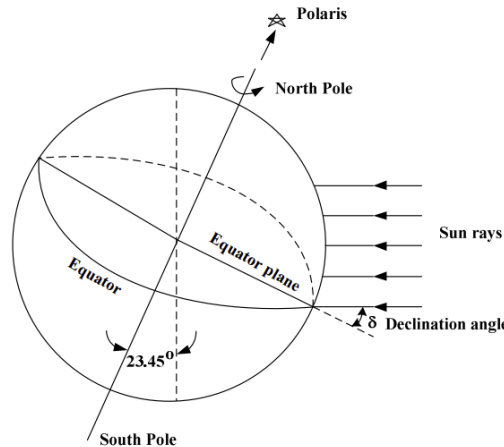


Figure 9: The reason there is a declination angle between the solar radiation and the earth is shown. [32]

The latitude (λ) is the latitude that the PV panels are installed at, which is a value between -90° and 90° [26], [27], [31]. The negative values are south of the equator and the positive north of it. For the case of Sweden, it is a country that is quite long and covers the latitudes between 55° and 69° [33], but this project is in the south of Sweden, at about 57° .

The azimuth (γ) is the angle between the normal from the surface of the solar panel and the south [26], [27], [31]. This angle determines if the panel is directed toward the

south, which is the best angle for a solar panel to be facing. However, having a solar panel that faces east increases its production early in the day and toward west increases its production in the evening. This angle is negative if it faces east and positive towards west. In this project, a rooftop that faces east at approximately a -60° angle and west at a 120° angle is investigated.

The hour angle (ω) is representing the sun's movement in the sky during a day on earth [26], [27], [31]. Since an earth day is 24 hours and the sun rotates 360° during that time, the sun moves 15° each hour. This is described from the perspective of someone on earth and in reality, it is the earth that rotates around itself. This results in the following equation [26], [27], [31]:

$$\omega = 15 * (hh - 12) \quad [6]$$

where:

hh: Solar hour [h]

mm: Solar minute [min]

However, there are small differences between the solar hour and the local time on earth [26], [27], [31]. This is because of the time zones that are based on the standard meridians. Each 15° meridian is a different time zone, but to get the actual solar time the difference between the standard meridian and the local meridian has to be included. Also, due to the tilt of the earth and the elliptical orbit around the sun, the solar hour does not coincide with our local times throughout the year. Therefore, "the equation of time" is needed to correct this [26], [27], [31]:

$$E = 229.2 * ((0.000075 + 0.001868 * \cos(B) - 0.032077 * \sin(B) - 0.014615 * \cos(2B) - 0.04089 * \sin(B)) \quad [7]$$

where:

E: Correction of minutes [min]

B: A variable, which varies each day and can be calculated through equation 8 [26], [27], [31]:

$$B = (d - 1) * \frac{360}{365} \quad [8]$$

where:

d: Day of the year in the Gregorian calendar

By adding these two corrections to equation 6, the following equation is received [26], [27], [31]:

$$\omega = 15 * ((hh - 12) + \frac{mm+E}{60} + (L_{ST} - L_l)) \quad [9]$$

where:

hh: Local hour [h]

mm: Local minute [min]

L_{st} : Standard meridian [$^\circ$]

L_l : Local meridian [$^\circ$]

Finally, the tilt (β) is the angle that the solar panels are installed at [26], [27], [31]. When installing PVs on rooftops, this is often the same angle as the rooftop [34], [35]. However, in the northern countries, the optimal angle is at about 40-45°, which means that if a rooftop has a smaller angle than 5° many companies recommend that the panels are installed at a larger angle. Yet, they are usually not installed at the optimal 45° since that results in the PVs shading each other when the solar radiation has a larger angle of incidence, but they are instead usually installed at about a 15° angle [34], [35]. The tilt that the investigated rooftop has is 10° and has therefore not been assumed to be installed at an increased angle.

If these five angles are known the angle of incidence can be calculated through equation 4. When the angle of incidence is known, the correction factor that is caused by it can be calculated according to equation 10 [26], [27], [31]:

$$K_b = 1 - b_0 * \left(\frac{1}{\cos(\theta)} - 1 \right) \quad [10]$$

where:

K_b : The correction factor caused by the angle of incidence [%]

b_0 : Impact of the angle of incidence (assumed to be 0.1 [26], [27])

2.2.3. Effects from the inverters

The current that is produced from a solar cell is DC (direct current) and cannot be used in our regular electrical appliances since they run on AC (alternating current) [36], [37]. Therefore, inverters are needed to convert the produced DC into AC, if it is supposed to run normal appliances and be able to be put on the grid. The inverters switch the current rapidly to convert it into AC [36], [37]. The inverters usually have a shorter expected lifetime, at about 10-15 years [38], which means that they usually have to be replaced once or twice during the PV installation's lifespan. When used together with a solar installation they can also function as a communication for the produced electricity. It is important to note that if the installation includes battery storage, a slight difference in the inverters will be needed to enable such an installation [39]. The inverters run on electricity and result in losses, which reduces the efficiency of the PVs, in addition to increasing the prices of the installation, but it is necessary for the electricity to be useable [37]. Therefore, a correction factor (η) for these losses will be included.

2.2.4. Total correction factor

By multiplying the three correction factors caused by temperature, the angle of incidence, and the inverter efficiencies, a total correction factor is received, which is done according to equation 11 [26], [27], [31]:

$$\varphi = K_T * K_b * \eta \quad [11]$$

where:

φ : Total correction factor [%]

K_T : The temperature correction factor [%]

K_b : The correction factor caused by the angle of incidence [%]

η : The efficiency of the inverter [%]

2.3. Seasonal variation of solar power performance

As discussed in a previous section, the solar radiation angle toward the solar panels varies throughout the year [40], [41]. This is caused by the varying angle between the sun and the earth during the year. This angle impacts the amount of solar radiation that hits the surface of the earth. Therefore, seasonal variations in the amount of solar radiation that hits an area are created. In Figure 10 [40], the seasonal variations in Sweden can be seen. It is important to note that the scales of the different graphs are not the same. The figure clearly shows that the solar radiation in the winter and fall is much lower than in the summer and spring and therefore it should be expected that those seasons also will provide less solar electricity from a PV installation [40], [41]. It can also be seen that the yearly variations during the summer and spring are much larger than for the other seasons. This is caused by the sunshine hours, which can vary greatly between years and between different areas [40], [41].

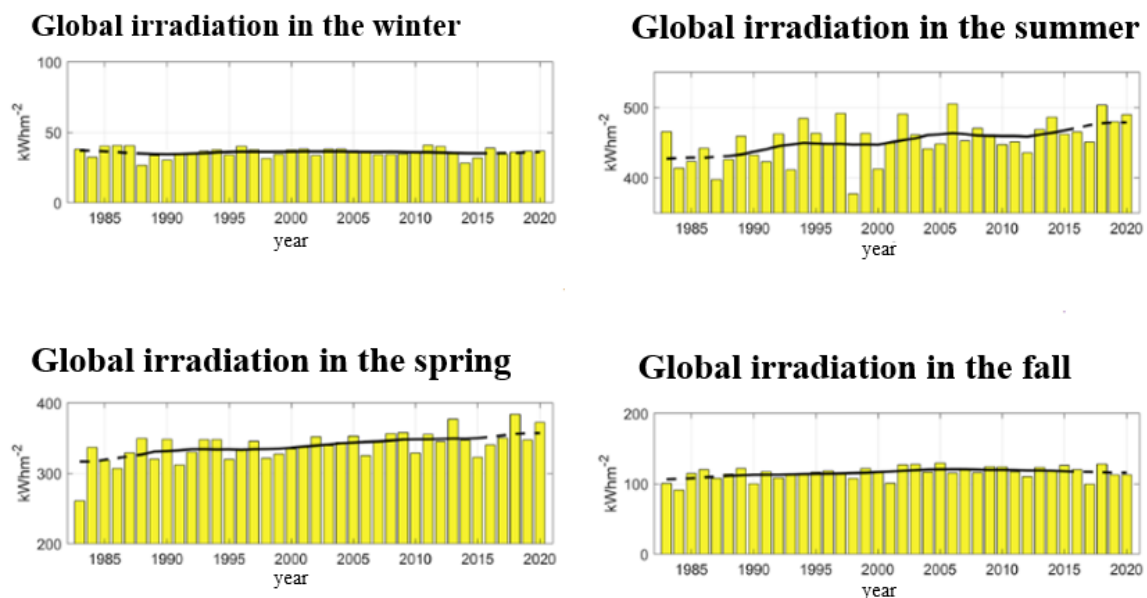


Figure 10: The global irradiation in Sweden during the four seasons since the 80s. [40]

2.4. Cost reduction of solar cells

As a result of the advancements in solar technologies, their cost has been reduced drastically [19], [42]. Only in the last decade, the cost has decreased by about 60 % [19], [42], which can be seen in Figure 11 [42]. This has led to a fast increase in installations around the world. In Sweden, in 2019 the installed capacity had increased by 70 % since the previous year and the number of facilities had more than tripled since 2016 [4], [43].

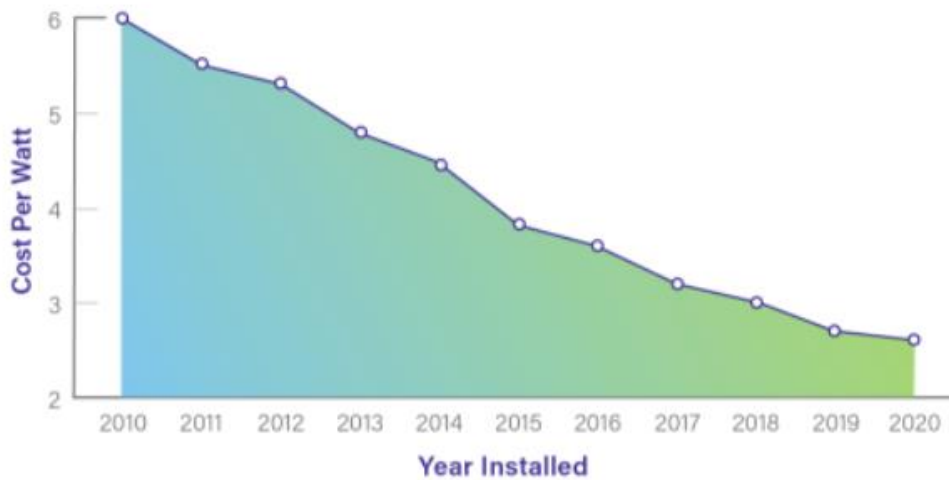


Figure 11: The cost reduction for solar power installations during the last decade. The cost per watt is stated in USD. [42]

Consequentially, the more investments in solar power that are done, the more research can be made to continually increase efficiency and decrease the cost [23]. Figure 12 [23] demonstrates the cost reduction of solar installations as a result of the increasing cumulative solar electricity production since 1980. The figure shows that for the last four decades when the cumulative production has doubled, the cost of solar panels has decreased by 24 % [23]. With the current rate of cost reduction, it is projected that the cost will continue to decrease in the coming decades and will almost be halved by 2050, which can be seen in Table 1 [23] and Table 2 [23]. The tables are two different cost projections for solar energy for the coming decades, which were done by IEA and BNEF. The cost reductions will mostly be for the investments in the technology, like the PV panels and inverters, while the rest of the costs will also be reduced slightly [23].

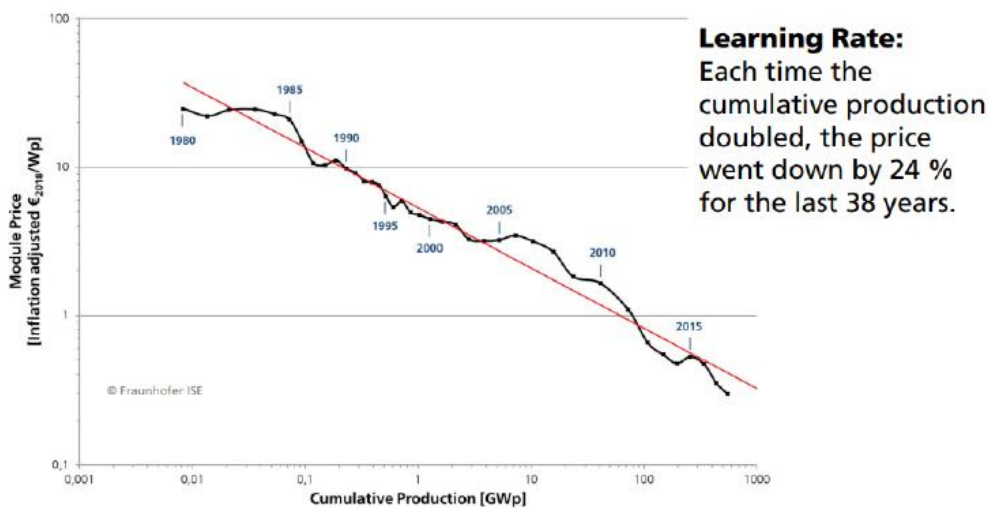


Figure 12: The cost reduction of solar panel investments when the cumulative solar electricity production has increased since 1980. [23]

Table 1: Projected cost reduction of solar power installations for the coming decades according to the “New Policies Scenario IEA 2018”. [23]

Mio. € - 2015/MW _p	2020	2030	2040	2050
PV module	0.22	0.14	0.11	0.10
Inverter	0.05	0.03	0.02	0.02
Transformer and grid connection	0.01	0.01	0.01	0.01
Installation	0.09	0.07	0.07	0.06
Residual balance of plant, mark-up and contingency costs	0.07	0.06	0.05	0.05
Total Investment	0.42	0.30	0.26	0.24

Table 2: Projected cost reduction of solar power installations for the coming decades according to the “BNEF New Energy Outlook 2019”. [23]

Mio. € - 2015/MW _p	2020	2030	2040	2050
PV module	0.22	0.12	0.09	0.07
Inverter	0.05	0.03	0.02	0.02
Transformer and grid connection	0.01	0.01	0.01	0.01
Installation	0.09	0.07	0.06	0.06
Residual balance of plant, mark-up and contingency costs	0.07	0.05	0.05	0.04
Total Investment	0.42	0.27	0.22	0.20

2.5. Electricity storage

Since PV technology uses the sun as its energy source, it cannot always produce electricity at the same time as it is needed. Multiple types of electricity storage technologies are being used to solve this issue, and they are used for different purposes, and more are currently being researched and developed [16], [17], [44]. However, lithium-ion batteries are the most common solution for storing self-produced electricity from variable renewable energy sources such as this and will therefore be the chosen electricity storing technology in this thesis. Battery storage allows for an electricity system that is less reliant on the current weather since it can store electricity when there is an oversupply and use the stored electricity when there is an undersupply. Therefore, the interest in battery storage has increased in recent years and is expected to increase rapidly, which can be seen in Figure 13 [44].

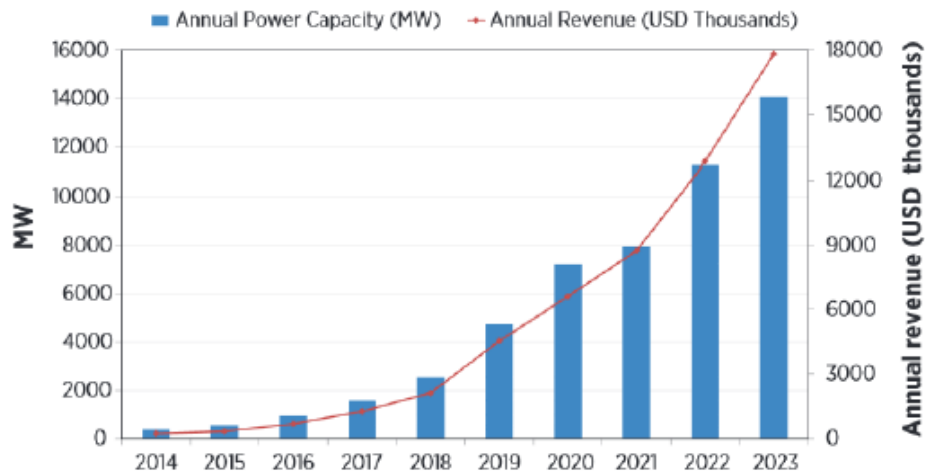


Figure 13: The expected annual increase in energy storage capacity from 2014 to 2023 and the annual revenue in the market. [44]

Due to the increasing interest in energy storage, technological advancements are happening quickly in the area [45]. The cost per kWh capacity has been reduced by more than 88 % in the last decade and it continues to be reduced every year. Even though the efficiency of batteries is high, it is important to note that they will result in further losses [44]. In addition, losses for storing electricity for longer periods or when the batteries get heated up can occur in reality, but these losses have not been accounted for in this thesis. The batteries also lose some of their effectiveness for each charge cycle, but for larger installations, they are expected to have a lifetime of 20 years [44].

2.6. Swedish solar power policies

There are many policies regarding solar power in Sweden. The most relevant will be described in this section. However, some of the policies identified are not relevant for the installation investigated in this thesis but could be for other cases.

2.6.1. Solar power regulations

One of the more important solar power regulations in Sweden is the classification of a smaller installation [46]. A company or homeowner that has a PV installation that has a maximum output that is lower than 500 kW_p is considered a “micro producer” of electricity. An installation that is considered a micro producer does not have to pay their electricity company anything for delivering electricity to the grid and does not have to pay an energy tax for the produced electricity [46], [47], [48].

Another regulation that enables easier solar power installations on rooftops is that they usually do not require a building permit [49]. A building permit is usually only required when the building is “culturally marked” or if it changes the exterior colour of a building in an area that has a detailed plan. A few other situations require a building permit, but that is often because the building’s exterior would change drastically from the installation. It is also required if the façade or roof material changes, which could

be from a renovation of the building at the same time or if PVs that are integrated into the rooftop are installed [49].

2.6.2. Economic solar power policies

There are multiple economic policies in place in Sweden that help support the Swedish transition from non-renewable energy sources to renewable ones [50], [51], [52]. One of these is the Swedish ROT-deduction, which reduces 30 % of the tax for the workforce needed when rebuilding, renovating, or repairing a building [50]. This can be used when installing solar panels, however, the tax reduction cannot be applied by companies and is therefore not relevant for this thesis work. Another policy that has been in place since 2009 has covered 20-30 % of the investment cost for both companies and homeowners [51], [52]. However, at the end of 2020, the grant was replaced with a tax deduction that can be applied for when investing in “green technology” [52]. This new tax deduction covers 15 % of the installation cost of solar panels and can also give tax deductions for electricity storage investments, covering 50 % of the installation cost. However, this new policy is only relevant to homeowners [52]. As a result, there are currently (as of 2022) no grants or tax deductions available or planned for the investment costs of a solar installation for companies and can therefore not be accounted for in this thesis.

On the other hand, there are tax deductions for the electricity that is sold to the grid [47], [48]. The deductions are only for the same amount of electricity that has also been bought from the grid and also has a maximum limit of 30 000 kWh/year. The tax deductions are at 0.60 SEK/kWh sold electricity, meaning that the yearly limit is at 18 000 SEK/year [47], [48]. As described, the deduction can only be accounted for if the solar installation leads to both sold electricity to the grid, and also some electricity that is bought back from the grid, which means that the results will have to be looked into further before knowing if this will be the case in this investigation.

There are also additional incomes that can be generated through selling electricity to the grid [48]. One of these is called “nätnytta” (grid service), in which the electricity supplier pays homeowners and companies that put electricity on the grid [47]. However, the amount is not set and can be fluctuating between suppliers [53]. “Elcertifikat” (electricity certificate) is another way of earning extra money from selling solar electricity [48], [54], [55]. It is a joint policy between Sweden and Norway and declares that energy-intensive companies and electricity suppliers have to purchase certificates equal to a share of their sold or used electricity. The certificates are granted to companies and homeowners for each MWh of “green” electricity that they produce [48], [54], [55]. However, the final date for new installations that were granted certificates was 31st December 2021, which means that this PV installation would not be granted any certificates.

3. Method

3.1. Case study – GEHAB

GEHAB is a company that is located in Alvesta, in the southern region of Småland, Sweden. That is in the Swedish electricity area SE4. The company produces special designs for truck bodies. They have a strong interest in improving their environmental impact and have a long-time goal of becoming self-sufficient in energy. Therefore, they want to invest in a rooftop solar installation so that they can produce a share of their electricity themselves. The rooftop that they have in mind for the installation, which is indicated in Figure 14 with arrows, was calculated by knowing the length of the outer walls (94 m x 18 m) and the angle of the roof (10°), which resulted in an area of about 1 720 m².



Figure 14: An overview of the company GEHAB and its surrounding area. The rooftop that is investigated is marked with arrows.

In 2021, GEHAB used 927 000 kWh. However, the electricity was not used evenly throughout the year. Figure 15 shows that during normal workdays, the electricity demand often reaches above 300 kWh in an hour. On the nights and weekends, it instead rarely reaches much more than 50 kWh. There were also seasonal variations in the electricity demand, which can be seen in the figure. In general, the demand was slightly higher during the winter, which probably was caused by a higher heating demand. However, in the middle of the figure, the electricity demand is much lower for a longer period. This is because the company shuts down their production for a few weeks during the summer.

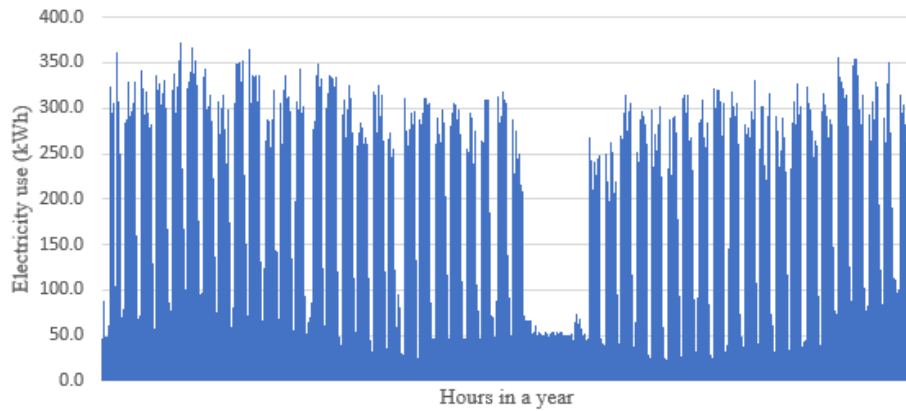


Figure 15: The company GEHAB's electricity demand throughout the year.

There is also a variation in their electricity demand during the days. On weekdays, between 07.00 and 18.00, most of the electricity is used, as can be seen in Figure 16. This favours solar PVs since they will produce most of their electricity during the middle of the day. During weekends and outside of working hours, the electricity use was usually lower than average throughout the year, as can be seen in Figure 17. This was expected since the company has normal working days.

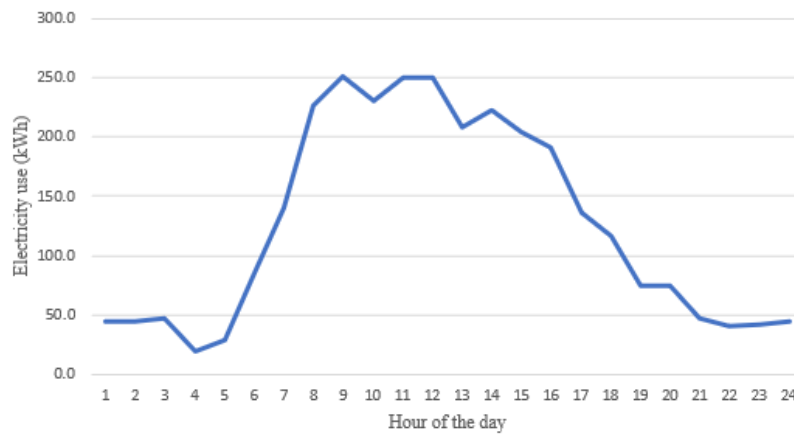


Figure 16: The electricity use throughout a normal weekday at the company GEHAB (15th June 2021).

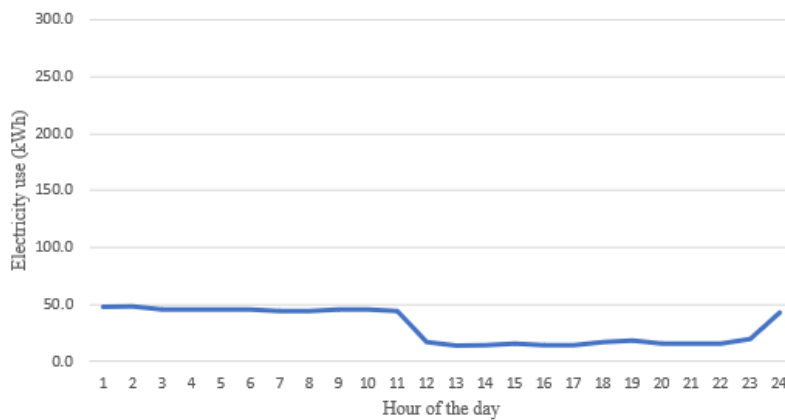


Figure 17: The electricity use throughout a normal weekend day at the company GEHAB (20th June 2021).

Based on the Nordpool electricity price for 2021, the yearly electricity demand at GEHAB would cost them approximately 902 000 SEK per year. It is important to note that the electricity cost is based on the market price and does not include the additional fees and taxes that the electricity supplier charges.

3.2. Simulation software and input data

In this thesis, the solar panel installations will be simulated by the dynamic software EnergyPLAN – Advanced Analysis of Smart Energy Systems [56]. The program was developed at Aalborg University in Denmark [56], [57]. The software was created to be able to simulate multiple sectors in an energy system, such as electricity, heating, and transport, simultaneously and can therefore be used to find interactions between these sectors [56], [57]. However, in this thesis, the program will be used to simulate the electricity system for the company GEHAB hour-by-hour and investigate how it would be affected by installing solar panels on the rooftops of one of the company's buildings. It will simultaneously be used to simulate the yearly savings and revenue from the produced electricity. The software requires the creation of hourly distribution files for the varying factors, which in this case are the electricity use of the company, the produced solar power for each installed kW of capacity, and the electricity price. This was done through calculations in Excel.

At the start of the project, data for the company's hourly electricity use for 2021 was gathered from their electricity supplier Alvesta Energy. The data was then converted into a distribution file that EnergyPLAN can use. This means that a percentage of the average hourly electricity price was needed, which shows which hours the electricity use was higher and when it was lower. When that distribution file was later used, the yearly electricity use was put into the software to create the hourly demand.

Solar power production was calculated through the equations described in the theory. The solar radiation data for 2021 was gathered from SMHI [58]. The result from the calculation is stated in produced kW per kW capacity installed. This is so that when it was later simulated in EnergyPLAN, the installed capacity could be varied in EnergyPLAN, which resulted in the software showing the produced electricity for each hour during a year for different capacities installed.

For the hourly electricity prices, data for 2021 in the electricity area SE4 was gathered from Nordpool [12]. The data for SEK/MWh could be used directly as a distribution file in EnergyPLAN, without any changes to it.

3.3. Scenarios and assumptions of PV installation

The analysis of this thesis was divided into four different scenarios, which were all based on the project description that was received from the company. The first scenario was made to establish the largest possible size at the case study location, where the available rooftop area is a limiting factor. The only available data for it was the angle of the rooftop and the length and width of the building, which meant that the area had to be calculated and a few simplifications had to be made. The size and maximum output of solar panels were assumed to be 1.8 m² and 350 W_p per panel, and they have

a conversion efficiency of 21 % [59], [60]. The lifetime of the PVs was assumed to be 35 years, which is stated as the technical lifetime in “Technology Data – Generation of Electricity and District Heating” [23]. The report was made by the Danish Energy Agency where they have gathered both technological and economic data for different energy generation technologies. The correction factor calculations for all of the scenarios can be seen in Appendix II, where the inverter efficiency was assumed to be about 95 %, but in reality, the losses might be varying more over time [38].

The second scenario was to find the most cost-optimal size of the installation. The factor for what was considered cost-optimal was based on LCOE. This was chosen since it can include all costs and avoided costs during the project’s lifespan and is easily compared to other research. The cost of the investment and the O&M costs that have been used are from the report that was mentioned in the previous scenario. A reinvestment in inverters every 12 years has also been included in all the scenarios. The avoided costs are a gathering of tax deductions, the revenue from the sold electricity and the reduced electricity bill. Afterwards, the reduction of CO₂ that a PV installation would lead to at the company was calculated. This was done by assuming that the produced solar electricity would replace a normal Swedish electricity mix. It was also compared to the EU electricity mix emissions.

The third scenario was based on the second scenario and adds a battery installation to it. This scenario aims to see how much the company’s self-use of electricity could be improved by being able to store the electricity that would otherwise be sold so that their reliance on the grid can be reduced further. Since this scenario is based on the second, it will still try to find the most cost-optimal size for the PV installation when a battery is added to the investment. This means that the size of the installation was varied to ensure that it was still the most cost-optimal for different battery sizes. The price of the battery installation was based on a report from the Danish Energy Agency that includes data from different energy storage technologies [44]. The batteries were assumed to have a 95 % round trip efficiency, meaning that they lose 5 % of the electricity they are used to store. They are also assumed to have a technical lifetime of 20 years [44], which means that they have to be replaced once during the lifetime of the PVs. The charging time of the batteries is assumed to be 20 minutes and discharged in 2 hours, which might be possible to optimize further by having batteries that can charge or discharge faster or slower, but that optimization is outside of the scope of this thesis. For the reduction of CO₂ in this scenario, the emissions from the manufacturing process of the batteries were included since the battery is not necessary to reduce CO₂ emissions through a PV installation.

The final scenario tried to find what the needed size for the installation would be to make the company a net-zero electricity user. This does not mean that the company was assumed to use all of the electricity by themselves and does therefore not include a battery installation. Instead, it assumes that they would buy electricity when not producing enough electricity but that they would sell the same amount of electricity back to the grid during the year when they would overproduce. This scenario was created to find the issues with reaching this goal today, and what would be needed to be able to become a net-zero electricity consumer in the future.

In the end, two sensitivity analyses were done to investigate how different factors impact the LCOE of the investment. The first factor that was investigated was the tax

deduction, and how the investment would be impacted if that deduction is removed. The second analysis focuses on the quick cost reduction of PV panels and how the LCOE of the investment would change if the investment would be done in 2030 instead. The cost of the PV installation in 2030 was based on the data in Table 1 and the cost of the batteries was based on the same report from the Danish Energy Agency [44] as the current cost was assumed.

3.4. Costs, benefits and avoided CO₂ emissions of solar PV installations

Since this thesis is investigating the most cost-optimal solution for the theoretical PV installation at a company, a choice for what factor should be considered as cost-optimal has to be made. The factor should include all of the lifetime costs and also the avoided costs that the installation would result in. It is also preferable to have a way to calculate it in a way that is easily compared to other results. Therefore, the Levelized Cost Of Energy (LCOE) will be used as a measurement of what the most cost-optimal choice is. The LCOE is calculated through the following equation:

$$\text{LCOE} = \frac{\text{Sum of cost over lifetime}}{\text{Sum of electricity produced over lifetime}} = \frac{\sum_{t=0}^n \frac{I_t + M_t - A_t}{(1+i)^t}}{\sum_{t=0}^n \frac{E_t}{(1+i)^t}} \quad [12]$$

where:

n: Expected lifespan of the investment

t: Year after the initial investment

I_t: Investment costs in the year t

M_t: Operation and maintenance (O&M) costs in the year t

A_t: Avoided costs in the year t

E_t: Electricity produced in the year t

i: Discount rate (%)

The cost of an installation has been assumed to be 4 880 SEK/kW_p, where the share of the PV panels is about 52 % of the total cost and the inverters about 12 %. The rest of the costs are related to the installation, grid connection and other smaller costs, which can be seen in Table 3. In addition, it has also been assumed that there is a need for reinvestment of inverters every 12 years, due to their life being around 10-15 years but the lifetime of the PV panels is 35 years. Since this would be done later on in the life span of the project, the cost of inverters could drastically change until then, but this has not been accounted for except through the discount rate. The discount rate that has been used is 3.0 %. Additionally, the O&M costs for the PV installation have been assumed to be 2.5 % [23] of the initial investments each year. Finally, for the scenario that includes a battery installation, the assumed cost of the investment is 5 844 SEK/kWh battery capacity and the O&M costs for the batteries are 0.1 % of the investment [44]. For the full LCOE calculations, see Appendix I.

Table 3: The different costs of a PV installation in 2020 [23].

PV installation costs	SEK/kW _p
PV module	2 556
Inverter	581
Transformer and grid connection	116
Installation	1 046
Residual balance of plant, mark-up and contingency costs	813
Batteries	1295*
Total Investment	4880**

* Is stated in SEK/kWh capacity

** Does not include batteries

The avoided costs are the sum of the revenue from the sold electricity and the savings that are gained through lower electricity bills. In addition, the tax deduction of 0.60 SEK/kWh that is received for the sold electricity, which can be a maximum of 18 000 SEK/year, will be collected. For the grid service, 50 SEK/sold MWh has been used as an assumption.

Solar panels use a renewable source to produce electricity, with no carbon emissions as a result. On the other hand, manufacturing them results in some emissions, which vary depending on the country where they are manufactured [61]. However, when calculating the reduction in CO₂ emissions from the PV installation, only the use phase of the PV panels should be considered, since the carbon emissions from the replaced electricity mix do not include any other life-cycle stages. The electricity mix in Sweden is already almost completely carbon-free and only results in about 13 g CO_{2-e}/kWh [3]. However, the replaced electricity mix could also be considered to be from the EU. This can be done since the EU electricity market is so closely interlinked, and by producing more renewable electricity in Sweden, the amount of fossil-based electricity somewhere else can be reduced. In 2020, the EU electricity mix resulted in about 241 g CO_{2-e}/kWh, which is considerably higher than the Swedish mix [3]. Consequentially, the avoided CO₂ emissions when replacing the two different electricity mixes will be presented in the results.

For the battery storage, the emissions are more difficult to assess since much of the CO₂ emissions related to batteries usually come from charging them. However, in this case, all of the electricity will be from solar energy and there should not be any emissions from the use phase. In addition, the battery is only used to store electricity and cannot be compared to the electricity mix in the same way as the PV panels. As a result, the manufacturing process has to be considered in the emissions, since they are not needed to reduce carbon emissions. Different sources state varying emissions from the manufacturing of batteries and results varied between 40–110 kg CO_{2-e}/kWh, mostly depending on the country they are manufactured in [62], [63]. As a result, the median of 75 kg CO_{2-e}/kWh will be used. However, by carefully choosing the batteries that are bought, the emissions could be lowered. Although a reinvestment in batteries

are needed, the future emissions from the manufacturing processes are difficult to assume and, as a result, only the emissions from the initial investment will be included. Calculating the emissions from the batteries in the way that was chosen does not favour self-use of the produced electricity.

4. Results

In the following section, the results of this thesis will be presented. As described in 3. Method, the software EnergyPLAN was used for the simulations and the distribution files were created as described there. Further calculations were done in excel.

4.1. Maximum production scenario

The maximum production scenario is aimed to find the largest possible size of a PV installation at the company, with the rooftop area and Swedish policies as limiting factors. The rooftop area was calculated to be 1 720 m², which allows for a total of 955 panels as the largest installation that is possible on the investigated rooftop. This size would result in a 335 kW_p installation. This is lower than the 500 kW_p that is the maximum allowed to be a micro producer and, as a result, some taxes can be avoided.

At the maximum installation of 335 kW_p, the yearly electricity production would be 255.0 MWh. Most of the time, the electricity production would not cover the demand at the company and more electricity would have to be purchased, as can be seen in Figure 18-20. However, during the summer, when the company shuts down most of its production, much of the solar electricity would be produced, as seen in Figure 21. During this time, they would instead have an overproduction of electricity, which they would sell to the grid. The exported electricity to the national grid would reach 62.5 MWh/year.

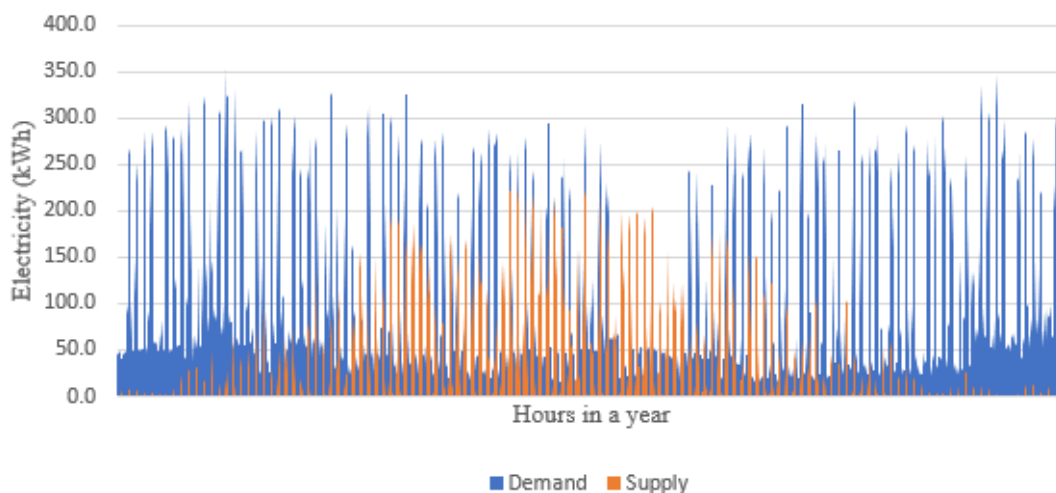


Figure 18: A comparison of the electricity demand and supply at the company during the year for a 335 kW_p installation.

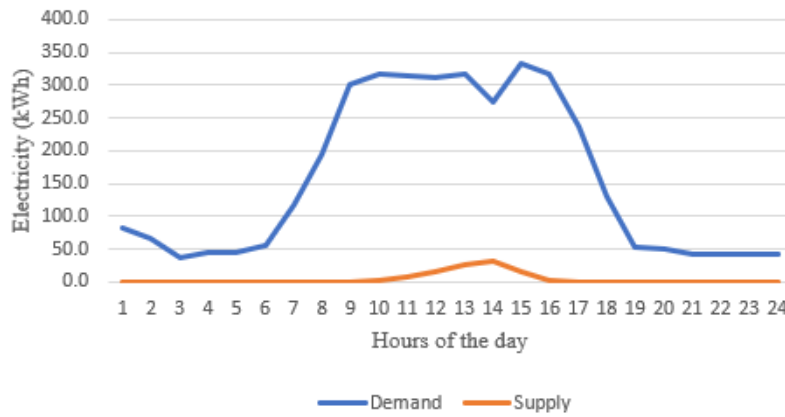


Figure 19: A comparison between the electricity demand and supply during a weekday in the winter (Jan 27th) with the maximum installation at the company.

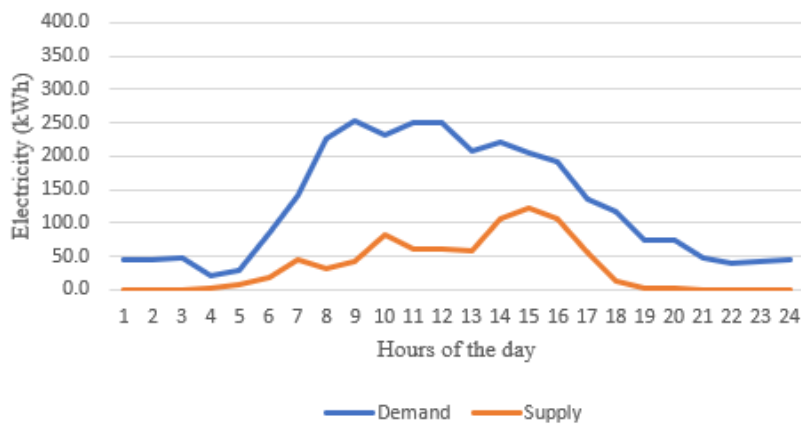


Figure 20: A comparison between the electricity demand and supply during a working day in the summer (June 15th) with the maximum installation at the company.

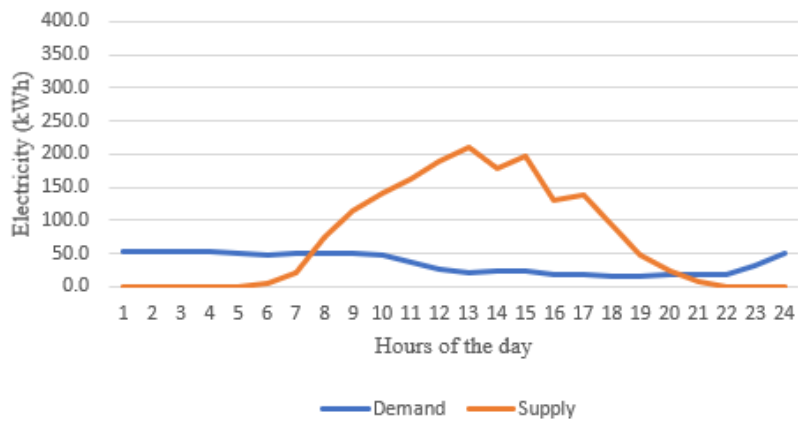


Figure 21: A comparison between the electricity demand and supply during a day when production is closed down during the summer (June 15th) with the maximum installation at the company.

With the assumed cost stated in 3.4. Costs, benefits and avoided CO₂ emissions of solar PV installations, the cost of a 335 kW_p would be approximately 1 635 700 SEK, as can be seen in Table 4. The O&M costs would be 36 700 SEK/year and the reinvestments of the inverter would in total cost 214 700 SEK, after including the discount rate. On

the other hand, the annual avoided costs would be 203 200 SEK/year. As a result, the LCOE of the installation would be -331 SEK/MWh. This means that the electricity production would save the company money for each produced MWh when a 3.0 % discount rate is included. The discounted payback time of the installation would be 12.6 years.

Table 4: The factors used in the LCOE and the payback time calculations for a 335 kW_p installation.

LCOE Factor	Amount	Unit
Investment costs - Year 0	1 635 700	SEK
O&M cost - 1st year	36 700	SEK
Lowered bill - 1st year	146 500	SEK
Tax deduction - 1st year	18 000	SEK
Savings - 1st year	164 500	SEK
Sold electricity - 1st year	35 600	SEK
Grid service - 1st year	3 100	SEK
Revenue - 1st year	38 700	SEK
Avoided costs - 1st year	203 200	SEK
Annual output	255	MWh
Project lifespan	35	years
Discount rate	3.0	%

4.2. Cost-optimal scenario

With the size of the PV installation presented in the last scenario, the yearly sold electricity would be more than what the tax deduction is limited at, which is 30.0 MWh/year. As a result, there could be a more cost-optimal size for the PV installation at the company. To test this, the size of the installation that is needed to sell 30.0 MWh/year was found through simulations in the software. It was found that an installation with the maximum output of 215 kW_p was needed for this. By calculating the LCOE for this size similarly to the previous case, the factors in Table 5 were used. The result of the LCOE was -366 SEK/MWh, which means that this is a more cost-optimal size in this case. The discounted payback time of 11.3 years shows the same result. With an installation of this size, the company would produce 164.2 MWh of electricity each year.

Table 5: The factors used in the LCOE and the payback time calculations for a 215 kW_p installation.

LCOE Factor	Amount	Unit
Investment costs - Year 0	1 053 700	SEK
O&M cost - 1st year	23 600	SEK
Lowered bill - 1st year	100 300	SEK
Tax deduction - 1st year	18 000	SEK
Savings - 1st year	118 300	SEK
Sold electricity - 1st year	16 900	SEK
Grid service - 1st year	1 500	SEK
Revenue - 1st year	18 400	SEK
Avoided costs - 1st year	136 800	SEK
Annual output	164	MWh
Project lifespan	35	years
Discount rate	3.0	%

To ensure that this was the most cost-optimal choice, other sizes were tested, and the result is shown in Figure 22. The figure clearly shows that the best economic choice is to invest in a PV installation that sells enough electricity to receive the maximum tax deduction but selling more electricity after that results in a worse economical choice. Therefore, the most cost-optimal choice is to invest in a 215 kW_p PV installation. The table that was used to create the LCOE figures can be seen in Appendix III.

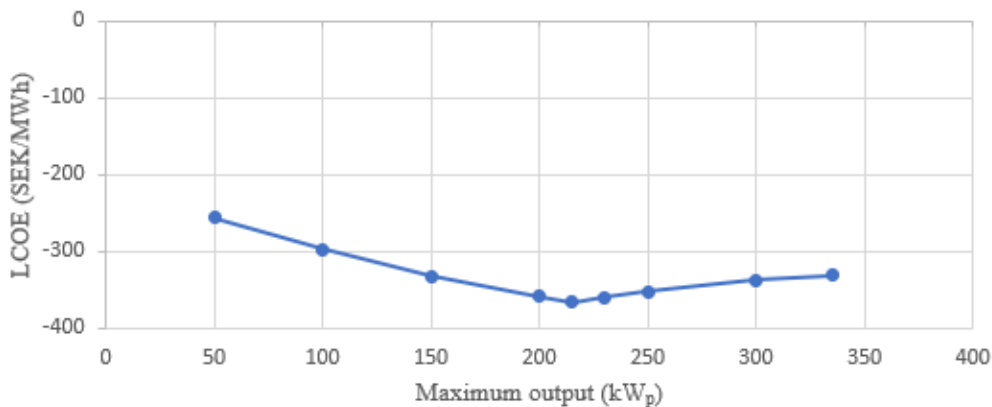


Figure 22: The LCOE for different sizes of PV installations at the company.

From an environmental view, the solar panels will produce carbon-free electricity at the company, which reduces their carbon emissions. With the cost-optimal option, the company will produce 164.2 MWh/year. As a result, that much electricity can be replaced. With the assumption that it will replace electricity from the Swedish electricity system, the avoided emissions that the PVs will result in are 2.13 tonnes CO_{2-e}/year. However, if the replaced electricity is considered to be the average EU electricity mix, the avoided CO₂ emissions are significantly higher, at 39.57 tonnes CO_{2-e}/year. As seen in Figure 23, when other sizes of the PV installation were investigated it was found that the largest possible installation of 335 kW_p would be the best environmental option when looking at the avoided CO₂ emissions. As a

result, if the aim is to reduce the carbon emissions as much as possible, the largest possible size to install on the rooftop is a better option than the most cost-optimal. Appendix IV shows the tables behind the avoided emission figures.

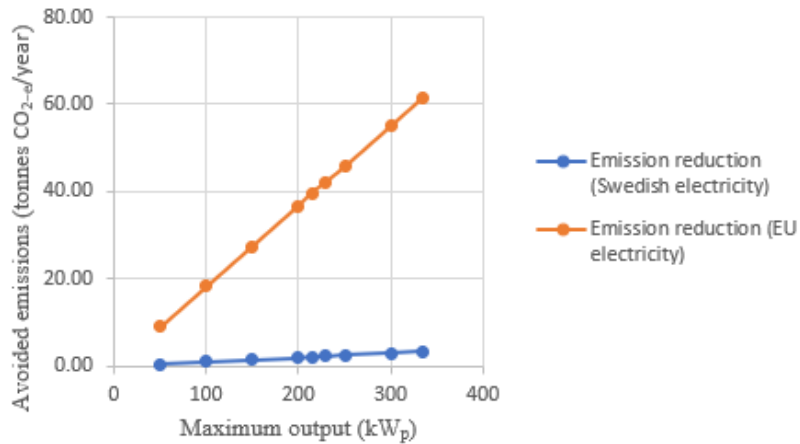


Figure 23: The reduced CO₂ emissions when replacing different electricity mixes at the company for different sizes of PV installations.

4.3. Battery installation scenario

Since the cost-optimal scenario showed that maximizing the tax deduction is the best choice, the battery installation scenario will investigate how the size of the facility can be varied by including a battery installation to it so that the deduction remains maximized without selling additional electricity. As a result, any size for the PV installation that is smaller or equal to the cost-optimal choice should not include a battery since that would worsen the important economic benefit that the installation would earn. Therefore, the investigation will only include sizes larger than 215 kW_p, up to a maximum of 335 kW_p, which is the largest possible size to install on the rooftop.

In this scenario, the maximum size that could fit on the rooftop of the case study building was investigated first. The PV installation would be 335 kW_p and had an LCOE of -331 SEK/MWh without a battery installation. The facility would sell 62.5 MWh/year, which is more than twice what is the maximum needed for the full tax deduction. To lessen the sold electricity to 30.0 MWh/year, a 424 kWh battery installation would be needed. This would increase the initial investment cost to 4 113 600 SEK, which can be seen in Table 6. The battery would represent 60 % of the cost. In addition, reinvestments in batteries and inverters would in total cost an additional 1 546 700 SEK, after including the discount rate, throughout the lifetime of the PV installation. The cost of electricity would be reduced slightly for the company but the revenue from sold electricity would as well due to it being stored instead. However, since the batteries result in some additional losses to the system, the total avoided costs would be lower than without a battery. With an increased investment cost and a lowered avoided cost, the LCOE of the investment would be 273 SEK/MWh, which is a much higher value than for the investment when batteries were not included. The discounted payback time would be longer than the lifetime of the solar panels.

Table 6: The factors used in the LCOE and the payback time calculations for a 335 kW_p PV installation and a 424 kWh battery storage.

LCOE Factor	Amount	Unit
Investment costs - Year 0	4 113 600	SEK
O&M cost - 1st year	39 200	SEK
Lowered bill - 1st year	165 200	SEK
Tax deduction - 1st year	18 000	SEK
Savings - 1st year	183 200	SEK
Sold electricity - 1st year	16 100	SEK
Grid service - 1st year	1 500	SEK
Revenue - 1st year	17 600	SEK
Avoided costs - 1st year	200 800	SEK
Annual output	253	MWh
Project lifespan	35	years
Discount rate	3.0	%

Afterwards, different sizes on installations and included batteries were tested to find how the LCOE varied with the sizes. The needed sizes of batteries to keep the tax deduction capped annually can be seen in Figure 24. The LCOE result can instead be seen in Figure 25. The second figure shows that when including a battery in the PV installation, the LCOE of the investment becomes much higher than when only installing solar panels. However, for smaller battery installations the LCOE is still negative, and the investment would pay back but in a longer time than without the batteries. Therefore, the battery option should not be included from an economic view. Nevertheless, if the main goal is to replace as much electricity as possible with self-produced solar energy at the company, a battery with a storage capacity of 424 kWh could be included with the largest possible PV installation on the available rooftop (335 kW_p) to still maximize the tax deductions available.

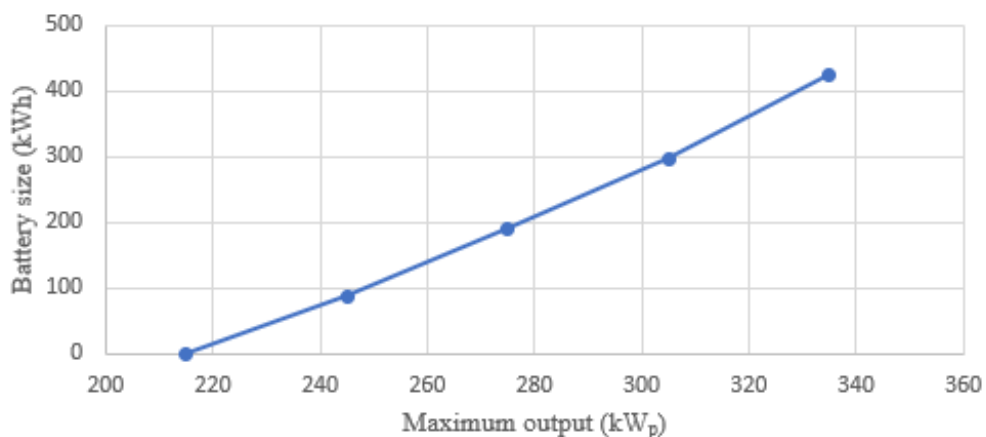


Figure 24: The battery size needed at the company to maintain the tax deduction capped, without selling more electricity than needed to do so.

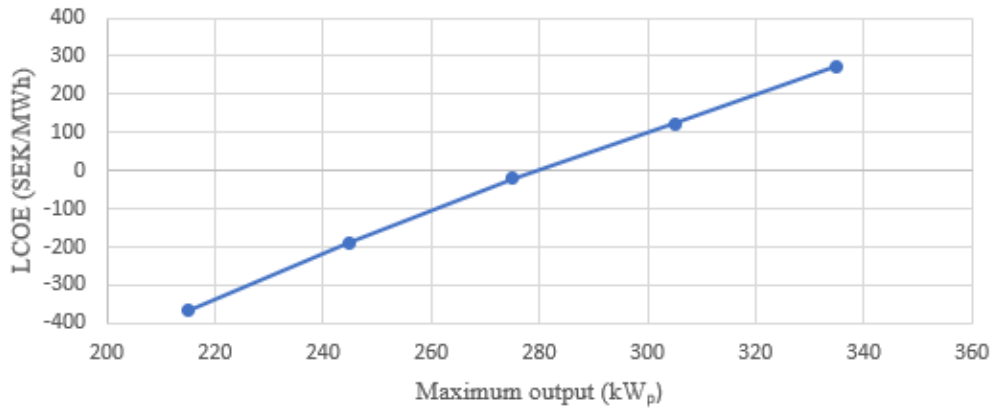


Figure 25: The LCOE for different sizes of PV installations at the company when including batteries.

For the environmental perspective, the manufacturing of the batteries was included in the CO₂ emissions, since they are not needed to reduce the emissions. On the other hand, they will increase the self-use of the produced electricity. As described in 3.4. Costs, benefits and avoided CO₂ emissions of solar PV installations, the emissions from battery manufacturing vary quite a lot between sources. Due to the difficulty in assuming the emissions from future manufacturing processes, only the emissions from the initial investment is included. Since a battery with the capacity to store 424 kWh was recommended to be included with a 335 kW_p PV installation if batteries are to be included, an extra 31.2 tonnes CO_{2-e}/kWh would be released as a result of the manufacturing of those batteries. In total, from an installation of this type, the avoided CO₂ emissions would be 29.27 tonnes CO_{2-e}/year if the EU electricity mix is assumed to be replaced. On the other hand, if the Swedish electricity mix is replaced instead, the carbon emissions would increase by 28.51 tonnes CO_{2-e}/year. In Figure 26, the avoided CO₂ emissions for the different sizes of PV installations with batteries are presented. The figure shows that including a battery installation does reduce the environmental gains that the company would get from a PV installation since the battery manufacturing emissions are accounted for. The larger the batteries become; the less CO₂ emissions are reduced from the installation. As a result, from an environmental view, a battery installation is not recommended.

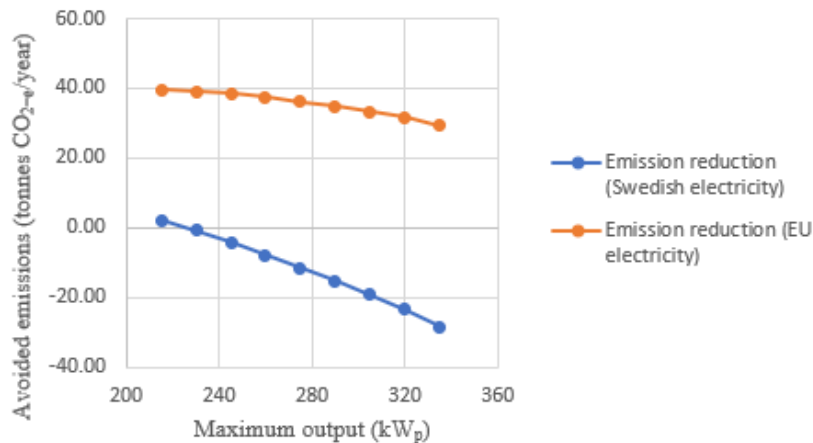


Figure 26: The reduced CO₂ emissions when replacing different electricity mixes at the company for different sizes of PV installations when including batteries. If the emission reduction is negative, it increases instead.

4.4. Net-zero electricity consumption scenario

As mentioned earlier, this scenario is a more theoretical investigation of what would be needed for the company to become a net-zero electricity user. With this scenario, being a micro producer will not be possible, which would result in extra tax costs and new regulations that would be relevant to recognise and follow. However, in this scenario, the additional costs and regulations will not be investigated further. Instead, the issues to reach this scenario are presented.

In 2021, the electricity use at the company was 927 000 kWh, which means that the same amount of electricity should be produced in a year to become a net-zero electricity user. Therefore, an installation with a capacity of 1 220 kW_p would be needed, compared to the 215 kW_p that was recommended in the cost-optimal scenario, which would only produce 17.7 % of the company's electricity demand yearly according to the simulations in EnergyPLAN. Figure 27 shows the amount of electricity produced yearly compared to the annual demand at the company for different sizes of PV installations. The figure also marks the important sizes of installations to clearly show the size needed for a net-zero installation and how much renewable energy these sizes would produce. The required area would be about 6 270 m², which is more than 3.6 times the size of the rooftop that is limiting the size in the other scenarios. This shows that the need for more rooftops or a large empty area would be needed to install such a large PV facility. It is important to note that if other areas are used, the orientation of that installation might be different than for the investigated rooftop, which means that in reality, the electricity production might differ a bit.

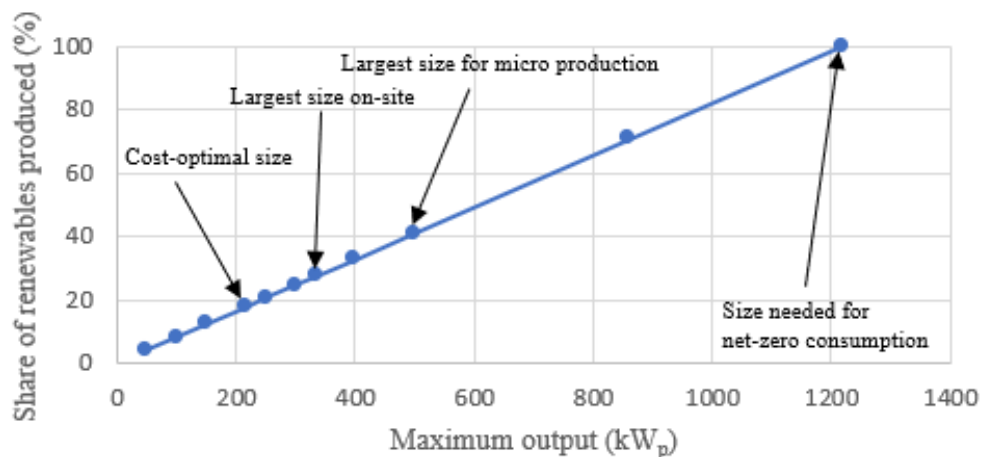


Figure 27: The amount of electricity produced, compared to the yearly demand at the company. Important PV sizes are marked in the figure to show how much electricity they would generate and for a clear picture of how large a net-zero PV installation would have to be.

With this size of PV installations, the company would not produce enough electricity during the winter and would instead have to purchase electricity from the grid, which can be seen in Figure 28 and Figure 29. These months are usually when the electricity is most expensive. During the summer months, they would instead overproduce electricity, especially when their production is closed down, which can be seen in

Figure 30 and Figure 31. This results in a lot of sold electricity when it is usually the cheapest.

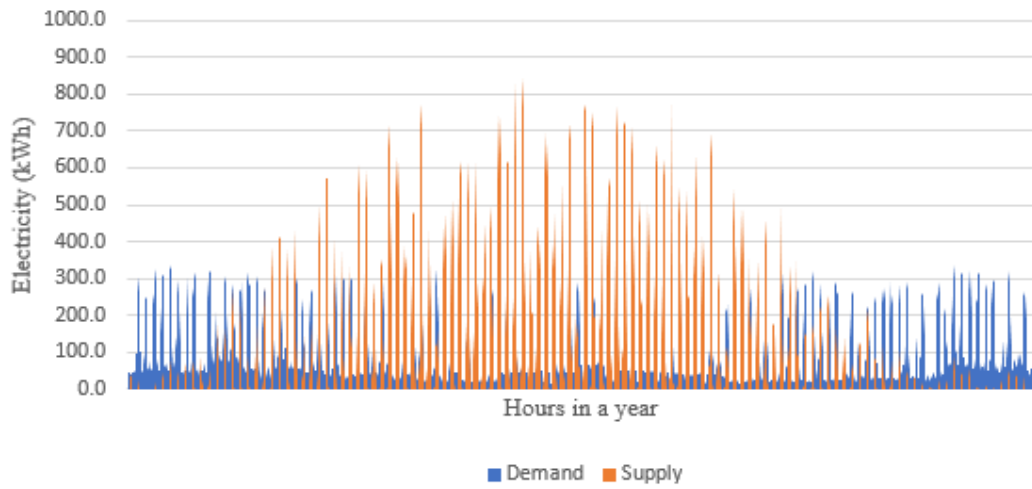


Figure 28: A comparison of the electricity demand and supply at the company during the year from an installation that makes the company a net-zero consumer of electricity.

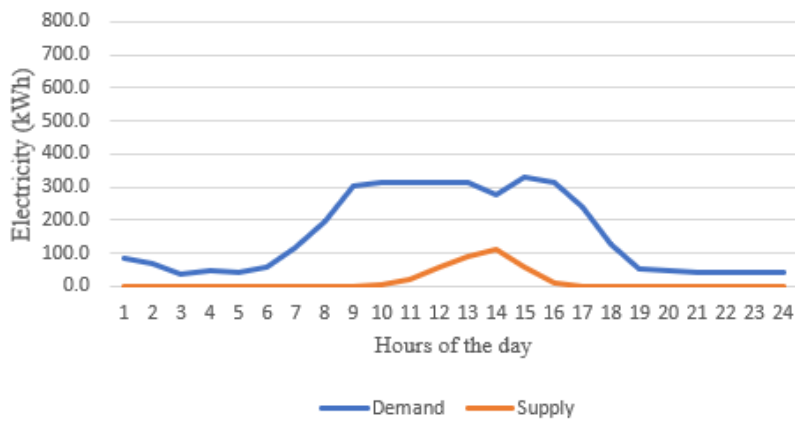


Figure 29: A comparison between the electricity demand and supply during a weekday in the winter (Jan 27th) with the net-zero scenario.

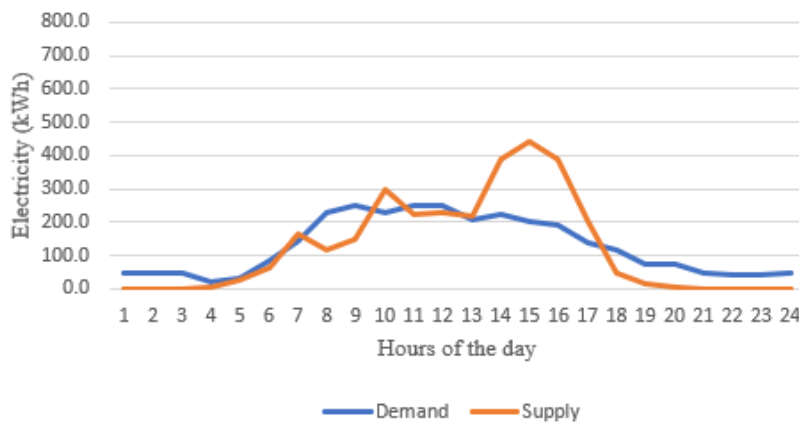


Figure 30: A comparison between the electricity demand and supply during a working day in the summer (June 15th) with the net-zero scenario.

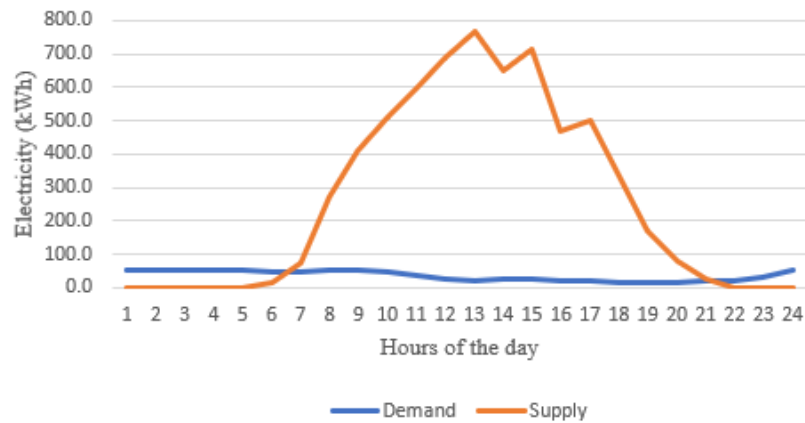


Figure 31: A comparison between the electricity demand and supply during a day when production is closed down during the summer (July 16th) with the net-zero scenario.

The needed size to achieve a net-zero consumption is more than twice the allowed installation to be classified as a micro producer and would therefore result in an additional tax. In addition, other regulations might be introduced and would have to be investigated further before an investment can be made. It would also overproduce a lot of electricity when it is not needed at the company, but it is also at its cheapest on the market, which would result in a bad economic solution. Therefore, the goal to become self-sufficient in electricity should be postponed until policies support the investment better, or by solving the presented issues with other options.

4.5. Sensitivity analysis

The results from the second scenario showed that the most cost-optimal choice was to ensure that the tax deduction of 0.60 SEK/MWh sold electricity was maximized, which is 30.0 MWh/year, without selling more electricity than that. Therefore, a sensitivity analysis where the tax deduction was removed was done to investigate what would be the deciding factor for the cost-optimal size of the investment. In addition, another sensitivity analysis was made, which investigates how the LCOE of the installation, both including and excluding a battery installation, would change if the investment was to be delayed until 2030.

Figure 32 shows the results of the first sensitivity analysis, where the tax deduction was removed. The figure shows that without the tax deduction, the largest size possible would be the most cost-optimal choice for the company, which would have an LCOE of -243 SEK/MWh. It can also be seen that the LCOE is still negative, although it is higher than when the tax deduction was available. This strengthens the statement that the tax deduction is the factor that decides how large the most cost-optimal size of a PV installation is at the company and that without it the best economic choice is to build the largest installation possible.

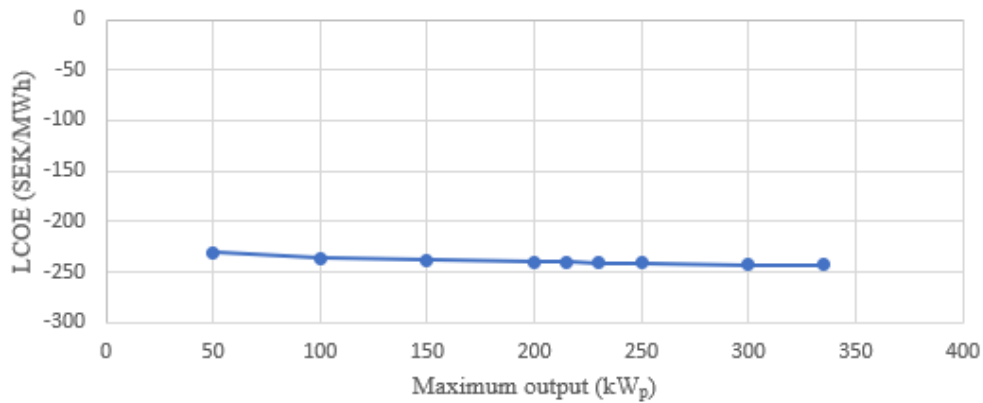


Figure 32: The LCOE of different sizes of PV installations at the company if no tax deduction was available.

The second sensitivity analysis was made to investigate how the investment will change in the future, since the price of both batteries and PV installations is still decreasing rapidly. In the analysis, the assumed costs in 2030 from the two technology data reports from the Danish Energy Agency [23], [44] were used. However, all of the other factors remained the same, which means that the electricity cost and economic policies were assumed to remain. The tables that were used for the figures can be found in Appendix V.

When investigating the cost of PV installations in 2030 it was found that it is assumed to be reduced by almost 30 % until then [23]. Since no other factors were changed, the most cost-optimal size of the installation would remain at 215 kW_p and would cost about 751 500 SEK. Also, since the investment already had a relatively large negative LCOE and would pay back in a reasonable time, it would be reduced even further. The new LCOE would be -488 SEK/MWh and the investment would have a discounted payback time of 7.2 years, which is considerably shorter than found in earlier scenarios. Figure 33 shows the LCOE for the same sizes as the cost-optimal scenario investigated. It shows a similar result to that scenario, except for the lower LCOEs for each size.

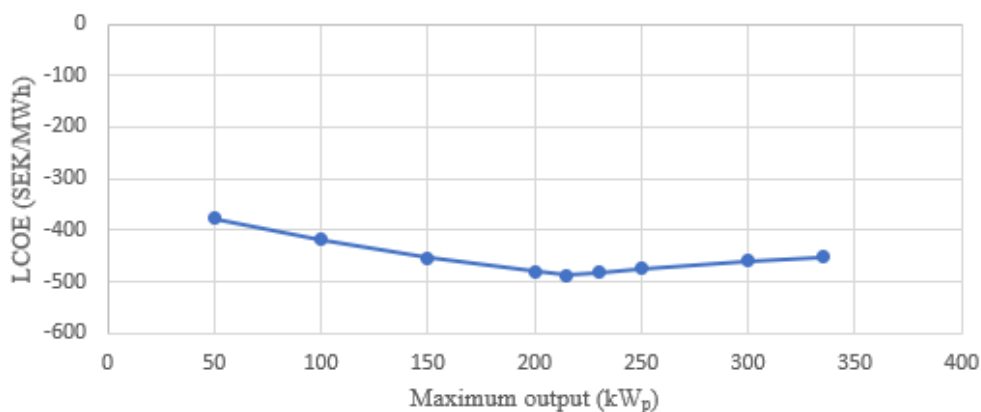


Figure 33: The LCOE of different sizes of PV installations at the company if the investment would be done in 2030 instead.

The same analysis was done with an inclusion of batteries. In addition to the reduced cost of the PVs, the battery costs is assumed to be reduced by 40 % until 2030 [44]. For the largest possible installation for the available rooftop area, the new LCOE would become negative, at -99 SEK/MWh, which can be seen in Figure 34. This means that it would payback within approximately 27 years, which is still quite a long time. However, this shows that battery installations might become a better investment in the near future. Yet, all of the battery installations will still result in worse economic investments than PV installations that do not include them.

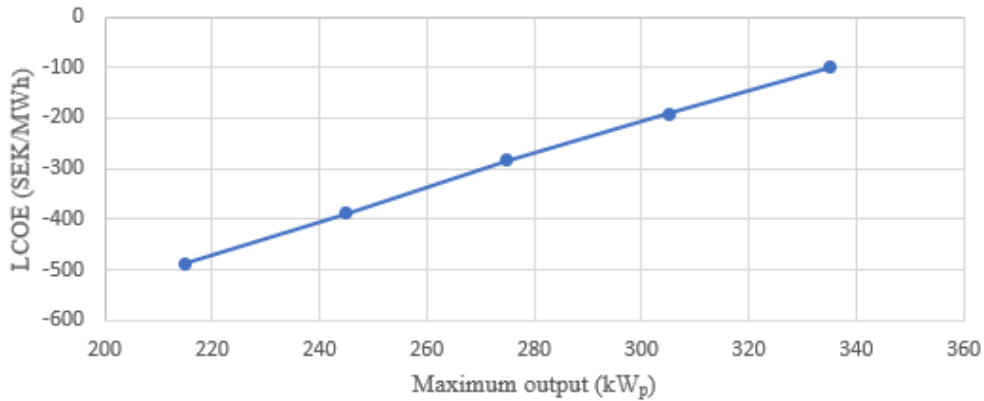


Figure 34: The LCOE of different sizes of PV installations at the company when including batteries if the investment would be done in 2030 instead.

5. Discussion

From the maximum installation scenario, it was clear that the available rooftop area would support a PV installation up to 335 kW_p. In this scenario, the sold electricity was larger than the annual cap for the tax deduction, which is why it was not the most cost-optimal choice. However, since the PVs were assumed to replace an electricity mix that resulted in carbon emissions, while the PVs were not, the largest installation would be the best from an environmental perspective.

The second scenario showed that the most cost-optimal PV installation should produce just enough electricity to sell 30.0 MWh/year, without selling more electricity than that. To do so, the needed size of a PV installation is 215 kW_p. The result also showed that investing in a PV installation would save the company money in the long run even when an additional discount rate of 3 % was added, even for sizes that were not the most cost-optimal. Normally, solar installations are stated to have an average payback time of 10-15 years by Swedish companies that sell and install them [64], [65]. In the results, the discounted payback time of the most cost-optimal size was found to be 11.3 years, which also includes the 3 % discount rate. Therefore, the installation seems to have quite a good payback time. The average LCOE of a medium-sized solar installation for commercial use was stated to be about 540 SEK/MWh in Denmark, according to the IEA [66]. However, the results from this study are a bit more difficult to compare to that since it also includes the avoided costs and the LCOE becomes, as a result, negative. Still, when removing the avoided costs from the calculations, the cost-optimal size has an LCOE of about 470 SEK/MWh. This shows that some of the

costs that are related to the investigation might have been underestimated but they should still not be too far from reality. However, the relatively large negative LCOE from this study shows that the investment would still, most likely, be a good investment and would save money for the company in the long term. From an environmental perspective, it was found that the larger the installation is the better it was. However, this is a simplification since it only included the use-phase of the solar panels. In reality, solar PVs result in some emissions when they are manufactured and when they are disposed of. Therefore, the emissions that these processes would result in should be further investigated.

The battery scenario showed that it would not be a good alternative to install batteries neither from an economic, nor an environmental perspective. However, this result might be a consequence of the choices for how the calculations were made. The electricity cost was based on the market spot price on Nordpool, which does not reflect the actual price of electricity for the company. In reality, they will have to pay additional fees and taxes to the electricity supplier and these amounts vary between different suppliers, which is why they were not included. If these costs would have been accounted for, there would have been a larger reason to use the produced electricity at the company since purchased electricity would be more expensive than what it is sold for. This was demonstrated through the result of this scenario. It showed that due to the losses that the battery installation caused, the avoided cost that the investment would result in would be less than without the battery. This clearly shows that the assumptions that were made did not favour a battery installation. On the other hand, many electricity suppliers also give an additional income for the sold electricity, which was also not included in the electricity price. For the environmental calculations, the choice to include the emissions from the manufacturing process for the batteries did not help justify them since those processes are not included for the PVs or the electricity mixes. However, excluding those processes would not be fair either since batteries are not essential for the installation of PVs. As a result, the battery installation is hard to justify with the current assumptions. To make the emission calculations fairer for the batteries, a reason for self-used electricity should probably be included in future investigations.

The battery installation can probably be further optimized through its charge and discharge time. Also, the size could be changed to fulfil different purposes. For example, if the aim of the battery is to supply the company with electricity during nights, the size and discharge time might have to be changed. Therefore, it is important to determine what the goal of the battery installation is before deciding if the battery is needed and how it should be sized.

In the net-zero electricity consumption scenario, the major focus was that there are currently some issues that have to be overcome to reach the long-term goal for the company. The first one is the limited space that is available to install PV panels. This could, however, be solved through other electricity generating methods, such as wind power. Still, that would not overcome the issue that a net-zero electricity consumption at the company would require a much larger quantity of electricity generation, which would result in the company not being able to stay micro producers. Staying a micro producer has multiple advantages, such as avoiding an additional energy tax and additional regulations that would have to be accounted for. As a result, currently, a larger installation than 500 kW_p cannot be justified. However, the regulations have

recently been changed to the current 500 kW_p, from 255 kW_p, which has increased the possibility to invest in larger PV installations than earlier. Since this regulation recently has been changed, it might change again in the future, which could allow for even larger installations for micro producers later on.

Even though the investigation resulted in a negative LCOE, the current policy situation do not support the choice to invest in PVs for companies as well as it has recently. As described in 2.6.2. Economic solar power policies, in 2020 the 20 % investment grant for PVs was replaced by a 15 % grant for PVs and a 50 % grant for battery installations that are only available for homeowners, not for companies. In addition, new PV installations will not get the electric certificates that grant an additional income for the sold electricity after 2021. As a result, the current policy situation is not as good as it could be, which might improve again in the future. Additionally, the cost of PVs and batteries continues to decrease, which means that if the investment cannot be supported at the company today, it could be in the future. The sensitivity analysis that investigated the same investments, but if they were to be done in 2030 instead of today, showed that their LCOE will become even lower in the future. Therefore, waiting with the investment could have its benefits. This is especially true for the battery installation since the results showed that it leads to a higher LCOE than when they are excluded from the investment currently. However, the cost will probably continue to decrease after that as well and other factors could change as well, which could impact the investment both positively and negatively. Still, since the battery installation could be justified from neither an economic, nor an environmental view, the investment should probably not be done at the moment. However, since the cost of battery installations decreases so rapidly, it could turn into a better investment in a few years, especially since the long term goal is to become self-sufficient in energy. If this is assumed to be the case, and the company thinks that a battery investment could become relevant in the future, it is possible to prepare for such an installation in the future by investing in specific inverters that are needed if batteries are installed later.

It is important to note that many factors in the calculations have been assumed and in reality, many of them might differ. As mentioned in the introduction, the cost of electricity is expected to increase in the future. Though, in this thesis, an assumption that the cost of electricity will not change during the 35 years was made. However, the cost is expected to increase in the coming years, which means that it should be more valuable to produce your own electricity in the future since it will reduce electricity bills more than what has been calculated in this report. Yet, the result that maximizing the tax deduction should stay important. The sensitivity analysis strengthens this since it found that without the deduction, the most cost-optimal size would be to build the largest possible PV size. This result shows how supporting economic policies can impact how appealing investment in a technology can be for companies. However, having a policy designed like this could also have the unwanted consequence that it might not always be the most cost-optimal choice to invest in the largest possible PV installation on the site, which it does in this case study.

6. Conclusions and recommendations

The results showed that a PV installation would be a good long-term investment since all sizes that fit on the rooftop would result in negative LCOE, meaning that they would save the company money for each produced MWh. They also showed that a 215 kW_p installation would be the most cost-optimal choice. This is explained by the tax deduction, which would reach the annual cap with this size, without selling additional electricity to the grid. However, investing in a larger PV installation is possible at the site, with a maximum of 335 kW_p, and would allow for a greater amount of avoided CO₂ emissions. In addition, it would result in a larger amount of self-used solar electricity at the company. However, the battery scenario showed that installing batteries would not result in an economic benefit and would instead lead to a cost per produced MWh for the company. As a result, the recommendation to the company is to invest in either a 215 kW_p, if the aim is to get the best economic choice, or a 335 kW_p if the goal is to produce as much solar electricity as possible. If there still is an interest to get a battery installation, it might be a better choice to wait a couple of years, until the cost decreases to a more reasonable level, or a grant becomes available.

In the net-zero electricity consumption scenario, it was clear that the goal is currently not achievable. The size that is needed for such a large installation is not available to the company. Therefore, it would require other renewable technologies, such as wind power. In addition, the limit for micro production has to be broken, which results in additional regulations, fees, and taxes that would have to be accounted for. For it to become more feasible, the Swedish energy and environmental policies would have to support such large electricity production installations better, otherwise, it will continue to be a worse economic choice than a smaller PV installation.

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Appendices

Appendix I

Appendix II

Appendix III

Appendix IV

Appendix V

Levelized Cost of Energy (LCOE)

Battery Scenario 424 kWh

LCOE Factor	Amount	Unit
Investment costs - Year 0	4 113 561	SEK
O&M cost - 1st year	39 153	SEK
Lowered bill - 1st year	165 243	SEK
Tax deduction - 1st year	18 000	SEK
Savings - 1st year	183 243	SEK
Sold electricity - 1st year	16 086	SEK
Gnd service - 1st year	1 500	SEK
Revenue - 1st year	17 386	SEK
Avoided costs - 1st year	200 829	SEK
Annual output	253	MWh
Project lifespan	35	year
Discount rate	0.03	

Year (t)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Discount Factor	1.000	0.971	0.943	0.915	0.888	0.863	0.837	0.813	0.789	0.766	0.744	0.722	0.701	0.681	0.661	0.642
Yearly Cost																
Investment	4 113 561															
Maintenance	0	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153
Avoided costs	0	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829
Sum of costs	4 113 561	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676
Sum of costs, including the discount factor	4 113 561	-156 967	-152 395	-147 957	-143 647	-139 463	-135 401	-131 458	-127 629	-123 911	-120 302	-116 798	-113 394	-110 094	-106 887	-103 774
Accumulated cash flow, including discount factor	4 113 561	3 956 594	3 804 199	3 656 242	3 512 595	3 373 132	3 237 750	3 106 273	2 978 644	2 854 233	2 734 431	2 617 632	2 502 748	2 392 748	2 282 655	2 171 994

Yearly Electricity Production

Electricity (MWh)	0	253	253	253	253	253	253	253	253	253	253	253	253	253	253	253
Electricity, including discount factor (ΔMWh)	0	246	239	232	225	219	212	206	200	194	189	183	178	173	168	163

LCOE (SEK/MWh) **273.2**
Payback time No

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35 Total
0.623	0.605	0.587	0.570	0.554	0.538	0.522	0.507	0.492	0.478	0.464	0.450	0.437	0.424	0.412	0.400	0.388	0.377	0.366	0.356	0.355

39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153	39 153
-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829	-200 829
-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676	-161 676
-100 751	-97 817	-94 968	-92 202	-89 516	-86 900	-84 378	-81 920	-79 532	-77 217	-74 968	-72 785	-70 665	-68 607	-66 608	-64 668	-62 785	-60 956	-59 181	-57 457	-55 784
2 171 243	2 073 426	1 978 458	1 886 257	1 796 741	1 709 811	1 625 464	1 543 690	1 464 397	1 387 584	1 313 251	1 241 397	1 172 024	1 105 131	1 040 719	978 788	919 336	862 353	806 840	752 807	700 255

253	253	253	253	253	253	253	253	253	253	253	253	253	253	253	253	253	253	253	253	253
158	153	149	145	140	136	132	128	125	121	118	114	111	108	104	101	98	96	93	90	87

Figure 3: The LCOE calculations for the battery scenario.

Appendix II

The calculations for the first day in 2021 to get the correction factor for the PV outputs. The results were used as distribution files in EnergyPLAN. The same calculations were made for the rest of 2021 as well.

hh	Radiation (W/m2)	Theoretical power (kW)	Temp. Corr	T... (°C)	T... (°C)	Kt	Inverter Losses	Angle Corr.	Day	Declination (°)	b	E (min)	Hour angle (°)				
1	0	0.000	0.000	0.8	0.8	1.109	0.950	-23.01	1	-23.01	0.00	-2.90	-168.23				
2	0	0.000	0.000	0.9	0.9	1.108	0.950	-23.01	1	-23.01	0.00	-2.90	-143.23				
3	0	0.000	0.000	0.8	0.8	1.109	0.950	-23.01	1	-23.01	0.00	-2.90	-128.23				
4	0	0.000	0.000	0.6	0.6	1.110	0.950	-23.01	1	-23.01	0.00	-2.90	-113.23				
5	0	0.000	0.000	0.1	0.1	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	-98.23				
6	0	0.000	0.000	0.2	0.2	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	-83.23				
7	0	0.000	0.000	0.3	0.3	1.111	0.950	-23.01	1	-23.01	0.00	-2.90	-68.23				
8	0	0.000	0.000	0.1	0.1	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	-53.23				
9	1.43	0.000	0.004	0.2	0.2	1.111	0.950	-23.01	1	-23.01	0.00	-2.90	-38.23				
10	17.83	0.006	0.006	0.4	1.0	1.108	0.950	-23.01	1	-23.01	0.00	-2.90	-23.23				
11	27.39	0.007	0.007	0.6	1.5	1.106	0.950	-23.01	1	-23.01	0.00	-2.90	-8.23				
12	33.15	0.009	0.009	0.7	1.7	1.105	0.950	-23.01	1	-23.01	0.00	-2.90	6.77				
13	45.83	0.010	0.010	1.0	2.4	1.102	0.950	-23.01	1	-23.01	0.00	-2.90	21.77				
14	40.52	0.009	0.009	0.5	1.8	1.105	0.950	-23.01	1	-23.01	0.00	-2.90	36.77				
15	11.06	0.002	0.002	0.1	0.4	1.110	0.950	-23.01	1	-23.01	0.00	-2.90	51.77				
16	2.05	0.000	0.000	0.5	0.6	1.110	0.950	-23.01	1	-23.01	0.00	-2.90	66.77				
17	0.09	0.000	0.000	0.6	0.6	1.110	0.950	-23.01	1	-23.01	0.00	-2.90	81.77				
18	0	0.000	0.000	0.6	0.6	1.110	0.950	-23.01	1	-23.01	0.00	-2.90	96.77				
19	0	0.000	0.000	0.2	0.2	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	111.77				
20	0	0.000	0.000	0.1	0.1	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	126.77				
21	0	0.000	0.000	0.1	0.1	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	141.77				
22	0	0.000	0.000	0.1	0.1	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	156.77				
23	0	0.000	0.000	0.1	0.1	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	171.77				
24	0	0.000	0.000	0.1	0.1	1.112	0.950	-23.01	1	-23.01	0.00	-2.90	186.77				
Angle Corr.	East	Cost(0)	Kb(0)	Kb(0) Corr.	Total Corr.	East	n	Real power (kW)	Angle Corr.	West	Cost(0)	Kb(0)	Kb(0) Corr.	Total Corr.	West	n	Real power (kW)
	-0.77	1.229	0.000	0.000	0.000	0.000	0.000	-0.79	1.227	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.67	1.249	0.000	0.000	0.000	0.000	0.000	-0.77	1.230	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.54	1.284	0.000	0.000	0.000	0.000	0.000	-0.71	1.240	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.40	1.351	0.000	0.000	0.000	0.000	0.000	-0.64	1.257	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.25	1.504	0.000	0.000	0.000	0.000	0.000	-0.54	1.285	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.10	2.098	0.000	0.000	0.000	0.000	0.000	-0.43	1.334	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.03	-1.928	-1.928	0.000	0.000	0.000	0.000	-0.31	1.422	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.14	0.402	0.402	0.000	0.425	0.000	0.000	-0.20	1.611	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.22	0.652	0.652	0.000	0.688	0.000	0.000	-0.09	2.206	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.27	0.726	0.726	0.000	0.764	0.000	0.000	0.00	45.466	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.27	0.732	0.732	0.000	0.769	0.004	0.004	0.06	-0.432	-0.432	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.24	0.679	0.679	0.000	0.713	0.005	0.005	0.10	0.104	0.104	0.004	0.104	0.181	0.002	0.000	0.000	0.000
	0.17	0.500	0.500	0.000	0.523	0.000	0.000	0.08	-0.081	-0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.06	-0.480	-0.480	0.000	0.000	0.000	0.000	0.03	-1.970	-1.970	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.06	2.639	0.000	0.000	0.000	0.000	0.000	-0.05	3.321	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.21	1.577	0.000	0.000	0.000	0.000	0.000	-0.14	1.800	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.36	1.377	0.000	0.000	0.000	0.000	0.000	-0.25	1.494	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.51	1.297	0.000	0.000	0.000	0.000	0.000	-0.37	1.369	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.64	1.256	0.000	0.000	0.000	0.000	0.000	-0.49	1.306	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.75	1.233	0.000	0.000	0.000	0.000	0.000	-0.53	1.269	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.83	1.220	0.000	0.000	0.000	0.000	0.000	-0.68	1.247	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.87	1.214	0.000	0.000	0.000	0.000	0.000	-0.74	1.234	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.88	1.214	0.000	0.000	0.000	0.000	0.000	-0.78	1.228	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	-0.85	1.218	0.000	0.000	0.000	0.000	0.000	-0.78	1.228	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Figure 1: The correction factor calculations for the first day in 2021.

Appendix III

The tables were created through the LCOE calculations and were the basis for the LCOE graphs in the cost-optimal and the battery scenario.

Maximum Output (kWp)	LCOE (SEK/MWh)
50	-256
100	-297
150	-332
200	-359
215	-366
230	-360
250	-352
300	-338
335	-331

Figure 1: The result from the LCOE calculations for different sizes of PV installations.

Maximum Output (kWp)	Battery Size (kWh)	LCOE (SEK/MWh)
215	0	-366
245	88	-188
275	190	-20
305	296	124
335	424	273

Figure 2: The result from the LCOE calculations for different sizes of PV installations when they include batteries.

Appendix IV

The tables were created in excel by knowing the emissions from the electricity mixes and assuming an emission from the battery manufacturing. They were used as the basis for the avoided emission graphs in the results.

Swedish electricity	Maximum Output (kWp)	Produced electricity (MWh/year)	Avoided emissions (ton CO ₂ -e/year)
13 kg/produced kWh	50	38.0	0.49
	100	76.0	0.99
	150	114.1	1.48
	200	152.1	1.98
	215	164.2	2.13
	230	175.1	2.28
	250	190.2	2.47
	300	228.1	2.97
	335	255.0	3.32

European electricity	Maximum Output (kWp)	Produced electricity (MWh/year)	Avoided emissions (ton CO ₂ -e/year)
241 kg/produced kWh	50	38.0	9.16
	100	76.0	18.32
	150	114.1	27.50
	200	152.1	36.66
	215	164.2	39.57
	230	175.1	42.20
	250	190.2	45.84
	300	228.1	54.97
	335	255.0	61.46

Figure 1: The results of the avoided emissions for different sizes of PV installations.

Swedish electricity	Maximum Output (kWp)	Battery capacity (kWh)	Produced electricity (MWh/year)	Avoided emissions (ton CO ₂ -e/year)
13 kg/produced kWh 75 kg/kWh battery capacity	215	0	164.2	2.13
	230	42	175.1	-0.87
	245	88	187.0	-4.17
	260	138	197.9	-7.78
	275	190	208.8	-11.54
	290	241	219.7	-15.22
	305	296	230.6	-19.20
	320	355	241.5	-23.49
	335	424	253.4	-28.51

European electricity	Maximum Output (kWp)	Battery capacity (kWh)	Produced electricity (MWh/year)	Avoided emissions (ton CO ₂ -e/year)
241 kg/produced kWh 75 kg/kWh battery capacity	215	0	164.2	39.57
	230	42	175.1	39.05
	245	88	187.0	38.47
	260	138	197.9	37.34
	275	190	208.8	36.07
	290	241	219.7	34.87
	305	296	230.6	33.37
	320	355	241.5	31.58
	335	424	253.4	29.27

Figure 2: The results of the avoided emissions for different sizes of PV installations that include batteries.

Appendix V

The tables were created through the LCOE calculations, but when one of the factors was changed. They were used as the basis for the graphs in the sensitivity analysis.

Maximum Output (kWp)	LCOE (SEK/MWh)	no tax deduction
50	-231	
100	-236	
150	-238	
200	-240	
215	-240	
230	-241	
250	-241	
300	-243	
335	-243	

Figure 1: The impact on the LCOE for the PV installation when removing the tax deduction.

Maximum Output (kWp)	LCOE (SEK/MWh)	PV price 2030
50	-378	
100	-419	
150	-453	
200	-481	
215	-488	
230	-482	
250	-474	
300	-460	
335	-452	

Figure 2: The impact on the LCOE for the PV installation if the investment is done in 2030.

Maximum Output (kWp)	Battery Size (kWh)	LCOE (SEK/MWh)	Battery price 2030
215	0	-488	
245	88	-389	
275	190	-284	
305	296	-192	
335	424	-99	

Figure 3: The impact on the LCOE for the installation, when including batteries, if the investment is done in 2030.

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