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Industrial Electrical Engineering and Automation

# A study of photovoltaics and of combining solar power with an existing wind power plant

**Daniel Mittel**
**Max Wither**

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

# Abstract

In this paper, the viability of integrating solar power with an already running wind power plant is examined. The study, conducted in cooperation with Eolus, takes place in Anneberg, Sweden, home to three wind turbines with a combined capacity of 10.8 MW. This study examines whether or not it would be profitable to integrate an additional intermittent power source to the wind power plant's existing grid connection point. Utilizing an existing grid infrastructure could lower the expenses for a new solar development considering that connecting power plants to the grid though new infrastructure can be fairly expensive.

Six different PV cases were studied and evaluated based on their profitability. These cases consisted of solar panel systems facing south, east/west, vertical south, vertical bifacial north/south, vertical bifacial east/west and using a single axis tracking system set on a horizontal axis. The performance and profitability for the different solar cases were evaluated using simulations results based on the site's historic weather data. Thereafter, it was determined that south facing stationary mounted panels were the most profitable; as a result, this method was used when modelling a hybrid setup.

Various different ratios of solar power when integrated to the wind power plant were simulated in an attempt to find an ideal ratio. In the simulations, the wind power took precedence, meaning that all the curtailed solar power was considered as losses. The results concluded that the smaller solar ratios were more desirable considering that less electricity was lost from overproduction due to the limited capacity of the grid connection point. These results were compared to the profitability of the PV systems should they instead act as a stand alone, grid connected system with the same power capacity. This allowed us to conclude that it could be financially viable to add photovoltaics to an existing wind power plant, based on the economic assumptions made in this study.

# Preface

This report was produced in partnership with Eolus in an effort to assess the feasibility of combining solar and wind energy using current grid infrastructure. The study is conducted in Anneberg, part of Tidaholm municipality Sweden, where three Eolus-built wind turbines with a combined capacity of 10.8 MW have been operating since 2018. For the wind power plant, Eolus kindly provided their wind output data, which was combined with solar simulations using weather data and assumptions from multiple sources. We would like to thank Nord Pool for granting us student access to the history of their hourly spot rates, which has helped us conduct a more thorough economic analysis.

Last but not least, we would like to express our gratitude to Jörgen Svensson, our supervisor at Lund University, Andreas Möser, and the entire Eolus team for their support, enthusiasm, and willingness to take time out of their busy schedules to help us.

# Nomenclature

| | |
|---|---|
| *AC* | Alternating current |
| *Agrivoltaics* | Using land for solar installations in combination with agriculture |
| *Air mass* | In meteorology, an air mass is a volume of air defined by its temperature and humidity. |
| *Capacity factor* | The average power generated divided by peak capacity |
| *DC* | Direct current |
| *Degradation factor* | Solar panel efficiency decrease per year |
| *GCR* | Ground coverage ratio |
| *GHI* | Global horizontal irradiation |
| *HSAT* | Horizontal Single-Axis solar tracker |
| *Inertia* | An object will continue its current motion until a force causes its speed or direction to change |
| *Irradiance* | Measurement of solar power per unit area expressed in $W/m^2$ |
| *Met mast* | Meteorological tower or measurement tower: used to measure wind data at a site |
| *NREL* | National Renewable Energy Laboratory |
| *Photon* | A particle of light that acts like a bundle of electromagnetic energy |
| *Power production* | Generating electricity from a source of energy |
| *PV* | Photovoltaic |
| *Spot price* | Hourly cost of electricity determined by Nord Pool |
| *STC* | Standard Test Conditions |
| *String* | A number of modules or panels interconnected electrically in series to produce the operating voltage required by the load. |
| *VSAT* | Vertical Single-Axis Solar Tracker |
| *WPP* | Wind Power Plant |

# Contents

# 1 Introduction

With the Swedish electricity grid becoming increasingly filled with intermittent power sources such as wind and solar, there are several challenges and opportunities that arise. These ways of producing renewable electricity create many problems for the grid stability, because they do not always deliver power when you need them to. It is still the norm to build these renewable energy power plants separately, but recently there has been a big interest in combining them to get the most out of their unique characteristics. The fact that wind and solar power plants often generate power at different periods of the day and year may make them an excellent complement to one another.

## 1.1 Objectives

The objective of this study is to evaluate the feasibility of connecting solar panels to an existing wind power plant's grid connection point so that money might be saved on grid connection costs. The wind power plant that will be studied was developed by a company called Eolus, which is who this project has been done in collaboration with. There will be times when the combined wind and solar power plant are producing over the maximum capacity of the grid connection and here the losses in terms of curtailed electricity and profit will be calculated. Different ratios between the installed wind power, solar power and connection capacity will be simulated to find the best investment. These results will in turn be compared to a standalone grid connected solar power plant to give further insight of how the profitability will differ. Additionally, a range of different installation methods for solar panels will be studied in order to find the most financially viable investment for the chosen site.

## 1.2 Limitations

This report does not discuss the possibility of adding electrical storage with the primary purpose to shift curtailed energy in time because the parties involved do not consider this to be a cost effective option yet.

The simulations carried out will be limited to a specific site in Tidaholm municipality, Sweden, over the years with available data. These years being 2019-2021.

In the analysis of the different solar installations the study is limited to six cases; fixed south, fixed east/west, vertically south mounted panels, vertically mounted bifacial panels facing east/west and north/south, and lastly a horizontal axis tracking system. Additionally, the system design will be thorough enough to get an overview of how profitable it is while not going in to the specific electrical design requirements.

## 1.3 Disposition

This report will begin with introducing the background on what Eolus has done in the past followed by background information about the site of which the wind power plant used for this study is located. In the theory section of the report, information about wind power will be presented but mainly this section will be presenting information about the technology behind solar cells and how photovoltaic systems can be designed. To tie this section together there will be a description on grid connection and the equipment that is needed for this, followed by an analysis on how to create a hybrid power generation system and what that entails. There will also be a short description of the economic terms and figures that will be used to evaluate profitability, along with some information on the Swedish electricity market and the history of solar module prices. Furthermore, the work process is described in the methodology section and the final results are presented in the results section. Finally the results are going to be discussed and evaluated in the discussion.

## 1.4 Eolus

Eolus is a leading wind power developer in the Nordic region with on- and offshore operations spread out in 7 countries; Sweden, Norway, Finland, the US, Poland, Estonia and Latvia. Since 2015, Eolus has been listed on the NASDAQ Stockholm stock exchange. Founded in 1990, Eolus sought to be wind power pioneers with a forward thinking sustainable approach on supplying the increasing global energy demand with renewable energies. By the fall of 2021, Eolus were responsible for 1 414 MW wind power in Sweden, Norway, the US and Estonia. Currently in an expansive phase, Eolus aim to create value while holding true to their core values and forward thinking sustainable mindset, with aspirations of venturing in to solar power and energy storage in addition to wind power. Eolus aspire to be the most profitable renewable energy developer and together with investors spearhead the energy transition to renewable energies (Eolus, 2022).

## 1.5 Anneberg, Tidaholm municipality

The location of which this study will take place is a farmyard called Anneberg, located in Tidaholm municipality, Västra Götaland county in Sweden. It is already home to three wind turbines with a total installed power of 10.8 MW, active since 2018. Sweden has four electricity sectors, also known as bidding areas, and they are depicted in figure 1 along with Anneberg's approximate location pinpointed. As the figure shows, Anneberg belongs to bidding area, SE3. The bidding areas will be described more in section 3.2.

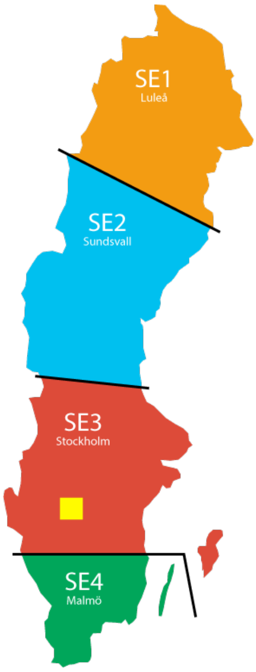


Figure 1: Map of Sweden's four electricity sectors with Anneberg's approximate location marked out by the yellow square (Elen, 2022)

The three turbines are connected to a 24 kV grid and each turbine has a transformer internally. The placement of the turbines and the grid connection point are shown in figure 2 along with an overview over the farmyard Anneberg. Figure 3 provided by Eolus, highlights where future PV installations might be feasible.

Figure 2: Map of Anneberg showing the available space, the placement of the three existing wind turbines and the location of the grid connection point marked by the red square (Lantmäteriet, 2022)

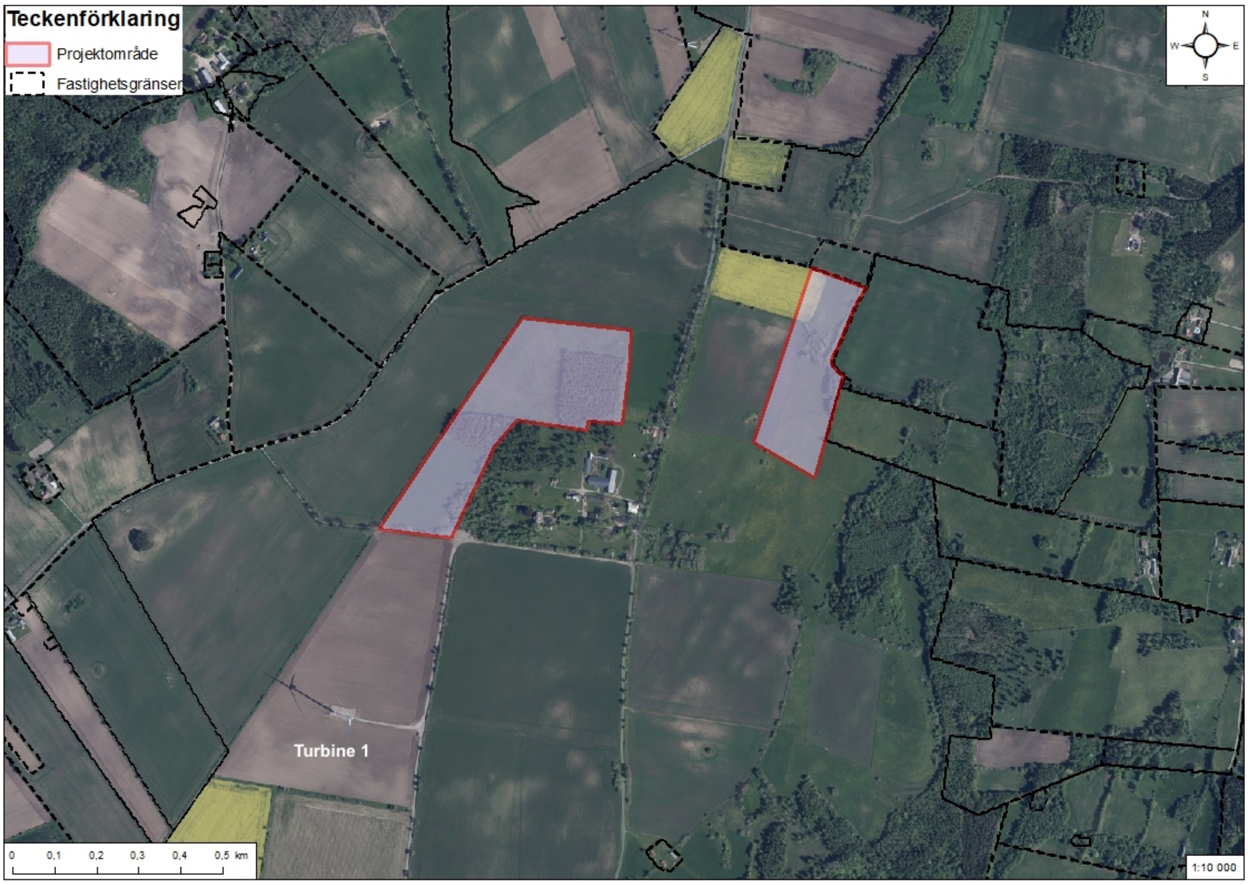


Figure 3: Map of Anneberg highlighting the available space applicable for PV installations

# 2 Theory - Wind & Photovoltaics

This chapter introduces the theory relevant for this study, starting with describing the two power sources used in the study, wind and photovoltaics. Considering that a large portion of this study focuses on optimizing solar power to an existing wind power plant, more attention is put on how PV systems function and how they are designed. This is followed by a description of the grid connection equipment and also some insight into hybrid systems.

## 2.1 Wind power

The subsections below will present the source of wind energy, how wind power is produced, how wind turbines function and how wind power plants are designed.

### 2.1.1 Wind energy

The source of the energy in the wind is the sun. Global winds are caused by differences in pressure on the earths surface due to uneven heating of the earth by solar irradiation. The amount of radiation absorbed at the earth's surface is larger at the equator than at the poles, and the variation in incoming energy sets up convective cells in the lower layers of the atmosphere. Simplified, air rises at the equator and sinks at the poles. The resulting circulation of the atmosphere from uneven heating is also influenced by the effects of the rotation of the earth, and seasonal variations in solar irradiation.

The power generated in a wind turbine can be calculated by:

$$P = C_p \frac{1}{2} \rho A U^3 \tag{1}$$

(Manwell et al., 2009)

- $P$ = Power [W]
- $\rho$ = Density of the air in [$kg/m^3$]
- $A$ = Swept area of rotor blades [m²]
- $U$ = Velocity of the wind [m/s]
- $C_p$ = Power coefficient

For example, if the radius of the rotor area is 60 meters, the wind speed is 10 m/s, the power coefficient is 0.4 and we know the density of air to be 1.225 $kg/m^3$ then the power can be calculated like this:

$$P = 0.4 * \frac{1}{2} * 1.225 * 60^2 * \pi * 10^3 = 2770884.72\ W = 2.77\ MW$$

The power coefficient is the efficiency of the wind turbine, meaning how much of the available power in the wind that can be converted into mechanical power. Theoretically, the maximum power coefficient is 59.3 % but in reality no wind turbines will have an efficiency that high (Manwell et al., 2009).

### 2.1.2 Wind turbines

A wind turbine generates electricity from wind by using the aerodynamic force from the rotor blades. When wind passes over the blade the air pressure on one side of the blade decreases. This difference in pressure creates lift and drag and since the force of the lift is larger than the drag, the rotor is forced to spin (Energy.gov, 2022). The rotor is then connected to the generator, usually through a gearbox. The purpose of the gearbox is to speed up the rate of rotation from the low-speed shaft of the rotor to a rate suitable for driving a generator. Most modern wind turbines are horizontal axis wind turbines. This means that the axis of rotation is parallel to the ground. Commonly they have three blades facing upwind (Manwell et al., 2009). A power curve is used to present the performance of a wind turbine and it shows at what wind speed the turbine starts generating as well as the wind speed when it needs to be shut down. Figure 4 is an example of what a power curve can look like (Sohoni, 2016).

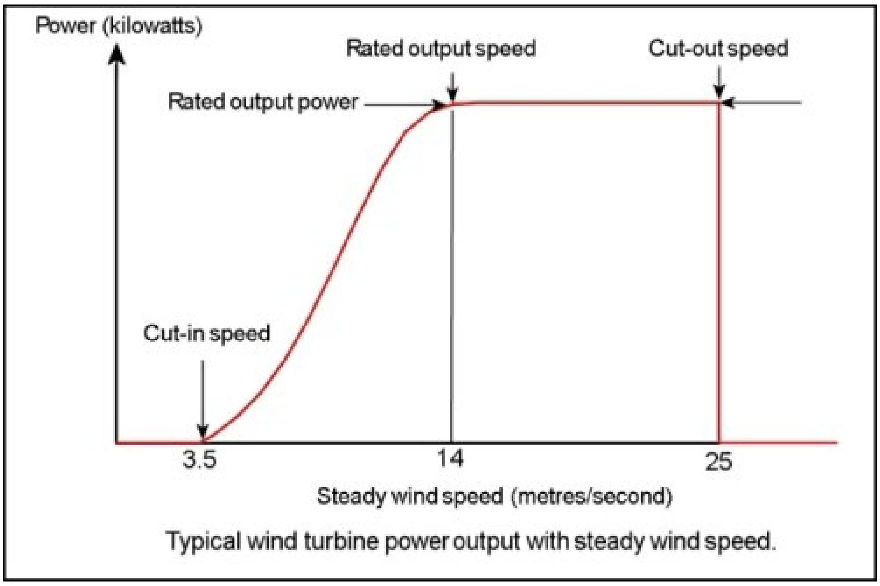


Figure 4: Illustration of a power curve for a wind turbine (Sohoni, 2016)

### 2.1.3 Wind power plant design

The first step when planning a wind power plant (WPP) is to make sure the site has sufficient wind and weather conditions. When a location has been chosen it is common to install a met mast in the area to get exact weather data to work with before the actual design of the power plant is set. This mast might be collecting data for a year or more and the collected data can be used to simulate the production a turbine will give in the area. Many things need to be taken into account when choosing the exact locations of the turbines as well. Examples of this are noise levels, access roads, wind turbulence from the landscape and visibility from local communities. Other factors such as environmental impacts need to be looked at as well. Often times when planning a WPP, there will be a lot of resistance from the local communities and in fact most planned projects are never built because of this. Careful planning and consideration is therefore needed to minimize the risk of this happening so that time is not wasted (Manwell et al., 2009).

One of the most important factor to take into account when designing a WPP, is the wake effect. This is what happens when wind turbines stand in rows, and the wind speed decreases with each step. It can be compared to the shading effect in solar panels which will be discussed more in the next section of the report. A visual illustration of the wake effect is presented in figure 5 below (Snieckus, 2019).

Figure 5: Illustration of the wake effect in wind power plants (Snieckus, 2019)

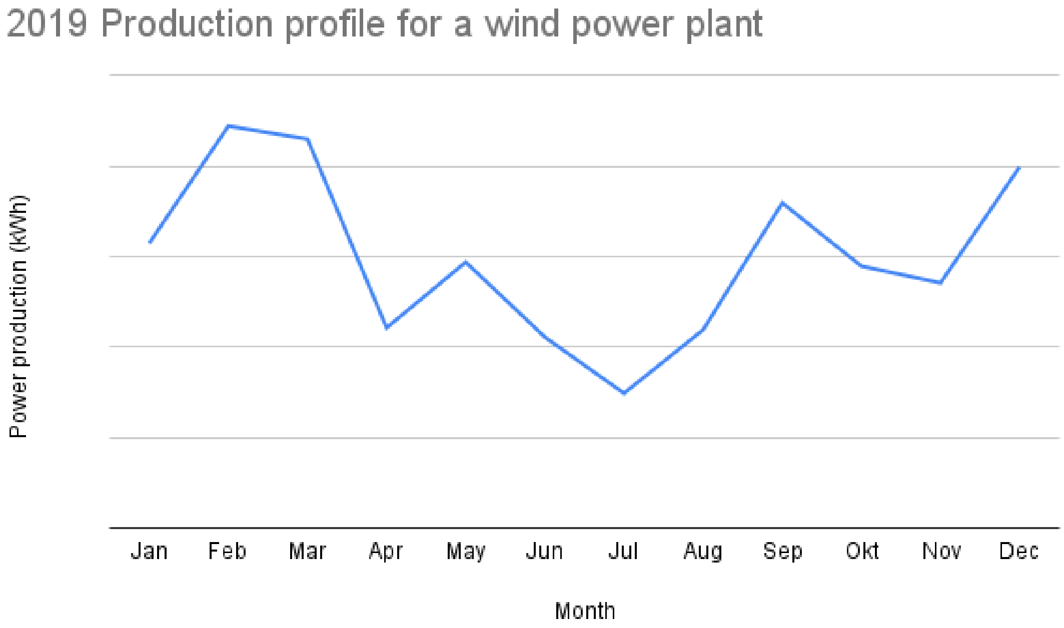


Figure 6: Production profile for a wind power plant

Wind power will generally generate most of its power during the winter months, and this is represented in figure 6 which shows the monthly variations in production for the Anneberg wind power plant in 2019. Furthermore, there will also be large day to day variations in wind availability which will increase the volatility of the power system. A visual representation of this is illustrated in figure 7 which shows how the production in a wind power plant can vary over the course of 24 hours. The vertical axis of these two figures have been hidden because the data is protected. The way to measure how well a power plant performs is by calculating its capacity factor, which is the produced energy in relation to the peak capacity. In Sweden the average capacity factor for onshore wind power in 2014 was around 24 % but in 2020 the turbines that were installed generated a capacity factor of 37 % (Svensk Vindenergi, 2022).

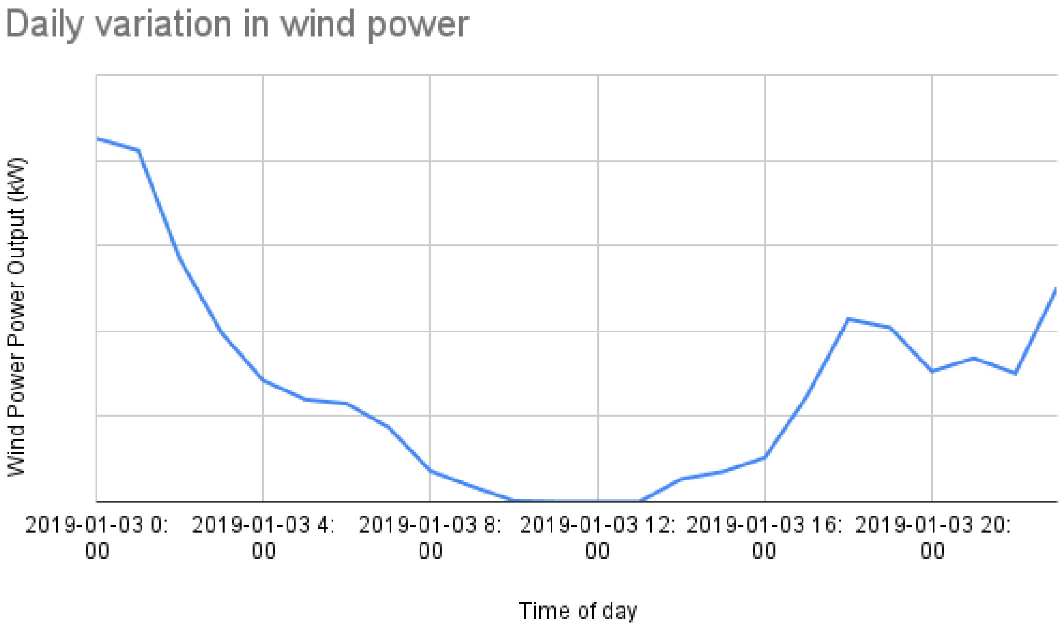


Figure 7: Daily variation in wind power

## 2.2 Photovoltaic technology

This section introduces all relevant theory related to the photovoltaic technology and explains all the steps from the conversion of solar energy to electricity.

### 2.2.1 Photovoltaic cells & modules

Photovoltaic (PV) technology consists of converting energy extracted from the sun to electrical energy. PV cells are thin semiconductor wafers consisting of two layers, one doped with boron and the other with phosphorous. Doping the layers creates a side with a surplus of electrons leaving the other with an electron deficit. When PV cells are exposed to the sun, or irradiance as it is referred as, photons in the sunlight prompt the electrons to move from the layer with excess electrons to the side with a deficit, subsequently generating a current. This process is illustrated in figure 8. The generated power of a cell is calculated using equation 2 and is related to the irradiance exposed on the cell, the area and the efficiency of the cell (Solar direct, 2022).

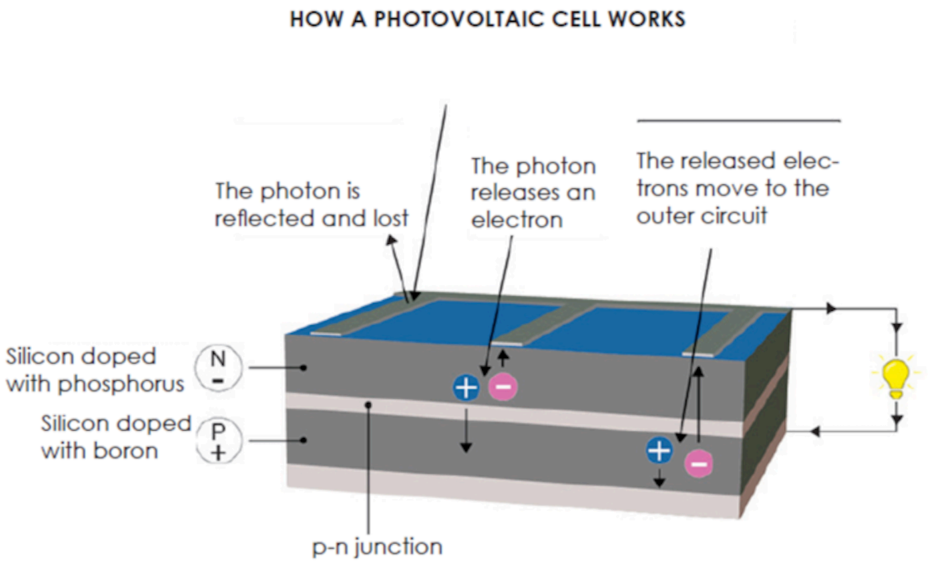


Figure 8: PV cell (Planete-energies, 2019)

$$P = \eta G A \tag{2}$$

- $P$ = Power [W]
- $\eta$ = Efficiency of a cell
- $G$ = Irradiance [W/m$^2$]
- $A$ = Area [m$^2$]

For example, if the efficiency of the cell is 20%, the irradiance is 1000 $W/m^2$ and the area 1 $m^2$ then the power can be calculated like this:

$$P = 0.2 * 1000 * 1 = 200\ W$$

There are several solar cell types available on the market today each with their own advantages and disadvantages. The most common solar type is the Monocrystalline solar panels (Mono-SI) with an approximate efficiency of 20%. They are more expensive than the other solar cell types but they have a higher efficiency rate, more optimized for for commercial use and they have a high lifetime value. Polycrystalline solar panels (p-Si) is a cheaper option with an efficiency of around 15%. These are slightly less space efficient, more sensitive to high temperatures and have a lower lifespan. Thin-Film solar cells (TFSC) has the lowest efficiency rate stretching so low as 7-10%. These solar cells are slightly cheaper than the Monocrystalline solar panels but the main advantages of these panels are that they are the easy to produce and they are flexible. This allows solar panels to fit in to spaces that traditionally have been unavailable for solar panels. Disadvantages on top of the low efficiency rate consists of shorter warranties and lifespans (GreenMatch , 2022).

There are a variety of solar panels in the research and development phase. Biohybrid solar cells are in the research phase but may be able to convert chemical energy to electrical energy in a much more effective manner. Cadmium Telluride Solar Cell (CdTe) is another example of a solar cell in development. Advantages so far of using CdTe is the relative low cost and quick payback. With that said, the characteristics of the solar cell is toxic if ingested or inhaled. This just highlights the complexity and barriers to overcome for new technological advances (GreenMatch , 2022).

Considering that sunlight prompts the electrons in the solar cells to move and generate electricity, a location with a lot of sunlight exposure is desired. Along with this, the more perpendicular the sun exposure is to the solar module, the more electricity it will generate. Figure 9 shows the daily variation of a solar power plant in London and the effects clouds can have on the solar PV generation. The figure compares two different days, two days apart, with the blue line illustrating a sunny day with a clean production curve throughout the day. The orange line on the other hand illustrates a cloudy day and a clear difference can be seen in the solar PV generation. Not only does the cloudy day not reach the same electricity production heights as for the sunny day, but the electricity production curve fluctuates more throughout the day.

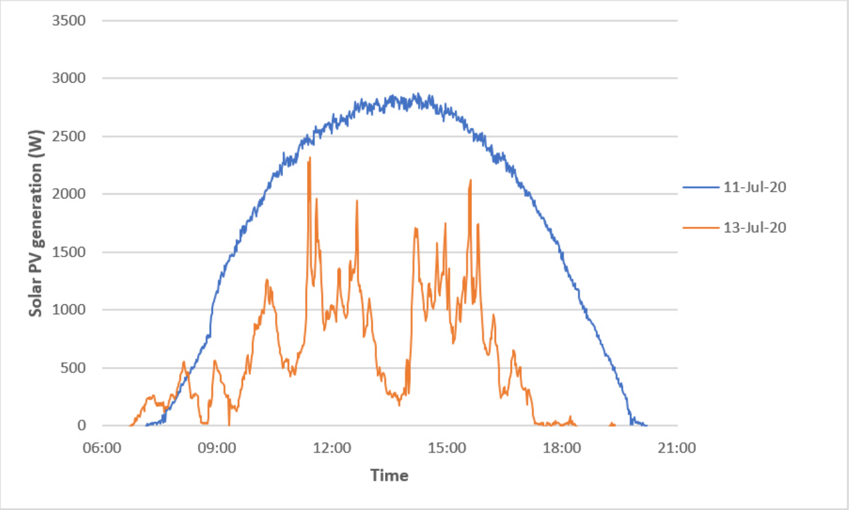


Figure 9: Daily variation in solar power in London (Blue line is for a sunny day and the orange line is for a cloudy day)(NEA, 2022)

PV cells connect to one another both in series and parallel, forming a PV module. Its purpose is to increase the current and voltage. The industry standard consists of using either 60 or 72 PV cells in each module when designing systems for large power production (PV Education , 2022b). Modules are assembled into arrays in the aim of obtaining an appropriate amount of electricity. The PV cells and modules are then wedged in between protective glass and plastic materials guaranteeing the cell's longevity in outdoor conditions (Solar direct, 2022). Figure 10 shows a visual illustration of a PV cell, module and array.

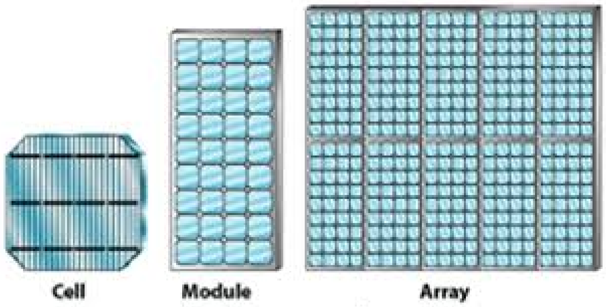


Figure 10: PV cell, module and array (Solareis, 2022b)

### 2.2.2 Internal system PV losses

A PV system's efficiency is an integral part when planning solar installations with several factors affecting a system's overall productiveness. Efficiency of a solar system is defined as the ratio between the total energy output and the input energy from the sun, and is calculated using the equations below (PVEducation, 2022a)(PVEducation, 2022b). The fill factor, abbreviated FF, which represents a PV cell's maximum conversion efficiency at its optimal operating voltage and current, is used to calculate cell efficiency (Svarc, 2022).

$$P_{max} = \eta V_{OC} I_{SC} FF \tag{3}$$

- $P_{max}$ = Maximum energy output [W]
- $V_{OC}$ = Open-circuit voltage [V]
- $I_{SC}$ = Short-circuit current [A]
- $FF$ = Fill factor

$$FF = \frac{P_{MP}}{V_{OC} I_{SC}} = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}} \tag{4}$$

- $P_{MP}$ = Maximum power from the solar cell [W]
- $V_{MP}$ = Voltage at max power [V]
- $I_{MP}$ = Current at max power [A]

$$\eta = \frac{P_{max}}{P_{in}} \tag{5}$$

- $\eta$ = Efficiency
- $P_{max}$ = Maximum energy output [W]
- $P_{in}$ = Energy input [W]

Solar energy conversion to electricity is never completely efficient with the usual efficiency for the commercially available monocrystalline solar panels, mentioned in the previous section, being approximately 20%. Figure 11 gives an overview of the losses that occur in each step of a PV system's conversion process. However, the output of electrical energy won't be significantly impacted if the efficiency-limiting variables are properly addressed. These variables consist of; temperature, mismatch between modules, inverter efficiency, age, soiling and shading (Eco Green Energy, 2022).

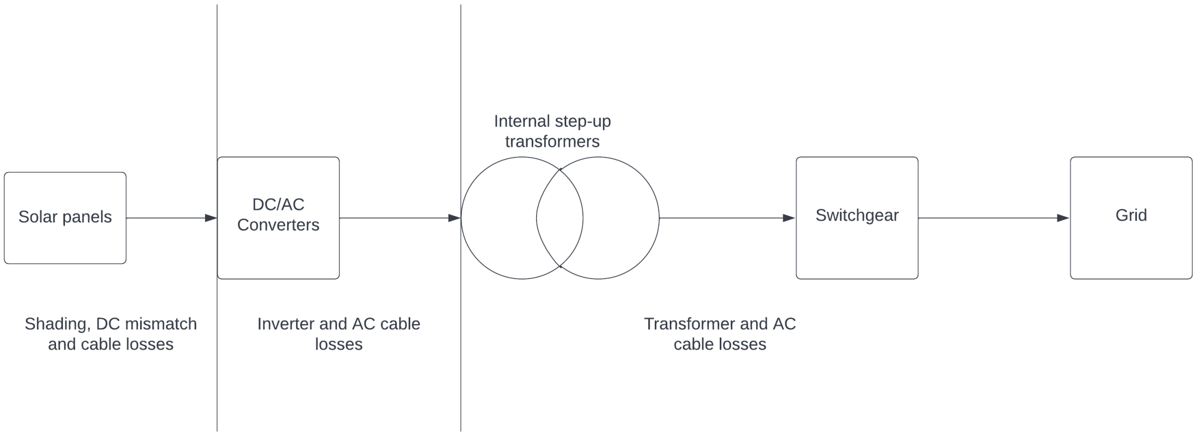


Figure 11: Block diagram for a PV system connected to the grid with some descriptions over the losses that occur in each step of the process

Temperature does not directly correlate to the amount of irradiance a solar cells receives, instead higher temperatures negatively impact the solar cell's performance, thus affecting the system's overall power production. The semiconducting materials the solar cells consists of are sensitive to temperature changes, leading to greater energy losses when temperatures exceed the standard test condition (STC) level of 25°C. The standard test conditions act as the industry standard for the conditions of which solar panels are tested allowing all panels to accurately be compared and rated against one another. The other two standard test conditions include a solar irradiance of 1000 $W/m^2$ and an air mass coefficient of 1.5 (Silicon Solar, 2022). PV panels surrounded by higher temperatures decrease the open circuit voltage of solar cells while colder temperatures increases the voltage, as is shown in figure 12. Most solar panels have a temperature coefficient between -0.20% and -0.50% per degree Celsius for every degree above the STC temperature level meaning that for every degree over the STC level, the efficiency decreases. The same applies for every degree under the STC level, instead the efficiency increases per degree Celsius with the same rate (Greentumble, 2022).

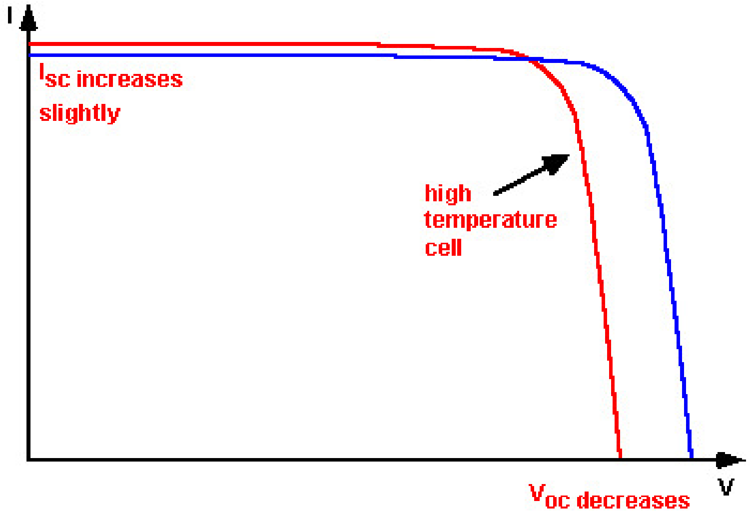


Figure 12: The open circuit voltage and the short circuit current's behaviour in relation to the change in temperature (PVEducation, 2022c)

Efficiency losses that occur from module mismatches are caused by manufacturing variations, for instance modules produced of the same type possessing different electrical characteristics. The inverters used for converting DC to AC are typically 96-97% efficient, thus also affecting the PV systems overall production and efficiency. Solar panels also produce less the older they get with an assumed decrease in electricity production of about 0.5% per year (Eco Green Energy, 2022). This decrease if referred as the degradation factor. Half a percent may not seem like a lot but over the years the losses will become quite significant. As a result PV systems generally have a lifetime of around 25-30 years, while in theory they could continue to function for several decades given that the panels aren't physically damaged. The decrease in efficiency however would be so great that the system would be extremely inefficient (Energysage, 2022). Lastly the soiling and shading of PV cells play a big role in a systems overall production considering that if the sunlight is prevented from reaching the solar cells, the system will struggle to generate power. Shading can even potentially damage the PV cells should a cell be shaded over a prolonged time. For instance if a single cell in a string, a series connected set of solar cells or modules, is shaded then the energy from the previous non shaded cells will dump the energy produced in to the shaded cell as heat, thus potentially damaging the cell (Eco Green Energy, 2022). This can be avoided by connecting a bypass diode in parallel to the solar cells which functions as an external circuit in case there is a shaded cell (PV Education , 2022a).

### 2.2.3 Solar inverter

Inverters play an integral part in solar energy systems as they convert direct current (DC) in to alternating current (AC). The electrical grid along with electronic devices and appliances are designed to run on an AC supply. DC electricity contains a constant voltage in one direction whereas AC electricity flows in both directions in the circuit and alternates from positive to negative. The DC to AC conversion is done rapidly and produces a clean voltage that can be used without damaging the electrical equipment adapted to operate at a certain voltage and frequency (Energy.gov, 2022). In addition to converting DC to AC, the inverters also constantly keep track of the solar array´s voltage in order to find the maximum power at which the modules can function and monitor the solar systems power output. There are three types of solar panel inverters; micro-inverters, power optimizers and string inverters. String inverters are the most common today as they are generally more efficient and the most economical inverter option available on the market. These inverters allow several strings of modules being connected to a single inverter (Manoj, 2022).

The ”DC-to-AC” conversion in the inverters are never 100% efficient with some electrical energy being lost in the DC-to-AC conversion. These losses are referred as the DC-to-AC losses which can account for up to 2% or more of the total energy losses in a solar PV system. The higher the efficiency the less electrical energy is lost in the conversion process. High-efficiency inverters with an efficiency as high as 98% or more are costly but could be beneficial in the long run as conversion losses are reduced and the systems overall efficiency is improved. Important to also factor in is the placement of the inverters and choice of wiring. The inverters should be kept close to the solar panels in order to minimize the electricity’s travel distance, thus reducing the resistance in the electricity flow. The same applies for the choice of the wiring as large gauge wires are desirable considering their low resistance qualities allowing the current to flow and losses to be minimized (Solartechadvisor, 2022).

Another feature when installing solar power systems is solar inverter sizing as it plays a predominant role in the overall electricity production. The size of inverters is referred in watts and a general rule of thumb when designing solar systems is to have a similar inverter output size as the solar systems DC rating. This is referred to as the array-to-inverter ratio and is calculated by dividing the solar systems DC power rating with the maximum AC power output of the inverter, as equation 6 demonstrates. An ideal array-to-inverter ratio is around 1. Inverter manufacturers recommend to avoid any ratios higher than 1.55 as it results in large clippings, see figure 13. This is a term that explains the inverter's struggle to convert all generated DC from solar panels, resulting in power losses, thus affecting the systems overall efficiency. The only positive aspect of having a high ratio, or oversizing the solar arrays relative to the inverter capacity is the inverters operating at lower watts are generally cheaper which is desirable and explains why most installations have a ratio between 1.15 to 1.25. The ratio should not be too low either as that system will not produce the desired amount of electricity. The geography and site conditions also play a role in the inverter sizing. The inverters should cope well with the locations temperature fluctuations without decreasing in efficiency (Thoubboron, 2018).

$$\text{Array-to-inverter ratio} = \frac{\text{Solar power systems DC rating}}{\text{Maximum AC output of the inverter}} \tag{6}$$

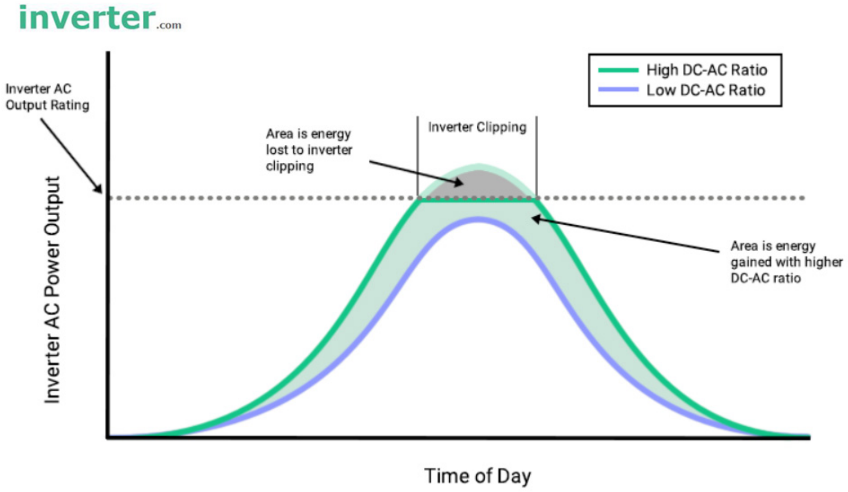


Figure 13: Solar inverter clipping (Inverter , 2020)

## 2.3 PV system design

The many methods for mounting solar panels to the ground will be discussed in this section, along with each technique's benefits and drawbacks. There are almost infinite ways to install solar panels with a number of different solar cell technologies, but the ones presented in this section have been selected as they give a wide perspective on why one might choose to vary the mounting set ups. The capacity factor for a solar power installation will vary depending on the location and installation method, but in Sweden the total capacity factor for solar was around 8% in 2021 (Svensk Solenergi, 2022).

### 2.3.1 Tilt configurations

When designing a PV system the tilt, direction and installation of the solar panels are crucial. PV cells need to be exposed to sunlight to produce electricity and the most power transpires when the sun's rays are perpendicular to the panels surface. Considering that the position of the sun changes throughout the day and the year, a pivotal part of the installation process consists of establishing the optimal tilt and direction to fulfil one's electricity needs. The tilt can also prove to be decisive for other environmental condition aspects, e.g avoiding dust and dirt from gathering on the panels reducing its energy conversion. If a PV panel is covered with snow for instance, the snow would prevent the PV cells from absorbing the sunlight, thus preventing the system from producing electricity. A solution to this specific problem would be to have a higher tilt preventing the snow from piling up and ultimately allowing the snow to slide off. The same concept applies to shading of PV cells. If the panels are situated in the shade away from direct sunlight, electricity production on the PV module will halt. This highlights not only the importance of the PV panels orientation but also its location (Negro, 2022). Most large scale fixed tilt solar installations in Sweden have a 30° tilt and are oriented to the south. Important to mention is that the tilt angle is defined as the angle from horizontal which means that a flat panel is 0°.

### 2.3.2 Stationary PV systems

Stationary PV systems consists of mounting PV panels to the ground on racks or substructures, rooftops or atop a single pole. What this means is that there are no moving parts and the tilt of the panels are constant, and they are therefore not perpendicular to the sun for most of the day. Installing stationary PV systems enables the production of fossil-free electricity with minimal upkeep and relatively low investment costs. As of 2022, rooftop PV systems dominate the solar energy market, with ground-mounted PV systems taking up a modest portion of the market. However, interest and activity have increased in Sweden as more and larger ground-mounted solar PV parks are anticipated much thanks to the increasing demand for renewable electricity and declining costs of PV systems (Mordor Intelligence, 2022). As there are alternative ways of orienting stationary PV systems, one must decide which of these that best suit the power production needs. Solar power is an intermittent resource that can generate power from sunrise to sunset and has a general production profile shown in figure 14 illustrating how the production in a solar power plant changes over the course of a year. The global horizontal irradiation is directly correlated to the suns position in the sky, meaning it is the highest during the summer in the middle of the day, assuming it's a sunny cloudless day. The electricity producing peaks occur at different times during the day depending on the orientation of the panels (Kankiewicz, 2015).

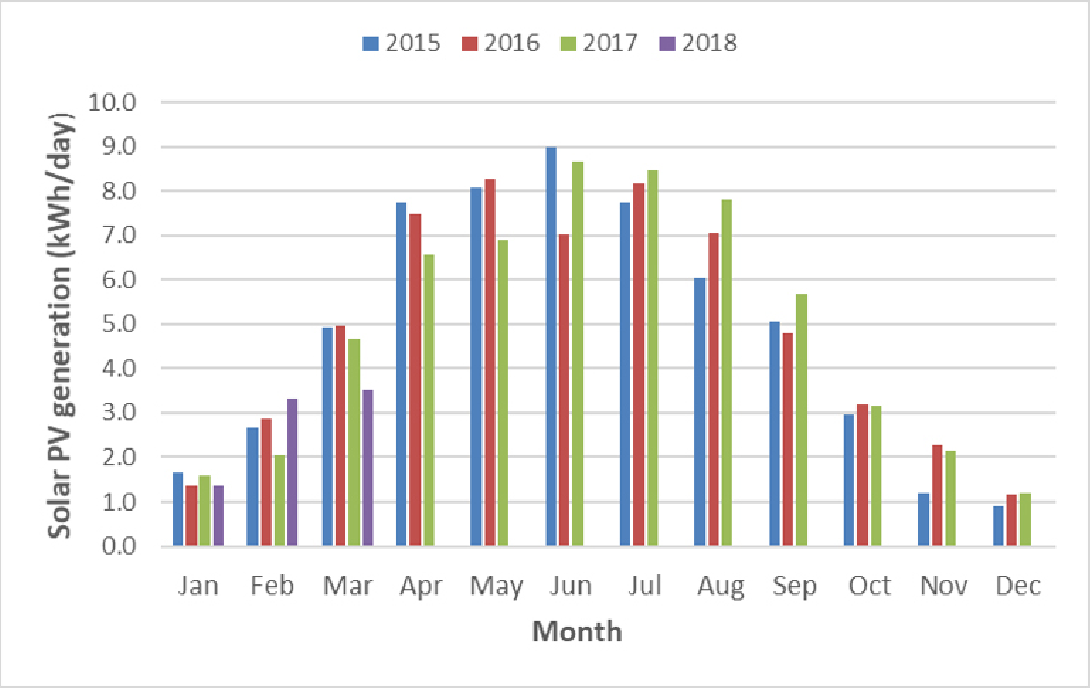


Figure 14: Monthly variation in produced solar power for an installation in London (NEA, 2022)

One must also look at the available space for mounting PV panels and gather enough solar data to estimate the solar production. Doing so helps determine the orientation, tilt and remaining characteristics ensuring that the PV system is installed to perform at the best of its ability. Here are a few different implementation methods one can use when installing stationary PV panels.

### South oriented PV panels

Panels located in the northern hemisphere are typically facing south to maximize the electricity production over the systems lifetime. The general rule of thumb when establishing the tilt angle for a site is to use the same tilt as the sites geographical latitude. Hence the closer to the equator the site is, the flatter the tilt and vice versa (Negro, 2022). The power production can be increased further should the tilt be 15° flatter during the summer and 15° steeper during the winter, due to the sun's positioning in the sky during the different seasons. Readjusting the solar panels tilt twice a year using a winter and a summer angle could increase the overall production by roughly 4% (Solar Panel Tilt, 2022). Figure 15 gives an example of what a typical south facing stationary PV system may look like.

Figure 15: PV system using monofacial panels implemented at a fixed tilt (Ramboll, 2022)

### East/west oriented PV panels

Mounting PV panels so they instead face east and west can also prove to be beneficial even though it reduces the system's total yearly electricity production. East-west mounted panels, as opposed to south facing panels, allow the system to supply more electricity during the hours with high demand. Most electricity in Sweden is consumed during mornings and evenings considering that more people are at home using appliances. East-west mounted panels stabilizes the electricity production throughout the day permitting consumers to utilize their generated power instead of importing expensive electricity from the grid (Rodríguez, 2021). This is further illustrated in figure 16 which shows how production will shift towards the morning or evening depending on the orientation of the panels.

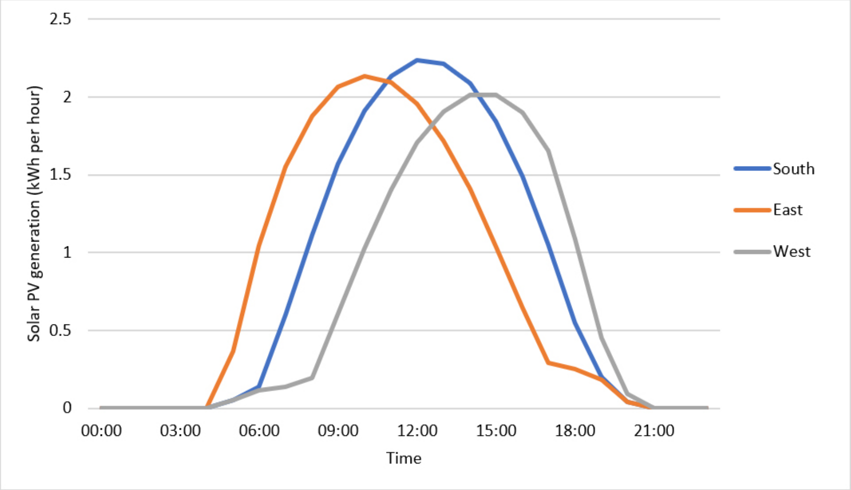


Figure 16: Daily variation in solar power for different orientations (NEA, 2022)

East-west oriented panels, see figure 17, are becoming increasingly common today as it allows structures to squeeze in more rows and panels in available spaces due to the lower installed tilt of the panels casting smaller shadows. An ideal east/west panel would lay completely horizontal as that would expose the panels to the most irradiance throughout the day. In reality however, that would cause soiling losses, mentioned in section 2.2.2, as snow and dirt would gather on the panels preventing electricity to be produced. Therefore there is a need for a small tilt allowing the rain and gravity to naturally wash off the panels. Installing east and west mounted panel allows one to fit more panels in a space, thus possibly increasing the generation capacity for the area but not the the overall generation capacity per module (Rodríguez, 2021).

Figure 17: East-West PV module (Solarge, 2022)

**Vertical PV panels**

Vertical PV modules can be effective as they can make use of traditionally unused spaces, e.g. the sides of buildings. They are also considered self cleaning as dirt will struggle to gather on a vertical surface, and if it does the rain will wash it off. What this report will focus on though, is ground mounted vertical PV installations. This installation method also allows the most ground area to be used for other purposes in surplus of electricity production, like growing crops or grazing animals. A typical vertical installed solar power plant can look like the one depicted in figure 18 showing plenty of potential space suitable for agricultural purposes. Keep in mind that the panels in the picture are bifacial but the mounting would look similar. The main drawback with vertical PV modules consist of lower power production. Mounting panels vertically exposes the modules to less irradiance due to the suns movement and angle. With that said, it could result in a higher electricity production during winter time as the sun generally sits lower in the sky. However, that also means that less electricity will be generated during summer, as the sun sits high in the sky (Go Smart Bricks, 2019). In the same fashion, mounting the panels east and west facing could result in a higher generation of electricity in the mornings and evenings but the generation during midday would probably be very low.

### 2.3.3 Bifacial solar panels

Solar cells in bifacial panels function exactly as they do for regular solar panels. The only difference being that bifacial panels absorb solar irradiance from both sides of the panel. Traditional solar panels have a non-transparent backsheet whereas bifacial panels allows sunlight to be captured from both sides of the panel increasing the efficiency and solar energy productivity with certain panels capable of increasing the production by 30%. These panels are best suited when installed near highly reflective surfaces, such as snow, water, glass and sand (Deegesolar, 2022).

Benefits of using bifacial panels include higher efficiency, but also more durability considering that the panels are frameless and are covered in tempered glass which is more weather resistant and can stand higher temperatures. This means that they can produce more and have a longer lifespan compared to regular solar panels. Disadvantages include higher initial system investment costs with bifacial solar panels costing up to 10% more than monofacial solar panels. The installation costs are also higher because of the fact that the bifacial panels are heavier than monofacial panels, thus requiring more specialized equipment (Deegesolar, 2022).

Figure 18: Vertical bifacial panels (pv-magazine, 2020)

### 2.3.4 Single axis tracking system

PV modules implemented with single axis tracking systems adjust their panels according to the suns movement. The trackers track the sun and make the required positional adjustments throughout the day in order to maximize the system's power production (Gregus, 2021). Figure 19 visually illustrates the two types of single axis trackers, horizontal and vertical. Panels implemented on an horizontal axis, Horizontal Single-Axis Solar Tracker (HSAT), revolve around a fixed horizontal axis rotating east to west following the suns movement. Panels implemented on a vertical axis, Vertical Single-Axis Solar Tracker (VSAT), instead rotate around a vertical axis. VSATs are typically found in high-altitude locations or places of higher latitudes because of the lower positioning of the sun in the sky (Rooij, 2022).

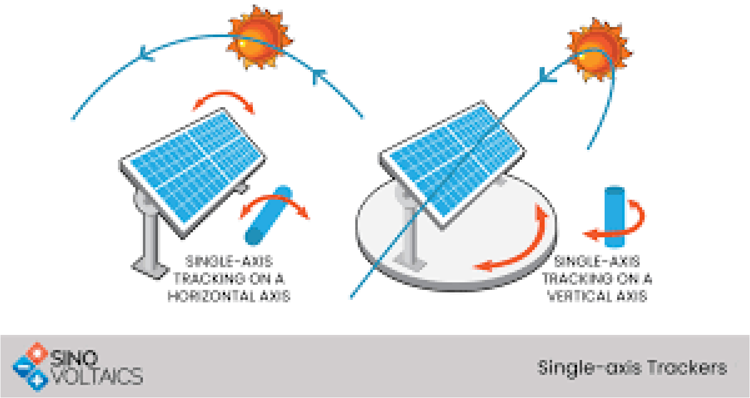


Figure 19: Single axis tracking system (Sinovoltaics, 2022)

Benefits using single axis tracking systems include increased electricity production by up to a third compared to stationary solar power systems. This technology is more costly compared to installing stationary solar power systems, however with the right choice of location, the additional power generated by the system could prove more economically beneficial (Gregus, 2021).

The cons of installing single axis tracking systems include challenging site layout and increased necessity of panel maintenance. The increased need for maintenance is largely due to all the moving part needed for the tracking system to function. This presents a list of possible maintenance issues such as appropriate weight/power ratio, optimized motors, solar tracking control and greasing. Horizontal axis tracking systems have a roughly 10% higher initial project costs compared to a fixed PV system (Mechatron, 2022). Using tracking systems require larger spacing between modules compared to stationary systems in the effort to eliminate possible shading losses. The typical ground covering ratio (GCR) for single axis tracking system lay between 0.33 and 0.5, and this metric will be described in section 2.3.6. Complications also occur in the trench system for cables and wire management considering that the panel moves throughout the day and are not as straight forward as for the stationary ground mounted panels (DCE Solar, 2022).

### 2.3.5 PV Losses

Various different losses occur internally in PV systems and these need to be taken into account. The assumed values of these in this study are presented below.

- Soiling: 2% (Losses from dust or snow gathering)
- Module/Array mismatch: 2% (Differences in manufacturing between modules)
- DC wiring: 2% (Resistive losses on the DC side)
- AC wiring: 0.5% (Resistive losses on the AC side)
- Connections: 0.5% (Resistive losses in connectors)
- Inverter: 3.5% (Inverter conversion losses)
- Shading: Calculated for different tilts in SAM simulations

(Lonin, 2022) (Bruce, 2022)

### 2.3.6 Land usage

When preparing a solar PV installation, it is critical to decide how to place the solar panels efficiently making good use of the available land. Land use efficiency describes the electrical power generated by area measured in either $W/m^2$ or $Wh/m^2$ and can be a useful tool when looking at a system's overall efficiency. Increasing the land use efficiency decreases the space between rows of the PV modules, which can both be positive and negative. Increasing the distances between modules minimize the risk of PV selfshading, shading caused from other PV panel rows, but also requires larger acreage for the solar installation (Hernandez et al., 2015).

Ground coverage ratio, GCR, is term representing the ratio between the module area to the total land area or the ratio of the array length to the row spacing. The equation in figure 20 shows how to calculate the GCR in relation to the array length and row spacing, and the figure helps to visualise it.

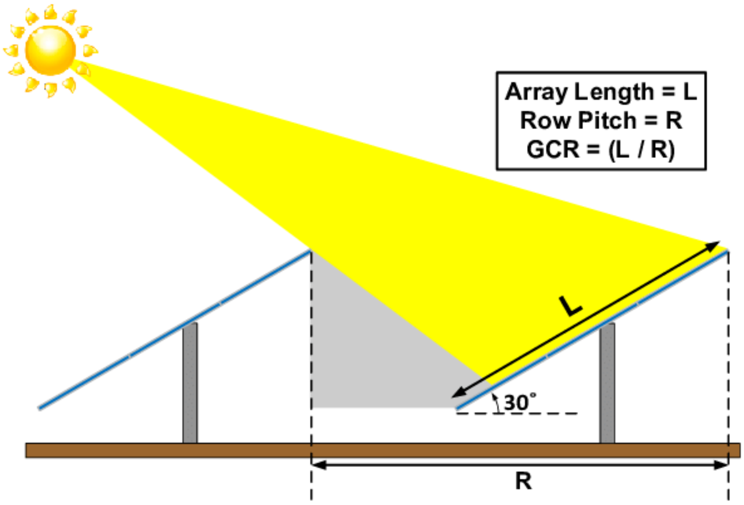


Figure 20: Figure displaying GCR (Deline et al., 2014)

The choice of GCR is critical as it correlates to the selfshading of the solar panels. The higher the GCR is, the closer the panel rows are to one another, thus increasing the risk of selfshading. This is illustrated in figure 21 demonstrating the importance of GCR and how the the different row spaces affect the shading losses for a fixed mounted panel with a 30° tilt. When deciding the GCR for a solar installation, the sites location is of great importance. More specifically the latitude of the site as the further north the site is, the higher tilt the solar panels should have which will also result in larger spacing between then panels. There is no fixed GCR to strive for as there are plenty of parameters to look at and varies based on the characteristics of each site. For instance, increasing the distances between the rows allows more sunlight to be converted to electricity but in the meantime limits the number of rows that can fit on an area of land (Farhat, 2022). Table 1 shows the land needed for a 1 MW solar system with a 30° tilt at different GCRs. The table points out the effects GCR has on the selfshading of the panels, and also the land use needs for a 1 MW installation. It shows that higher GCR's reduce the acreage needed for a solar installation.

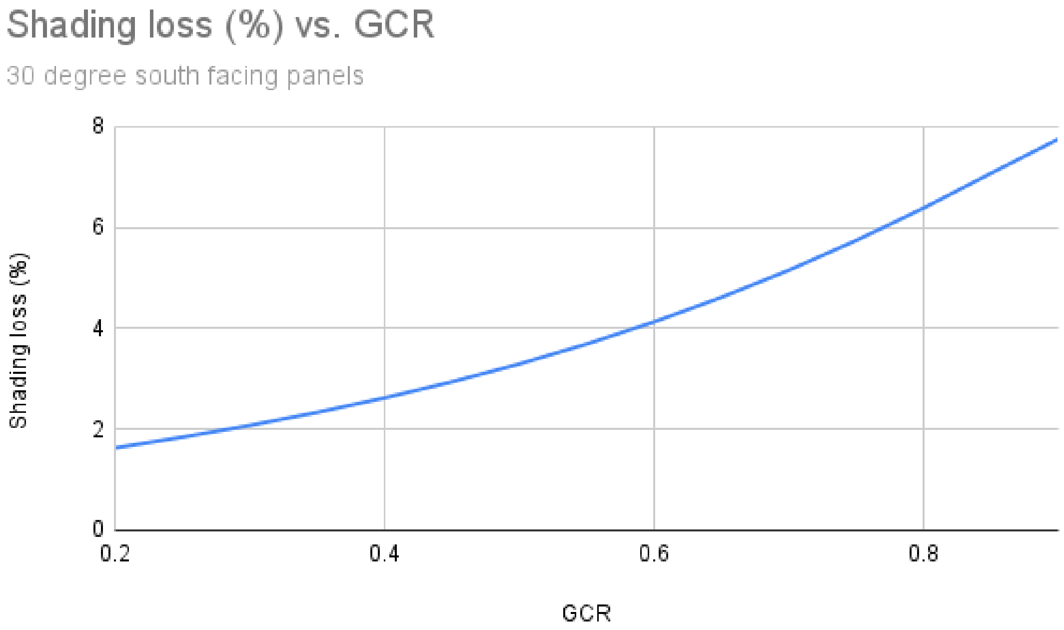


Figure 21: Figure showing how the row spacing affects the internal shading power losses of the PV panels in Anneberg

| GCR | Row space (m) | Land use (ha) | Difference in land use compared to 0.4 GCR (%) | Shading loss (%) |
|---|---|---|---|---|
| 0.4 | 9.492 | 1.244 | 0 | 2.6 |
| 0.5 | 7.594 | 1.000 | -19.6 | 3.3 |
| 0.6 | 6.328 | 0.836 | -32.8 | 4.1 |

Table 1: Table showing the difference in land usage and the selfshading losses for a fixed 30° south facing PV system compared to 0.4 GCR in Anneberg

Large spacing between PV panel rows do however allow the land to be used for other purposes in addition to electricity generation. Agrivoltaics is a term describing the combination of agriculture and solar power working in harmony. Not only does it serve the solar developer but also those in the local community who care for the land. In addition of making extra use of the land, it could even reduce the systems maintenance costs. A flock of sheep or other livestock keep the plants under the panels trimmed, saving the owners the costs of mowing. The land gets mowed for free while the sheep are fed. Other benefits apart from livestock grazing include growing crops, cultivating pollinator-friendly native plants, providing ecosystem services and restoring degraded soil. Installations of this kind set requirements for good partnerships between the solar developer and the landowner as the priorities over how the land is best used can differ. Therefore, a solution that works for all parties needs to be established (Dreves, 2022).

Potential negative impacts solar installations have on land usage apart from the solar facilities interfering with the existing land uses, consist of impacts on the soil, water and air resources. Constructing solar facilities require large areas of land being cleared and in some examples graded resulting in soil compaction and potential alteration of drainage channels, increased runoff and erosion. Clearing large areas of land could negatively affect native vegitation and wildlife in many ways, resulting in loss of habitat, interference of rainfall and drainage. These impacts being amplified should the affected species be threatened, sensitive or endangered. Then there is also the visual impact of solar installations which are not perhaps known for being aesthetically pleasing (Solareis, 2022a).

## 2.4 Electrical grid & limitations

Aside from all the positives that come with renewable energy generation, there are several challenges and limitations that arise. The main limitation of wind- and solar power is that the sources are intermittent, but there are also grid stability challenges involved. Mainly, this is related to the low or non existent inertia in these power generation sources. Inertia is very important for the overall frequency response of the system.

Power quality issues also arise when integrating renewable energy into the electrical grid. These include frequency fluctuation, flickers, unbalanced voltage and current harmonics, and voltage variations. These challenges come from switching components used in power electronics devices which are now important parts of renewable energy systems (Basit et al., 2020).

### 2.4.1 Grid connection

Grid connections are what electrically tie together power plants, transmission grids and distribution grids to homes or businesses. Without them, no electricity would be distributed. Figure 22 gives an overview of the typical electrical path from large scale generation to the consumers. Transmission grids typically transmit electricity of higher voltage and low amperage, and are usually directly connected to the power generation facilities. Distribution grids on the other hand are responsible for electrically supplying homes and businesses. When connecting a transmission grid to a distribution grid the the voltage is lowered making it better suited for short distances. This is accomplished by using step-down transformers along with other equipment. Distribution grids are directly connected via power lines to consumers. Homes and businesses also contain a grid connection typically equipped with a step-down transformer lowering the distributed voltage suitable for residential, commercial or industrial use (Laukkonen, 2022).

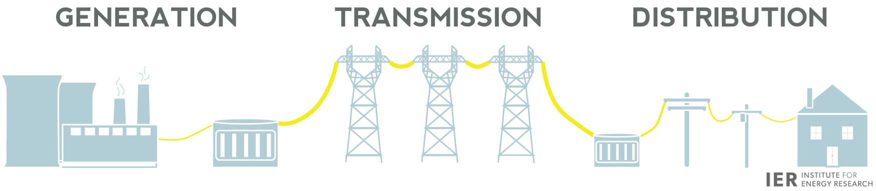


Figure 22: Visual illustration of the grid connections (IER, 2022)

### 2.4.2 Transformer

Between the different parts of the grid such as distribution, transmission and production, there is a need for transformers. Their main purpose is to convert the voltage in the different parts of the network up and down while maintaining the same power. This is accomplished by using magnetic induction between coils to convert between voltage and/or current levels (The Electricity Forum, 2022). One reason transformers are used is because with a high voltage and low current when transmitting energy, losses are minimized. Transmission losses in power lines are purely dependent on the electrical resistance over the distance and the square of the current, according to equation 7 (Cadence PCB Solutions, 2020).

$$P_{losses} = R * I^2 \tag{7}$$

Transformers consist of three main parts: a core typically in ferromagnetic iron, and two different wire coils. These coils are referred to as the primary and secondary windings. When AC is applied to the primary winding the coil induces a pulsating magnetic field. The core of the transformer then works to direct the magnetic field between the primary and secondary windings. When the field reaches the secondary coil it induces movement of electrons in the windings, creating an electric current via electromotive force. How a transformer then steps up or steps down the voltage is by adjusting the ratio of turns between the primary and secondary windings. If a transformer has 4 coils on the primary and 8 on the secondary the ratio will be 1:2 meaning the voltage doubles from the primary to the secondary coils. The same is true for the reverse case, where the voltage would be halved (Awalt, 2020). See figure 23 for a visual illustration.

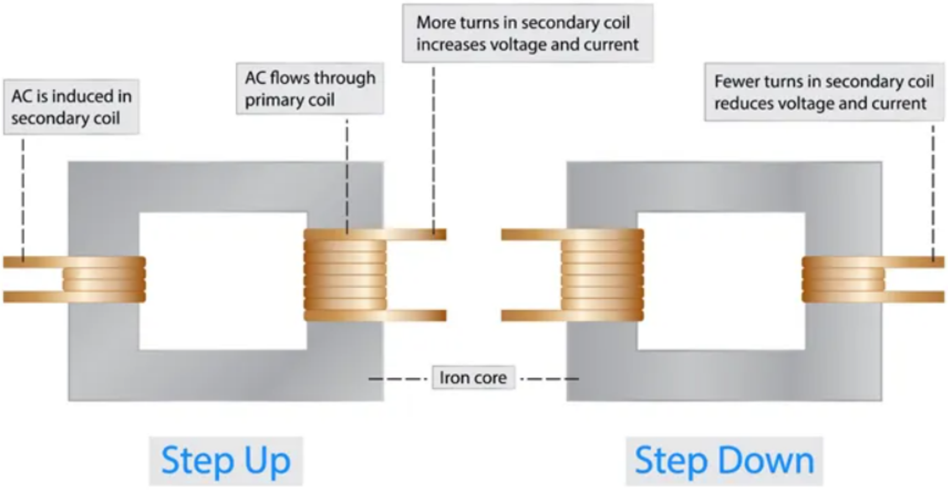


Figure 23: Visual illustration of how a transformer works (Shalom Education, 2022)

Typically, power transformers will have a 97-99% conversion efficiency and therefore it has been chosen for this report to use an assumption of 98% (Roderick, 2021). When choosing the size of a transformer for a specific power system, it is ideal to match the power rating of the transformer to the output of the system. If it is regarding a wind power plant, it might be tough to find a transformer with the same rating as the rated power of the WPP and in that case it is common to choose the closest available one, even if it might be slightly undersized (Power Engineering, 2011). When looking at solar power plants it is most effective to size the transformer with a 1:1 ratio to the solar inverter, and not the solar panel array. This is because it is common to oversize the solar array to the inverter which means the inverter controls the power output.

### 2.4.3 Switchgear

Switchgear is a broad term that describes a variety of switching devices that all fulfill a common purpose: to protect, isolate and control power systems. Since electrical components are designed to handle a limited amount of current and will overheat and damage if too much passes through, switchgears are used to protect this equipment. In the event of an electical surge, a protection system will open a circuit breaker, interrupting the flow of power and protecting the electrical systems. They can also be used for de-energizing equipment for maintenance and testing (ASCO Power Technologies, 2022).

Often times the turbines in a wind power plant will be connected together in a common transformer. In the specific case of Anneberg, the three wind turbines have transformers internally that convert the voltage from 0.69 up to 24 kV. Here the 24 kV lines from the turbines are connected to switchgear that is used for protection and control of power supply. Figure 24 shows the way the wind turbines in the Anneberg WPP on the top are connected to the switchgear on the bottom.

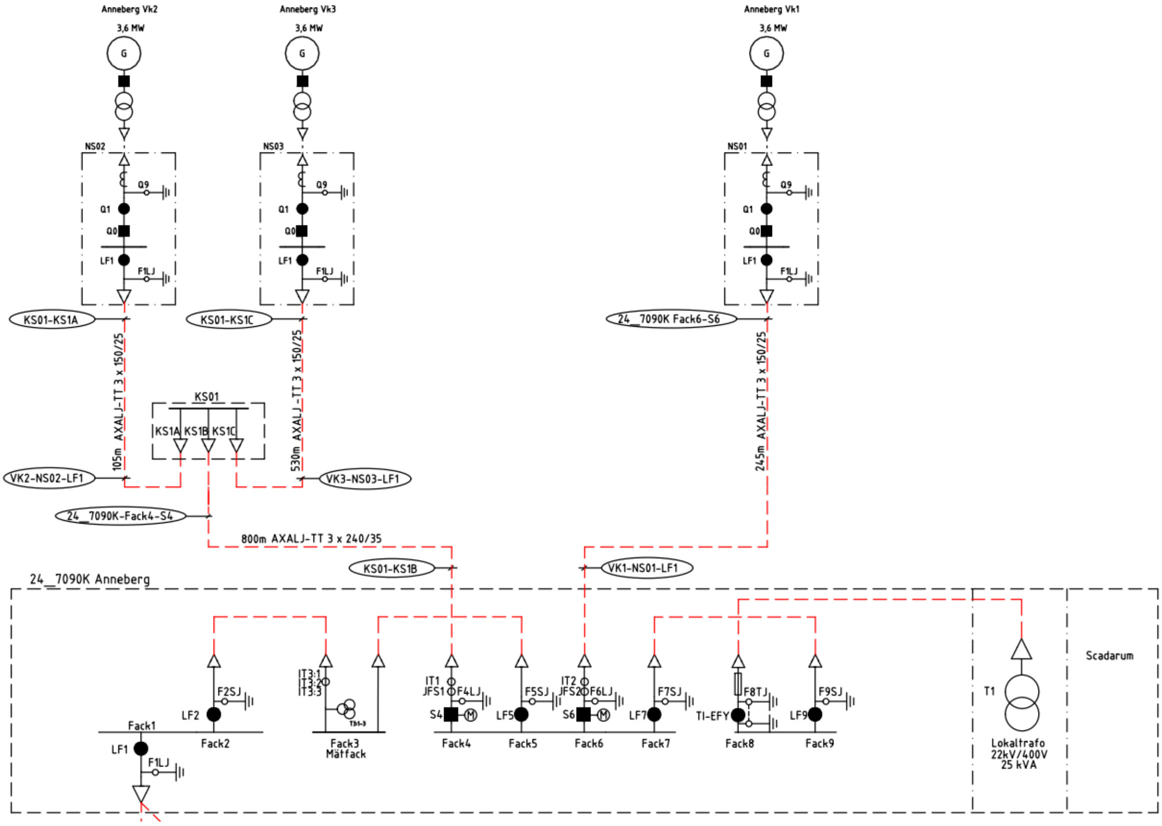


Figure 24: Electrical diagram of the Anneberg WPP. The circles on the top are the wind turbines, and the switchgear is within the markings on the bottom.

## 2.5 Hybrid power generation

When the word hybrid is mentioned it is not obvious exactly what that means and what it could entail. In this study there is a focus on an existing wind power plant where a solar power facility is built in the same general area and using the same grid connection as the wind power plant. As has been mentioned, each wind turbine contains a transformer internally so there is no common transformer for the WPP. The voltage that the switchgear is connected to is 24 kV which is a medium voltage, meaning it is for local distribution. It is common for larger WPP's to have an internal grid that feeds to a large transformer which will step up the voltage so that the electricity can travel farther with less losses. This transformer might be connected to the regional grid around 130 kV, or the transmission grid with an even higher voltage. Other ways of building hybrid solar and wind power plants could be to mount solar panels on the wind turbine towers to save space, or adding energy storage for when there is overproduction. The differences in building a hybrid power generation facility in the way that is studied in this report or doing it through a large scale transformer at a higher voltage would probably be quite significant in terms of costs and the technical difficulty. What it all comes down to is knowing how well solar and wind power complement each other over the course of the lifetime of the systems. Even if the cases studied here are not relevant everywhere, the results can still be useful for future projects.

It has been presented earlier on what a normal capacity factor is for both wind and solar power, but what would the hybrid capacity factor look like? To get a more specific number to work with, two websites were used to estimate the yearly electricity production that they will give. Vindbrukskollen is a website where Länsstyrelsen monitors all the wind power plants in Sweden, and for Anneberg it estimates a yearly production of 37.8 GWh for the total installed power of 10.8 MW (Vindbrukskollen, 2022). Solarlab.se has a page where one can put in the postal code, installed power and tilt of the solar panels and it will give an estimate on the yearly solar power production. For an installed power of 10.8 MW, it estimates that the solar panels will produce roughly 10 GWh of electricity without any system losses (Solarlab, 2022). These figures will give two individual capacity factors for the systems, and how they are calculated is presented below. The capacity factor shows the correlation between the produced power and the maximum capacity multiplied by the hours in a year.

$$C_{f_{wind}} = \frac{37.8 * 10^9}{10.8 * 10^6 * 8760} = 0.4$$

$$C_{f_{solar}} = \frac{10 * 10^9}{10.8 * 10^6 * 8760} = 0.11$$

The hope of building a hybrid power generation facility is to increase the capacity factor with regards to the maximum grid connection capacity of 10.8 MW. By adding the solar power to the connection point, the existing wind power plant capacity factor of 0.4 will be increased. A rough estimate of what this figure might look like if there is the same amount of solar power as wind power is calculated below. Keep in mind that this is assuming that there is no curtailment and all the electricity is sent to the grid.

$$C_{f_{hybrid}} = \frac{(10+37.8)*10^9}{10.8*10^6*8760} = 0.51$$

In reality, this figure will probably be lower because of the internal system losses and the curtailment that has to be done when the two sources are above the maximum capacity of the grid connection point. If however either the wind or solar power produce more than what is assumed here, the total capacity factor could be higher. The fact that the capacity factor can be increased if solar and wind power are combined has to do with the negative correlation of the two sources. This is visually represented in figure 25 below (Widén, 2011).

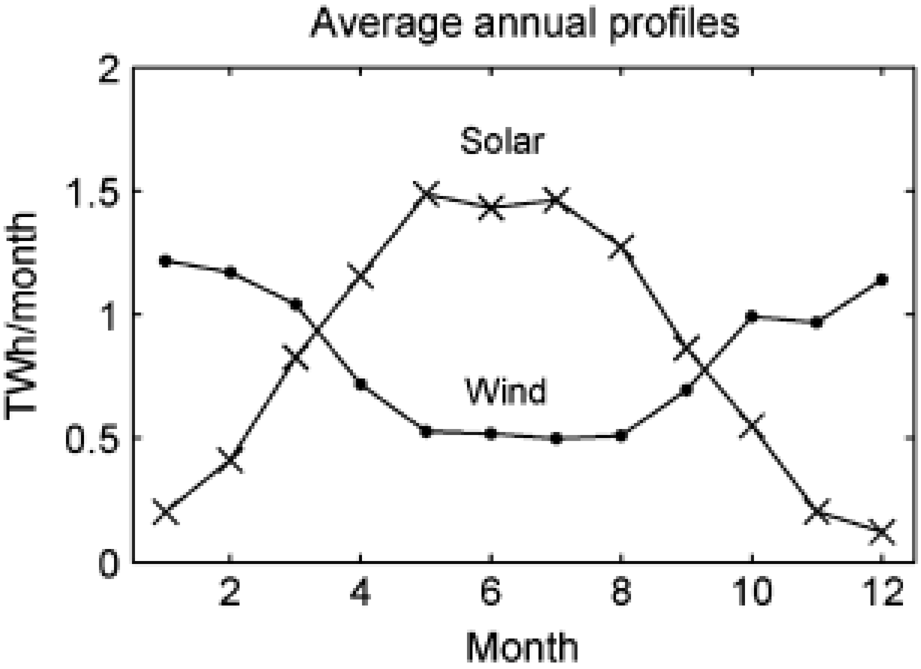


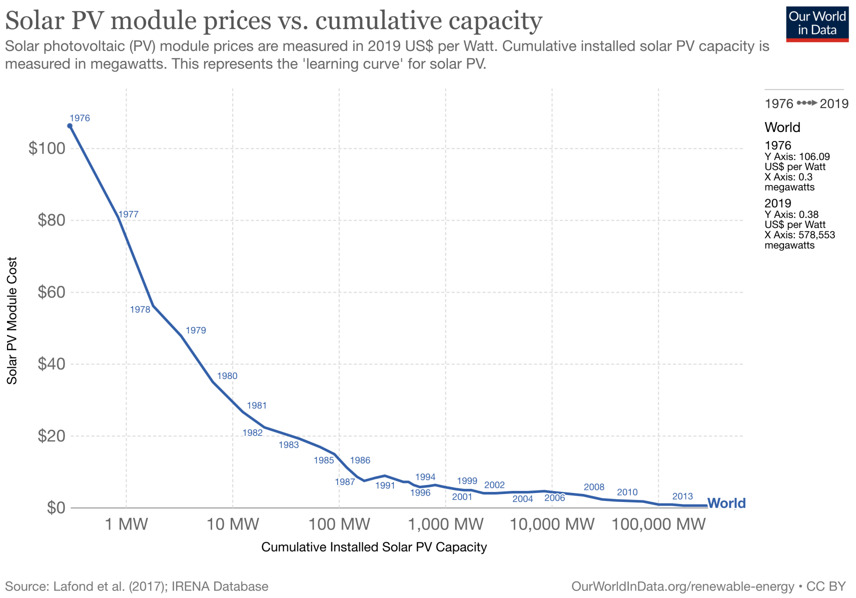
Figure 25: Visual illustration of the negative correlation between wind and solar (Widén, 2011)

# 3 Theory - Economics

This chapter introduces the development of the solar module costs and the electricity market in Sweden. The economic tools as well as the cost assumptions used for this study are also presented here. These assumptions are supported by a variety of different sources and reasoning with the collaborating partners.

## 3.1 Costs of solar modules

The global installed solar capacity has increased significantly over the last few decades, in large part due to technological advancements that have decreased the cost of such systems. Figure 26 plots the cumulative installed solar PV capacity in relation to the solar PV module costs from 1976-2019. The world's installed solar PV capacity has expanded tremendously, although this is largely because solar module prices have dropped so dramatically. Even just looking back at the price development from 2010-2019, shown in figure 27, the solar PV module price has reduced significantly.



Solar PV module prices vs. cumulative capacity

Solar photovoltaic (PV) module prices are measured in 2019 US$ per Watt. Cumulative installed solar PV capacity is measured in megawatts. This represents the 'learning curve' for solar PV.

Source: Lafond et al. (2017); IRENA Database

OurWorldInData.org/renewable-energy • CC BY

Figure 26: Historic solar PV module prices vs cumulative capacity from 1976-2019 (Our World in Data, 2022)

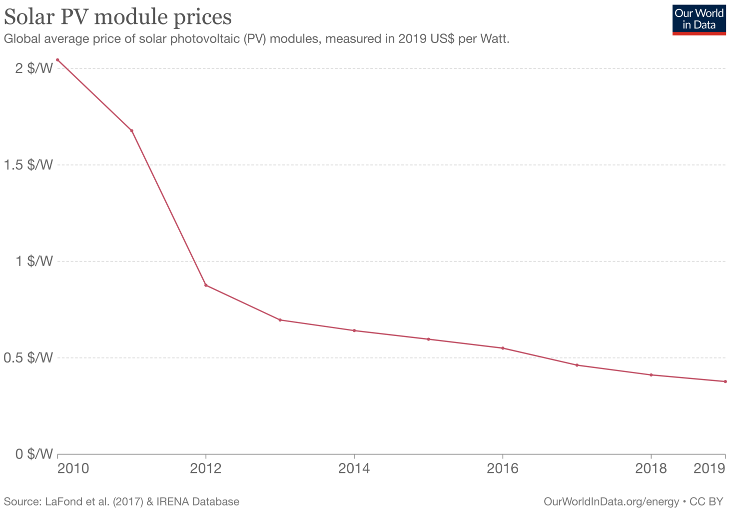


Figure 27: Historic solar PV module prices from 2010-2019 (Our World in Data, 2022)

Solar is often the cheapest power source with expert analyst projecting the costs to continue to decrease over the years. However with an increasing demand for solar power, the costs of core materials needed for solar installations have now risen as illustrated in figure 28. Not so dramatic that developers are put off from investing in solar power but it has halted the rapid decrease of the solar module costs.

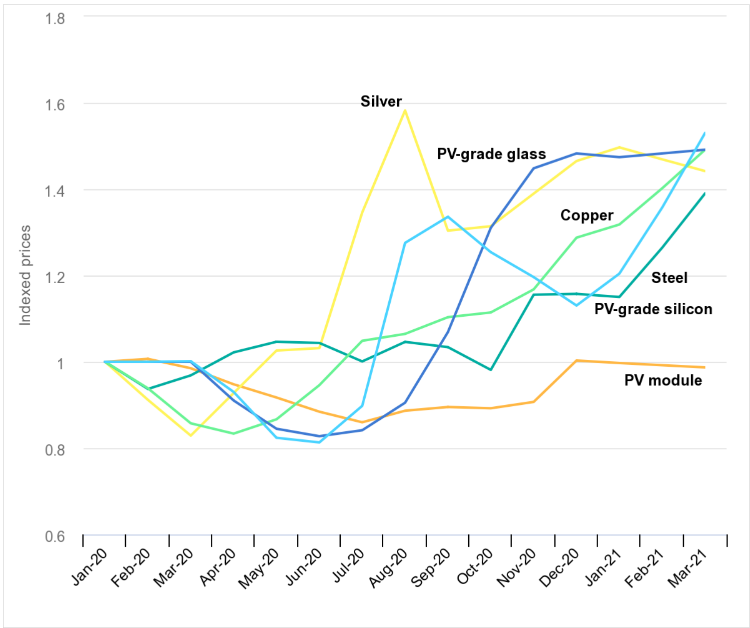


Figure 28: Raw Materials Tendencies for PV Sector Jan 2020 – March 2021 (IEA , 2022)

## 3.2 Swedish electricity market

The Swedish electricity trade has been deregulated since 1996. This has created competition with approximately 120 electricity suppliers competing for customers. All the electricity in Sweden is distributed in a common electricity network run by Svenska Kraftnät, a state owned authority (Energimarknadsinpektionen, 2021). Svenska Kraftnät is the transmission system operator (TSO) responsible for the system as a whole, and also responsible for ensuring that Sweden's transmission of electricity is safe, environmentally sound and cost effective. Regional distribution grids are run by other distribution system operators (Svenska Kraftnät, 2022a).

The Nordic power market Nord Pool is an electricity market, owned by Svenska Kraftnät and their fellow Nordic and Baltic counterparts, where players can buy and sell electricity in a spot market. This is a market where the price for electricity, the spot price, shifts hourly determined by the electric supply and demand (Svenska Kraftnät, 2022b). The hourly shifts in spot prices for SE3 during a day are shown in figures 29-32, each representing a different season of the year. This highlights the volatility of the spot market. The spot price is comprised of the electricity costs energy suppliers need to pay when purchasing electricity. Additional tariffs, tax and VAT are later included in the cost for the final consumers. Looking back at section 1.5, figure 1 shows how Sweden is divided into four electricity price areas, each with a spot price set by Nord Pool based on the region's supply and demand for electricity (Elen, 2022). Figure 33 shows sector 3's, SE3, monthly average spot price from 2019 and onward. The figure shows that the spot prices have risen rapidly from mid 2021 with the average spot price in December 2021 nearly four times higher than the previous year. The spot price has continued to increase in 2022 reaching record heights. For context, figure 34, shows SE3's spot prices 2015-2018. The graph demonstrates that spot prices were consistent over a period of years, showing similar values for 2019 and 2020. There are several reasons for this sudden increase, such as rising gas prices in Europe caused by geopolitical conflicts, but also transmission constraints and unavailability of wind-, water- and nuclear power. The Swedish electricity prices are also affected by neighboring countries electricity prices since they are involved in a common European electricity market. One of the biggest reasons for the large day to day variations in prices is the intermittency of wind power. When large amounts of wind power is produced, prices are lower and vice versa (Energimarknadsinspektionen, 2022). Several organisations predict that the prices will continue to increase and have bigger fluctuations, especially with the increasing development of intermittent renewable energies (Konsumenternas Energimarknadsbyrå, 2022).

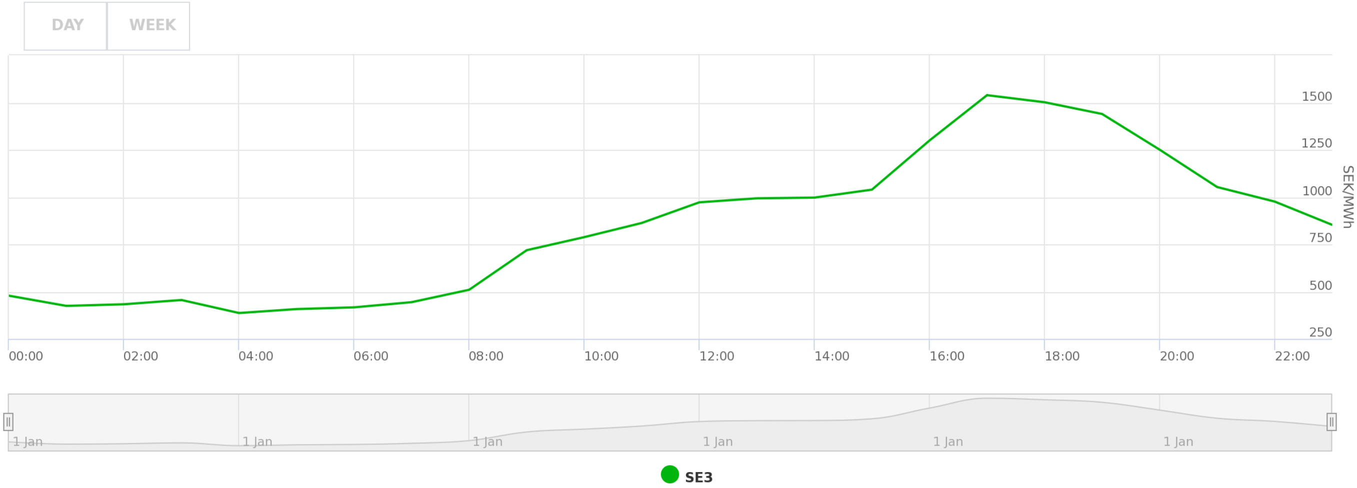


Figure 29: Hourly variation in spot price January 1 2022 (Nordpool, 2023)

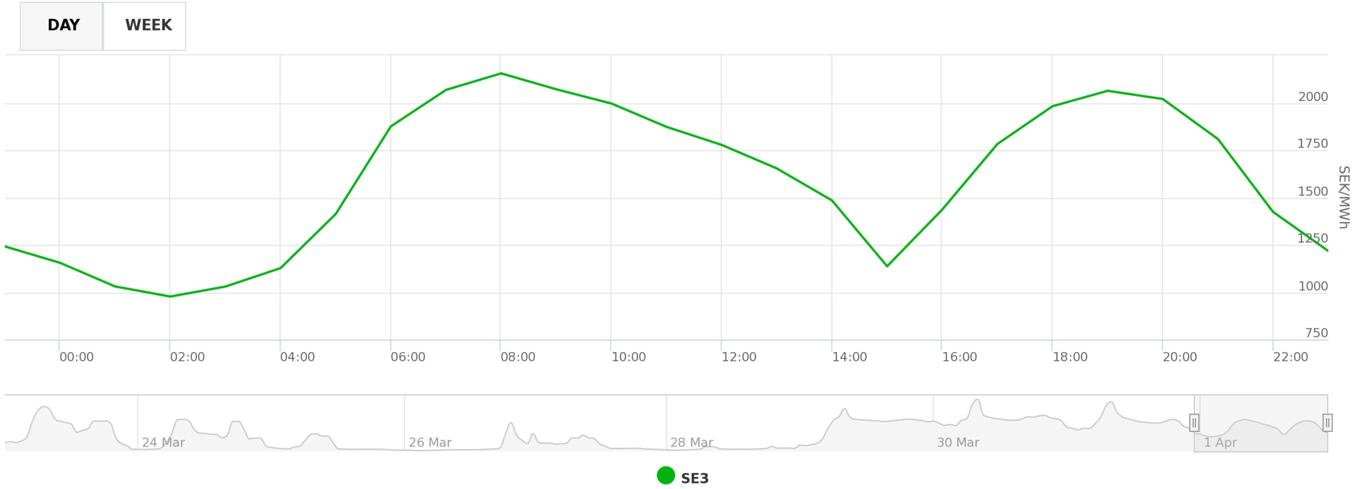


Figure 30: Hourly variation in spot price April 1 2022 (Nordpool, 2023)

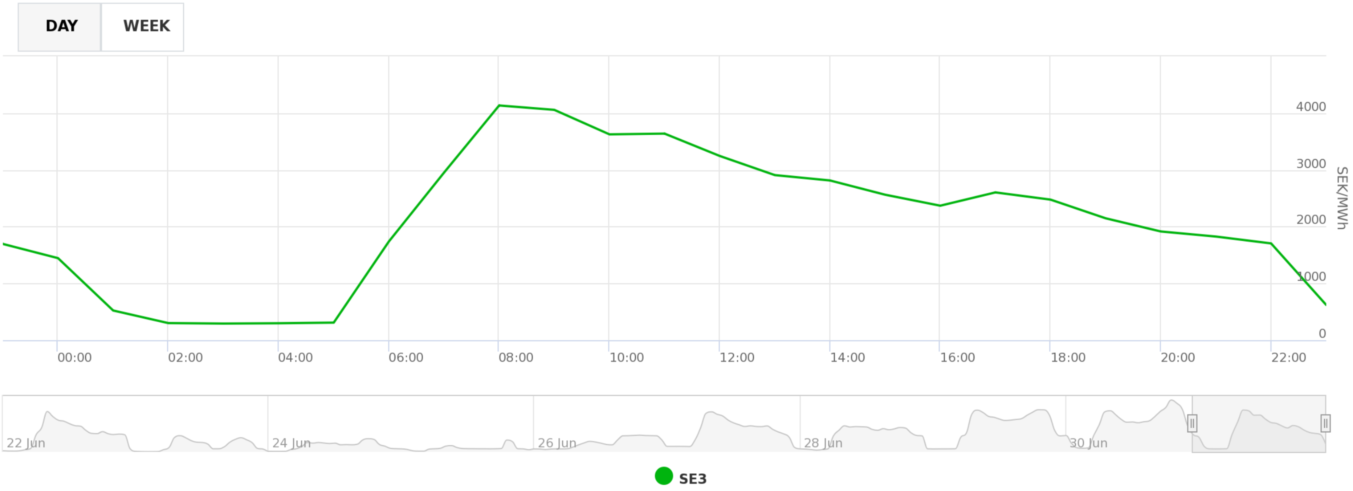


Figure 31: Hourly variation in spot price July 1 2022 (Nordpool, 2023)

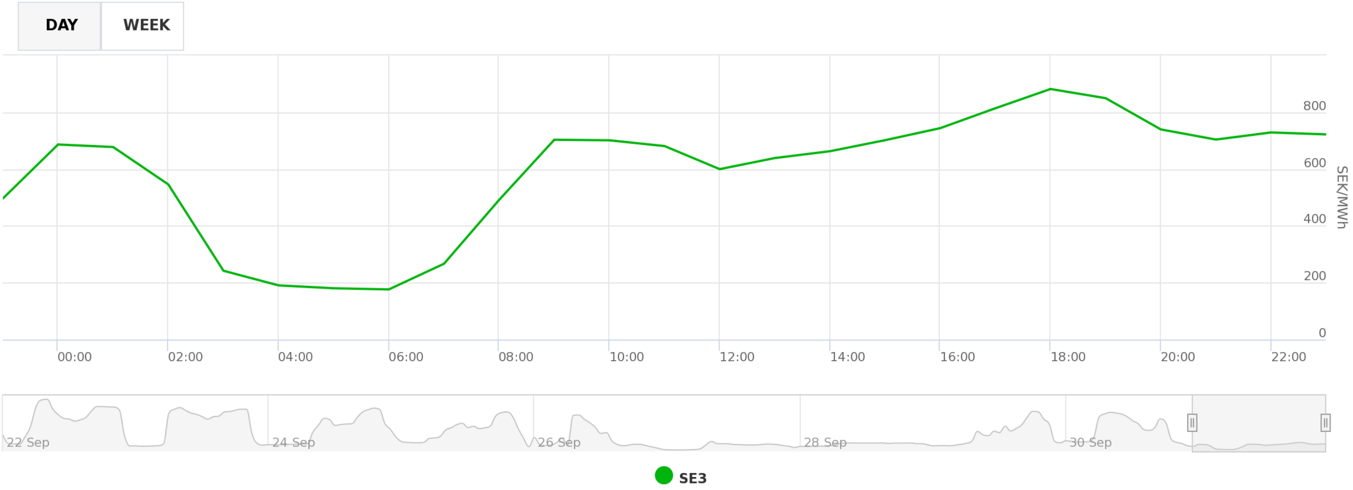


Figure 32: Hourly variation in spot price October 1 2022 (Nordpool, 2023)

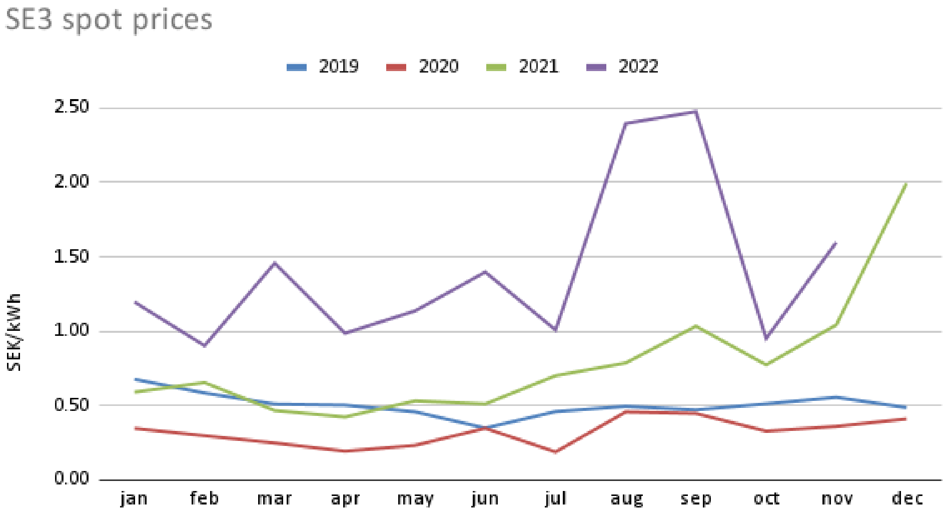


Figure 33: SE3's spot prices 2019-2022 (Vattenfall, 2022)

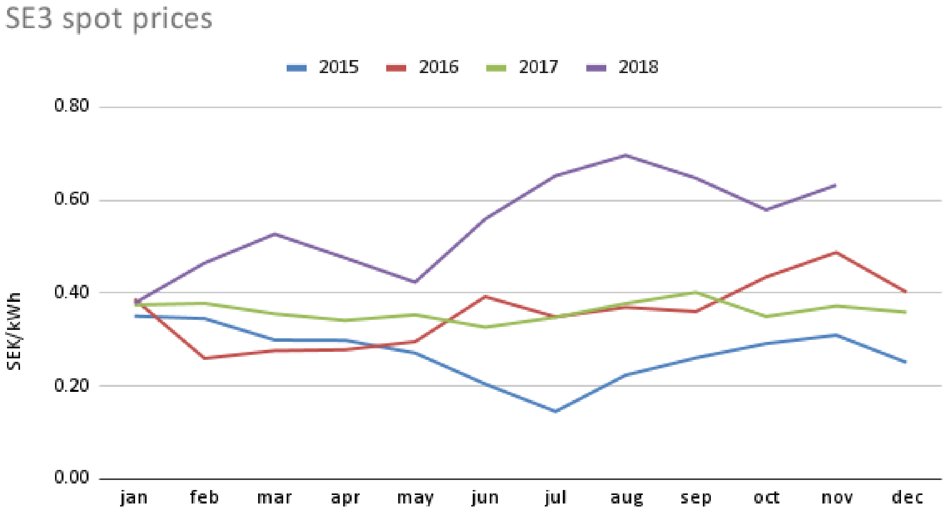


Figure 34: SE3's spot prices 2015-2018 (Vattenfall, 2022)

## 3.3 Economic tools & Assumptions

This section describes the economic tools and the costs assumptions used in this paper.

### 3.3.1 NPV, Net present value

Net present value is the difference in the present value of cash inflows and the present value of cash outflows over a period of time. The value is used in investment planning to estimate profitability of projects or investments. It finds the current value of a future stream of payments and can be calculated using equation 8.

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+i)^t} - C_0 \tag{8}$$

Where:

- $C_t$ = Net cash flow during the time period t
- $C_0$ = Total initial investment costs
- i = Discount rate
- t = The number of time periods

NPV takes into account the time value of money and it can be used to compare the rates of return for different projects. The time value is represented in the formula by the discount rate, which might be the minimum rate of return for a project based on a company's cost of capital. A negative NPV will show that the expected rate of return will fall short of the discount rate, meaning that the investment or project will not be profitable.

There are a few cons of using NPV for financial analysis though. One of the biggest issues is that it relies heavily on estimates and long term projections. This is related to the discount rate which is chosen and also the projected income over a long period of time. The NPV formula also does not evaluate a projects return on investment, which is a key figure for determining if the project is an efficient use of an investors money. What it does give though, is a number which is fairly easy to interpret which makes it a good baseline for investment decision making (Fernando, 2022a).

### 3.3.2 IRR, Internal rate of return

Internal rate of return, or IRR, is a metric used to estimate the profitability of an investment. IRR is the discount rate which makes the net present value (NPV) of all cash flows equal to zero. The calculation of this value relies on the same formula as NPV and it is the annual return that gives an

NPV equal to zero. The formula is represented in equation 9 which is the same as equation 8 but here you solve for IRR instead.

$$0 = NPV = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{9}$$

Where:

- $C_t$ = Net cash flow during the time period t
- $C_0$ = Total initial investment costs
- IRR = Internal rate of return
- t = The number of time periods

In general, the higher the IRR value, the more desirable the investment is. One can think of the metric as the rate of growth an investment is expected to generate annually. Normally an investment will not generate the same return every year, so the actual rate of return will most likely differ from the calculated IRR (Fernando, 2022b).

### 3.3.3 Assumptions on costs

With solar costs falling every year, it is difficult to make an exact estimate on what a solar generation system will cost. All estimates that are available on the internet are based on different markets and different sizes of installations. Assumptions had to be made nonetheless, and the costs that will be used in the economics analysis are presented below:

- Total solar capital expenditures: $693/kWp –> 6 SEK/Wp [1] (IRENA, 2022)
- Total solar operating expenditures: $9-10/kW/year –> 100 SEK/kW/year (IRENA, 2022)
- Total cost for bifacial panels: 10% increase –> 6.6 SEK/Wp (Deegesolar, 2022)
- Total cost for solar tracking system: 10% increase –> 6.6 SEK/Wp (Mechatron, 2022)
- Grid connection cost: 15% of total capital expenditures: 0.9 SEK/Wp (Eolus)
- Update of switchgear: 25% of grid connection cost: 0.225 SEK/Wp (Eolus)

In the total solar capital expenditures, the total costs for the installation, modules and grid connection are included. Furthermore, the grid connection costs are assumed to be 15% of this based on conversations with people at Eolus. In the total operating expenditures, all operating costs and replacement costs for inverters and other components are included.

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[1] With regards to the total solar capital expenditures, it is assumed that they have dropped and will continue to drop going forward based on information from a field trip the authors made to a local solar power plant. This is the reason for the assumption that it is 6 and not 7 SEK/Wp.

# 4 Methodology

A number of different cases were considered in the simulations that were carried out. The first analysis was done on the different tilt configurations that were presented in section 2.3. The goal of this was to find the most financially viable installation method to use in the hybrid system design. The results from this part were then used to simulate hybrid power generation systems of different ratios and in turn an economical analysis was done on these systems.

## 4.1 Simulation programs

Two simulation programs were used in carrying out this study, System Advisor Model (SAM) and HOMER Pro. SAM is useful when doing a more technical and detailed analysis of a solar power plant design, while HOMER Pro is more ideal when designing and analysing a hybrid power generation system. SAM was therefore used for the analysis of the optimal installation method and set up of the solar panels and the results from these were used in combination with HOMER to find the optimal design of the hybrid wind and solar power plant.

HOMER Pro and SAM allows analysis of values with various sizes of time steps. For consistency it was chosen to use hourly values for all inputs because it is the most common format for different data types. The data sets that were used as inputs for the simulations include ambient temperature measurements, global horizontal radiation, power prices and hourly averages of wind power production.

## 4.2 Data collection

For the simulations it was important to use consistent input data so that the right relationship between all the parameters for each year is represented. Firstly, the global horizontal irradiation (GHI) was needed. SAM and HOMER take different formats of inputs which meant using two different sources for this. In the SAM simulations, the weather data was retrieved from the National Solar Radiation Database by NREL. This database only had data up until 2019 which meant that this was the year to be studied for the solar panel analysis. For the HOMER simulations, the GHI was downloaded from a website that the Swedish Metereological and Hydrological Institute (SMHI) runs. It is called ”STRÅNG” and it is a model that has estimated all historical radiation data for Sweden and the Nordic countries from 1999 forward using measured data.

A key part of this study was to retrieve the hourly electricity prices for the right area of Sweden. As mentioned in section 3.2, these are called the spot prices and a company called Nord Pool handles this market. It was not possible to download this data online for free but after contacting the customer support, student access was given to their database. It was requested that none of the raw data would be published and therefore this will not be included in this report.

The final two data sets that were retrieved were the wind turbines hourly production data and the hourly temperature data. The turbines have only been running since late 2018, making the years 2019-2021 the ones to be looked at. This data was supplied by Eolus which means that it is protected and can also not be published. Not publishing this data will however not affect any understanding of the results and the conclusions of this report.

## 4.3 PV tilt configurations

PV systems can be installed at different tilts, directions, stationary mounted or implemented with a solar tracking system allowing the panels to adjust in relation to the sun's movement thus maximizing the solar production. All these factors influence a solar system's overall production, efficiency and profitability. Considering that there are countless configurations that can be used when integrating a PV system, six cases were studied and discussed. All considered cases were ground mounted solar installations using the same PV panels, the LONGi LR4-72HPH-435M, and the same installed power capacity in order to find the best suited installation method for the site's location. This solar panel has monocrystalline cells. The same inverter, Sungrow SC250KU, was used for each case with an array-to-inverter ratio 1. This is a string inverter with an efficiency of 96.5%. The optimal tilt and design was simulated using SAM which takes into account all forms of possible losses in a solar power system. The most important factor to take into account when comparing different tilts is the effect of self shading depending on the chosen row spacing. SAM does this effectively and the results concluded the system's optimal tilt for a given system design when shading is also taken in to account. Important to note is that self shading of the PV panels is the only assumed shading to occur on the panels in the simulations. In this study it is assumed that no objects, such as trees or tall building, are in proximity to the PV system causing shading of the panels. All losses were assumed to be the same for each case except for the self shading losses. For each PV case, an ideal system design was chosen under matching conditions so that an accurate and realistic comparison could be made. These conditions consisted of having a fixed GCR, which meant that the row space between the panels for each of the cases would be the same. The chosen row space was 10 m so that the land would be able to serve other purposes in excess of electricity production, for instance grazing animals.

The six PV cases in this study consist of PV system's facing; south, east/west, vertical south, vertical bifacial north/south, vertical bifacial east/west and a single axis tracking system implemented on a horizontal axis. These cases are visually illustrated in figure 35, showing the type and orientation of the panels for the different PV cases. Note that the first two cases are solar panels installed at a tilt, whereas the following three cases are installed vertically and the the last case studies a horizontal axis tracking system.

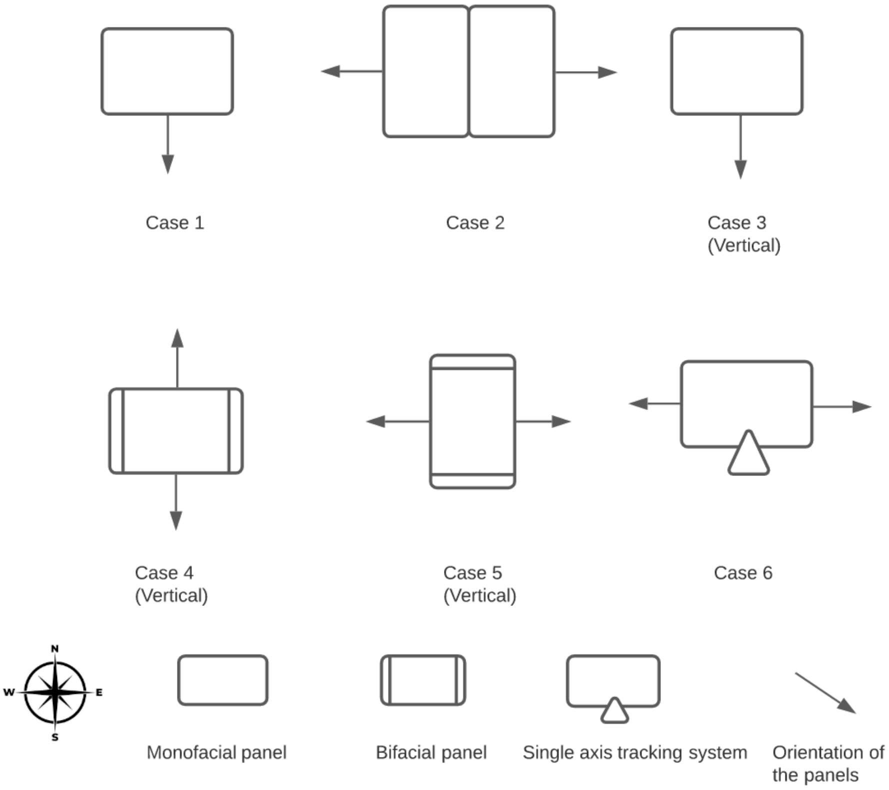

Figure 35: Visual illustration of the six PV cases with the first two cases representing monofacial panels installed at a tilt.

For each of the cases, except for the horizontal axis tracking system, two PV panels were assumed to be stacked on top of one another just as figure 36 shows. This allows more panels to be installed in a given area. However, the shading will play a greater role considering that the bigger and higher the panels are mounted, the more shading will occur. For the second case evaluating the east/west mounted panels, a minimum tilt of 15° was chosen. Flatter tilts for east/west panels produce more power but without any tilt, dust or snow would be allowed to gather thus requiring the need for maintenance. Also regarding the last case, only a horizontal axis tracking system was studied even though the theory says that a vertical axis tracking system may be more efficient considering the site's high latitude. The reasoning why the vertical axis tracking system was not looked at is due to the difficulty in finding accurate data and costs of such installations thus making it hard to accurately compare the economic profitability and performance between the cases.

Figure 36: Stacked PV panels (Linquip Team, 2021)

## 4.4 Modeling of a new solar power plant with an existing wind power plant

For these simulations HOMER Pro was used. The components library in HOMER are a few years old which meant that a different solar module had to be used here than the one in the SAM simulations. The module is the monocrystalline SunPower X21-335-BLK and it has a 21% efficiency and 335 W peak power. HOMER does not take into account shading and electrical design effects, meaning it simulates the production on one panel and multiplies it so that the rated power of the system is right. Therefore, only the efficiency of the chosen module will have an effect on the results. Since the efficiency of these modules is roughly the same as the LONGi modules used in the SAM simulations, the shading loss factors from the SAM results could be used on the HOMER results to get a realistic representation of the actual produced power. The same Sungrow inverter was used in these simulations as well.

A number of different ratios between the solar and wind production were simulated to give a better idea of how the amount of curtailed power relates to the overall profitability. The base case here was a 1:1:1 ratio between wind power, connection capacity and solar power. This process is repeated with the ratios 1:1:1.5, 1:1:1.25, 1:1:0.75 and 1:1:0.5 which gives an insight of how a higher or lower amount of installed power from PV modules will affect the overall systems profitability. The results from these ratios acted as a guideline and was the basis in an attempt to find the ideal ratio to maximize the systems efficiency and profitability. Important to note that the simulations were made on an existing wind power plant with an installed power of 10.8 MW. Hence, only the installed power of the PV system was altered considering that the wind power plant is already operational. The same applies for the maximum capacity of the connection point. The aim of integrating solar power was partly to use as much of the wind power plants existing grid infrastructure as possible, and also hopefully get a more evened out production curve from the combined system. A block diagram of the assumed system set up including where the losses occur is represented in figure 37.

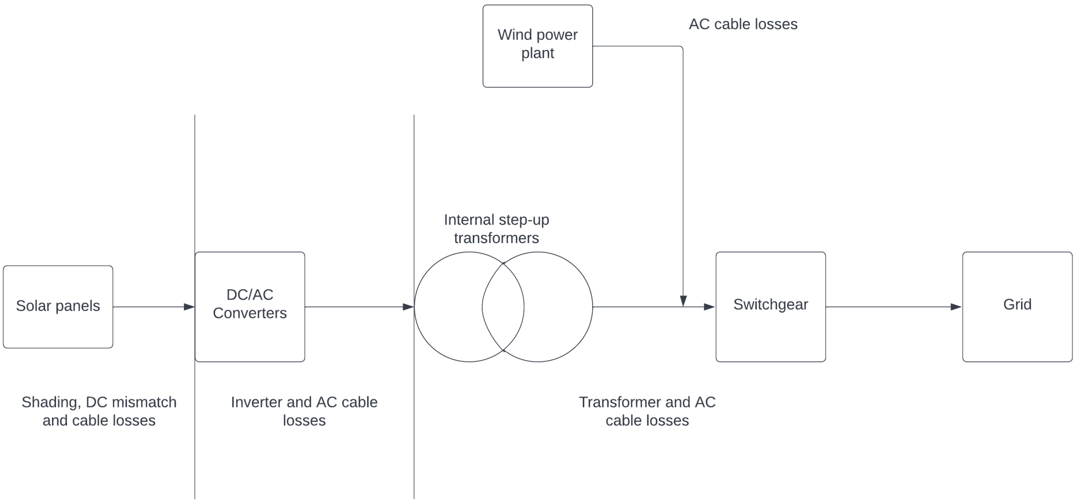

Figure 37: Block diagram of the hybrid system

## 4.5 Standalone grid connected solar

The results from the method described in the previous section needed to be compared to something. It made the most sense to do this by modeling a system that has no wind power to limit production. The same simulation results were used here but instead of using the wind to determine how much is curtailed, it is assumed that all the produced solar power is sold. A visual illustration of how this system was assumed to be connected was presented in figure 11. It is almost identical to the one in figure 37 but without the WPP.

## 4.6 Calculation of economic parameters and profitability

The main objective of this study was to make a conclusion on if it would be economically profitable to connect a large scale solar power plant to a point of connection that was already being used for a wind power plant. The limiting factor in the Anneberg case, is the maximum capacity of the connection point, or switchgear, connected to the turbines. If the capacity of the switchgear is 10.8 MW and the installed wind power is 10.8 MW, the solar power will have to be curtailed when the total wind and solar production amounts to more than 10.8 MW.

The first case to be studied was when there is an existing wind power plant, and only the costs for the solar installation and update of the switchgear are taken into account. When the results from HOMER simulations are exported they are saved into an excel sheet with hourly values for a full year. The production values for the wind and solar power were then lined up with the electricity prices and also multiplied with the loss factor for the solar power plant according to the assumed values in section 2.3.5. Before this could be done though, for every hourly value it needed to be determined if the total production was above 10.8 MW. In google sheets this could be done with an IF function where the curtailed power was saved in one column, and the sold power in another. From this, the value of the sold power and curtailed power was determined. The total income from the produced solar power minus the value of the curtailed power was then used for each ratio and year to determine the internal rate of return (IRR) and payback time of the system. An annual degradation factor of 0.5% was also assumed on the production since this is standard for solar panels. The power price varied a lot between the years 2019-2021, therefore a fourth calculation was also done when the income was assumed to be the average of these three years.

The second case, which the first case was to be compared with, was if a solar power plant of a certain size would be installed from scratch without any wind power. The difference in the economic calculations here are that the full connection cost for the facility was taken into account, and also that the income was from the total produced solar power without curtailment. Since the income and all the costs were assumed to be proportional to the amount of installed solar power, the IRR and payback time was the same for all ratios but different for each year in this case. Similarly to the first case, a fourth calculation with the average income of the three years was also done here.

The IRR was calculated in google sheets using the built in function. This was done by making 30 rows, corresponding to the lifetime of the system, and for each row determining the net cash flow for that year. The IRR function then takes theses rows along with the initial capital cost and calculates the estimated IRR for the project. The payback time was calculated by determining the average net cash flow over the lifetime, and then taking the total capital cost and dividing this by the average cash flow. Worth noting is that the lifetime of the wind power was assumed to be 25 years from 2022 forwards, even though it has been in operation since 2018. This means that for the case of a hybrid system, the last five years have no curtailment due to the wind power not being present. The lifetime for the PV system was assumed to be 30 years from 2022, starting at the same time as the wind power.

# 5 Results

This section presents all the relevant results that were gathered from the simulations that were conducted.

## 5.1 Solar panel tilt & GCR configurations

In this chapter, the six different PV cases shown in figure 35 will be studied and compared using the same PV panels and array-to-inverter ratio. This helps to determine the best suited installation method for the site's location from an electricity production and economic standpoint. Several factors are considered when comparing these PV cases, the losses are assumed to be the same for each case except for the self shading losses. The electricity production and shading losses were simulated in SAM, using Anneberg's coordinates and 2019's weather data with the intention to give an accurate representation of the financial and power producing viability of the site. This chapter also highlights how the GCR and tilts of the panels affect a systems overall electricity production for the different PV cases.

### 5.1.1 South oriented PV panels

Figure 38 shows the tilt which produces the most electricity for a 1 MW south facing solar park of which no shading losses occur. The figure shows that for Anneberg's location and no shading losses, a 40° tilt is desirable. However, should the shading losses for the same system now be taken in to account, the tilt of which produces the most annual electricity varies depending on the choice of GCR. This is depicted in figure 39 with table 2 describing the row space for each GCR.

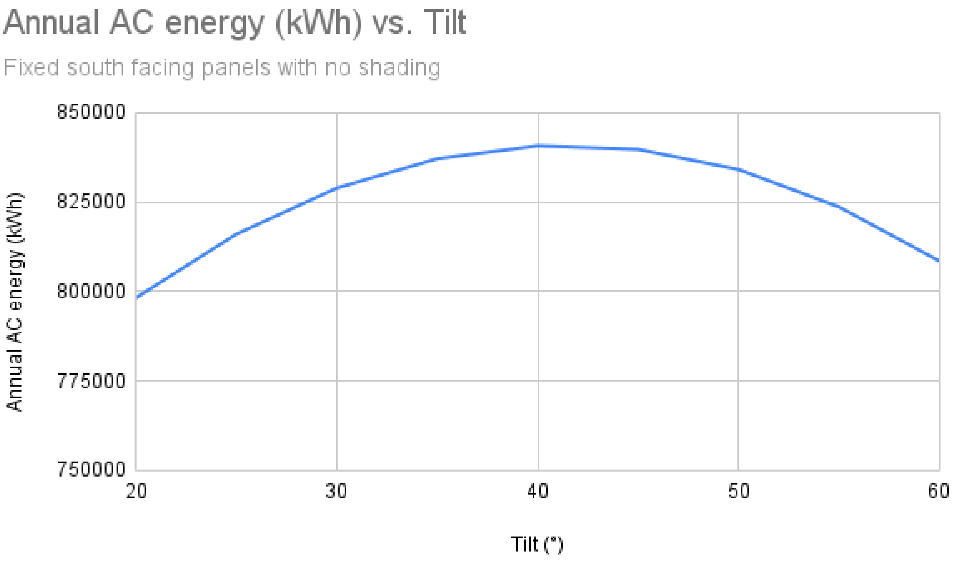

Figure 38: Optimal tilt without any shading

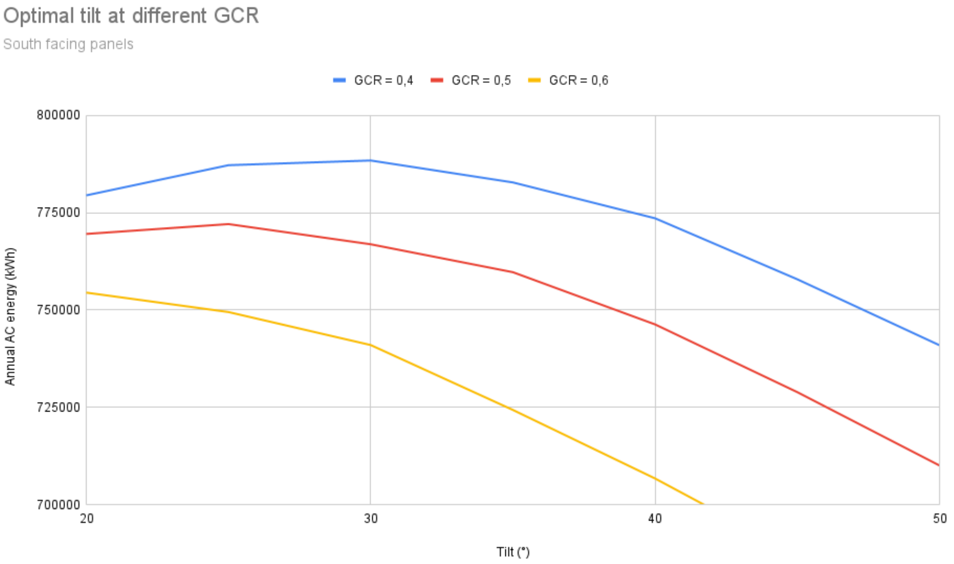

Figure 39: Optimal tilt for south facing panels at different GCR

| GCR | Row spacing (m) |
|---|---|
| 0.2 | 18.984 |
| 0.3 | 12.656 |
| 0.4 | 9.492 |
| 0.5 | 7.594 |
| 0.6 | 6.328 |
| 0.7 | 5.424 |
| 0.8 | 4.746 |
| 0.9 | 4.219 |

Table 2: Table showing the correlation between row space and GCR

Looking at figure 39, a few interesting tilt and GCR combinations can be found. The first and most power efficient installation method is installing the system with a 0.4 GCR and a 30° tilt. The other two being when installing a system with 25° tilt and the GCR 0.5 or 20° tilt with a GCR of 0.6. Table 3 compares these cases based on their land usage needs and power outputs, but also the PV selfshading losses and how much potential extra power capacity could be installed using the same area should the chosen GCR and tilt for the installation be different. This does not demonstrate how profitable the systems are, but it does emphasize the potential for using less space while having a greater installed power and producing more electricity.

| GCR & Optimal tilt | Installed Power (MW) | Shading loss (%) | Expected land usage (ha) | Land usage difference (%) | Energy output (kWh) | Energy output difference (%) |
|---|---|---|---|---|---|---|
| 0.4 & 30° | 1.005 | 2.62 | 1.244 | 0 | 788 426 | 0 |
| 0.5 & 25° | 1.005 | 2.43 | 1.001 | -19.53 | 772 084 | -2.07 |
| 0.5 & 25° | 1.218 | 2.43 | 1.214 | -2.47 | 937 177 | +15.87 |
| 0.6 & 20° | 1.005 | 2.15 | 0.838 | -32.64 | 754 437 | -4.31 |
| 0.6 & 20° | 1.523 | 2.15 | 1.257 | +1.05 | 1 120 508 | +42.12 |

Table 3: Table comparing south facing panels at different GCR and tilts

### 5.1.2 East/west mounted PV panels

Figure 40 shows the annual electricity production for different tilts at different GCRs for the second PV case. The GCR's have the same row spacing as for the south facing panels and these can be found in table 2. The figure shows that for the lower tilts there will be an increase in the power production regardless of the choice of GCR. It does however not simulate the annual AC energy for tilts under 15° considering that 15° was chosen to be the minimum tilt for an installation in the attempt to avoid dirt to gather and cause losses.

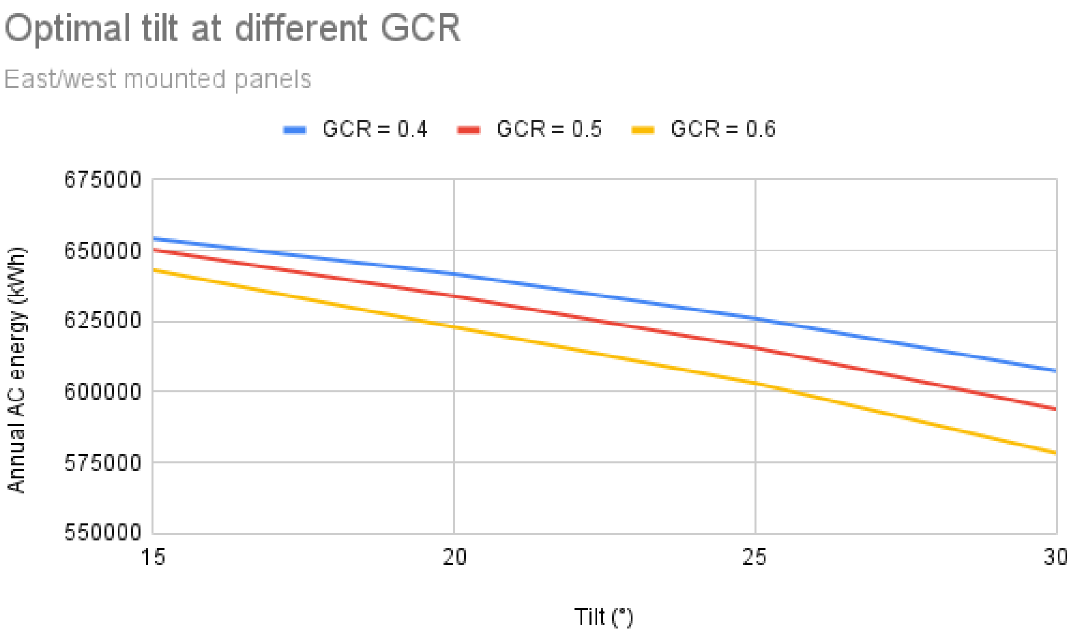

Figure 40: Optimal tilt for east/west mounted panels at different GCR

Figure 41 compares a daily solar production for an east/west mounted 1 MW PV system tilted 15° should the same system instead be facing south with a 30° tilt. It shows how there is a very slight increase in production during the peak load hours of the day for the east/west PV system. However, the overall solar power production is significantly less than for the south facing PV system.

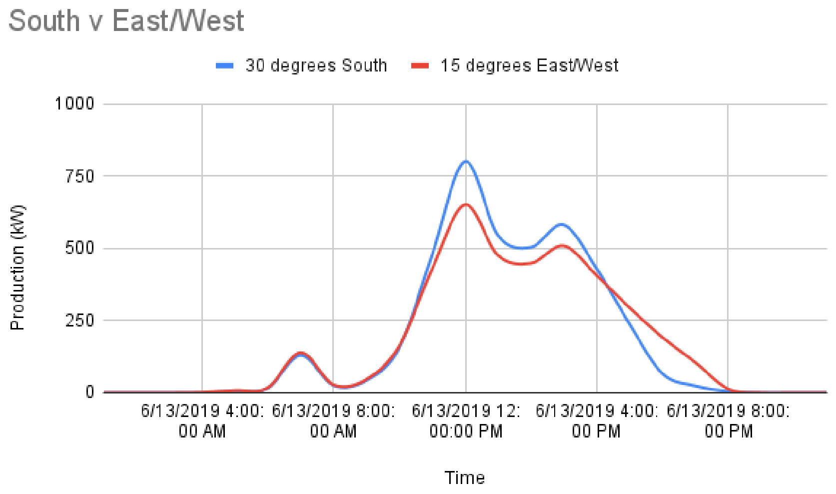

Figure 41: Production comparison between fixed south and east/west panels for June 13th 2019

### 5.1.3 Vertically mounted monofacial panels facing south

Figure 42 shows hows the GCR affects the annual production for the third PV case. The figure shows that for a monofacial south facing vertically mounted panel, the annual AC energy decreases when the GCR increases. Table 2 shows the row space between the panels for the given GCR.

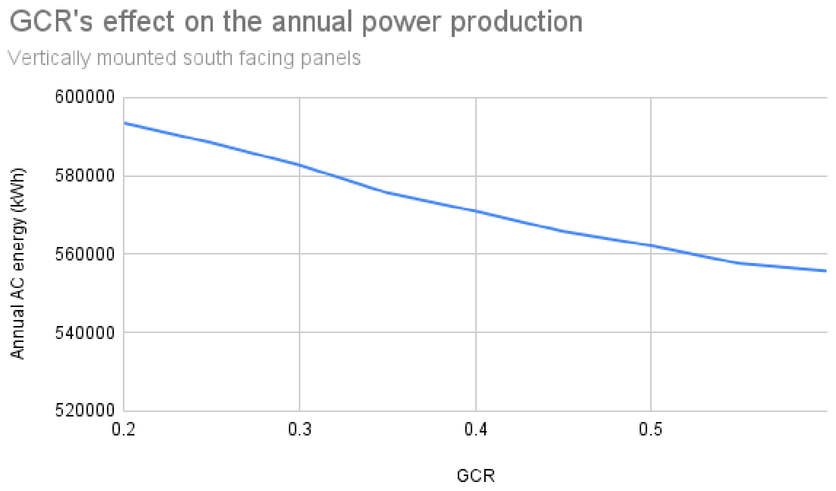

Figure 42: Figure showing the GCR’s effect on vertically mounted monofacial PV system’s annual power production

### 5.1.4 Vertically mounted north/south bifacial panels

This section shows the annual electricity production the fourth PV case. The only difference between this section and the previous section, 5.1.3, is that in this case the solar installation uses bifacial panels instead of monofacial panels. The results are displayed in figure 43 and shows how the GCR affects the annual production for a vertically mounted bifacial PV system facing north and south. A clear decrease in annual production can be seen for the increasing GCRs. Table 2 shows the row space between the panels for the given GCR.

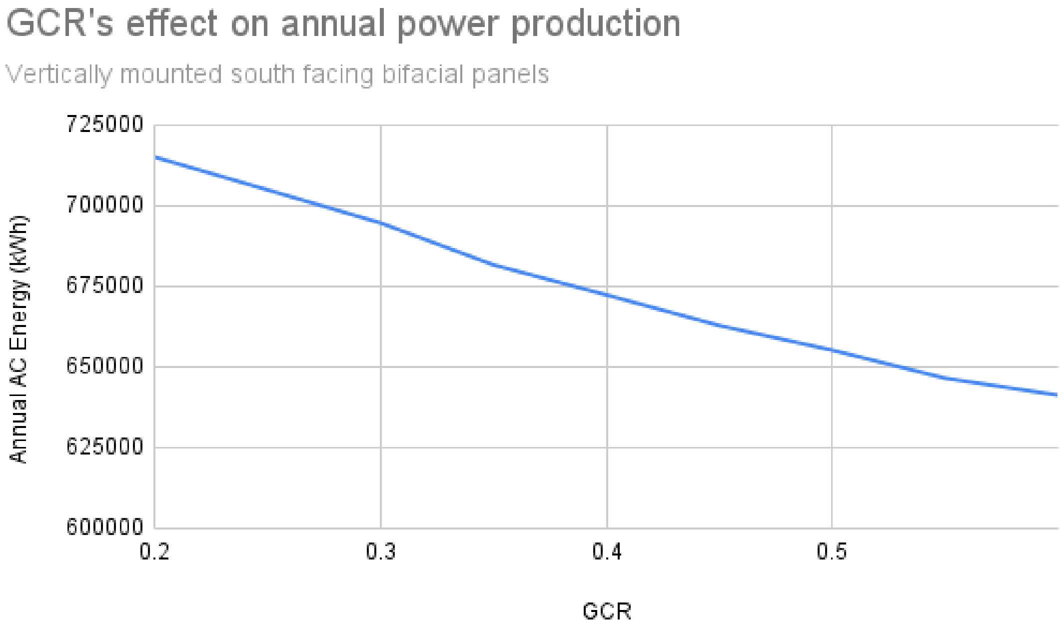

Figure 43: Figure showing the GCR's effect on vertical bifacial north/south mounted PV system's annual power production

### 5.1.5 Vertically mounted bifacial panels facing east and west

This section shows the annual electricity production for the fifth PV case. Just like the previous section, 5.1.4, this studies the use of vertically mounted bifacial panels instead facing east and west. Figure 44 shows hows the GCR affects the annual production for a vertically mounted bifacial PV system facing east and west. Just like for the previous PV case, a clear decrease in annual power production is seen for higher GCRs. Table 2 shows the row space between the panels for the given GCR.

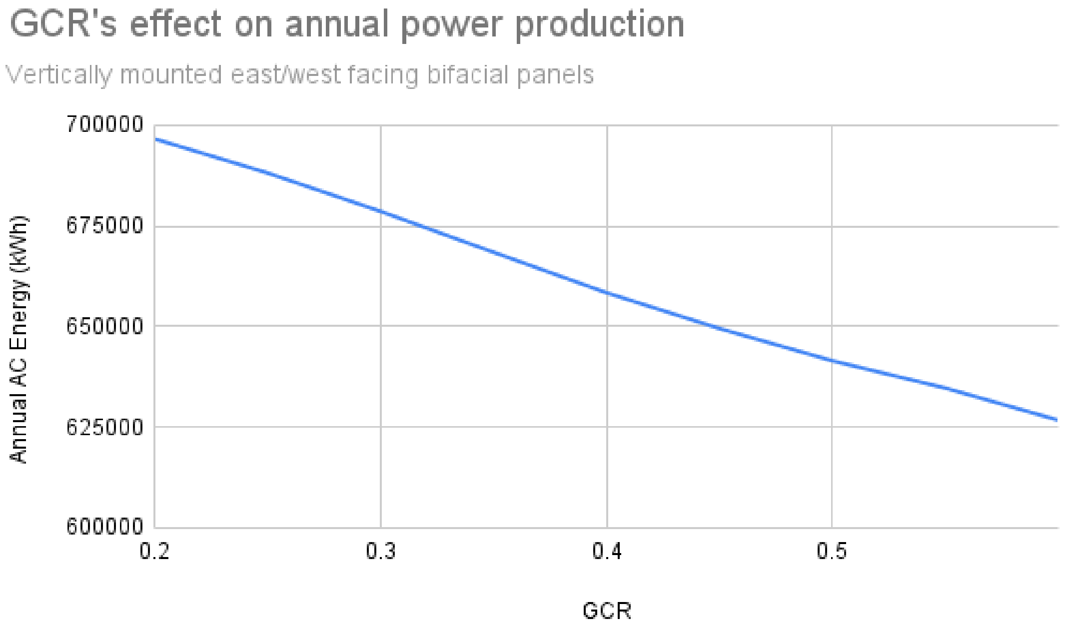

Figure 44: Figure showing the GCR's effect on vertical bifacial east/west mounted PV system's annual power production

The last three PV cases, which study vertically mounted monofacial and bifacial panels, have a similar trend when looking at the annual electricity production at different GCRs. Therefore it could be interesting to also compare these electricity yields for these three cases, which can be seen in table 4. In order for an accurate comparison to be made, a fixed GCR was set at 0.4. The reason a roughly 10 m row spacing was chosen is because it enables alternative uses of the area in between the panels, such as agriculture. The table shows an increased electricity production for the bifacial panels with the best scenario being the bifacial panels facing north and south.

| Installation method | Annual production (MWh) | Difference in electricity yield (%) |
|---:|---:|---:|
| Vertical south | 571.0 | 0 |
| Vertical bifacial north/south | 672.3 | +17.7 |
| Vertical bifacial east/west | 658.4 | +15.3 |

Table 4: Table comparing the three vertically mounted PV cases based on their annual electricity yield with a GCR of 0.4

### 5.1.6 Horizontal axis tracking system

This case studied a tracking system implemented on an horizontal axis, allowing the panel to rotate from east to west following the sun's movement. Figure 45 shows how the GCR affects the annual productivity of said system. The row spacing for the different GCR's are shown in table 5. The row spacing does not match the values of table 2 because of the fact that for this case no panels are stacked on top of another due to the difference in the installation methods. Looking back at how GCR is calculated, figure 20, considering that the length of the solar panel is now half compared to how it was for the other cases, the GCR for the same row space is then also half. A similar trend is seen in figure 45 for the annual electricity as in figures 42-44 with the production decreasing in relation to the GCR.

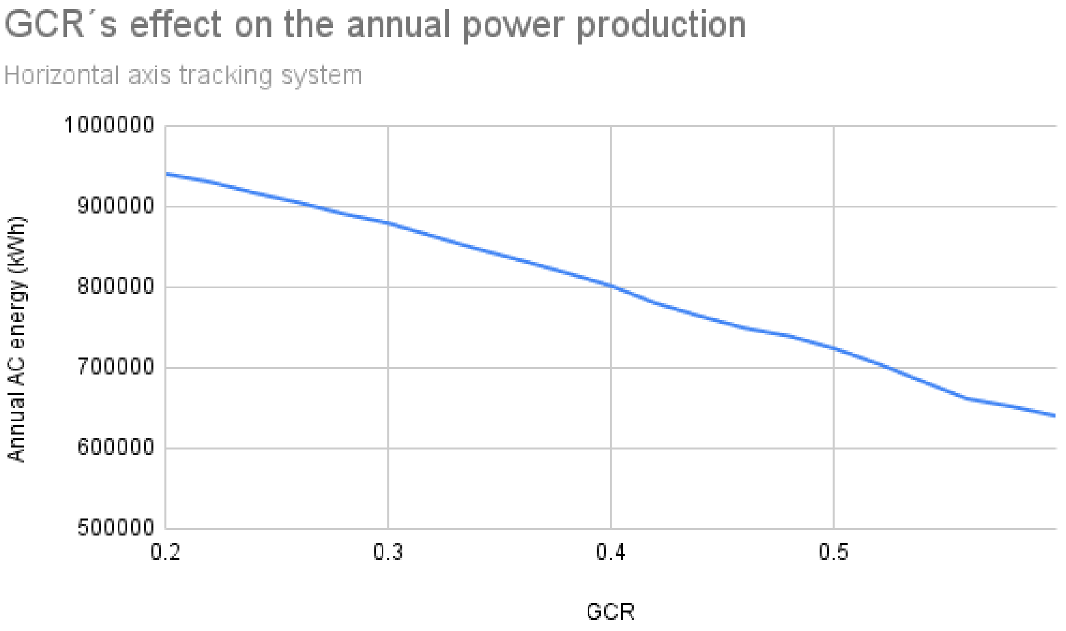

Figure 45: Figure showing how the choice of GCR affects the annual solar production for horizontal axis tracking systems

| GCR | Row spacing (m) |
|---|---|
| 0.2 | 9.492 |
| 0.3 | 6.328 |
| 0.4 | 4.746 |
| 0.5 | 3.797 |
| 0.6 | 3.164 |

Table 5: Table showing the correlation between row space and GCR for the horizontal axis tracking system

## 5.2 Comparison of the economic profitability for the different PV set ups

In order to find the best suited solar installation method for the site's location, an economic comparison for the different PV cases was assembled. Table 6 contrasts the various system designs in terms of land use efficiency, electricity output, IRR, and payback period. Keep in mind that the row space was assumed to be 10 m for each installation method. The table shows that the south facing stationary panels have the highest land use efficiency and are the most profitable, hence this was the installation method used for the subsequent hybrid simulations.

| Solar installation method | Land use efficiency (kWh/m$^2$) | Annual electricity production (kWh) | Difference in production from 30 south (%) | IRR (%) | Payback time (years) |
|---|---|---|---|---|---|
| 30 south | 63.4 | 788 426 | 0 | -0.16 | 30.7 |
| 15 east/west | 52.1 | 654 137 | -17.0 | -2.21 | 42.6 |
| Vertical south | 46.7 | 571 016 | -27.6 | -3.25 | 50.9 |
| Vertical bifacial north/south | 55.1 | 674 132 | -14.5 | -2.25 | 42.9 |
| Vertical bifacial east/west | 53.9 | 660 213 | -16.3 | -2.68 | 46.2 |
| Horizontal axis tracking | 38.2 | 940 550 | +19.3 | -2.72 | 46.7 |

Table 6: Table showing the land use efficiency, annual electricity production, IRR and payback time for 1 MW solar systems with the GCR 0.4, using 2019's weather data and spot prices

## 5.3 Results of a new solar power plant with an existing wind power plant

### 5.3.1 Simulation results

Tables 7-9 present the simulation results from HOMER Pro. Here the total produced and curtailed PV electricity and losses in terms of income with regards to sold PV electricity are shown. The far right column shows the hybrid capacity factor. Tables 10 and 11 are labeled self curtailment which means when the 1-1-1.25 and 1-1-1.5 ratios solar modules alone produce above the 10.8 MW capacity of the connection point. The values in all these tables represent what the PV systems would perform like if they were brand-new throughout their first year of operation. This means that no degradation losses have been taken in to account.

| 2019 | Produced PV (MWh) | Curtailed PV (%) | Lost PV income (%) | Hybrid $C_f$ |
|---:|---:|---:|---:|---:|
| 1-1-0.5 | 4 983.8 | 4.92 | 5.05 | 0.42 |
| 1-1-0.75 | 7 475.7 | 7.09 | 7.19 | 0.44 |
| 1-1-1 | 9 967.6 | 9.50 | 9.55 | 0.46 |
| 1-1-1.25 | 12 459.4 | 12.62 | 12.65 | 0.48 |
| 1-1-1.5 | 14 951.3 | 16.63 | 16.67 | 0.50 |

Table 7: Results for 2019 simulations

| 2020 | Produced PV (MWh) | Curtailed PV (%) | Lost PV income (%) | Hybrid $C_f$ |
|---:|---:|---:|---:|---:|
| 1-1-0.5 | 4 971.1 | 9.37 | 5.76 | 0.47 |
| 1-1-0.75 | 7 456.7 | 11.75 | 7.37 | 0.49 |
| 1-1-1 | 9 942.2 | 14.29 | 9.17 | 0.51 |
| 1-1-1.25 | 12 427.8 | 17.16 | 11.46 | 0.53 |
| 1-1-1.5 | 14 913.4 | 20.79 | 14.91 | 0.55 |

Table 8: Results for 2020 simulations

| 2021 | Produced PV (MWh) | Curtailed PV (%) | Lost PV income (%) | Hybrid $C_f$ |
|---:|---:|---:|---:|---:|
| 1-1-0.5 | 4 914.8 | 6.09 | 4.09 | 0.42 |
| 1-1-0.75 | 7 372.3 | 8.02 | 5.53 | 0.44 |
| 1-1-1 | 9 829.7 | 9.99 | 7.00 | 0.46 |
| 1-1-1.25 | 12 287.1 | 12.36 | 8.91 | 0.48 |
| 1-1-1.5 | 14 744.5 | 15.63 | 11.82 | 0.50 |

Table 9: Results for 2021 simulations

| 1-1-1.25 | PV self curtailment (%) |
|---:|---:|
| 2019 | 0 |
| 2020 | 0.001 |
| 2021 | 0 |

Table 10: Results of the self curtailed PV from 2019-2021 with the ratio 1-1-1.25

| 1-1-1.5 | PV self curtailment (%) |
|---:|---:|
| 2019 | 0.86 |
| 2020 | 0.92 |
| 2021 | 0.76 |

Table 11: Results of the self curtailed PV from 2019-2021 with the ratio 1-1-1.5

Looking at the results above, there are a few patterns that were expected. In tables 7-9 we can see that with more installed solar power and unchanged connection capacity, there will be a higher percentage of curtailed power which in turn leads to loss of potential income. The simulations on the years 2019-2021 had very similar results in terms of the produced solar energy. Differences in the amount of curtailed energy here comes from the variations in wind power production, where 2020 had the most. These differences can be observed in column 3 of tables 7-9. One thing that is worth noting from column 4 of tables 7 and 8 is that the lost income is higher for 2020 on the lower ratios but is then surpassed by 2019 for the higher ones. This most likely comes from the fact that the spot prices tend to be lower when wind power is being produced, which is also the only time solar power is curtailed. The exception for this is for the ratio 1-1-1.25 and 1-1-1.5 where the installed peak power of the solar exceeds the grid connection capacity. The extent of this effect is presented in tables 10 and 11, showing how much of the total produced solar energy would be curtailed by the limiting grid connection capacity if there was no wind energy involved. In these tables we also see the result that with 25% higher installed solar power than the grid connection capacity, it virtually never will produce above the limit. Even with 50% higher installed power the numbers are still very low. The fifth and final column of tables 7-9 show the hybrid capacity factors and only in 2020 did the $C_f$ manage to match the theoretical one calculated in section 2.5. As was mentioned there the figure of 0.51 was for a 1:1 ratio between solar and wind with no curtailment, so the fact that the same ratio in 2020 also had a $C_f$ of 0.51 shows that it was a good year for hybrid power production.

### 5.3.2 Economic results

Below the results from the case described in section 4.4 are presented. Tables 12-16 show the economic results that were calculated according to the process described in section 4.6. The left most column represents the assumed annual income from year 2022-2053, the second column presents the internal rate of return and the third shows the payback time.

| 1-1-0.5 | IRR (%) | Payback time (years) |
|---:|---:|---:|
| 2019 income | 1.73 | 24.3 |
| 2020 income | -2.91 | 50.2 |
| 2021 income | 6.95 | 13.3 |
| 2019-2021 average income | 2.49 | 24.7 |

Table 12: Results using the ratio 1-1-0.5

| 1-1-0.75 | IRR (%) | Payback time (years) |
|---:|---:|---:|
| 2019 income | 1.52 | 25.0 |
| 2020 income | -3.06 | 51.6 |
| 2021 income | 6.77 | 13.5 |
| 2019-2021 average income | 2.32 | 25.2 |

Table 13: Results using the ratio 1-1-0.75

| 1-1-1 | IRR (%) | Payback time (years) |
|---:|---:|---:|
| 2019 income | 1.29 | 25.8 |
| 2020 income | -3.22 | 53.3 |
| 2021 income | 6.58 | 13.7 |
| 2019-2021 average income | 2.13 | 25.8 |

Table 14: Results using the ratio 1-1-1

| 1-1-1.25 | IRR (%) | Payback time (years) |
|---:|---:|---:|
| 2019 income | 0.99 | 26.9 |
| 2020 income | -3.42 | 55.6 |
| 2021 income | 6.35 | 14.0 |
| 2019-2021 average income | 1.90 | 26.6 |

Table 15: Results using the ratio 1-1-1.25

| 1-1-1.5 | IRR (%) | Payback time (years) |
|---:|---:|---:|
| 2019 income | 0.58 | 28.5 |
| 2020 income | -3.74 | 59.4 |
| 2021 income | 5.98 | 14.4 |
| 2019-2021 average income | 1.55 | 27.9 |

Table 16: Results using the ratio 1-1-1.5

The obvious patterns that can be observed in the tables above is that with more solar power installed, the IRR decreases and the payback time increases. Based on the results in the previous section this makes sense. More installed solar results in more curtailed energy which leads to a higher loss of income. Furthermore these tables make it very clear that the electricity price during the year will have a significant impact on the profitability of the system. Even though 2021 had the lowest PV production and lower capacity factors than 2020, it still had a much higher IRR for all the simulated systems.

## 5.4 Standalone grid connected PV system

Below the results from the case in section 4.5 are presented. The left most column represents the assumed annual income from year 2022-2053, the second column presents the internal rate of return and the third shows the payback time. Since the costs were assumed to be proportional to the amount of installed solar power, the economic numbers in the table below are the same for all amounts of installed solar power.

| Standalone solar power | IRR (%) | Payback time (years) |
|---:|---:|---:|
| 2019 income | 1.33 | 25.8 |
| 2020 income | -3.10 | 51.6 |
| 2021 income | 6.23 | 14.3 |
| 2019-2021 average income | 2.02 | 26.3 |

Table 17: Results for all ratios solar power from scratch

The results in the table above are meant to be compared to the results in the previous section. Looking at the cases with the assumed income and production of 2019 and 2020, the hybrid system only looks to be more profitable if the ratio is between 1-1-0.5 and 1-1-0.75. In the case for 2021 though, the hybrid system produces a higher IRR than a standalone solar power plant for all ratios up to 1-1-1.25. Lastly, looking at the case which uses 2019-2021 average spot price, the hybrid system is more profitable than a standalone PV system for the 1-1-1 ratio but not for 1-1-1.25. The figures below use the results from tables 12-17 to compare the profitability of a standalone PV system and a PV system implemented to an existing wind power plant. The profitability, determined using IRR, is compared for all different calculated PV ratios. Four figures are presented, one for each years spot prices except for the last one as it uses the average spot price for the three years. Each figure visually illustrates at which ratio it is no longer more financially viable to connect a PV system to an existing WPP than building a standalone solar power plant.

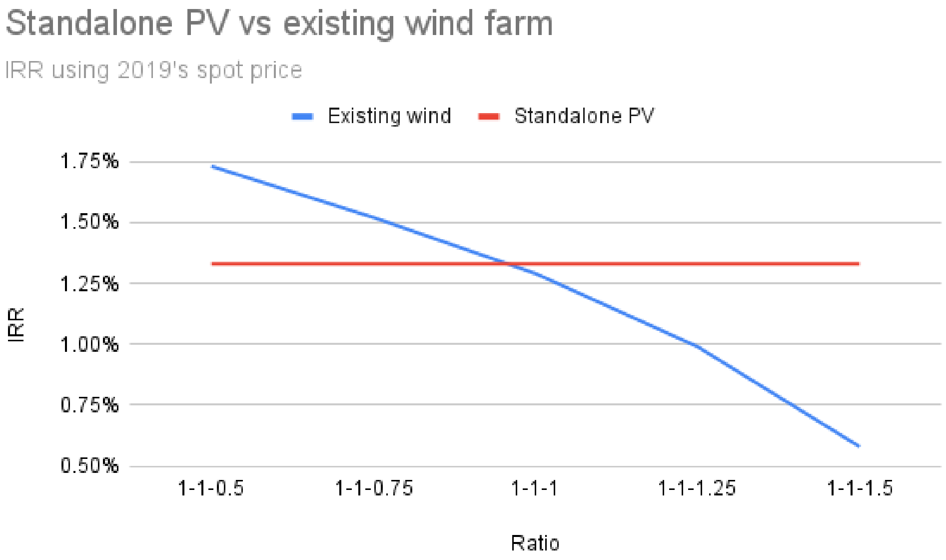

Figure 46: Profitability comparison for different ratios using 2019’s spot prices for a standalone PV system vs using existing wind farm

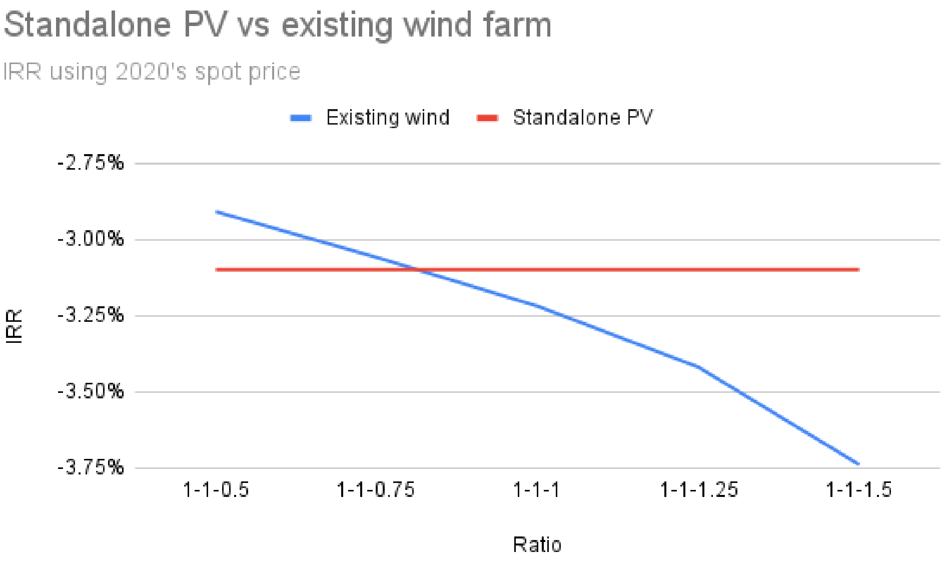

Figure 47: Profitability comparison for different ratios using 2020’s spot prices for a standalone PV system vs using existing wind power plant

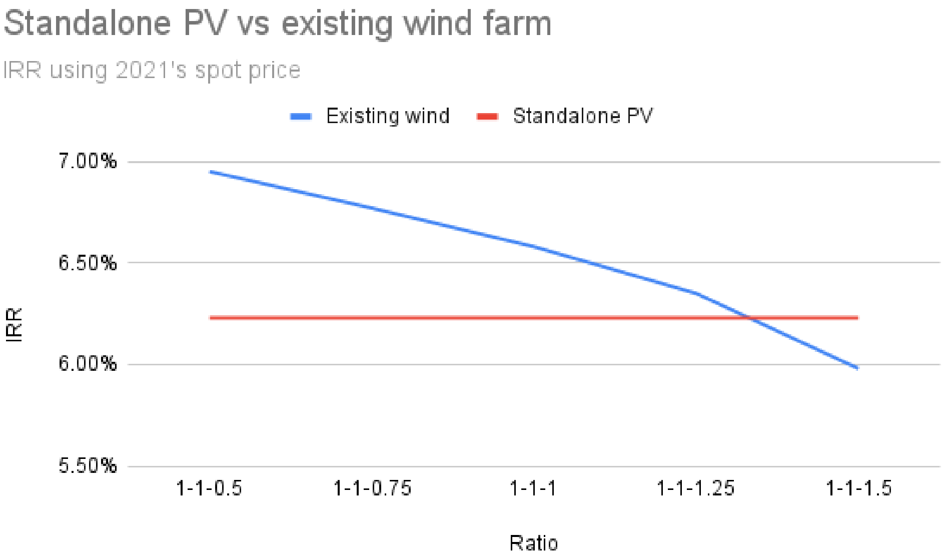

Figure 48: Profitability comparison for different ratios using 2021’s spot prices for a standalone PV system vs using existing wind power plant

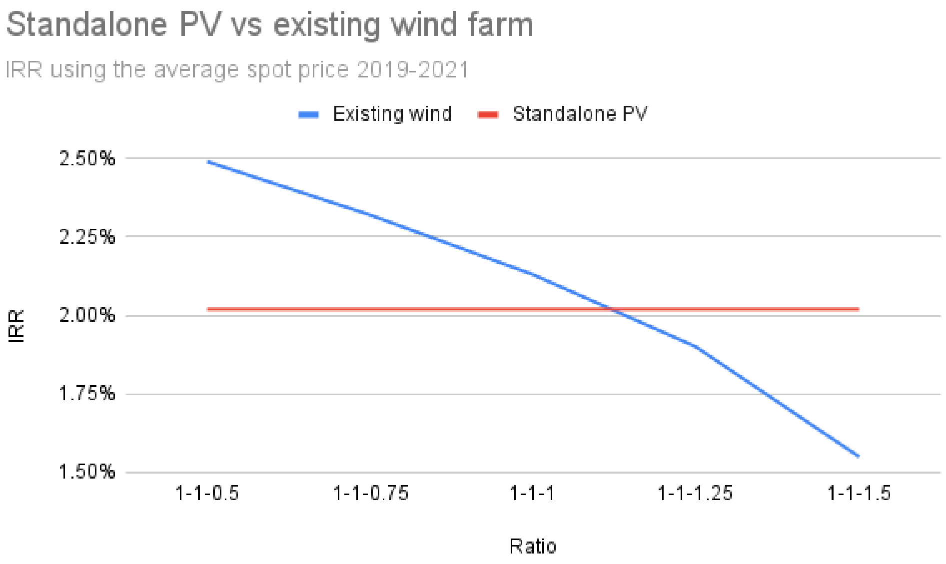

Figure 49: Profitability comparison for different ratios using 2019-2021 average spot prices for a standalone PV system vs using existing wind power plant

# 6 Discussion

A solar park needs to have a number of qualities and specifications established before construction can begin. Finding a decent location, for instance, with suitable land and adjacent existing grid infrastructure. The PV system design and the PV tilt configuration sections, 2.3 & 4.3, provide insight into how there are many different ways to install solar panels while building a solar park, provided that the set-up and equipment are mounted and adjusted correctly. These sections emphasize that a variety of technologies and designs may prove useful when constructing a solar power plant for commercial purposes. Instead, solar developers should pay greater attention to reaching their goals for power production and making the best use of the land that is available for such installations. In this paper, six PV cases were studied and compared by their performance and financial viability if placed in the vicinity of Eolus WWP in Anneberg.

The first PV case studied south facing stationary mounted panels. In theory the panels should have roughly the same tilt as the site's latitude, give or take 15° depending on if it's winter or summer. Figure 38 displays the annual electricity production for a 1 MW solar park located in Anneberg at different tilts under ideal conditions. This means that the modules are considered to be spaced far enough apart so that no shading occurs and the panels would have an ideal production based on the entered weather data. Looking at the figure, the ideal tilt angle for a south oriented system without shading losses is 40°. Considering that Anneberg has a latitude of 55°, a 40° tilt matches the theory. Bear in mind that more solar energy is produced during the summer therefore the tilt should be installed to ensure optimal performance during that period, which is accomplished by lowering the tilt 15°. In reality however, shading losses occur and need to be taken in to account when designing a solar park. Figure 39 shows how the optimal panel tilt varies depending on the GCR and indicates that the annual electricity decreases for the higher GCRs. This is further demonstrated in figure 21 showing how the shading losses increase in relation to the GCR for a panel with a 30° tilt. This shows that smaller row spacing provide higher shading losses, reducing the system's overall efficiency and total electricity generation. When shading losses are taken into account, figure 39 shows that the highest electricity output for the PV system is acheved when designed with a 30° tilt and a GCR of 0.4, meaning a row spacing of around 10 meters.

Figure 39 shows the performance of a system should the GCR be 0.5, meaning roughly 7.6 m between panels, and a panel tilt of 25°. The difference in annual produced electricity is just slightly lower than the production peak for a 0.4 GCR design. Benefits of having higher GCR's include smaller row spaces, reducing the land required for the system, thus allowing more solar panels to be installed for a given area. Table 3 compares the required land and the power output for three different PV designs. For the design using the GCR 0.5 it shows how the power output only differs 2.07% while requiring 19.53% less acreage. The table also shows how an increase in installed power, stacking panels tighter together, can increase the overall production by 15.87% using the same area. This means that if one's aim is to produce as much power as possible for a given space using south facing panels, then a 25° or 20° tilt might be a more viable option.

Section 5.1.2 studies the second PV case where east and west mounted panels are in focus. Figure 40 shows the annual electricity production for different tilts at different GCRs. The GCRs have the same row spacing as for the south facing panels and can be found in table 1. Once again, the figure shows that the annual production decreases the closer packed the rows are. It also shows that the flatter the tilts are, the more electricity is produced. In theory the best tilt would be completely horizontal, however that would allow for instance dust or snow to gather requiring maintenance to avoid losses. Therefore, the optimal tilt in this case was chosen as 15° allowing dirt or other particles to naturally fall off and get washed off by rain, thus eliminating the need for extra maintenance.

Similar simulations were made for vertically mounted panels, found in sections 5.1.3-5.1.5. The effects of shading for both traditional and bifacial panels show a downward trend in electricity output at higher GCR's. However, what the figures also show is an increase in electricity production when using bifacial panels. Comparing figure 42 and 43, both showing vertical implemented panels facing the same direction, a clear increase in production is seen for the bifacial system. Figure 44 on the other hand shows if bifacial panels were facing east and west which is useful for power production during mornings and evenings following the sun rises and sets. The annual production and difference in electricity yield for the different vertical PV cases are shown in table 4.

Looking at the table, the annual electricity produced for the east/west facing vertically mounted bifacial panels is slightly smaller than for the bifacial panels facing north and south. Reasons for this mainly consist of the geographic location of the site not ideal for capturing the solar irradiance for east/west bifacial panels. Perks of having bifacial panels facing east and west are similar to the perks for stationary mounted east/west panels. More energy is produced during the morning and evenings which is beneficial considering that these are often the times when the electricity consumption is at it's highest. What table 4 does show is a clear increase in annual production for the bifacial panels which also explains why bifacial panels are mostly used when PV panels are vertically mounted on the ground. This is a common design for agrovoltaic purposes, when combining solar production with agriculture. Monofacial vertically mounted panels do however have their advantages should the PV system instead be mounted on the side of a building for instance. There it allows solar power to be produced in spaces that traditionally have not been applicable for electricity production. These installation could however prove to be more costly considering that the mounting process is not as straight forward when installing panels on a vertical surface.

Horizontal axis tracking systems allow the panels to adjust along a horizontal axis from east to west ensuring that the solar beams meet the panel at an optimal angle throughout the day, increasing the systems overall efficiency. Figure 45, just like the previous cases, show how the efficiency decreases in relation to the GCR but it also shows a significantly higher annual output. However, these systems are more costly and contain more moving parts compared to fixed mounted panels. Moving parts leads to more components getting damaged needing to be replaced, consequently increasing the need for upkeep and increasing the maintenance costs. These systems also require larger spacing between the panel rows not making them very land use efficient as table 6 shows.

Section 5.2 ties together all the different PV cases, comparing them based on land use efficiency, annual electricity production and profitability for 1 MW systems designed with 10 m between panel rows. Looking at the IRR, which gives an estimate of the profitability of an investment, each system would result in a loss. With that said, these results were only simulated using 2019's weather data and spot prices, due to limitations in weather data applicable for the simulation software used for this study. Looking back at figure 33 showing the historic development of the spot prices over the last couple of years, the spot prices have increased quite significantly. Therefor, these installations should not be seen as unsuccessful investments. What table 6 does show is that the fixed mounted south panels are the most profitable and have the highest land use efficiency, hence this case was used for the subsequent hybrid simulations. It has also been mentioned that east/west mounted systems can prove to be more profitable because of the higher production at high load times. Our results show though, that this is not the case for the location that was studied. This was shown for both the 15° and vertical bifacial east/west mounted panels. If however the volatility in electricity prices increases in the future, these set ups could become more profitable than fixed south installations. The profitability of east/west panels could possibly be different if the purpose of the installation is to save instead of make money. If someone has a roof which is facing east and west, there will be reduced costs for the high load hours.

Section 5.3.1 presented the results from the simulations that were conducted in HOMER Pro. We saw that the electricity production from the PV was fairly similar for the three years that were studied, but that the amount of curtailment varied between them because of the differences in wind power production. As expected, the percentage of curtailed electricity increased as we increased the installed peak power of the solar modules. The hybrid capacity factor also increased with installed power and the results showed that it is possible to reach a $C_f$ of 0.5 or even higher, depending on the year. One has to weigh if the importance of keeping the curtailment and loss of potential income to a minimum outweighs the importance of increasing the capacity factor significantly.

The two tables that presented the self curtailment for the solar panels give an interesting insight in how one can choose to size a solar power plant. It was mentioned in the theory section that it is common to oversize the installed power of the solar modules in relation to the inverters as it can save the project a lot of money. When doing this you risk the occurrence of clipping which is when the panels produce over the conversion capacity of the inverter. For the simulations that we conducted, the inverter capacity was assumed to be the same as the solar panel capacity. This means that there was no clipping at any point and all the produced electricity could go through the inverter. The results on self curtailment therefore showed that one could choose an array-to-inverter ratio of 1.25 or higher, meaning that you oversize the panels to the inverter by 25% or more, and still have a close to zero loss of electricity. In turn one could size the grid connection point or transformer at a 1:1 ratio with the inverter instead of the panels, and save money.

Sections 5.3.2 and 5.4 shows the results from the economic calculations. As we mentioned in the results, the higher ratios lead to more curtailed electricity which makes them the least profitable with regards to IRR and payback time. These tables don’t make it completely obvious that the lowest ratio of installed solar is the best investment though, as it does not give the actual return on investment. Which one is best for the specific case of Anneberg depends on a lot of things. A few of these are how much land area is available for solar panels, if the cost of the land is the same even though not all of it is utilized, if there needs to be sufficient row spacing for agriculture and if the cost of updating the switchgear varies linearly with installed power or not. Moreover, the results show that the electricity prices will very strongly impact the profitability of the investment.
Comparing the economic results of the hybrid systems with the standalone solar system, building a hybrid power generation system in this manner could prove a better investment than building a standalone solar park from the ground up. As we already mentioned in the results, a combined wind and solar power plant will have a higher profitability than a standalone solar power plant between the ratios 1-1-0.5 and 1-1-0.75. It might even prove more profitable for higher ratios but our results only show that this is the case for the simulated year 2021 up to the ratio 1-1-1.25, or for the case with the average spot prices. Because of the fact that our economic assumptions are very general and based on a number of different sources, it can not be concluded that this exact

relationship would be true in an actual project. What can be concluded though, is that there is a strong possibility that the saved money on grid connection costs can result in an investment that is just as, if not more, profitable as building solar power alone. Utilizing existing grid infrastructure and equipment to its maximum potential is also a big positive for saving materials and space.

As section 5.3.2 suggests, when using 2021's spot prices for the entirety of the systems lifetime in the economic analysis, a more desirable IRR is established. However, this is not entirely realistic considering that the spot prices change from year to year. This is explained in section 3.2 where it displays how the spot prices set by Nord Pool can fluctuate and how they have risen rapidly in the past couple of years. From an economic standpoint based on the results in this paper, an increase in spot prices would result in an increased system profitability. Electricity producers should seize this chance given that some experts believe the spot prices will continue to grow. Nevertheless when planning an installation with a long lifetime, it is good to be cautious considering the variability of the market. The spot prices have risen now and are projected to continue to grow for the coming years, but who knows what the spot market will look like 20 years from now. Here is where power purchase agreements, PPA, can prove to be useful. In short it is an agreement between a buyer and a producer of electricity outside of Nord Pool, where they establish a fixed price for the electricity for a longer period of time, anything from 7-20 years. This ultimately lowers the risk involved and the threshold for a positive investment (Wretborn, 2017) .

# 7 Conclusion

The first part of this study was focused on specific ways to mount solar panels and to see how the profitability related to this. Normally in the northern hemisphere, solar panels are mounted with a fixed tilt and oriented to the south because it results in the best overall profitability. The results in this report conclude the same thing, and that the optimal tilt angle for the Anneberg location was 30° when the GCR is 0.4. With this result in mind the study on the hybrid system was conducted. If however there is a requirement from the landowner to make the space between the rows sufficient for agriculture, one might want to choose vertically mounted solar panels. In this case, it is best to choose bifacial solar panels, as they will produce significantly more than monofacial panels. Mounting these in a north/south orientation is a slightly better investment than doing it east/west.

Results on the hybrid simulations showed that it can be a good investment to utilize a wind power plant grid connection point for solar photovoltaics. Whether or not it is more or less profitable than installing solar alone can not be fully concluded unless more detailed and location specific economic data is made available. What can be concluded though, is that it has similar profitability and that it is more sustainable to use as much of the existing equipment as possible. It would also probably be a much less complicated process to build as the application for a new connection to the grid would be avoided.

## 7.1 Future works

For future studies on this subject, the authors of this paper would like to suggest a few points to address. There have not been enough studies on how connecting a hybrid system as described here would work technically. It would be good to know how complicated it is to add the extra connection slots to the transformer or switchgear, and also if the combined system could provide more ancillary services to the grid. As the technology on electrical storage develops and gets cheaper, it would also be interesting to know if adding storage to a hybrid power generation system could increase the profitability.

The economic analysis could be improved if there was access to detailed and location specific cost data for all the components involved. As mentioned, the general nature of the cost assumptions used in this report give a slight uncertainty to the accuracy of the results. Going forward, it will be interesting to see how the electricity prices change the profitability of projects like this and in a few years a similar study to this might end up being a lot more profitable.

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