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Feasibility of solar PV in Norway, to increase the flexibility of the Norwegian electricity system.

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Renewable Energy

Acknowledgements:

I am writing this thesis in the last semester of my master's degree in Renewable Energy at the Norwegian University of Life Sciences (NMBU). The topic for this thesis was decided after the completion of several subjects at NMBU during my master's program. I gained further knowledge of all the types of renewable energy technologies that are currently implemented both around the world and in Norway. I became particularly interested in solar energy and was intrigued as to why solar energy is not a larger portion of the Norwegian energy mix. Due to the long sunny days and land areas suitable to solar energy, I felt that the feasibility of Norway introducing more solar energy into the energy mix would be an interesting topic for my thesis.

I would like to thank my supervisor Muyiwa Samuel Adaramola for all his help and guidance through this process.

Abstract

This thesis examines the feasibility of solar energy playing a more significant role in the Norwegian energy mix. In Norway, more than 98% of electricity is generated from either water, wind, solar or biofuels, with water being the most dominant source for hydropower generation. Additionally, about 9TWh of electricity is imported each year.

The use of solar energy for electricity generation is only a minor component of the electricity mix in Norway. This is because the optimal production is limited to approximately six months of the year and the previously high investment / startup costs were seen as barriers to the feasibility of solar PV in Norway.

This thesis will calculate the electricity output from six locations, mostly in the south of the country, to determine what component of imported electricity could be met from this source. This would enable water saved from reduced hydropower generation during the summer months to be used during an alternative period, or to provide for other electricity options such as increased export.

With a combined installed capacity of 600MW, six solar PV farms produce 11,6 % of Norway's imported electricity of 3 810GWh during the summer period, requiring a land area of more than 840 acres. While this would be a difficult policy issue and further research is needed on the cost versus benefits of such an investment, including the concept of dual utilization of these land areas, for example, combined agriculture and renewable energy projects such as animal grazing.

In addition, there are benefits from having an additional electricity generation element in the Norwegian electricity mix that increases its flexibility and security, especially during times of unexpected disturbances or changes in weather patterns.

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List of Abbreviations

NMBU	Norwegian University of Life Sciences
TWh	Terra Watt hours
GHG	Greenhouse Gases
CO_2	Carbon Dioxide
Solar PV	Solar Photovoltaic
NVE	Norwegian Water Resources and Energy Directorate
UNFCCC	United Nations Framework on Climate Change
COP	Conference of the Parties
SAM	System Advisor Model
NSL	North Sea Link
NSRDB	National Solar Radiation database
GWh	Gigawatt hours
TWh	Terawatt hours

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1.0 Introduction

1.1 Background

Future global energy sources and methods of producing electricity will be drastically different to current sources and methods. In 2022, the global energy resources used for electricity generation were fossil fuels (crude oil, coal, and natural gas) with 63,3% of installed global capacity, nuclear energy 10,4%, hydropower 15,8%, solar and wind energy 8% and other sources 2,5%. (Ritchie, Roser and Rosado, 2022) Due to the impacts of climate change, environmental concerns, natural and regional energy security related issues, adoption of renewable energy sources, the national and global transition away from fossil fuels was inevitable and continues to accelerate. This is leading to a significant change in the energy mix of many countries, especially those that depend on fossil fuels for their energy needs, including their electricity generation.

When discussing the issue of energy usage, the terms energy and electricity are sometimes used interchangeably. Energy is derived from sources such as oil and gas (known as fossil fuels) in the form of petroleum products through processing oil and gas, to power vehicles or for heat generation. Oil and gas, as well as coal, are also used to generate electricity to power domestic and commercial operations, to increasingly power vehicles and for heating and cooling. Importantly, electricity can also be generated from renewable sources such as water, wind, and the sun. As the world becomes more aware of the effects of consuming fossil fuels, renewable sources of energy and the importance of electricity as a form of energy, continue to grow.

Unlike any other country, Norway produces almost all its electricity from renewable sources, principally water and to a lesser extent wind. However, Norway still imports, on average, around 9TWh each year from countries within Europe (SSB, 2023) and, while Norway has considerable flexibility with its electricity production, recent events have shown there can never be too much flexibility regarding energy supply. The current flexibility in the Norwegian energy mix is provided through hydropower which can be quickly altered to meet changes in daily demand while the extensive reservoir network enables storage of large amounts of water for use as required on a monthly and seasonal scale.

The first wind farm was installed in Norway in 2002 and energy produced by wind has grown substantially in the past twenty years. Today wind is responsible for approximately 10% of electricity production. (SSB, 2023) However, there has been a backlash against onshore wind farms in recent years due to their perceived environmental impacts.

Historically solar energy has not been embraced in Norway since it is only available for any significant electricity production during the warmer months, along with the high investment and startup costs. Solar photovoltaic (PV) generation is currently a very small component of the Norwegian electricity mix, with production in Norway for 2022 being only 0,225TWh. (NVE, 2023) However, the views on solar energy could be changing as the costs of solar generation fall, the efficiency of the technology increases and the realisation that an additional generating resource would further enhance the flexibility of the Norwegian system by saving water from reduced hydropower production in summer, for use at a later date.

Global energy demands, especially for electricity, have been increasing steadily for the past 20 years and are still dominated by fossil fuels. Figure 1 shows global electricity production by energy source from 1985 – 2021. Global demand for electricity continues to grow but that demand is still mostly met by traditional fossil fuel sources, especially gas. There is a clear increase in the use of renewable sources, yet they are making only a small impact on the overall use of fossil fuels.

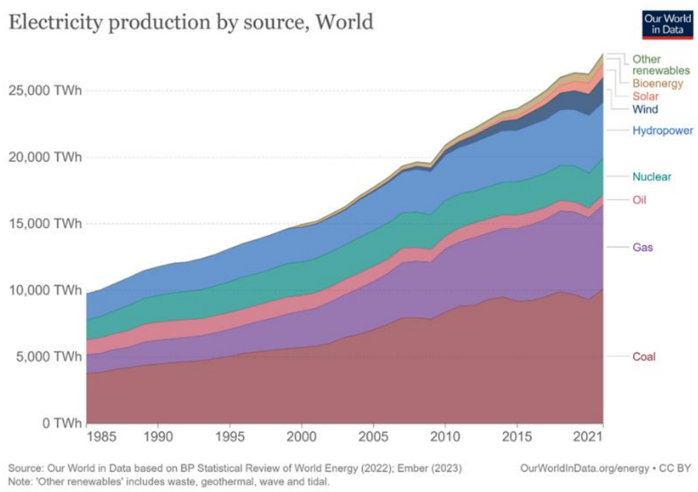


Figure 1: Global electricity production by source in TWh per year. (Ritchie, Roser and Rosado, 2022)

To reduce greenhouse gas (GHG) emissions, many national governments have adopted policies and set targets to significantly reduce Carbon Dioxide (CO_2) output compared with 1990 levels. In addition, most countries are signatories to international agreements, such as Paris - 2015, that have set targets to cap the global temperature rise to less than 2°C above pre-industrialisation levels, by agreeing that GHG emissions peak in 2025 and reduce by 43% within 10 years. (United Nations, 2023) To reach these goals and targets, a combination of several factors needs to change. These include the transition from using fossil fuels to renewable energy sources, flexibility and diversity in energy systems and government policies which will, in combination, hopefully see GHG emissions fall and global temperatures plateau. To meet international greenhouse gas reduction targets and the growing electrification of sectors such as transport, there is an increasing demand across Europe for electricity from renewable sources. (Spilde et.al., 2018)

Electricity production in Norway varies from year to year, but over the past 20 years there continues to be an upward trend in electricity production, as shown in figure 2. Although the Norwegian electricity mix is primarily based on hydropower, there are both the resources and available sites on land and at sea, to increase production from other renewable sources, namely wind and solar. While the use of wind power has been growing steadily over the past twenty years, there has been a much slower uptake of solar as a source of electricity. It has been emphasised in the Norwegian Governments climate plan, that solar energy is an important energy source in Norway. (Meld. St. 13, 2020-2021)

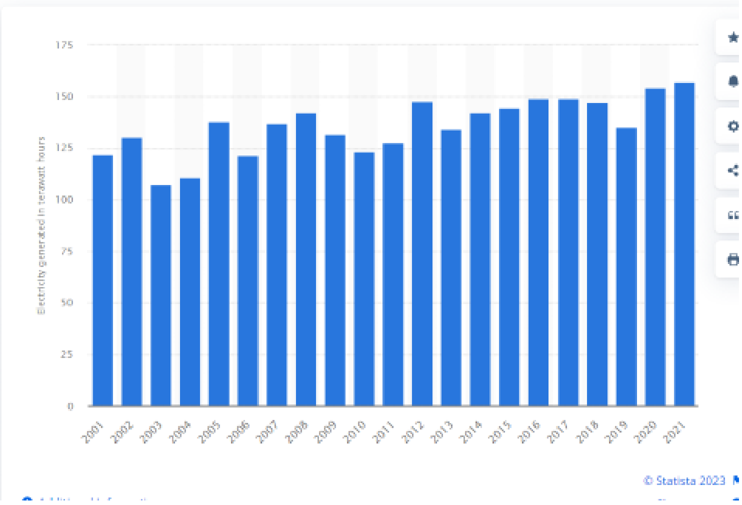


Figure 2: Total Electricity Production in Norway (2001 – 2022) (Statista, 2023)

Energy security has proven to be more important in recent times, with the war in Ukraine causing variations in gas and oil prices as well as the apparent need to transition to greener energy sources. As stated in Statkrafts Low Emission Scenario, energy security is the availability of energy sources at a reasonable price. Rynning -Tønnesen states that by diversifying the supply and dependence on different energy sources, a country can increase its energy security by reducing the need to import electricity.

1.2 Aims and objectives of the thesis.

This thesis focuses on the feasibility of increasing the use of solar PV in Norway in the warmer months that will:

- Lead to a reduction in the import of electricity
- Save water from the resultant reduction in hydropower production to be used during high demand periods in winter.
- Increase the flexibility and diversity of the Norwegian energy mix.
- Assist in meeting the growing domestic demand for electricity.
- Assist Norway and other countries to meet national and international agreements.

1.3 Structure of the document

Chapter 2: explains the methodology used in the thesis and theoretical approach to the calculations.
Chapter 3: presents the calculations and results of prosed solar PV in Norway
Chapter 4: presents discussions orientated around the results in chapter 3
Chapter 5: conclusions
Chapter 6: recommendations to further study

2.0 Literature Review

The aim of this chapter is to summarise the research and conclusions found in the literature that discuss aspects of the research question for this thesis. This will involve looking specifically at solar PV electricity production, electricity demand, comparisons with existing renewable energy sources in Norway and Norway's import and export policies. The findings in this literature review are based on research conducted by accessing various peer reviewed articles and websites of relevant government agencies.

The intention of introducing a greater portion of renewable energy technologies, such as wind and solar power into the Norwegian electricity mix was to increase its diversity, increase energy security in Norway, meet growing demand, increase flexibility, and meet targets set in national and international agreements. The current energy system in Norway consists of approximately 98 percent renewable energy. (IEA, 2022)

2.1 History of electricity in Norway

The Norwegian landscape with its high mountains, fjords and river systems is ideal for hydropower. The Norwegian energy mix has been dominated by hydropower from the early 1900's. From 1906 a legal framework was established to secure national control of hydropower resources through the facilitation and organization of municipal ownership and electrification in general. (NVE NORAD, 2016)

Electricity has been available to approximately 70% of the population since 1930 and 100% by 1960. Electricity has always been an important part of the Norwegian economy and culture, shaping the way for industrialisation, from the use of electricity to power electricity-intensive industries such as aluminium, ferro-silica, and pulp and paper, which were often owned by foreign investors (NVE NORAD, 2016)

2.2 Increased demand for electricity in Norway and Europe

Demand for electricity grew steadily throughout the last century but despite almost universal availability of electricity across the country, there continues to be increasing demand for electricity in Norway. Energy consumption in Norway has increased by 70% since the 1970's (NVE, 2021) and will continue to increase as the population increases and a greater number of goods and services become electrified. The demand for electricity has increased due to the expansion of industry generally in Norway and other existing sectors converting from fossil fuels to electricity. For example, the transport sector in Norway is currently 21.5% electric. (Elbilforeningen, 2023) This sector is an example of how demand will most likely increase for both public transport, light transport, and increasingly heavy vehicles. Spilde et al. emphasised further growth of the metal industry and continuing electrification of the petroleum sector will add to the demand while an emerging sector in Norway with significant electricity needs, is large data centres. Annual electricity consumption is expected to increase drastically from 136TWh in 2018 to 159TWh in 2040. (Spilde et.al., 2019)

With other countries aiming to reduce fossil fuel consumption in all sectors it is likely that an increased uptake of electric vehicles will occur in other European countries. Also, with the price of battery production decreasing (down 70% since 2010) electric cars will become more affordable and the increase in the range in which electric cars can drive is increasing, further driving that demand. (Spilde et.al., 2019)

There is no doubt that there will continue to be an increase in power intensive industries in Norway, with strong growth in that sector over the past 10 years. (Spilde et.al., 2018)

The Norwegian government has been pushing for decreased energy usage, with a ban on fossil fuel heating systems in new buildings since 2016. While there is a target to reduce building energy use by 10TWh by the year 2030, the overall demand for electricity will still exceed that in 2020, as most of the sector heating requirements will have been electrified with little or no fossil fuel systems. (IEA, 2022). Figure 3 shows the break down the of energy demand per sector in Norway.

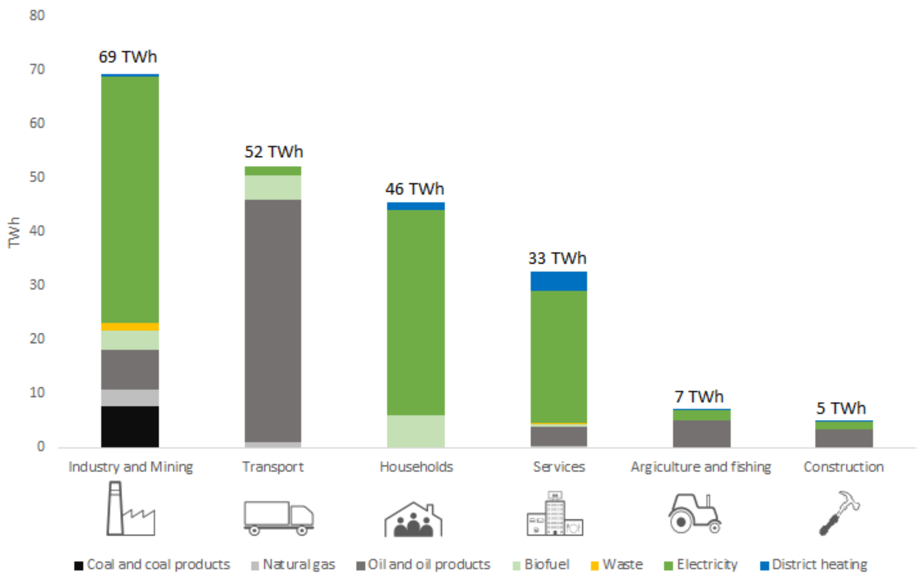


Figure 3: Energy demand per sector, 2020. (Energy Factors, 2017)

Although the estimated increase in electricity consumption from growth in some sectors, and transition from petroleum-based energy to electricity within Norway will contribute to an increased demand, the same transition in other countries can contribute to increased demand for Norwegian green energy. Spilde et al. emphasised across Europe in countries such as Germany, France and Great Britain, the transition from fossil fuels to electricity has contributed to increased electricity demand. These and other countries are expected to continue that transition with further reduction in domestic use of gas for cooking and heating. Germany, France and the United Kingdom are already the largest users of electricity in Europe. (Spilde et.al., 2019) To meet this growing demand and satisfy emission reduction targets, they will have to import green electricity. This is a potential export market that Norway could well satisfy.

The increase in demand for electricity from renewable sources has come at a time when two variables in the energy mix of countries will come in to play at the same time. As power intensive industry will see a growth in Norway, it will happen at a time when a shift from fossil fuels to greener energy resources will be paramount. (Spilde et.al., 2019)

With the increased demand for electricity in the future, it will be of great importance for Norway to diversify its energy mix to ensure greater energy security throughout all months of the year and within the five different energy regions.

2.3 Flexibility of the Norwegian Energy System

The importance of having a flexible and diverse energy system is because the demand for electricity is not constant, but rather has both peaks and valleys through days, weeks, months, and seasons. There is both short term flexibility i.e., being able to meet short term fluctuations in demand and then long-term flexibility, where there are several different components of the energy mix that allow the overall system to withstand unexpected shocks such as drought or global political events.

Electrification, combined with the new power demanding industries – such as battery factories and hydrogen production – will lead to a higher electricity consumption across Norway. NVE has calculated that could raise the annual electricity consumption by 23TWh. NVE estimates this is the equivalent of building forty-six new wind power plants, five hundred and seventy-five large new scale solar systems on commercial buildings or thirty-three medium sized hydro power plants. (IFE, 2021)

This growth will require an increase in the flexibility of the electricity system's ability to adapt to variations and insecurities in connection with production and consumption of electricity. Historically Norway has used the large water storage reservoirs to provide that flexibility against unexpected variations in demand. (IFE, 2021)

Renewable energy, apart from storage hydropower, does not currently have the option for large storage units, meaning that all electricity produced must be used immediately. This is a disadvantage with renewables. Being able to introduce different types of renewable energy into the energy mix in Norway would be one way to ensure that there is more flexibility in the system. Currently battery storage for solar energy is expensive and requires large areas to install, while not having the capacity to make a significant impact on a country's energy system. As Norway has the advantage of having large reservoirs for hydropower, these reservoirs could be used as "batteries" for solar PV. This would be achieved by "saving" the water that would normally be used in the summer months to generate electricity, the need to import electricity in the summer months or use it in the winter months when the possibility for production is lower.

Increasing the capacity of Solar PV in Norway will further increase its flexibility and harness another energy source that can be converted into electricity that is not currently utilised on a large scale. If a country is too reliant on one type of renewable energy, problems can occur if there is not enough "fuel" required, for example water, wind, or sun to generate the electricity requirements.

2.4 International Agreements

The move towards agreed reduction targets has been a slow process, commencing with the **Montreal Protocol 1987.** This agreement was not about climate change or greenhouse gases, but rather about countries agreeing to limit the production and emission of chlorofluorocarbons that it was universally agreed were damaging the ozone layer. The model of achieving this treaty would be the basis for future agreements around climate change. However, while the Montreal Protocol has resulted in almost the complete elimination of CFCs, climate change agreements have yet to be so successful.

The next significant conference was the **UN Framework Convention on Climate Change (UNFCCC), 1992.** This was the first global treaty to address climate change and was signed by almost 200 countries. It established amongst other things, the concept of an annual Conference of the Parties (COP) to address different aspects of the greenhouse gas issue. (Untied Nations, 2023)

This led to the **Kyoto Protocol, 2005.** The protocol was first established in 1997 but not ratified until 2005, demonstrating how difficult were the issues around compelling developed countries and not developing countries, to reduce their greenhouse gas emissions by 5% compared with 1990 levels. China and India for example, were classified as developing countries and yet were major emitters of greenhouse gases. (Untied Nations, 2023)

However, the **Paris Agreement, 2015** was the most significant of the COP meetings to date. After the Paris agreement countries are required to set individual emission reduction targets that will collectively keep global average temperatures from rising more than 2 deg C above pre-industrial levels. The Agreement also aims for the world to reach a carbon neutral state by the middle of this century i.e, where greenhouse gas emissions are equal to the amount removed from the atmosphere. (Untied Nations, 2023)

As a result, countries have agreed to certain goals to achieve before 2030 and 2050, so that total emissions worldwide can be reduced, thus helping to slow the warming of the oceans and the atmosphere.

2.5 Cost of Solar PV's

The cost of solar PV panels has fallen steadily since the 1970's as shown in figure 4, but quite dramatically in the last 12 years, to now be less than $US1 per watt. At the same time solar PV panels have become more efficient. In 2012, cells typically achieved 18% efficiency but in 2020 that figure has risen to 44%. (energysage, 2021)

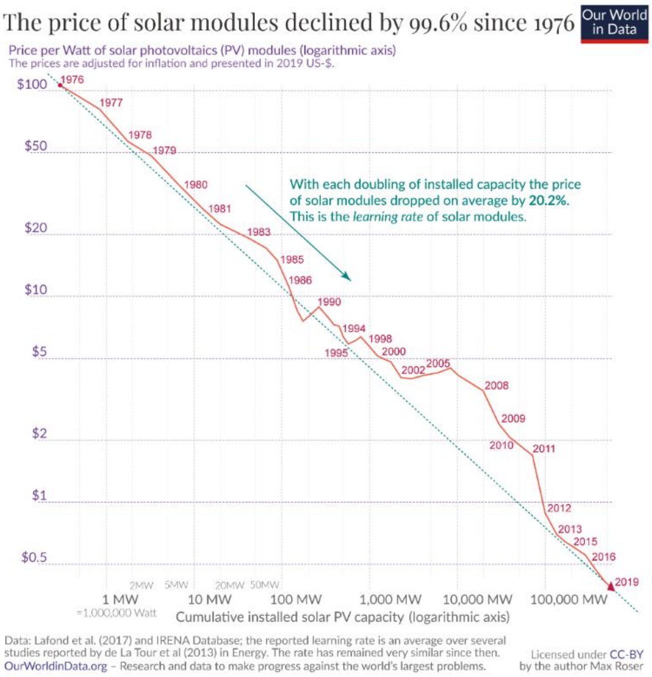


Figure 4: Solar PV Panel Prices 1975-2021 (Roser, 2020)

2.6 Export Potential

Norway is already the largest exporter of electricity in Europe and although there is some variability in the amount exported, it has been as much as 20% of the total quantity of electricity generated annually. (Baker, J, 2021)

Europe already imports 50% of its energy requirements (Energy Facts Norway, 2019) and as Russian energy resources diminish along with increasing targets for renewably sourced electricity, that demand will grow even though there are some efforts to increase home-grown renewable energy generation capacity. Given that almost all of Norway's energy is produced from renewable energy, the country has the potential to possibly export larger quantities of renewable energy to parts of Europe.

For Norway to achieve the goal of having greater flexibility and security in its electricity system, as well as reducing a portion of the electricity imported, there are several factors that must be considered. Flexibility, policies, technology, and politics are all paramount in achieving this goal. If there is a goal of altering the rate in which the climate is changing and meeting the requirements to policy goals, and Norway wants to be a part of that change, it needs to increase its production and export of green electricity. This can be achieved through diversifying the electricity mix, thus increasing its flexibility. Flexibility and variability of the electricity production is going to be the most important aspect of the transition. Most renewable energy sources, except for dammed hydropower, have the disadvantage that they can only produce electricity when the weather is suitable. A key to future energy systems that are fully renewable is having a mix of different types of renewables. Finding the right mix will be different for all countries due to geographical differences, however Norway has a distinct advantage, as they have the possibility of harnessing energy from several different energy sources.

After significant research, it was concluded that there was no similar research conducted on the feasibility of solar PV in Norway to cover the imported electricity during the summer months. Similar research has been conducted in Norway; however, the research was addressing the combination of solar and wind. There were also no research articles conducted on solar PV farms of the size that is addressed in this report. This report addresses industrial size solar PV farms of 100MW per location. These solar PV farms are of considerable size, while other reports address the possibility of solar PV on a significantly smaller scale.

3.0 Methods

The sun as an energy source, is not widely used in Norway. While there are long days during late spring, summer, and early autumn, (primarily April to September), the days are much shorter during the winter months, with limited light availability. As a result, there has been a long-held view that solar PV is not a useful electricity source in Norway. However, improving solar panel and inverter technologies are making solar a more viable option resulting in a rapid uptake in solar PV in recent years, albeit at low levels compared with total electricity production in Norway, as shown in figure 5. The research question for this feasibility study is "the feasibility of solar PV to increase the flexibility and security of the Norwegian energy system and reduce import during the summer months."

The aim of this feasibility study is to assess the electricity that solar PV can provide across various specified locations in Norway, with the view of adding solar PV to the Norwegian electricity mix in a reasonably significant way. Not only would this increase the flexibility of electricity generation as a mitigation against risk but enhance the capability and reliability of the hydropower generating component by saving water during the summer months for use in the winter, or as other opportunities such as increased export markets arise.

While Norway is in the envious position of having multiple sources of energy available for electricity generation, the recent Ukraine war and increasing variability in rainfall, as well as ongoing pressure on the utilisation of fossil fuels, demonstrate that seeking even further flexibility in the energy mix is a sound strategy.

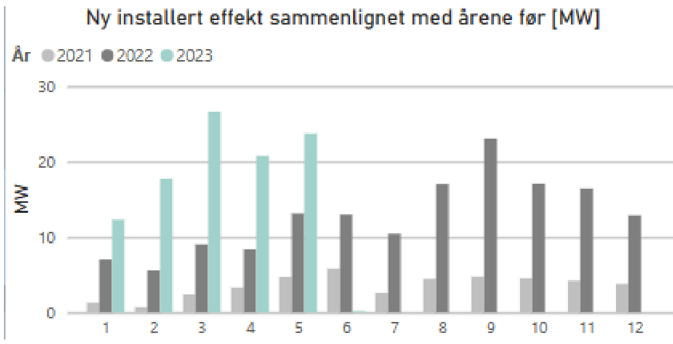


Figure 5: New installed effect of solar PV capacity in Norway (2021-2023). (NVE, 2023)

3.1 Factors affecting solar PV performance

There are several factors that affect the performance of solar PV panels. These factors include ambient temperature, wind speed, solar radiation and the tilt and angle of panel installation. The sun's position in the sky and the resultant solar radiation at a location, can be defined at any given time on any day and is paramount in the calculation of how much electricity can be produced per square meter of solar panel.

3.1.1 Solar Radiation:

As the earth rotates around the sun the amount of solar radiation reaching any location varies from season to season due to the tilt of the earth's axis and time of day, with maximum radiation occurring around the middle of the day. The radiation is also affected by the earth's atmosphere due to scattering, absorption, and reflection. Figure 6 illustrates the three different types of solar radiation.

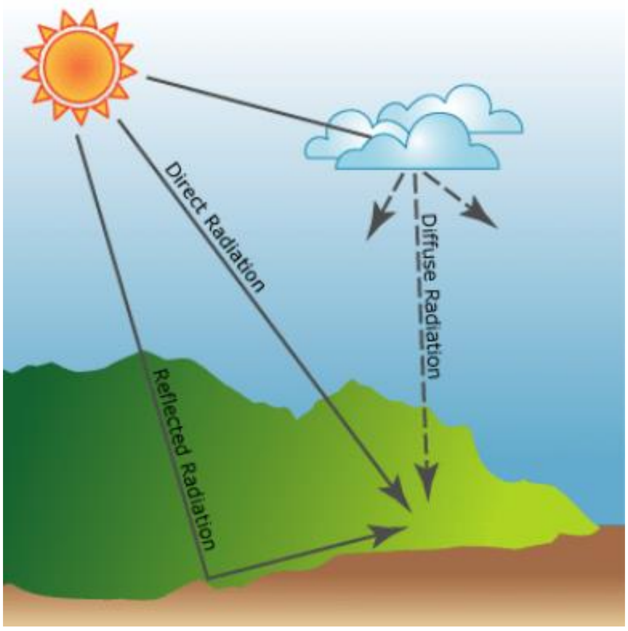


Figure 6: Solar radiation showing reflected, direct and diffuse radiation. (esri, 2019)

3.1.2 Azimuth (ϕ) and Altitude Angle (β)

The location of the sun at any time of the day can be described by altitude angle (β) and azimuth angle (ϕ). These angles are dependent on latitude, number of day and time of the day. From figure 8, the altitude is the sun's height in the sky at a given time while the azimuth angle is the compass direction from where the solar radiation arrives. For the northern hemisphere, the sun is at a position in a southward direction and the best orientation will therefore be facing south.

The position of the sun on any day is defined by its azimuth angle and its altitude angle. These angles vary across the planet and are a function of:

- Latitude of the location
- Time of day
- Day of the year

The solar resource is shown in figure 7.

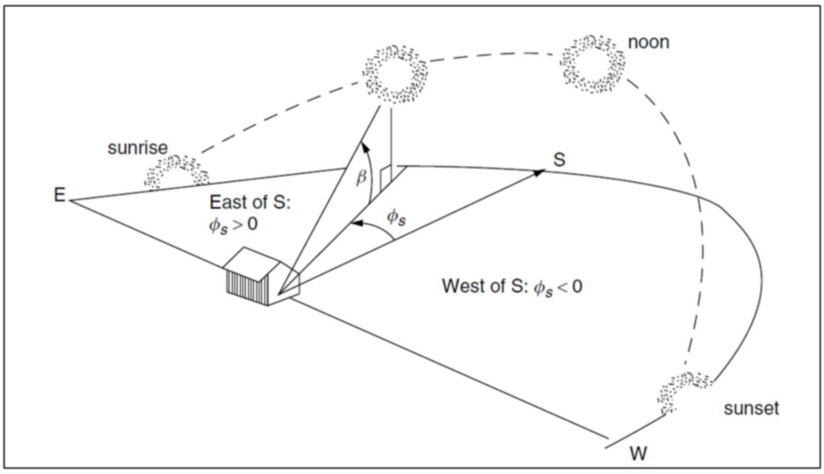


Figure 7: The solar resource (Masters, 2004)

Altitude Angle (β)

The altitude angle refers to how high the sun is in the sky as shown in figure 8.

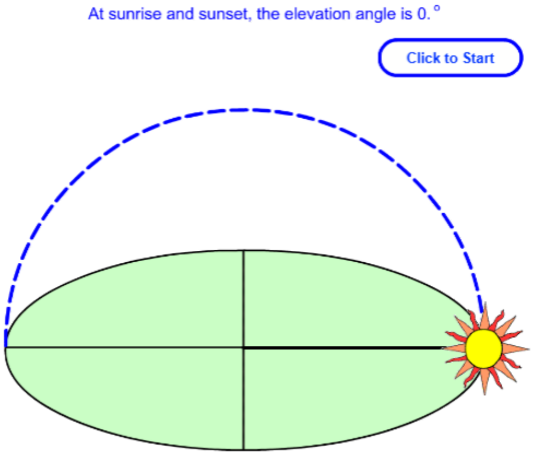


Figure 8: Altitude Angle (Honsberg, Bowden, 2019)

Azimuth Angle (ϕ)

The azimuth angle describes the compass direction from which the sun’s rays originate as shown in figure 9.

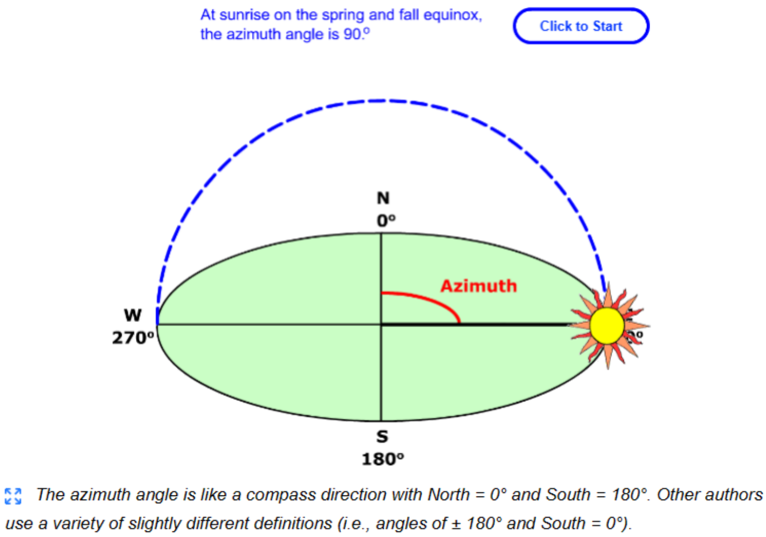


Figure 9: Azimuth Angle (Honsberg, Bowden, 2019)

The formulae for calculating the altitude (β) and azimuth (ϕ) angles are:

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta \qquad [3.1]$$

And

$$\sin\phi = \frac{\cos\delta \sin H}{\cos\beta} \qquad [3.2]$$

(Masters, 2004)

Where L is the latitude, H is the hour angle and δ is the declination angle.

The hour angle (H) is calculated by using the following formula (Masters, 2004):

$$H = \left(\frac{15deg}{hour}\right) hours\ before\ solar\ noon \qquad [3.3]$$

3.1.3 Declination Angle (δ)

This information about the solar angles giving the position of the sun in the sky is used for determining the best tilt angle for the solar PV modules that would expose them to the greatest amount of solar radiation. As shown in figure 10, the declination angle is the angle formed between a line from the equator and a line drawn from the centre of the sun to the centre of the earth, also known as solar declination.

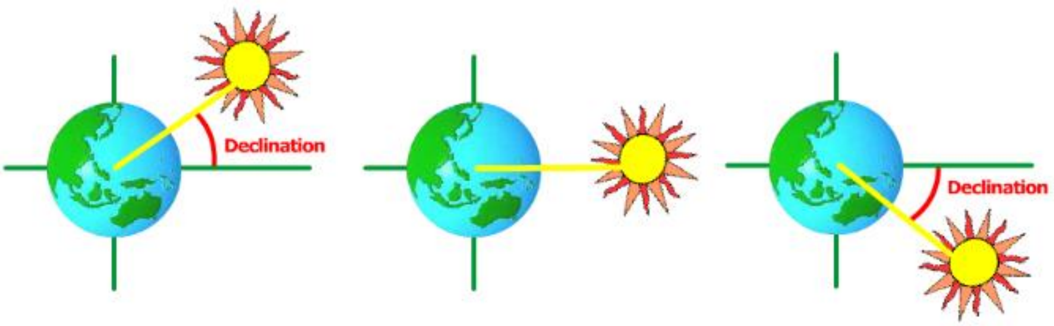


Figure 10: Declination Angle (Honsberg, Bowden, 2019)

The Declination Angle is calculated using the following equation:

$$\varrho = 23{,}45 \sin\left(360/365\ (n - 81)\right) \qquad [3.4]$$

Calculating the day in the month (n)

Table 1: Day numbers for the first day of each month. (Masters, 2004)

January	n = 1	July	n = 182
February	n = 32	August	n = 213
March	n = 60	September	n = 244
April	n = 91	October	n = 274
May	n = 121	November	n = 305
June	n = 152	December	n = 335

3.1.4 Optimum tilt angle (θ)

The tilt angle (θ) is the angle of the solar panels with reference to the sun and optimizing that angle will lead to maximum output from the panels. The optimum tilt angle varies between summer and winter and tracking systems are sometimes used to alter the angle of the solar panels. The difference in power output from changing the tilt once every month and a fixed system is less than 4% (Stanciu & Stanciu 2014) and the cost of the system can outweigh the benefit.

The optimum tilt angle is calculated by using the following equation.

$$\theta = 90 - \beta n \rightarrow L - \delta \qquad [3.5]$$

3.1.5 Solar radiation window

Considering all these factors we can determine the optimum solar radiation window, which unsurprisingly is focused around the middle of the day and tapers off to sunrise and sunset. Figure 11 demonstrates this particularly well in particular the variation by month.

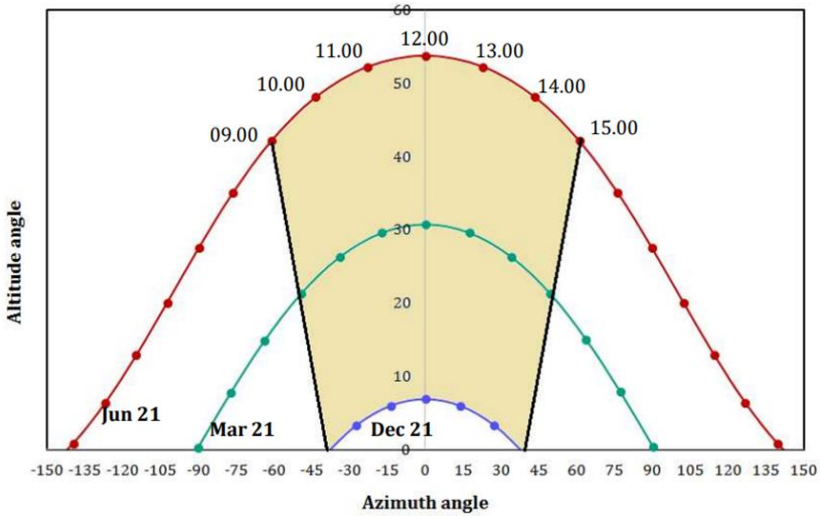


Figure 11: Solar radiation window (Masters, 2004)

3.2. Locations

Six reference points (locations) for solar PV assessment have been selected across 3 of the 5 energy regions that make up the Norwegian energy system; they are NO1, NO2 and NO5. These regions were selected as they currently produce large amounts of hydropower, therefore we can assume there would be no need for upgrading or extending the current grid system.

This means that the current electricity production in these areas would be able to accommodate the same amount of electricity produced from solar PV as the electricity usually produced from hydro. Another factor for the decision to focus on these three regions is that they are in the southern half of the country where solar production would be more productive. Demand for electricity is also greatest in the southern part of the country, as that is where the largest portion of the Norwegian population reside. The areas and locations that were chosen are as follows:

NO 1

- Location 1: Sarpsborg: Latitude: 59° 17' 2.08" N, Longitude: 11° 06' 34.63" E
- Location 2: Minnsuend: Latitude: 60° 23' 38.60" N, Longitude: 11° 13' 14.80" E

NO 2

- Location 3: Kristiandsand: Latitude: 58° 08' 48.16" N, Longitude: 7° 59' 44.16" E
- Location 4: Stavanger: Latitude: 58° 58' 12.18" N, Longitude: 5° 43' 59.95" E

NO 5

- Location 5: Bergen: Latitude: 60° 23' 49.47" N, Longitude: 5° 19' 27.78" E
- Location 6: Vaksdal: Latitude: 60° 28' 42.79" N, Longitude: 5° 44' 7.85" E

Figure 12 shows the different electricity regions in Norway. Of the six locations used for the calculations, two solar farms are situated in each of the regions NO1 (light blue). NO2 (purple) and NO5 (green).

Figure 12: The 5 regions of the energy system in Norway (NVE)

3.2.1 Oslo (NO1)

Table 2: Weather information for NO1 (Climates To Travel) og (Travelchime Inc, 2023)

	April	May	June	July	August	September
Sun light hours	14.5	17.1	18.7	18.0	15.7	13.0
Temperature (°c)	2.1 – 11.0	6.8 – 16.7	10.8 – 20.4	13.4 – 22.7	12.5 – 21.3	8.6 – 16.4
Wind speeds (mph)	9.3	9.0	8.7	8.4	8.6	9.7
Rain days	14	15	17	16	18	15
Humidity (%)	78	76	75	77	82	86

3.2.2 Kristiansand (NO2)

Table 3: Weather information for NO2 (Climates To Travel) og (Travelchime Inc, 2023)

	April	May	June	July	August	September
Sun light hours (hrs)	14.3	16.7	18.1	17.5	15.4	12.9
Temperature (°c)	1.9 – 10.5	5.9 – 15.4	9.6 – 18.8	12.1 – 21.2	11.6 – 20.4	8.8 – 16.5
Wind speeds (mph)	14.1	13.3	13.1	12.9	13.1	14.8
Rain days	9	9	9	8	11	12
Humidity (%)	79	78	77	80	83	85

3.2.3 Bergen (NO5)

Table 4: Weather information for NO5(Climates To Travel) og (Travelchime Inc, 2023)

	April	May	June	July	August	September
Sun light hours (hrs)	14.5	17.2	18.8	18.1	15.7	13.0
Temperature (°c)	3.9 – 11.1	7 – 15	10 – 17.5	12.5 – 19.7	12.4 – 19.3	9.9 – 16.2
Wind speeds (mph)	11.7	11.2	10.3	10.1	10.8	12.5
Rain days	14	13	13	15	17	16
Humidity (%)	79	78	80	82	82	84

3.3 Grid:

Norway currently has in place a grid system that has the capacity to transport electricity from areas in which hydropower production already exists to other parts of the country. It would be most beneficial and practical that new solar farms for solar PV be constructed, if possible, in the same areas that the storage hydropower plants are located.

The basis for this recommendation is that the avoidance of constructing new grid systems should be prioritised where possible to reduce the negative impacts on the environment, reduce installation costs and reduce the time frame in which these new solar farms could come into operation.

If new grid networks need to be built, both costs incurred, and environmental factors need to be considered. The extra costs involved in constructing new solar farms, as well as a grid system that could accommodate the extra capacity, could outweigh the benefits of increasing solar energy in the Norwegian energy mix. With the construction of the new solar farms, changes to the environment will no doubt be necessary. When introducing new technologies into an energy mix and constructing new renewable energy facilities, it is important to minimise the environmental impacts. If grid networks must be erected as well as new solar farms, this would increase the possible negative impact on the environment. This may result in resistance from lobby groups or the government, when attempting to gain the necessary approval for both installation and applications of any new solar farms.

As stated earlier, Norway is divided into five different energy regions as shown in figure 12. NO1 (east), NO2 (south), NO3 (middle), NO4 (north) and NO5 (west). A barrier with the current situation of the Norwegian grid system is that there is a bottle neck with the flow of electricity from the North of the country to the south. A bottleneck in the energy grid system arises when there is a deficit of electricity in one region and a surplus in another region without the grid system having the capacity or infrastructure to transport electricity from one region to the other. (Daloub et.al., 2016)

To overcome the problem of this bottleneck there is strong connectivity between the Norwegian and Swedish electricity networks. Electricity is transported from the northern parts of Norway into Sweden and then back across the border into Norway in the southern part of the country.

3.4 Technology

Solar PV converts solar energy into electricity by absorbing sunlight and utilising the photoelectric effect. This process occurs when semiconductors release electrons when exposed to light, causing an electricity to flow. (energy.gov) The assumed construction of the solar panels for this thesis are mounted on the ground using frames as supports that the solar panels are fixed to.

3.4.1 Solar PV cells

There are several varieties of solar PV cells available however, the solar PV that we used in this study was the REC Solar REC280TP: The REC Solar REC280TP has a nominal efficiency of 17,65% and a maximum power of 280W. This solar PV panel is made of polycrystalline and is not a bifacial solar panel. Figure 13 shows the picture of the solar panel (REC Solar REC280TP) chosen in this feasibility study. Refer to appendix A for further information on the solar PV module.

Figure 13: REC Solar REC280TP (Solar Electric Supply, 2023)

3.4.2 Inverter

The inverter that was used in this thesis is an inverter produced by SMA America technologies, the model number SMA America: SB5,0-1SP-US-41 [240V] (energysage, 2023) Refer to appendix B for further information on the inverter.

3.4.3 DC AC ratio

Direct current (DC) is flow of current in one direction and comes from different sources like batteries or solar cells. Alternating current (AC) is when the current inverts direction. AC is the method in which electricity is delivered through grid systems to the final user, such as households. The desired DC to AC ratio that was used is 1,34. The optimal DC to AC ratio for low efficiency inverters and medium efficiency inverters in northern Europe are, 1.3 to 1.8 and 1.2 to 1.5 respectively. (Mondol, Yohanis and Norton, 2006)

3.5 Data Sources

The data that was collected to undertake this thesis was collected from a variety of different sources. All data collected is data that is available to the public, is from reliable and credible sources, and mostly obtained from Norwegian government agencies.

The weather data used to perform the calculations was obtained from the National Solar Radiation Database (NSRDB). This database is compatible with the system advisor model that was used to calculate the total energy production per location. The weather parameters used were:

- Temperature
- DHI – Diffuse Horizontal Irradiance
- DNI – Direct Nominal Irradiance
- Clear sky DHI
- Clear sky DNI
- Relative Humidity
- Solar Zenith Angle
- Surface Albedo
- Precipitable Water
- Wind Direction
- Wind Speed

3.6 Method of calculation

The average level of imported electricity over the past five years, across the warmer months, as a target for solar PV to match and potentially exceed. This would be achieved in two ways. The electricity generated would firstly directly replace the imported electricity per month, for every month during the warmer months. The second would be to generate enough electricity throughout the summer months (as a total period), to meet the total imported electricity during the same period, not directly replacing all hydropower production during the summer. This electricity would be used as an alternative to electricity normally generated from hydropower during this period, saving the water normally used for that component to then be used in winter to increase hydro power production and thus replace energy normally imported at that time.

Water as an energy source is the dominant resource in the Norwegian electricity mix. There are two different types of hydro power production in Norway. Storage hydropower and run-of-river hydropower. Storage hydropower utilises reservoirs in catchment areas to hold large volumes of water that can be stored and used to produce electricity as needed. Run-of-river hydropower is installed in smaller areas such as rivers or streams and has no storage system. The water continuously flows through the turbines generating electricity which must be used at the same time. (iha, 2022)

For the purpose of this thesis an assumption has been made that Norway has the potential to store all water in storage hydropower reservoirs that would be saved during the summer months to be used at a later date.

3.7 System Advisor Model

The calculations of energy output at the different locations were obtained using the System Advisor Model (SAM). SAM is a program used to calculate the power generated from solar PV sites.

SAM is a software program that has all the data that is required for the different variables, which are used when calculating the energy output from solar PV at different locations. By using such a software program, it is easier to get an accurate calculation of the energy output rather than calculating the different parameters manually. The ease in which it is possible to access reliable weather data from the NSRDB website (NRSDB, 2022) and that SAM can calculate largescale solar PV systems was a deciding factor in SAM being chosen as the preferred software for this thesis. Another advantage of SAM is that by simply adjusting one or more of the variables, it is quick and easy to compare the results of the simulations.

There are a several variables that can be adjusted, however the main variables that were adjusted for this thesis were:

- Location (weather data)
- Solar panel (type)
- Inverter
- Size of installed capacity
- AC – DC ratio

SAM has the option to calculate economical outcomes, however, this service is not used in this thesis as no economical calculations will be addressed.

The interface that SAM uses, is simple and easy to learn and use. This advantage makes the software perfect for designing solar PV projects and calculating outcomes from different variables associated with solar PV production.

The first step when commencing a project in SAM, is to choose the option Photovoltaic, detailed PV model, power purchase agreement single owner option. This gives the user the option to start modelling their desired Solar PV model. The Location and Resource tab is where the weather data is uploaded. The weather data is collected from NREL: National Solar Radiance Database.

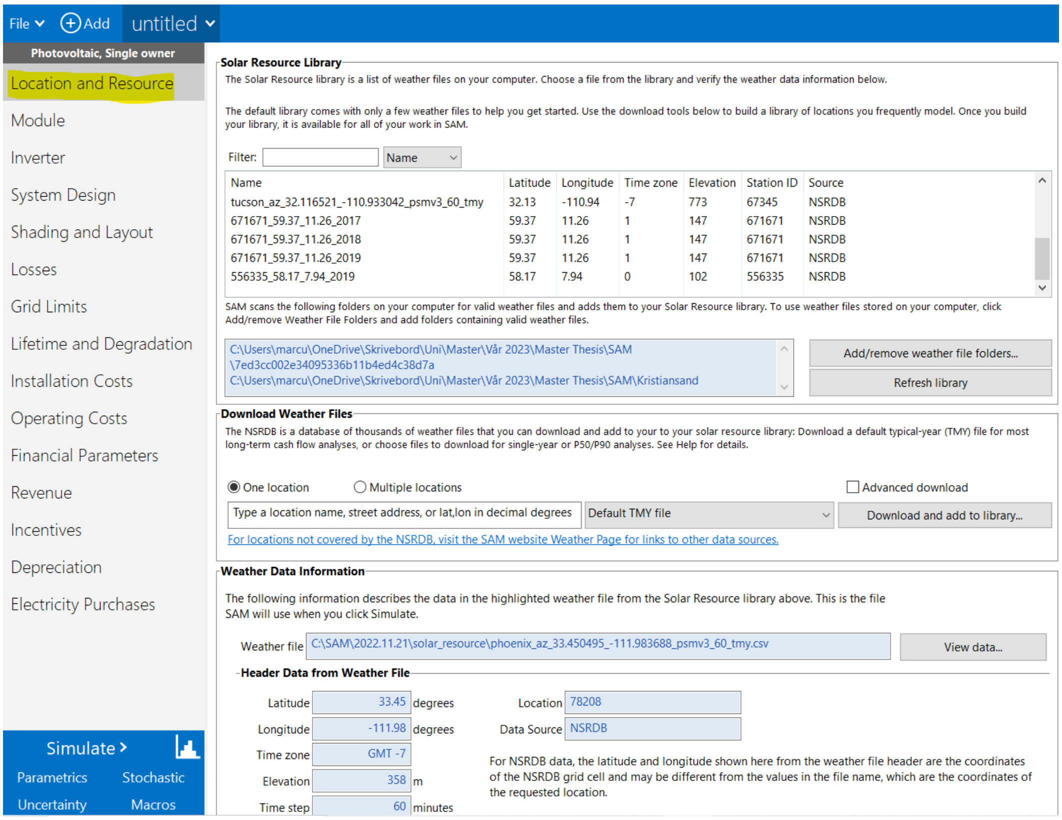


Figure 14: Interface SAM (Location & Resource)

Next the module and inverter need to be selected. The interface is shown in figure 15.

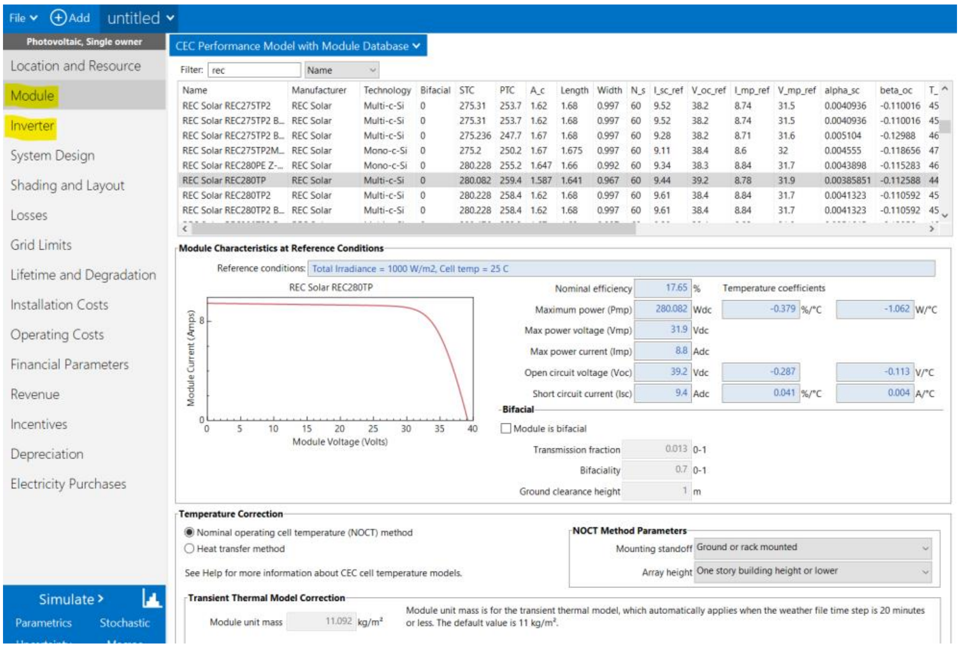


Figure 15: Interface SAM (Module & Inverter)

The system design section as shown in figure 16, is an important function as this is where the desired array size is chosen, as well as the desired DC to AC ratio. After determining these two parameters, SAM will calculate the number of inverters and modules that are required.

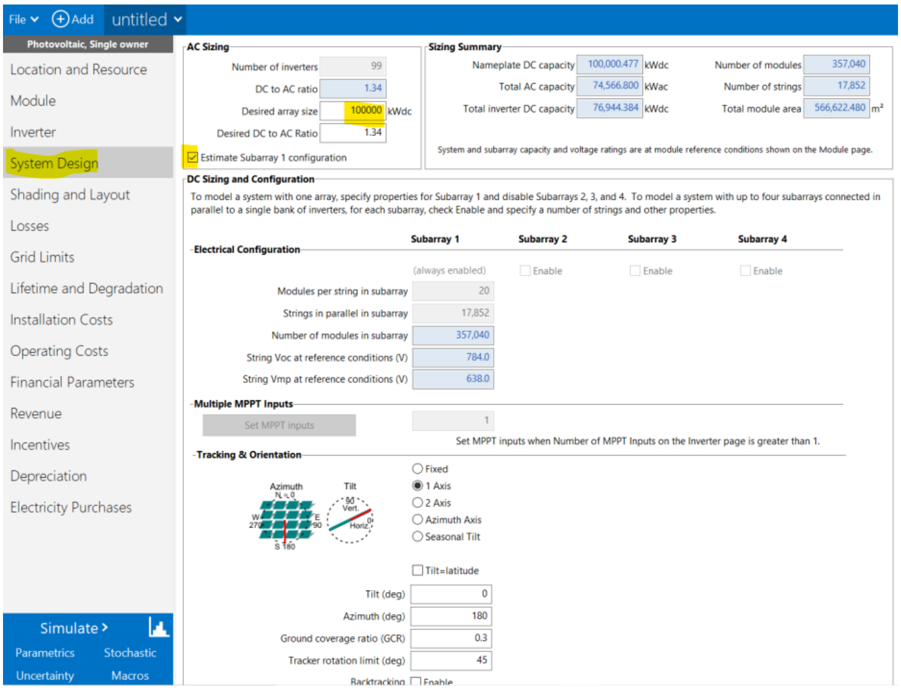
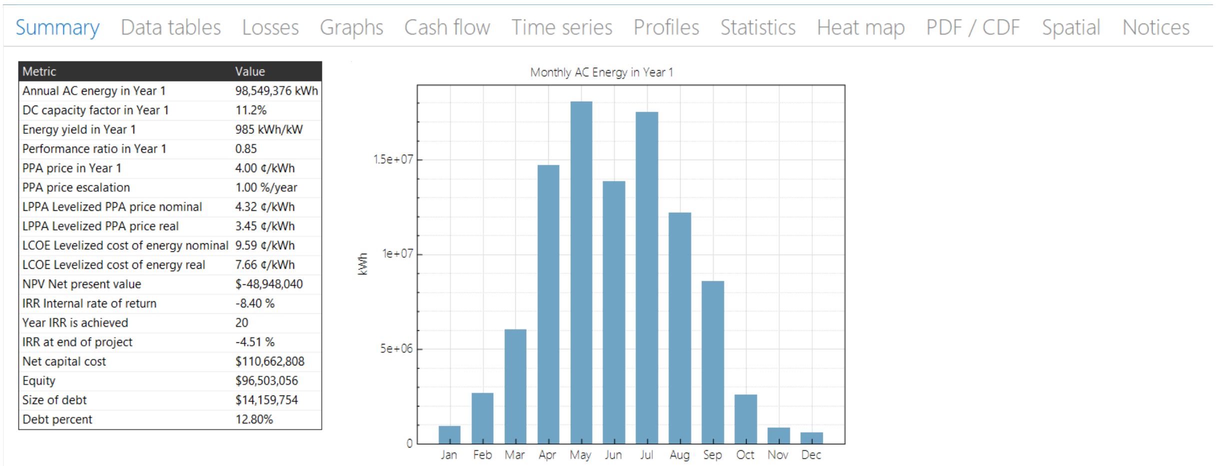


Figure 16: Interface SAM (System Design)

Total Production

The total electricity production from six selected locations in Norway was calculated, to determine how much electricity could be produced by six locations in three different energy regions. The monthly production for each location was also calculated to determine how much combined electricity is produced per month per location, as well as the total combined production per month from all six locations.

After completing all the inputs stated previously, by clicking “simulate” the total production is calculated. Production is also displayed in a bar graph, that is dived into production per month.



Metric	Value
Annual AC energy in Year 1	98,549,376 kWh
DC capacity factor in Year 1	11.2%
Energy yield in Year 1	985 kWh/kW
Performance ratio in Year 1	0.85
PPA price in Year 1	4.00 ¢/kWh
PPA price escalation	1.00 %/year
LPPA Levelized PPA price nominal	4.32 ¢/kWh
LPPA Levelized PPA price real	3.45 ¢/kWh
LCOE Levelized cost of energy nominal	9.59 ¢/kWh
LCOE Levelized cost of energy real	7.66 ¢/kWh
NPV Net present value	$-48,948,040
IRR Internal rate of return	-8.40 %
Year IRR is achieved	20
IRR at end of project	-4.51 %
Net capital cost	$110,662,808
Equity	$96,503,056
Size of debt	$14,159,754
Debt percent	12.80%

Figure 17: Interface SAM (Production)

To access the data for production and other variables, the data tables tab is selected, where single, monthly, or annual data can be accessed.

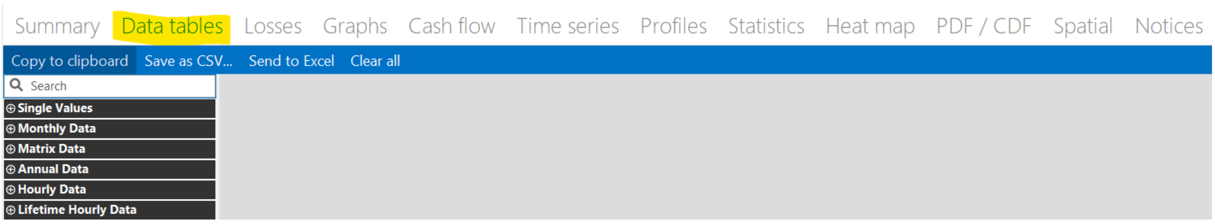


Figure 18: Interface SAM (Data tables)

Land area

The total land area was calculated to ascertain how much land area would be required for the construction of the solar farms, to produce the required amount of electricity.

In the system design section, SAM also calculates the total land area that is required to construction the modules.

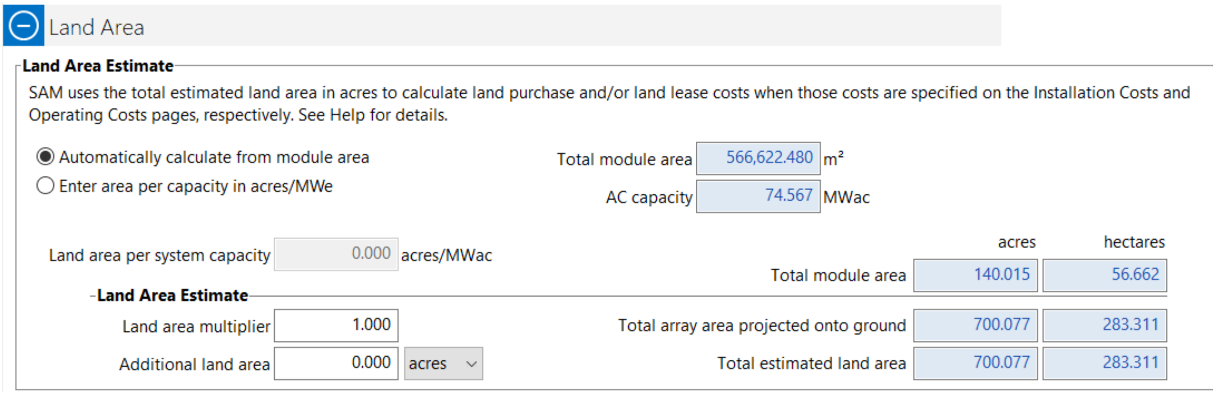


Figure 19: Interface SAM (Land area)

3.8 Scenarios:

There are 3 scenarios that were conducted in the calculations.

- Scenario 1: a preliminary calculation to determine the total production of the solar farms for 6 locations in Norway.
- Scenario 2: to ascertain the minimum number of locations required for solar PV to cover electricity imported every month from April - September.
- Scenario 3: to ascertain the total number of locations required to cover import during the period of April – September.
- Scenario 4: do not include September as part of the summer months.

3.8.1 Scenario 1

Weather data was collected from NSRDB for the six locations in Norway and uploaded to SAM where the total production for each location was calculated. Further calculations were conducted to ascertain the total production per month (April – September).

3.8.2 Scenario 2

Scenario 2 was conducted to ascertain the minimum number of locations required to cover import every month, thus eliminating the need to import electricity at all during the summer months (April – September). To determine the minimum number of locations, the month that required the most locations would be used. This was decided as the volume if electricity imported in every month would need to be meet.

As the chances of having many locations in scenario 2 was high, it was decided to investigate the possibility of solar PV not meeting the import demands every month, but rather across the summer months as a whole. In Scenario 3 this possibility will be addressed.

3.8.3 Scenario 3

Scenario 3 discusses the possibility of solar PV producing enough electricity during the summer months to cover the total electricity imported during that same period.
To calculate the total number of locations that would be required for this scenario, there were several steps that needed to be completed.

1. Calculate the total import for the summer months (April – September).
2. Calculate the total number of minimum locations required.
3. Divide the minimum number of locations required by the number of months during the summer period.
4. Multiply the answer in Step 3 with average electricity production from solar PV for that month.
5. Determine the differential for each month, between the import level and the projected production.
6. Calculate the total of the differential for each month to determine if the total production would be equal to the import level or greater.

3.8.4 Scenario 4

Scenario 4 addressed the possibility of solar PV producing enough electricity during the summer months to cover the total import during that same period, however scenario 4 will exclude the month of September in the calculations. The same 6 steps were undertaken as in scenario 3.

3.9 Export

The possibility for Norway exporting electricity was also addressed. The water that is saved from not using hydropower production from April to September, could not only be used during other periods to increase flexibility and security in the Norwegian electricity market, but could be used to produce electricity that could be exported.

4.0 Results and Discussion

This chapter includes the results and discussion section of the thesis. It was determined that six locations are evidently not adequate to cover the total imported electricity into Norway during the summer months. The calculations of the four scenarios will be presented in this chapter, Scenario 1 identifying the total production of the preliminary six locations, Scenarios 2 and 3, that will identify two different possibilities of solar PV covering average import during the summer months and Scenario 4, that will exclude September from the calculations. In addition to the scenarios, export will be discussed as a possible use for the energy resources saved by the electricity production of solar PV during the summer months as well as issues that may arise with the construction of new grid connections and possible issues related to land area.

4.1 Estimation of solar PV energy output to cover imported electricity.

Norway is both an importer and exporter of electricity. With Norway's proximity to Europe, it is part of the European Energy system which enables countries to import and export electricity. (IEA,2022) Norway has an interconnected electricity network with some European countries and other non-European countries, in particular Sweden, Germany, the United Kingdom and the Netherlands. (Fasting, 2022) This partnership allows countries to import and export energy as required, thus allowing a relatively free flow of energy between countries. A free-flowing energy system is vital for keeping the energy balance both in Norway and in Europe.

In all months throughout the year, Norway imports a portion of its electricity needs. Several factors influence the volume of imported electricity to Norway in different months. These include weather conditions, estimated demand throughout the remaining months of the year, costs associated with importing electricity and the water level in the reservoirs. Figure 20 shows the variability in total imported electricity into Norway while figure 21 shows the variability in imports during the summer months in the years 2018-2022. On average, over the past five years, Norway imported 9TWh of electricity annually. However, this total has varied from between 4 to 13TWh.

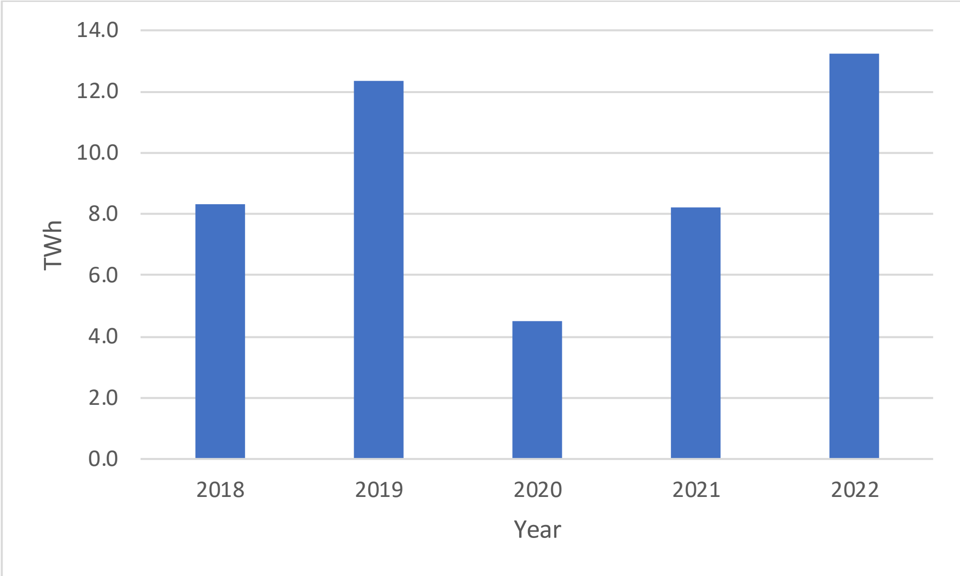


Figure 20: Electricity import, Norway per year

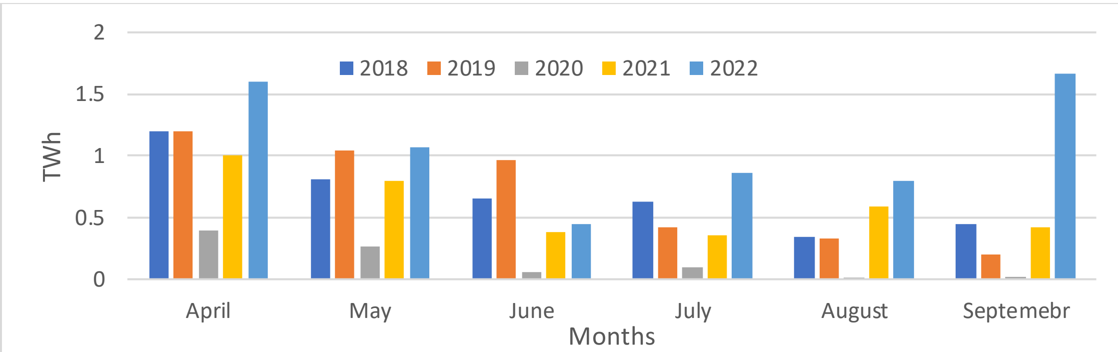


Figure 21: Electricity import, Norway per year (April – September)

Table 5: Shows the total electricity imported in TWh over the last 5 years*. (SSB, 2023)

Year	Total Import (annually)
2018	8,3
2019	12,4
2020	4,5
2021	8,2
2022	13,3
Average for the past 5 years	**9,34**

Table 6 shows the monthly imported electricity in TWh over the past five years. The months that are highlighted in yellow indicate the months with the most potential for generating electricity from solar PV.

Table 6: Import per month for the last 5 years*. (SSB, 2023)

	2018	**2019**	**2020**	**2021**	**2022**
January	0,8	1,2	1,1	0,4	1,2
February	0,4	1,2	0,9	0,7	1,5
March	1,0	2,1	0,6	1,0	0,9
April	1,2	1,2	0,4	1,0	1,6
May	0,8	1,0	0,3	0,8	1,1
June	0,7	1,0	0,1	0,4	0,5
July	0,6	0,4	0,1	0,4	0,9
August	0,3	0,3	0,01	0,6	0,8
September	0,4	0,2	0,02	0,4	1,7
October	0,3	0,8	0,2	1,0	1,4
November	0,4	1,1	0,5	0,7	0,5
December	1,4	1,8	0,4	0,9	1,4

The average level of electricity imported into Norway for each month was calculated by taking the average for each month over the past five years and dividing it by the number of years.

$$\text{Average import per month (TWh)} = \frac{\text{Monthy1} + \text{Monthy2} + \text{Monthy3} + \text{Monthy4} + \text{Monthy5}}{\text{Number of years}} \quad [4.1]$$

Table 7: shows the average import of electricity in Norway for the months of April – September over the last 5 years.

	April	May	June	July	August	September	**Total**
TWh	1080	800	500	480	400	550	**3 810**

4.2 Scenarios

4.2.1 Scenario 1:

The total annual electricity production for each site is shown in table 8.

Table 8: shows the total production at each of the 6 locations.

Region	Location	Total annual production (GWh)
NO1	Sarpsborg	94,4
NO1	Minnesund	90,8
NO2	Kristiansand	98,8
NO2	Stavanger	74,8
NO5	Bergen	79,8
NO5	Vaksdal	73,8

Appendix C: shows the figures of the total production at each of the 6 locations.

The total monthly production of the six locations was calculated using the SAM software program as can be seen in table 9.

Table 9: Production per month per location (GWh)

	April	May	June	July	August	September
Sarpsborg	15,9	13,2	14,3	16,5	10,8	6,7
Minnesund	15,8	12,7	13,5	16,3	10,2	6,7
Kristiansand	14,7	18,1	13,9	17,5	12,2	8,6
Stavanger	13,9	15,2	11,7	14,7	8,7	5,0
Bergen	13,3	15,2	11,5	15,6	8,6	5,4
Vaksdal	13,1	13,0	10,6	14,6	7,9	5,2

The total monthly production was calculated by combining the total production per month from each of the six locations. Table 10 shows the total monthly production of the six locations.

Table 10: Total monthly production (GWh)

	April	May	June	July	August	September	**Total production**
GWh	86,7	87,4	75,5	95,2	58,5	37,6	**440,9**

The results determined that a total of six solar PV farms, where each have an installed capacity of 100MW per location, spread across the three electricity regions do not produce enough electricity during the summer months to cover current levels of imported electricity during that period. As shown in table 7, the total average import during April – September is 3 810GWh while the total production from six locations during April – September is 440,9GWh, as shown in table 10.

4.2.2 Analysis of the data

An assumption has been made that by adding additional solar farms within the same electricity region, no new weather data would need to be collected as the data would be similar due to the longitude and latitude positioning of the new locations. The average of the weather data of the six already existing solar farms in this feasibility study will be used as the data for the additional calculations that will be conducted. Table 10 shows the total monthly production of the six locations in GWh.

Table 11 compares the total production of the six locations and the total average import per month to see if the production from only six locations could in fact cover the total imported electricity into Norway during the summer months.

Table 11: Comparison of total production and average import (GWh)

	April	May	June	July	August	September
Total Production	86,7	87,4	75,5	95,2	58,5	37,6
Average Import	1080	800	500	480	400	550
Remaining Import	-993,3	-712,6	-424,5	-384,8	-341,5	-512,4

After calculating the data by month, the average production per site was calculated in each month. The month of September is used as an example to visualise the answers in Table 12. As there is a total of 37,6GWh produced in September from the six locations, the average production per location in the month of September is 6,3 GWh.

Table 12: Average production per location per month (GWh)

	April	May	June	July	August	September
Total Production	86,7	87,4	75,5	95,2	58,5	37,6
Location	6	6	6	6	6	6
Average production per location	14,45	14,57	12,58	15,87	9,75	6,27

4.3 Scenario 2:

Table 13 shows the number of locations that would be required if solar PV would produce enough electricity to cover the import every month.

Table 13: Number of locations required to cover all import every month (GWh)

	April	May	June	July	August	September
Average production per location	14,45	14,57	12,58	15,87	9,75	6,27
Import	1080	800	500	480	400	550
Number of locations needed	75	55	40	31	42	**88**

As seen in Table 14 for solar PV to meet current electricity imports every month, 88 locations would be required. As import volumes start to increase and production from solar PV is decreasing in September, the need for more sites is evident. As the need to meet all import for each month must be covered by the total number of solar farms, the month of September is used, when determining the minimum number of locations required.

Table 14: Combination of the tables and information provided above.

	April	May	June	July	August	September
NO1	15,9	13,0	13,9	16,4	10,5	6,7
NO2	14,3	16,6	12,8	16,1	10,5	6,8
NO5	13,2	14,1	11,1	15,1	8,3	5,3
Total average	14,5	14,6	12,6	15,9	9,8	6,3
Import	1080	800	500	480	400	550
Total sites needed	75	55	40	31	41	**88**

Therefore, there will need to be a minimum of 88 locations for solar farms spread across regions NO1, NO2 and NO5 to directly cover average monthly import levels throughout the summer months without the use of hydropower generation.

4.4 Scenario 3:

The calculations in scenario 2 of average production per month will be used to calculate the total number of locations required to meet total import for the period April – September. The calculations will aim to ascertain how many locations would be required to achieve this.

The first step was to ascertain the total import for the six months assessed, calculated in scenario 2. By combing the average import per month an average of 3 810GWh of electricity is imported into Norway between the months of April – September, as shown in Table 15.

Table 15: Total average import April – September.

	April	May	June	July	August	September	Total
Import (GWh)	1080	800	500	480	400	550	<u>3810</u>

The next step was to calculate the total number of sites that would be required to cover the average import per month as shown in table 16. Results from table 14 which shows the total number of locations required to cover the total average import per month was calculated was used in this step.

Table 16: shows the total number of locations required to cover average import per month.

	April	May	June	July	August	September	Total
Number of sites	75	55	40	31	41	88	<u>330</u>

To calculate the new minimum number of locations required if the total average import would be covered during the months of April – September as a period <u>not</u> per month. A total of 55 sites would be required. See Appendix D for formula.

Steps 4 & 5:

Table 17: shows the calculations of 55 locations (GWh).

	April	May	June	July	August	September	**Total**
Locations	55	55	55	55	55	55	55
Average production	14,5	14,6	12,6	15,9	9,8	6,3	73,7
Total production	797,5	803	693	874,5	539	346,5	4 053,5
Import	1080	800	500	480	400	550	3 810
Difference	<u>-282,5</u>	<u>-3</u>	<u>193</u>	<u>394,5</u>	<u>139</u>	<u>-203,5</u>	<u>243,5</u>

Total production from the six locations during the months of April – September from a total of 55 locations spread across the three electricity regions would be 4 053,5 GWh, as shown in table 18.

Table 18: is the total production in GWh of 55 solar PV farms in Norway during the months of April – September.

	April	May	June	July	August	September	Total
Production	797,5	803	693	874,5	539	346,5	4053,5

The total production of 4 053,5GWh is greater than the total import for the same period of 3 810GWh. This means that the total production of 55 solar PV farms located in NO1, NO2 and NO5 will produce 243,5GWh more of electricity than the average imported electricity in Norway.

This scenario shows that a total of 55 new locations are required for solar PV is to meet average import levels during the period April – September. It can be argued that the aim of solar PV is not to cover the entirety of the import level every month, but rather cover the total import during the period of April – September. A possible strategy could be to use hydro power to top up the demand for electricity in the months that demand is greater than production from solar PV, and then save the water in the months that production is greater than domestic demand. This method will give the same outcome, as the same volume of water would be conserved during this summer period.

4.5 Scenario 4:

In Scenario 4, September was excluded from the calculations. By doing this, the total number of locations required decreased dramatically. By using the same calculations as in Scenario 2, the minimum number of locations required for scenario 4 would be 75, to cover the import for the month of April as shown in table 19. This is a dramatic decrease from 88 that was the minimum required locations in scenario 2.

Table 19: shows the total number of locations required to cover average import per month excluding September.

	April	May	June	July	August	Total
Number of sites	75	55	40	31	41	242

When the same calculations were undertaken as were undertaken in Scenario 3 to determine the minimum locations required to meet average import for the period of April – August, the total of 242 sites divided by five months requires 49 locations.

Table 20: shows the calculations of 49 locations.

	April	May	June	July	August	**Total**
Locations	49	49	49	49	49	49
Average production	14,5	14,6	12,6	15,9	9,8	67,4
Total production	710,5	715,4	617,4	779,1	480,2	3 302,6
Import	1080	800	500	480	400	3 260
Difference	-369,5	-84,6	117,4	299,1	80,2	42,6

With 49 locations and the exclusion of September in the calculations, the total average production from 49 locations over the five-month period exceeds the total average import for the same period, as shown in table 20.

These calculations did not consider the impact of the total number of locations if the installed capacity of the solar farms was increased, or additional solar farms being constructed in the energy regions that have the highest average production per month.

4.6 Land Area:

Solar PV is land intensive and unless new solutions to develop for example dual use activities such as, agriculture (sheep grazing) or combined wind and solar farms, issues may arise with finding suitable and sufficient land for solar PV in Norway. As the average land area required for each solar PV farm is 140 acres, it is highly unlikely that this amount of land would be made available for new solar projects. If scenario 4 was to be implemented, 49 locations for solar PV farms, 6 860 acres of land would be required to produce enough electricity to meet the average import during the summer months from solar PV.

4.6.1 Different types of technologies and land uses

There are several different types of technologies that could be assessed when looking at introducing solar PV into the Norwegian electricity mix. Solar PV was the technology that was focused on in this thesis, but other solar technologies could also be a viable option for the Norwegian market.

There are also possibilities for combining two different sectors. An option that is currently being assessed is the combination of agriculture and solar power. The installation of solar panels on already existing agricultural land is something that should be considered. This option decreases environmental impacts by reducing the amount of land that needs to be made available up to construct a solar farm, as well as not having a significant impact on reducing productivity for farmers. A combination of agriculture and solar PV electricity production can give already existing land an even higher usage rate, by utilising the land area for two different sectors. (Maicrosoft Europe, 2021) The combining of already established and new wind farms and solar farms in one location, could also increase the possibility of providing enough land area for solar PV. Floating solar farms could potentially be a possibility for Norway, as Norway has a large coastline and substantial river systems. An advantage of floating solar farms is that they are dual use and can reduce disputes over land use. (intersolar, 2022)

4.7 Export

Although the aim of the thesis is to examine the flexibility and security of the Norwegian energy system, by reducing levels of imported electricity, there is also an opportunity for Norway to look at increasing its export activities. The water saved from reducing hydropower production during the summer months could be used to produce electricity for the export market. Current high prices for electricity across Europe make this an attractive option as seen in figure 22.

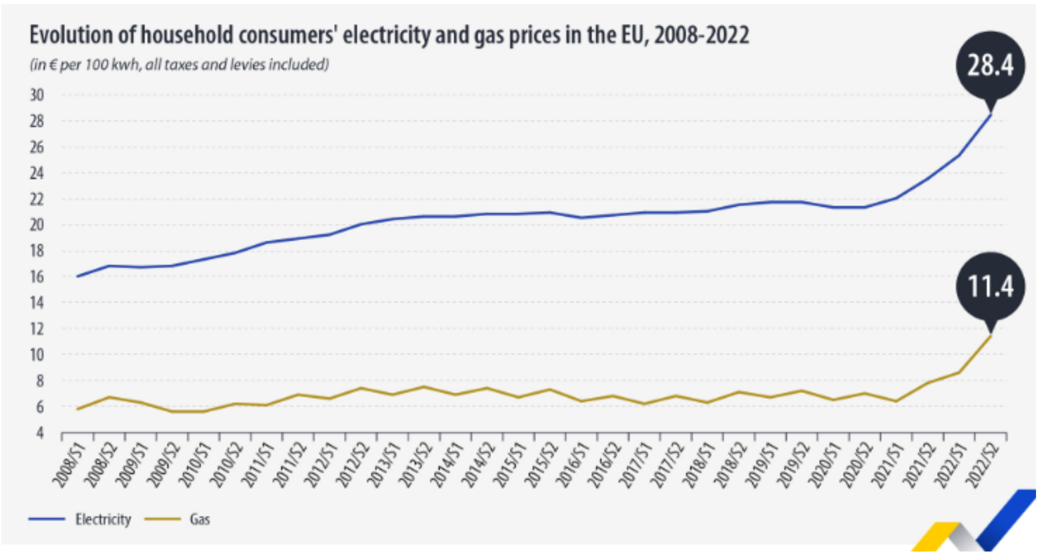


Figure 22: Electricity and gas prices, Europe (2008-2022). (Eurostat, 2023)

Located in the southern part of Norway have underground electricity cables that connect Norway's electricity system to electricity markets of other European countries been installed. The North Sea Link (NSL) is an interconnector power line that connects the United Kingdom and Norway's electricity systems. The cable runs from the southern part of Norway (NO2) to the mid northwest of England. (North Sea Link, 2023) NordLink is a subsea interconnector that connects Germany and Norway. (Statnett, 2023)

Both the United Kingdom and Germany has substantially increased its portion of locally produced renewable electricity as the countries look to transition to a greener approach electricity production. (Spilde et.al., 2019) There has also been a move away from fossil fuel as an energy source of electricity production. In periods of reduced wind capacity, the United Kingdom and/or Germany may need to import electricity. With Norway producing electricity from renewable energy sources and the completion of NSL and NordLink, Norway was an attractive import provider for both countries.

Figure 23 represents the total export from Norway over the past 5 years.

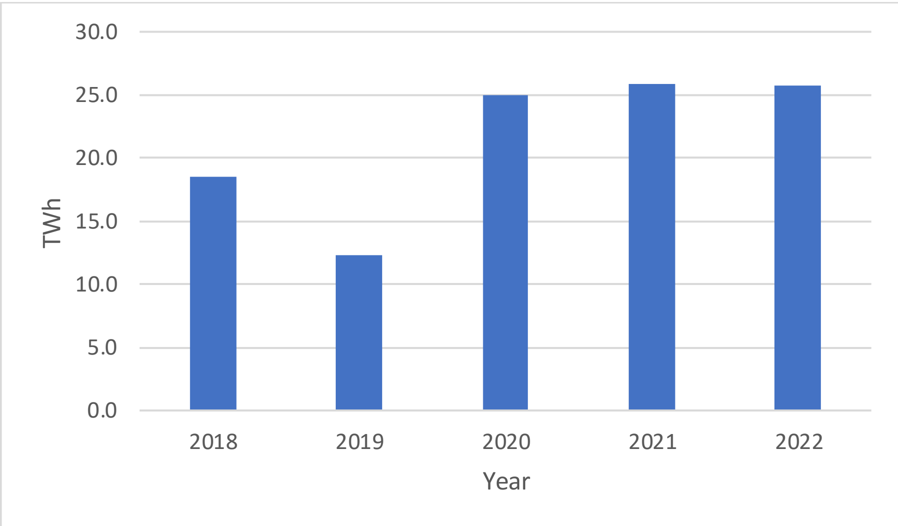


Figure 23: Electricity export, Norway per year (TWh)

Figure 24 illustrates electricity export per year for the months of October to March.

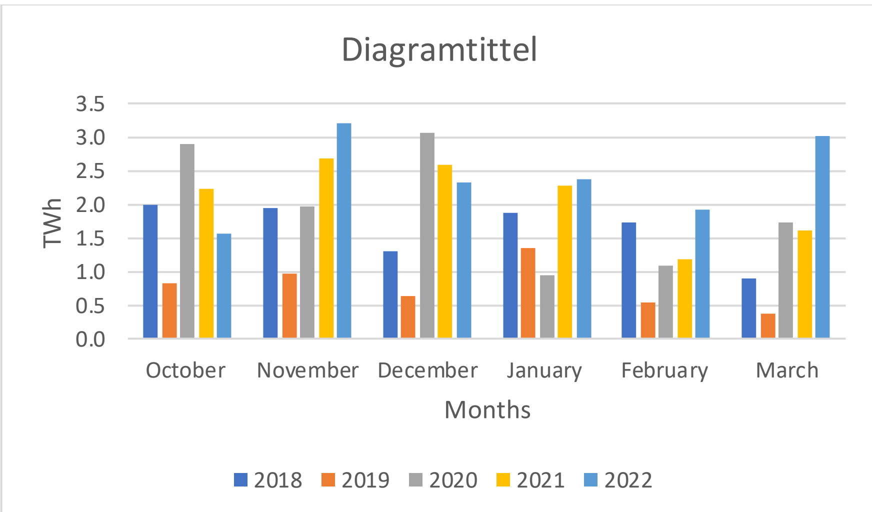


Figure 24: Electricity export, Norway, per year (October - March)

5.0 Conclusions

This thesis has addressed the feasibility of solar PV in Norway, to increase flexibility and electricity security, particularly the possibility of solar PV production during the warmer months to meet the volume of existing imported electricity during the same period. The SAM software program has been used to assist in the calculation of the total production of 6 solar PV farms could produce in six different locations located in three of the five electricity regions in Norway. Based on the calculations and findings in this thesis some conclusions will be proposed.

It has been shown that electricity from solar PV is viable in Norway, and that a total of 440,9GWH could be produced from six sites that have a combine installed capacity of 600MW. This amount represents 11,6% of the average electricity imported during the warmer months into the country. However, by increasing the number of sites or the installed capacity of an individual site, the potential for the sector grows.

Even though solar PV does not meet the target of replacing average import per month, there is a possibility that solar PV can produce enough electricity during the summer period to partially replace imported electricity during the same period.

The best option discussed in this thesis is to replace imported electricity at least partially from April – August. Of the discussed scenarios in this thesis, Scenario 4 would be the most suitable scenario for solar PV production in Norway. This scenario requires the fewest number of locations (49) to eliminate imported electricity during this period, while still being able to increase flexibility and security. The average import in the period April – August is 3 260GWH, while average production is 3 302,6GWh. This scenario uses a combination of hydropower and solar PV to meet the domestic demand, and in the months where solar PV production is greater than import the water stored in the reservoirs can be saved for production at alternative time periods. This scenario means that during the months of April – August 3 302,6GWh of electricity can be saved and stored in the reservoirs to be used during other periods to increase flexibility and electricity security in Norway.

A barrier to increased use of solar PV is the land area required for construction of the solar farms. The total land area needed for the favoured scenario is 6 860 acres. It would be difficult with political standpoint currently in Norway, for these projects to be approved unless further analysis of the economic benefits or for dual usage opportunities that could make the concept viable and more appealing.

6.0 Recommendations

Further research will need to be done to discover the possibilities of investment in solar PV. This work includes:

- Cost benefit analysis of start-up infrastructure for solar PV versus savings from imported electricity
- Public and political will, to allow utilisation of land for solar PV parks given the already strong views against onshore wind production.
- Investigate shared use of land for solar farms.
- Calculate the extra environmental and monetary costs associated with connecting the solar farms to the grid.
- Assess increasing demand, can solar PV in different forms play a role in meeting that demand.
- The use of bifacial solar panels

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Appendices

Appendix A: Product description of solar module

REC TwinPeak BLK SERIES

PREMIUM SOLAR PANELS WITH SUPERIOR PERFORMANCE

REC TwinPeak BLK Series solar panels feature an innovative design with high panel efficiency and power output, enabling customers to get the most out of the space used for the installation.Combined with industry-leading product quality and the reliability of a strong and established European brand, REC TwinPeak BLK panels are ideal for residential and commercial rooftops worldwide.

General data

- Cell type: 120 REC HC multi-crystalline 6 strings of 20 cells (6" x 3")
- Glass: 0.12" (3.2 mm) solar glass with anti-reflective surface treatment
- Back sheet: Double layer highly resistant polyester (white)
- Frame: Anodized aluminum (black)
- Junction box: 3-part with bypass diodes, IP67 rated 4 mm² solar cable, 35" + 47"
- Connectors: Multi-Contact MC4 (4 mm²)

Mechanical data

- Dimensions: 1665 x 991 x 38 mm
- Area: 1.65 m²
- Weight: 18 kg

Electrical data

- Nominal Power - PMPP (Wp) 205
- Nominal Power Voltage - VMPP (V) 29.5
- Nominal Power Current - IMPP (A) 6.97
- Open Circuit Voltage - VOC (V) 36.1
- Short Circuit Current - ISC (A) 7.50

Maximum ratings

- Operational Temperature: -40 ... +85°C
- Maximum System Voltage: 1000 V
- Design Load*: 75.2 lbs/ft² (3600 Pa)
- 33.4 lbs/ft² (1600 Pa) *Refer to installation manual
- Max Series Fuse Rating: 15 A
- Max Reverse Current: 15 A

Warranty

- 10 year product warranty
- 25 year linear power output warranty (max. degression in performance of 0.7% p.a.)

More information:

- REC 280 TP BLK Data Sheet
- REC 280 TP BLK Installation Manual
- REC 280 TP BLK Packaging Datasheet
- REC 280 TP BLK Warranty Conditions (Europe)

Appendix B: Specification sheet SMA inverter

SUNNY BOY 3.0-US / 3.8-US / 5.0-US / 6.0-US / 7.0-US / 7.7-US

Value-Added Improvements

- SunSpec certified technology for cost-effective module-level shutdown
- Advanced AFCI compliant to UL 1699B for arc fault protection

Reduced Labor

- New Installation Assistant with direct access via smartphone minimizes time in the field
- Advanced communication interface with fewer components creates 50% faster setup and commissioning

Optimized Power Production

- ShadeFix, SMA's proprietary shade management solution, produces more power than alternatives
- Reduced component count provides maximum system reliability

Trouble-Free Service

- SMA Service Mobile App provides simplified, expedited field service
- Equipped with SMA Smart Connected, a proactive service solution that is integrated into Sunny Portal

SUNNY BOY 3.0-US / 3.8-US / 5.0-US / 6.0-US / 7.0-US / 7.7-US

Power with a purpose

The residential PV market is changing rapidly. Your bottom line matters more than ever—so we've designed a superior residential solution to help you decrease costs at every stage of your business operations. The Sunny Boy 3.0-US/3.8-US/5.0-US/6.0-US/7.0-US/7.7-US join the SMA lineup of field-proven solar technology backed by the world's #1 service team. This improved residential solution features ShadeFix, SMA's proprietary technology that optimizes system performance. ShadeFix also provides superior power production with a reduced component count versus competitors, which provides maximum reliability. No other optimized solution generates more power or is as easy as systems featuring SMA ShadeFix and SunSpec certified devices. Finally, SMA Smart Connected will automatically detect errors and initiate the repair and replacement process so that installers can reduce service calls and save time and money.

www.SMA-America.com

Technical data	Sunny Boy 3.0-US		Sunny Boy 3.8-US		Sunny Boy 5.0-US	
	208 V	240 V	208 V	240 V	208 V	240 V
Input (DC)						
Max. PV power	4800 Wp		6144 Wp		8000 Wp	
Max. DC voltage	600 V					
Rated MPP voltage range	155 - 480 V		195 - 480 V		220 - 480 V	
MPPT operating voltage range	100 - 550 V					
Min. DC voltage / start voltage	100 V / 125 V					
Max. operating input current per MPPT	10 A					
Max. short circuit current per MPPT	18 A					
Number of MPPT tracker / string per MPPT tracker	2/1				3 / 1	
Output (AC)						
AC nominal power	3000 W	3000 W	3330 W	3840 W	5000 W	5000 W
Max. AC apparent power	3000 VA	3000 VA	3330 VA	3840 VA	5000 VA	5000 VA
Nominal voltage / adjustable	208 V / ●	240 V / ●	208 V / ●	240 V / ●	208 V / ●	240 V / ●
AC voltage range	183 - 229 V	211 - 264 V	183 - 229 V	211 - 264 V	183 - 229 V	211 - 264 V
AC grid frequency	60 Hz / 50 Hz					
Max. output current	14.5 A	12.5 A	16.0 A	16.0 A	24.0 A	21.0 A
Power factor (cos φ) / harmonics	1 / < 4 %					
Output phases / line connections	1 / 2					
Efficiency						
Max. efficiency	97.2 %	97.6 %	97.3 %	97.6 %	97.3 %	97.6 %
CEC efficiency	96.0 %	96.5 %	96.5 %	96.5 %	96.5 %	97.0 %
Protection devices						
DC disconnect device / DC reverse polarity protection	● / ●					
Ground fault monitoring / Grid monitoring	●					
AC short circuit protection	●					
All-pole sensitive residual current monitoring unit (RCMU)	●					
Arc fault circuit interrupter (AFCI)	●					
Protection class / overvoltage category	I / IV					
General data						
Dimensions (W / H / D) in mm (in)	535 x 730 x 198 (21.1 x 28.5 x 7.8)					
Packaging dimensions (W / H / D) in mm (in)	600 x 800 x 300 (23.6 x 31.5 x 11.8)					
Weight / packaging weight	26 kg (57 lb) / 30 kg (66 lb)					
Temperature range: operating / non-operating	-25°C ...+60°C / -40°C ...+60°C					
Environmental protection rating	NEMA 3R					
Noise emission (typical)	39 dB(A)					
Internal power consumption at night	< 5 W					
Topology / cooling concept	transformerless / convection					
Features						
Ethernet ports	2					
Secure Power Supply	●*					
Display (2 x 16 characters)	●					
2.4 GHz WLAN / External WLAN antenna	●/○					
ShadeFix technology for string level optimization	●					
Cellular (4G / 3G) / Revenue Grade Meter	○/○**					
Warranty: 10 / 15 / 20 years ***	●/○/○					
Certificates and approvals	UL 1741, UL 1741 SA incl. CA Rule 21 RSD, UL 1998, UL 1699B Ed. 1, IEEE1547, FCC Part 15 (Class A & B), CAN/CSA V22.2 107.1-1, HECO Rule 14H, PV Rapid Shutdown System Equipment					
● Standard features ○ Optional features — Not available						
NOTE: US inverters ship with gray lids. Data at nominal conditions * Not compatible with SunSpec shutdown devices **Standard in SBX.X-1TP-US-41						
Type designation	SB3.0-1SP-US-41 / SB3.0-1TP-US-41		SB3.8-1SP-US-41 / SB3.8-1TP-US-41		SB5.0-1SP-US-41 / SB5.0-1TP-US-41	

Accessories

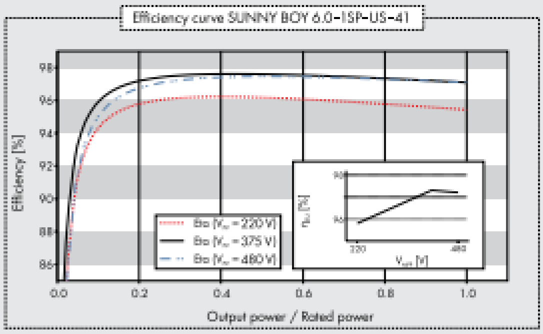
External WLAN antenna EXTANT-US-40

SunSpec Certified Rapid Shutdown Receivers

Revenue Grade Meter Kit RGM05KIT-US-10

Cellular Modem Kit CELLMODKIT-US-10

*** Listed warranty terms are applicable in SMA-designated primary support countries, including the U.S., Canada, and Mexico. Reduced terms or restrictions may apply in other Americas regions and territories including the Pacific and Caribbean.



Technical data	Sunny Boy 6.0-US		Sunny Boy 7.0-US		Sunny Boy 7.7-US	
	208 V	240 V	208 V	240 V	208 V	240 V
Input (DC)						
Max. PV power	9600 Wp		11200 Wp		12320 Wp	
Max. DC Voltage	600 V					
Rated MPP Voltage range	220 – 480 V		245 - 480 V		270 - 480 V	
MPPT operating voltage range	100 – 550 V					
Min. DC voltage / start voltage	100 V / 125 V					
Max. operating input current per MPPT	10 A					
Max. short circuit current per MPPT	18 A					
Number of MPPT tracker / string per MPPT tracker	3 / 1					
Output (AC)						
AC nominal power	5200 W	6000 W	6660 W	7000 W	6660 W	7680 W
Max. AC apparent power	5200 VA	6000 VA	6660 VA	7000 VA	6660 VA	7680 VA
Nominal voltage / adjustable	208 V / ●	240 V / ●	208 V / ●	240 V / ●	208 V / ●	240 V / ●
AC voltage range	183 – 229 V	211 – 264 V	183 – 229 V	211 – 264 V	183 – 229 V	211 – 264 V
AC grid frequency	60 Hz / 50 Hz					
Max. output current	25.0 A	25.0 A	32.0 A	29.2 A	32.0 A	32.0 A
Power factor (cos φ) / harmonics	1 / < 4 %					
Output phases / line connections	1 / 2					
Efficiency						
Max. efficiency	97.3 %	97.7 %	97.3 %	97.9 %	97.3 %	97.5 %
CEC efficiency	96.5 %	97.0 %	96.5 %	97.0 %	96.5 %	97.0 %
Protection devices						
DC disconnect device / DC reverse polarity protection	● / ●					
Ground fault monitoring / Grid monitoring	●					
AC short circuit protection	●					
All-pole sensitive residual current monitoring unit (RCMU)	●					
Arc fault circuit interrupter (AFCI)	●					
Protection class / overvoltage category	I / IV					
General data						
Dimensions (W / H / D) in mm (in)	535 x 730 x 198 (21.1 x 28.5 x 7.8)					
Packaging Dimensions (W / H / D) in mm (in)	600 x 800 x 300 (23.6 x 31.5 x 11.8)					
Weight / packaging weight	26 kg (57 lb) / 30 kg (66 lb)					
Temperature range: operating / non-operating	-25 °C ...+60 °C / -40 °C ...+60 °C					
Environmental protection rating	NEMA 3R					
Noise emission (typical)	39 dB(A)		45 dB(A)			
Internal power consumption at night	< 5 W					
Topology / cooling concept	transformerless / convection		transformerless / fan			
Features						
Ethernet ports	2					
Secure Power Supply	●*					
Display (2 x 16 characters)	●					
2.4 GHz WLAN / External WLAN antenna	● / ○					
ShadeFix technology for string level optimization	●					
Cellular (4G / 3G) / Revenue Grade Meter	○ / ○**					
Warranty: 10 / 15 / 20 years ***	● / ○ / ○					
Certificates and approvals	UL 1741, UL 1741 SA incl. CA Rule 21 RSD, UL 1998, UL 1699B Ed. 1, IEEE1547, FCC Part 15 (Class A & B), CAN/CSA V22.2 107.1-1, HECO Rule 14H, PV Rapid Shutdown System Equipment					
● Standard features ○ Optional features — Not available						
NOTE: US inverters ship with gray lids. Data at nominal conditions * Not compatible with SunSpec shutdown devices **Standard in SBX.X-1TP-US-41						
Type designation	SB6.0-1SP-US-41 / SB6.0-1TP-US-41		SB7.0-1SP-US-41 / SB7.0-1TP-US-41		SB7.7-1SP-US-41 / SB7.7-1TP-US-41	

POWER+ SOLUTION

The SMA Power+ Solution combines legendary SMA inverter performance and SunSpec certified shutdown devices in one cost-effective, comprehensive package. In addition, SMA ShadeFix technology optimizes power production and provides greater reliability than alternatives.

This rapid shutdown solution fulfills UL 1741, NEC 2014, and NEC 2017 requirements and is certified to the power line-based SunSpec Rapid Shutdown communication signal over DC wires, making it the most simple and cost-effective rapid shutdown solution on the market.

Visit www.SMA-America.com for more information.

SIMPLE, FLEXIBLE DESIGN

Speed the completion of customer proposals and maximize the efficiency of your design team with the Sunny Boy-US series, which provides a new level of flexibility in system design by offering:

» Hundreds of stringing configurations and multiple independent MPPTs

» SMA's proprietary ShadeFix technology optimizes power production

» Diverse application options including on- and off-grid compatibility

VALUE-DRIVEN SALES ENABLEMENT

SMA wants to enable your sales team by arming them with an abundance of feature/benefit support. Show your customers the value of the Sunny Boy-US series by utilizing:

» The opportunity to join the SMA PowerUP network of installers who receive in-depth training, enhanced service, and prioritized marketing support

» SMA's 35 year history and status as the #1 global inverter manufacturer instills homeowners with peace of mind and the long-term security they demand from a PV investment

» The most economical solution for shade mitigation with superior power production

IMPROVED STOCKING AND ORDERING

Ensure that your back office business operations run smoothly and succinctly while mitigating potential errors. The Sunny Boy-US series can help achieve cost savings in these areas by providing:

» An integrated DC disconnect that simplifies equipment stocking and allows for a single inverter part number

» All communications integrated into the inverter, eliminating the need to order additional equipment

STREAMLINED INSTALLATION AND COMMISSIONING

Expedite your operations in the field by taking advantage of the new Sunny Boy's installer-friendly feature set including:

» Direct access via smartphone and utilization of SMA's Installation Assistant, which minimizes time/labor spent in the field and speeds the path to commissioning

» Simple commissioning and monitoring setup in a single online portal

» The fastest, easiest installation thanks to SMA ShadeFix and SunSpec certified shutdown devices

SUPERIOR SERVICE

SMA understands the factors that contribute to lifetime PV ownership cost, that's why the Sunny Boy-US series was designed for maximum reliability and backstopped by an unmatched service offering. Benefit from:

» SMA Smart Connected, a proactive service solution integrated into Sunny Portal that automatically detects errors and initiates the repair and replacement process

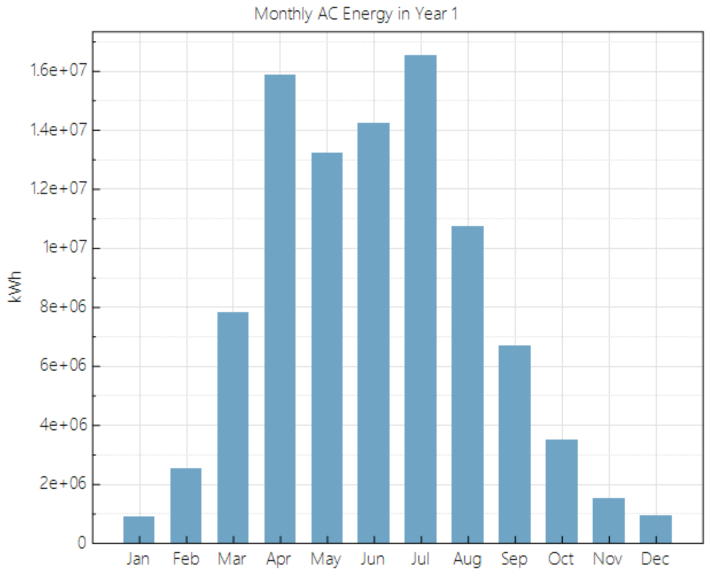
» The SMA Service Mobile App, which provides simplified, expedited field service

Appendix C: Graphs showing total production of the 6 preliminary locations.

The graphs were generated using the software program SAM.

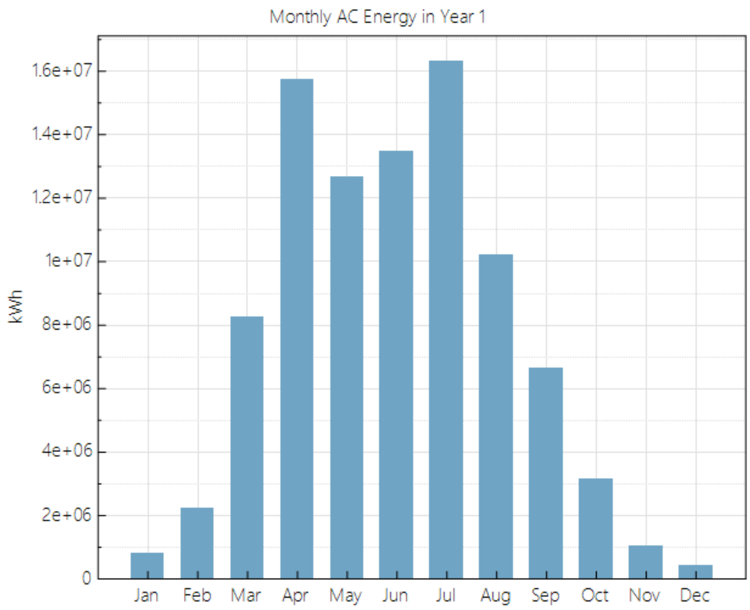
<u>Sarpsborg</u>

Total production for the solar park located in the Sarspsborg area.



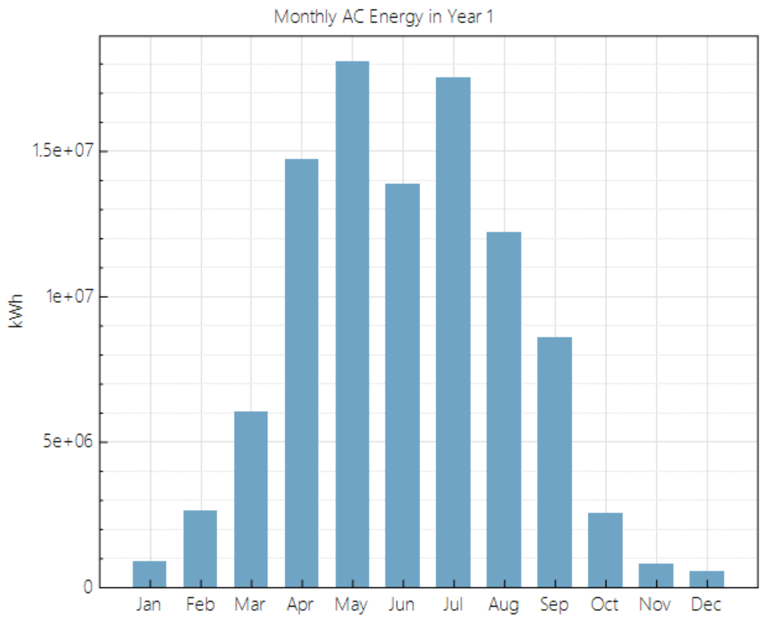
Minnesund

Total production for the solar park located in the Minnesund area.



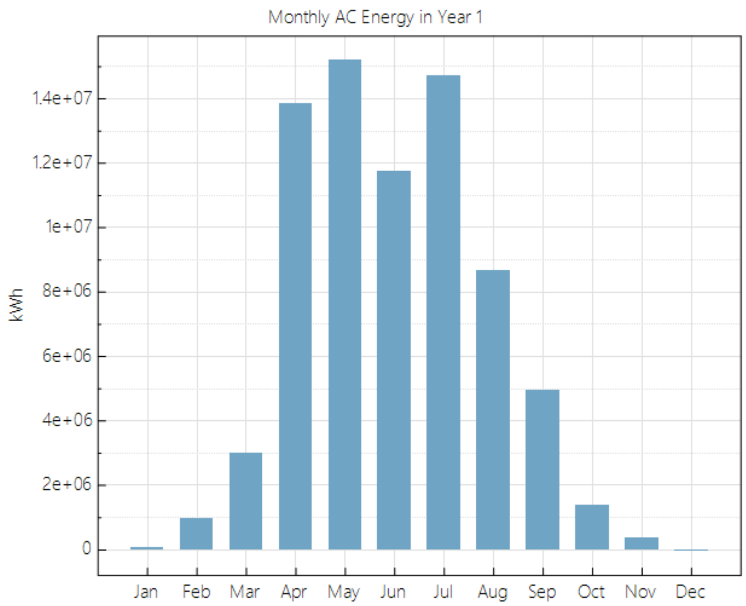
Kristiansand

Total production for the solar park located in the Kristiansand area.



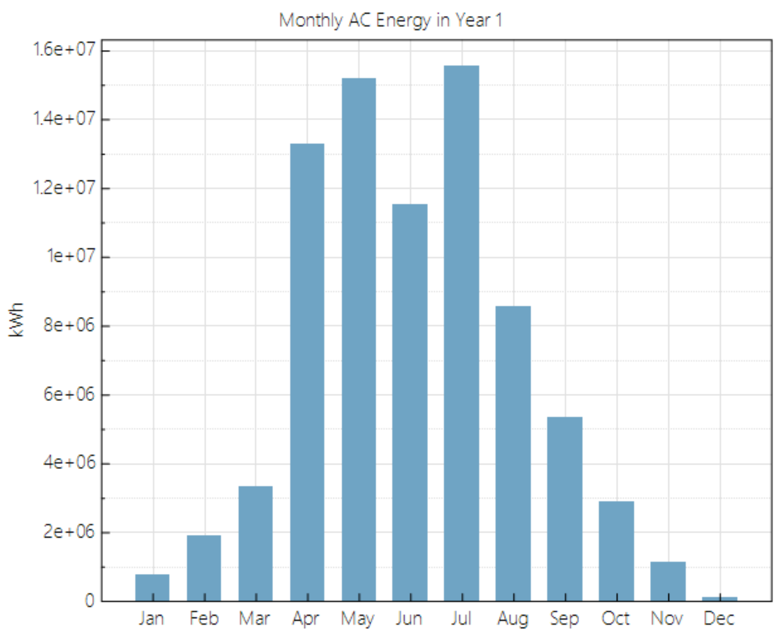
Stavanger

Total production for the solar park located in the Stavanger area.



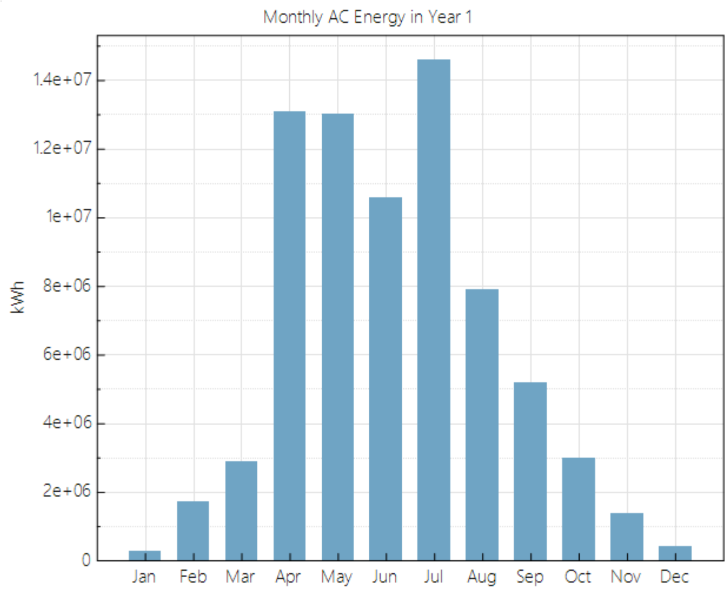
Bergen

Total production for the solar park located in the Bergen area.



Vaksdal

Total production for the solar park located in the Vaksdal area.



Appendix D:

Calculation of the new locations required.

$$\text{New minimum locations required} = \frac{\text{Step 1}}{\text{Step 2}}$$

$$= \frac{330 \text{ (total sites)}}{6 \text{ (total months)}}$$

$$= \underline{55}$$

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