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A Study of Solar Power Implementation in the Norwegian Poultry Industry

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Preface

This report is written in cooperation between Kari Hembre and Vilde Kvålsvold as a final project for the engineering bachelor program Renewable Energy at the Norwegian University of Science and Technology. The bachelor thesis is completed for the course TFNE3001 Bachelor Thesis Renewable Energy during the spring semester of 2020. The course consists of 20 credits.

The purpose of this report is to look at the possibilities for implementing solar power at a poultry farm in Trondheim. Solar power is selected since the interest of solar technology has increased over the past decade and become remarkably cost-effective. Three scenarios have been examined in this project. Scenario 1 and 2 consists of an economic profitability analysis. A major suspense in the Scenario 2 will be the possible changes in the Norwegian electrical grid tariffs. Scenario 3 will investigate the correlation between air temperature and actual efficiency of solar modules.

We would like to express our gratitude towards our external supervisors at TrønderEnergi, Mats Håkon Grøn Jønland and Kristoffer Tvinnereim, for providing us with a challenging project. They have given information and guidance throughout the process and supplied us with solution-oriented ideas. A great thank you is given to our internal supervisor at NTNU, Kjell Kolsaker, for valuable help and inputs during the project.

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Trondheim, 21.05.2020

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Abstract

A combination of solar- and wind power is expected to be the main renewable electricity sources in the future. Solar technology has had a major global breakthrough in recent years, and the prices of photovoltaic cells are expected to drop with further 60 % by mid-century. Early in the solar industry development, it was assumed that solar power was not suitable in Nordic climates. This incorrect assumption, in combination with Norway's dominating hydro power industry, have been two main factors for the slow development of the domestic solar market.

Electricity is a perishable product. Meaning that self-produced electricity needs to be used immediately when generated, or sold back to the electrical grid. A uniform correspondence between the building's load profile and the system power output is an advantage when installing a solar energy system. In the poultry industry, these parameters correspond well and it is, therefore, beneficial to install a solar energy system.

The Norwegian grid tariff system is about to undergo a drastic change, which might affect the profitability of a solar energy system. The load on the electrical grid has increased due to electrification of the society. Grid expansion will eventually become necessary, but before this happens, the goal is to utilize the grid in a more efficient way. This will affect how grid tariffs are presently payed. The Norwegian Water Resources and Energy Directorate (NVE) has proposed three new tariff models, that will be considered in this project.

This project consists of three scenarios. Scenario 1 is an economic profitability analysis with focus on system optimization. The impacts of spot price fluctuations are also examined. Scenario 2 investigates the impacts the new tariff system may have on the profitability of the projected solar energy system. Scenario 3 is a temperature analysis that studies a possible occurrence of correlation between air temperature and module efficiency.

A major observation in duration of the temperature analysis was that the solar modules rarely operated with the efficiency provided by the manufacturer. In addition, an observation was that the solar energy system is complex, and minor changes in parameter values may lead to substantial changes in the results.

The economic profitability analysis in Scenario 1 suggests that installing 48 solar modules gave the highest net present value (NPV). A NPV of 26 847 NOK after 25 years was obtained. This was achieved when an installation price of 10 NOK/Wp was applied. For Scenario 2, all three tariff models had a positive impact on the economic profitability compared to Scenario 1, as the yearly tariff fees were reduced. A conclusion was drawn that installing a solar energy system as projected in Scenario 1 will be profitable after 25 years for the poultry barn at Byneset, regardless of the examined grid tariff changes. For Scenario 3, the conclusion is made that no obvious correlation between these factors were present, when applying the selected data and method.

Abstract in Norwegian

Det er forventet at sol- og vindenergi kombinert skal utgjøre de største fornybare energikildene i fremtiden. Solteknologien har globalt opplevd et stort gjennombrudd de siste årene, og det er videre forventet en 60 % reduksjon av prisene på solceller innen 2050. Tidlig under utviklingen av solceller var det antatt at solenergi ikke var tilpasset det kjølige klimaet i Norden. Denne antagelsen, som i senere tid viste seg å være feil, sammen med Norges dominerende vannkraftindustri, har vært to avgjørende faktorer for den langsomme utviklingen av solenergi i Norge.

Elektrisitet er en ferskvare. Det betyr at selvprodusert elektrisitet må brukes øyeblikkelig etter produksjon, eller selges tilbake på strømnettet. Det er en fordel med samsvar mellom bygningens lastprofil og systemets kraftproduksjon når et solcelleanlegg skal installeres. Å installere et solcelleanlegg innen hønseindustrien er derfor gunstig siden de to nevnte parameterne harmonerer.

Norske nettariffer er i ferd med å endres, og dette kan påvirke lønnsomheten til et solcelle anlegg. Lasten på strømnettet har økt kraftig på grunn av elektrifisering av samfunnet. Målet er å utnytte strømnettet på en mer effektiv måte før en utvidelse blir nødvendig. En slik endring vil påvirke dagens måte å betale nettleie. Norges vassdrags- og energidirektorat (NVE) har foreslått tre nye tariffmodeller som vil bli undersøkt i dette prosjektet.

Prosjektet består av tre scenarier. Scenario 1 er en økonomisk lønnsom-
hetsanalyse med fokus på optimalisering av et solcellesystem. Påvirkningen av svingninger i spotprisene er også undersøkt. Scenario 2 studerer tariffendringenes påvirkning på lønnsomheten av det prosjekterte solcelleanlegget. Scenario 3 er en temperaturanalyse som undersøker mulighetene for korrelasjon mellom lufttemperatur og solcellenes faktiske effektivitet.

En av observasjonen som ble gjort i løpet av temperaturanalysen var at solcellene sjeldent opererte med den nominelle effektiviteten oppgitt av produsenten. En annen observasjon var den tydelige kompleksiteten til et solcelleanlegg. Små endringer i parametere førte til vesentlige endringer i resultater.

Den økonomiske lønnsomhetsanalysen i Scenario 1 fikk høyest nåverdi med 48 solcellepaneler. Nåverdien var da 26 847 NOK etter 25 år. Disse resultatene ble kalkulert med en installasjonspris på 10 NOK/Wp. For Scenario 2 hadde alle tre tariffmodellene en positiv påvirkning på den økonomiske lønnsomhetsanalysen i forhold til Scenario 1, grunnet en reduksjon i den årlig nettleien. Det ble konkludert med at det prosjekterte solcelleanlegget i Scenario 1 var lønnsomt etter 25 år for hønsefjøset på Byneset. Dette uavhengig av de undersøkte tariffendringene. I Scenario 3 ble det konkludert at ingen tydelig korrelasjon mellom datasettene fant sted, ut ifra utvalgt datasett og metode.

Terms

Term	Definition
AC	Alternating current.
Albedo	The fraction of global incident irradiation reflected by the ground in front of a tilted plane.
AM	Air mass.
AMS	Advanced metering system.
Array	A collection of multiple solar modules.
Broiler	Chickens bred for meat production.
Array-to-inverter ratio	Ratio between inverter power and installed nominal power.
Azimuth	The angle between south and the collector plane of the solar module in the northern hemisphere.
Busbar	Link between high voltage equipment and the end of the distribution grid.
Cash flow	Net amount of annual cash earned.
Conduction band	Electron orbital.
CPI	Consumer price index.
Daily measured tariff	A tariff model reflecting the load peak on a daily basis.
DC	Direct current.
Fill factor	A quality measurement determining the maximum power output from a solar module.
Fixed tilted plane	A solar module that is permanently placed in position.
Fuse differentiated tariff	A tariff model based on yearly maximum power peak.
Gaussian distribution	Also known as normal distribution.
Green profitable	When the net present value equals zero at 25 years. No direct economic loss occurs.
Grid tariffs	A monthly payment from consumers to keep the electrical grid operational.
Inverter	Equipment converting DC current to AC current.
IT-grid	A type of distribution grid.
IRR	Internal rate of return.
Module	Also known as solar panels. A group of photovoltaic cells.
MPP / MPPT	Maximum power point / Maximum power point tracker.
Monthly subcription tariff	A tariff proposal based on a monthly kW subscription.
NOK	Norwegian kroner.
NPV	Net present value.
Peak load	Electricity demand or usage at its highest.
Pearson's correlation coefficient	A coefficient determining the correlation between two data sets.
Performance ratio	The ratio between theoretical and actual power output.

PV	Photovoltaic.
Prosumer arrangement	An arrangement to sell overproduced electricity back to the grid for a price approximately equal the purchase price.
P-n junction	A boundary area between two semi-conductor materials.
Spec sheet	A document that summarizes the performance of a product.
Prosumer	A person who consumes and produces a product.
STC	Standard test conditions. 25 ^{o}C, 1000 W/m^2 and AM1.5.
Semi-conductor	A substance that can conduct electricity under certain conditions.
Spot price	The current electricity price at the market given by Nord Pool.
String	The connection between modules in series
Tilt angle	Angle between the plane and the horizon.
Tier-1	Scaling system of bank-ability or financial stability presented by Bloomberg New Energy Finance Corporation. Tier 1 is the highest ranking.
TN-S grid	A type of distribution grid.
Valence electron	Electrons in the outer shell of the atom.
Zenith	The point with an 90^{o} angle vertically above a specific location.

Symbol List

Symbol	Unit	Definition
A	m^2	Area.
–	^oC	Celsius.
E	–	Electricity.
FF	–	Fill factor.
–	h	Hours.
i	%	Internal rate of return.
I_{MPP}	A	Maximum power point current.
I_{SC}	A	Short circuit current.
n	–	Number of years when calculating the NPV.
–	N	Newton.
η_{max}	%	Solar module efficiency.
–	Wp	Watt peak.
ϕ	^{o}	Angle between zenith and solar irradiation path.
R	–	Pearson's correlation coefficient.
R_0	NOK	Investment cost.
R_t	NOK	Annual surplus.
R^2	–	Determination coefficient.
S	W/m^2	Solar irradiation.
t	–	Years.
U_{MPP}	V	Maximum power point voltage.
V_{OC}	V	Open circuit voltage.
Wp	W	Watt peak.
P_{max}	W	Maximum power.
–	Hz	Frequency.
x	–	Data set 1: Pearson's correlation equation.
y	–	Data set 2: Pearson's correlation equation.
z	–	Number of data set pairs: Pearson's correlation equation.

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1 Introduction

Solar power is a renewable energy source that converts the radiation from the sun into thermal or electrical energy. Every day the sun supplies far more energy than is required for the total energy demand on Earth. A limitation when extracting solar energy, is the conversion of this energy in an efficient and cost-effective way. Prices of photovoltaics (PV) have been reduced by approximately 80 % since the end of 2009 [1]. This price reduction is a factor to why PV currently is one of the fastest growing technologies on the energy market [2].

The interest of solar power in the poultry industry is increasing. This due to the similarities between the typical electrical load profile in this industry and the solar irradiation. Generally in a poultry barn, the load profile peak is at mid-day. Comparing this to a traditional Norwegian household, the load profile is relatively low in the middle of the day. The two load profile peaks in a household are in the morning and afternoon. One of the main advantages of installing solar power in the poultry industry is, therefore, the correlation between the load profile and solar irradiation. This comparison is illustrated in Figure 1.1. The figures are rough estimations and are presented to get a brief idea of how the load profile corresponds to the system power output.

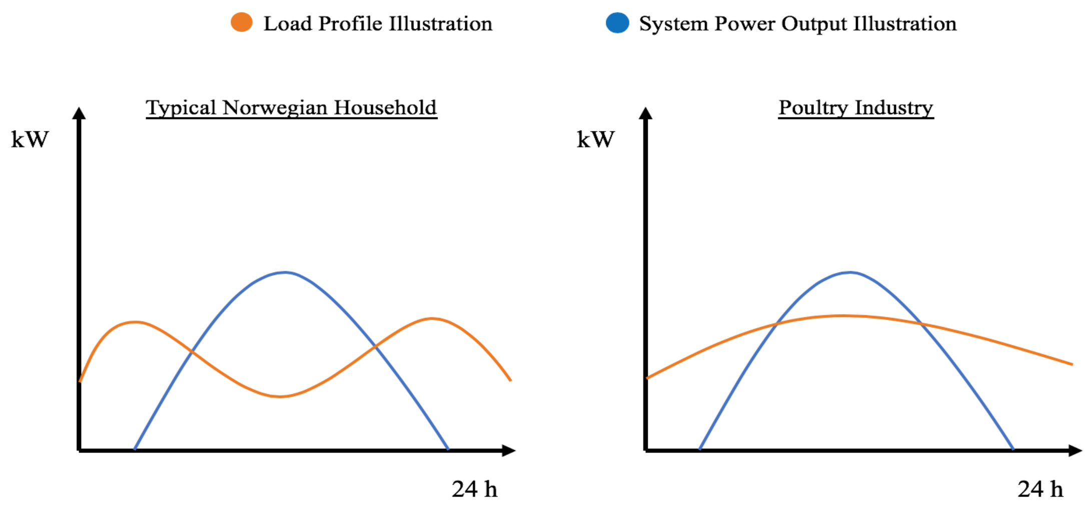

Figure 1.1: Comparing load profile and solar power output in a typical summer month. [3]

A key factor for a poultry barn is ventilation. Achieving adequate air quality is crucial for removal of harmful gases. Poor air quality will reduce meat production and increases the susceptibility for diseases. This ventilation process requires electricity [4]. Heating is also strictly regulated in the poultry industry, as chickens require specific temperatures during the growing period. The heating is often completed using propane furnaces [5]. It is necessary that the wooden chips, which soften the concrete floor, stay dray. This is increasingly challenging as the chickens grow bigger and create more vapor through breathing. Heating and ventilation is increased as the chickens grow due to the appearance of this vapor [4].

1.1 Purpose of the Thesis

The aim for this project was to firstly examine the economic profitability when implementing a solar energy system at a poultry barn. The selected farm is located at Byneset in Trondheim. Historical data from 2019 was used to create a model from the beginning of 2020 till the end of 2044. An objective was to construct a solar energy system guide, working as a supporting document for similar future projects within agricultural industries, especially the poultry industry. Another objective was to investigate how electrical grid tariff changes would affect the solar energy system over a 25-year period. It was also desired to examine the effects of temperature fluctuations relative to the efficiency of the solar modules.

TrønderEnergi has over 20 years of experience with water- and wind energy, and will during 2020 be the co-owner of the largest land-based wind farm in Europe [6]. As it is predicted that the combination of solar- and wind energy will represent the majority of the future electricity mix, TrønderEnergi aims to develop valuable knowledge about solar energy to compete on the growing Norwegian solar market [7]. A report investigating the economic implications regarding installation of solar power at the poultry farm was requested, as well as a temperature analysis at an already existing solar farm at Rye. The solar farm at Rye is located 11.7 km from the poultry barn at Byneset. The problems to address in this report were decided in close dialogue with TrønderEnergi. The problems are listed below respectively representing Scenario 1, 2 and 3.

- What are the economic implications for a poultry farm when converting to a solar powered system over a 25 year period?
- What are the possible impacts on these implications given a set of changes to the grid tariffs?
- How do decreasing temperatures have an effect on the solar module's efficiency?

1.2 General Approach

This project consists of an economic profitability-, a tariff- and a temperature analysis. These will be referred to as Scenario 1, Scenario 2 and Scenario 3 respectively. A chart representing the project's structure is shown in Figure 1.2. Scenario 1 will contain research regarding the optimal installation parameters for a solar energy system, and evaluate the effects of spot price variations. The Norwegian Water Resources and Energy Directorate (NVE) has proposed three new tariff models in their latest consulation document [8]. In Scenario 2, the impacts these tariff proposals have on the economic profitability are examined. Scenario 3 includes investigations regarding a possible relation between air temperature and the efficiency of the solar modules.

This report begins with a supporting theory section. Further, the method for completing all scenarios are described. The net present value method is central throughout the project. All relevant results are presented in illustrative graphs and tables. Detailed results can be found in Appendix. A comprehensive discussion is constructed to clearly understand how various assumptions have affected the obtained results. Lastly, a conclusion is drawn answer the addressed problems.

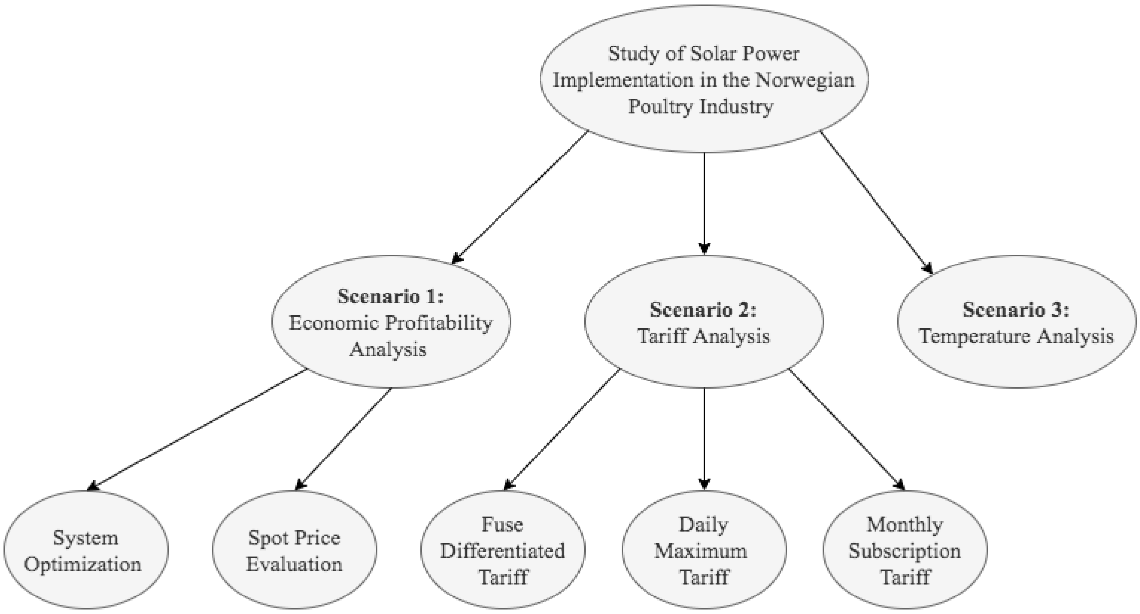

Figure 1.2: The structure of the project. [3]

1.3 Limitations

Throughout the project, the Norwegian solar industry and the Norwegian electrical grid will be in focus. A few global aspects will be presented to further explain the solar market in Norway. However, the assumptions stated in this project are made with limitations to this specific location of the poultry farm. This includes equipment selection, weather data, governmental support, installation costs and local electricity prices. The selection of equipment also considers present technology and availability on the market.

The results in this report will only reflect and be reliable concerning this specific system, but can be used as a guideline for similar projects. The whole poultry barn and solar installation is included when referring to the description *system*. The report presents results and data sourced from both Excel and PVsyst. The unit kW will consistently be used throughout the report, and will be referred to as power. However, the unit $kWh/year$ will be applied when referring to the yearly electricity consumption. Electricity will also be referred to as energy.

The installation will be designed to produce power under 100 kW, to benefit from the prosumer arrangement provided by the grid company [9]. All scenarios examine the usage of monocrystalline silicon solar modules. The maintenance cost of the system is assumed to be negligible during the entire project. The cost of uninstalling the system after 25 years is excluded. Possibilities regarding battery installation with the solar energy system are not considered.

1.4 Scenario 1 – Economic Profitability Analysis

The purpose of Scenario 1 is to project a profitable solar energy system for the poultry barn at Byneset. This is mainly completed by calculating the optimal number of modules. Estimating a relevant system price and discount rate is also necessary to complete the net present value method.

Spot prices have fluctuated drastically in recent years [10]. Comparing the spot prices from 2017, 2018, 2019 and the available months in 2020, shows that prices in 2019 were exceptionally high. The effects of spot price variations are examined. This is completed by calculating a mean value of the spot price reduction between 2019 to 2020.

1.5 Scenario 2 – Tariff Analysis

Considering announcements of major changes in the Norwegian electrical grid tariffs, a scenario regarding these changes are investigated. The changes are predicted to take place in the near future. The reason for this necessity is the increased load on the Norwegian electrical grid due to electrification of society. Moving away from energy tariffs and towards power tariffs is one way of cutting peak loads. Meaning a larger segment of the total electricity bill will be reflected in how much power in kW is consumed, rather than how much energy in kWh is consumed. [8]

Scenario 2 is based on present information that is given by the latest consultation document from NVE. The development of the conversion is still undergoing, and it is substantial to state that the results found in this report might not be future relevant if the consultation document is changed. The three grid tariff proposals are the *monthly subscription tariff*, the *daily measured tariff* and the *fuse differentiated tariff*. The goal for this scenario is not to obtain accurate results, but rather to see if the tariff changes will have a positive or negative impact on the economic profitability of the solar energy system. [8]

1.6 Scenario 3 – Temperature Analysis

Meteorological factors such as wind velocity, temperature and humidity have an impact on the system power output through the efficiency of the solar modules [11]. In this scenario, temperature is investigated to examine if there is a relation between temperature and the efficiency of solar modules. Historical temperatures at the nearest weather station in Trondheim is collected from the Norwegian Climate Service Center [12].

Solar irradiation- and system power output data is collected from an operating solar farm at Rye, and has no direct link to the farm at Byneset. Yet, the topography and weather conditions in the two locations are quite similar. Results from the temperature analysis are, therefore, assumed to be relevant for the poultry barn.

2 Theory

Renewable energy sources can be separated into inexhaustible and exhaustible sources. Despite that hydro power is a renewable energy source equivalent to solar energy, it will no longer be available for energy extraction if the resource is used faster than natural processes can replace it. Solar energy is, therefore, categorised as an inexhaustible energy source since it will not disappear regardless of how much it is used. [13]

2.1 Common Solar Expressions

In the northern hemisphere, the **azimuth** is defined as the angle between south and the collector plane of a solar module [14]. In other words, it is the angulation of the building correlated to the south. This means a building built with a south orientation has a azimuth of 0 ° and will obtain optimal solar irradiation. The **air mass index** (AM) represents the proportion of atmosphere that the light must pass through before it reaches the Earth. Equation 1 illustrates how the air mass index is calculated [15]. The shortest path through the atmosphere is called **zenith**, also defined as AM1. This is achieved when ϕ is equal to 0 °. This is illustrated in Figure 2.1. [16]

$$AM = \frac{1}{cos\,(\phi)} \tag{1}$$

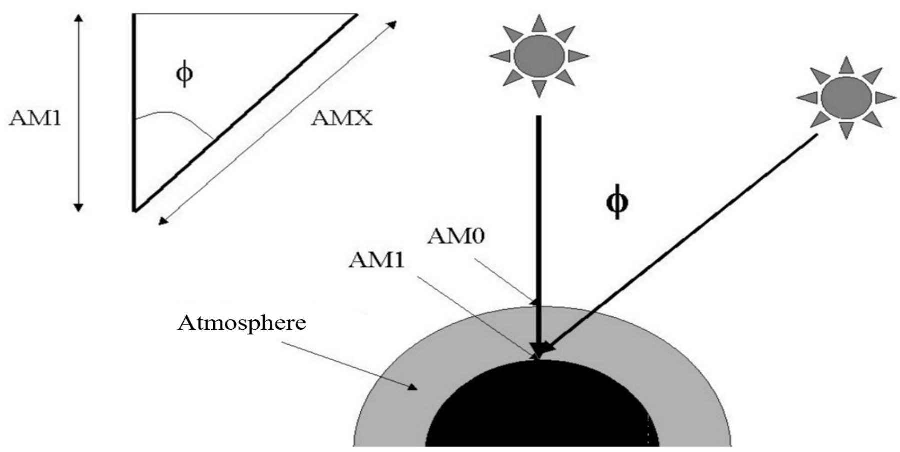

Figure 2.1: Solar irradiation on Earth. The figure is edited from its original form. [16]

There are various parameters included in solar irradiation data. Three alternatives are **direct normal irradiation**, **diffuse horizontal irradiation** and **global horizontal irradiation**. The direct normal irradiation is received when the sun is perpendicular to the plane, in other words in the zenith position. The diffuse horizontal irradiation only includes the reflected sunlight that goes via a surface and is directly from the sun. This reflection, typically coming from snow or other surrounding objects, is calculated by the **albedo coefficient**. Snow has an albedo coefficient of 0.82, meaning the snow will strongly reflect the solar irradiation [17]. The global horizontal irradiation, however, includes the reflected sunlight as well as the direct solar irradiation and is particularly interesting for solar installations. [18]

The **tilt angle** is the angle between the collector plane and the horizon, independent of location [19]. The optimal angle will be dependent on the specific location. Variables like annual seasons need to be taken into consideration, as the sun path varies at different times of the year. This especially occurs in Norway, compared to regions closer to the equator. In Norway the sun is vertically oriented during the summer and low on the horizon during the winter. Before determining the tilt angle it should be discussed whether the optimization should be made on behalf of the summer period, winter period or an annual average. Both definitions for azimuth and tilt angle are defined for fixed tilted planes.

Performance ratio describes the ratio between the theoretical and actual power output from a solar module or a solar energy system. It measures the quality of the solar module and is expressed in percent. A 100 % ratio is not achievable since losses in solar energy systems are unavoidable. Energy losses can be explained as thermal- or conduction losses, or impacts from weather conditions. A solar module with a 80 % performance ratio is considered high-performance. [20]

The **fill factor** (FF) is a parameter that determines the maximum power output from a solar cell as a quality measurement, similar to the performance ratio. FF will have a value between 0 and 1. A typical commercial solar cell will provide a FF-value of 0.83 [21]. Equation 2 and 3 illustrate how the FF is calculated. The parameter can also be graphically illustrated such as in Figure 2.2. The ratio of the blue rectangle to the red rectangle illustrates the value of FF for a specific solar cell. [16].

$$P_{max} = I_{MPP} \cdot U_{MPP} \tag{2}$$

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

P_{max} is the maximum power given in W. I_{MPP} is the maximum power point current given in A, U_{MPP} is the maximum power point voltage given in V, V_{OC} is the open-circuit voltage in V, and I_{SC} is the short-circuit current in A.

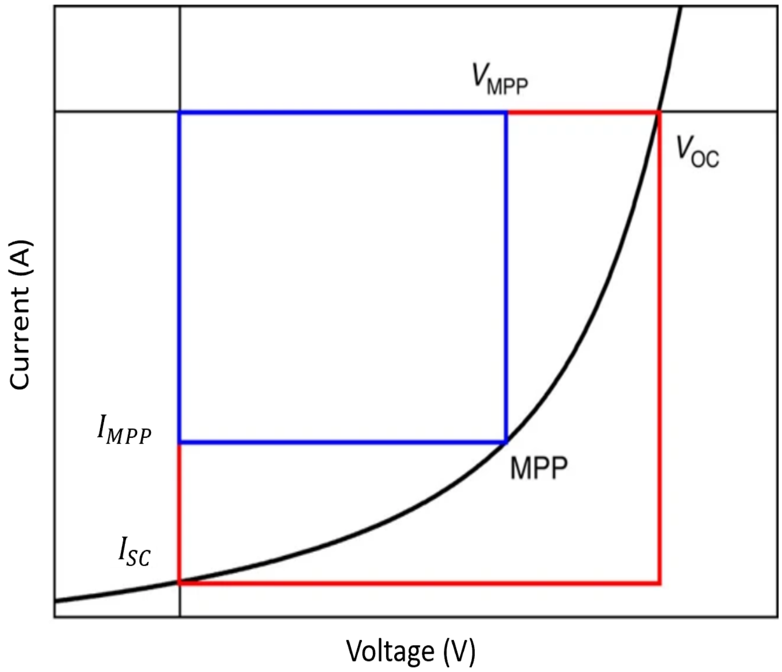

Figure 2.2: Illustration of FF. The figure is edited from its original form. [22]

2.2 Advantages

Even though Norway mostly generates electricity from renewable energy sources, with the main supply being hydro power, import of electricity from other countries is still necessary to cover the annual energy demand. There is no guarantee that the imported electricity is produced from renewable energy sources. Self-sufficient electricity production ensures an environmental friendly origin. [23]

Another benefit of solar power is the possibility to reduce the costs of electricity and grid tariffs. An overproduction of electricity creates possibilities to profit from the installed solar energy system, as electricity may be sold back to the grid. If the solar energy system is not connected to the electrical grid, grid tariffs are negligible. This way a household can gain independence from changes in both national and international electricity costs. This might be an advantage as it is predicted that the electricity prices will increase in the future due to major electrification of the society. [24].

The implementation of certain renewable energy sources can have a negative impact on nature, ecosystems and wildlife. The constructions of wind farms have especially caused heated debates in Norway in recent years as infrastructure is constructed on undeveloped land areas, so-called green fields [25]. Solar energy systems are often placed on rooftops and the necessity of large green fields are, therefore, not needed to implement a well functioning solar energy system. This illustrates that one of the major advantages of solar power is the minimal interference with nature. The agricultural industry is well suited for solar installation because of the large available roof areas. A photo of a solar energy system installed on a barn in Marnardal in Norway can be observed in Figure 2.3. Ground-mounted solar installations are also suitable on already developed land areas, so-called brown fields. This solution will decrease the natural disturbances and leave no additional footprint, as nature already has been industrialised. [26]

Figure 2.3: Solar energy system in Marnardal. The system is installed with 98 kWp. [27]

2.3 Photovoltaics Technology

Solar technology can be used variously, but most commonly is the usage of PV solar cells that directly generate electricity. The electronic process in PV systems occurs naturally in semi-conductors. The most frequently used semi-conductor in the solar industry is crystalline silicon. The reason for the natural electronic process in silicon is because photons from the sun ionize the semi-conductor material causing electrons to break out from their atomic bonds. The electrons are then forced to travel in a specific direction through an electrical load, creating a flow of electrons which produces an electric current and eventually generates electricity. [16]

Silicon is initially not suitable as a conductor since the valence shell is filled up of four electrons and holds a strong structure. Doping of the semi-conductor is necessary to create an impurity which will generate an electric current [28]. Solar cells are made up of thin slices of 99.999 % pure silicon, also known as wafers [16]. A group of solar cells are called a module, and a group of modules are called an array. One part of the 0.3 mm thin silicon wafer is supplemented with small portions of boron, called p-doped. There will be a positive charge on the p-side, since a hole is created from the missing electron. Small portions of phosphorous are then supplemented to a different silicon wafer, called n-doped. There will be a negative charge on the n-side, since an electron is present. The two wafers are combined at the p-n junction, which is illustrated in Figure 2.4. [16]

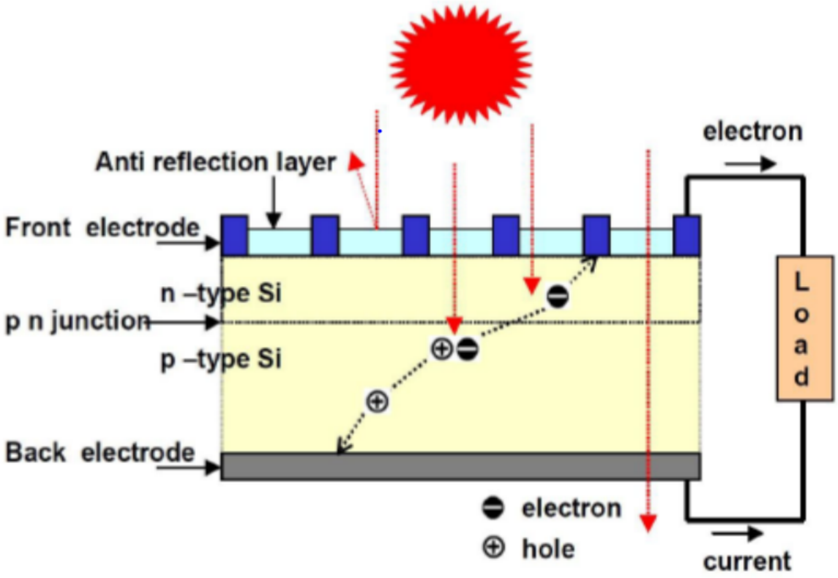

Figure 2.4: PV solar cell with doping. [29]

The two crystalline silicon module options include mono- and polycrystalline solar cells. Polycrystalline solar cells have lower efficiencies than monocrystalline, and are known for being less expensive. In recent years, a large amount of the production has been relocated to Asian countries such as China and Taiwan [16]. This has resulted in a cost decrease, and monocrystalline silicon cells have become more competitive on the market. When excluding the most expensive brands, Tier-1 monocrystalline modules are in 2020 equally priced as Tier-1 polycrystalline modules [30].

2.4 Temperature Effects

The band gap is the energy required to free a valence electron from its bound state and move it to the conduction band. When the temperature increases, the band gap in the semi-conductor decreases. When the band gap decreases, lower amounts of energy is needed to free the electron. However, the electrons do not carry as much energy. [31, 32]

As the temperature reaches higher than 25 ^oC (above STC), the current rises minimally while at the same time the voltage rapidly declines. When temperatures drop, the voltage increases more rapidly than the current declines. There are fewer electrons flowing, but each electron carries more energy. Since the power output is a product of voltage and current, the power output increases at lower temperatures. A visualization of the temperature effect on V_{OC} can be observed in Figure 2.5. [33]

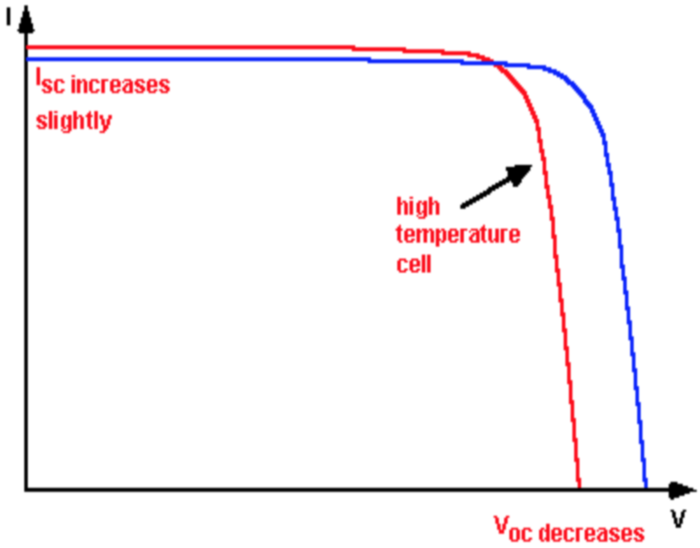

Figure 2.5: High temperatures result in a current reduction, and even greater voltage decrease. [32]

In a study completed by SINTEF in Trondheim, it was observed that the module efficiency decreases by approximately 0.3 % for each degree the temperature increased [34]. This observation was made in a climate laboratory, where parameters were closely regulated in a closed chamber. Even though this research was made for increasing temperatures, it illustrates a correlation between air temperature and efficiency. The efficiency of a solar module is defined as the ratio between the power output and the input solar irradiation [35]. The formula for maximum efficiency is shown in Equation 4. When the power output increases with constant irradiation, the efficiency increases.

$$\eta_{max} = \frac{P_{max}}{S \cdot A} \cdot 100\ \% \tag{4}$$

P_{max} is the maximum power output in W, S is the solar irradiation given in W/m^2 and A is the area of solar collector in m^2.

The ambient air temperature does not necessarily have an impact on the efficiency of solar modules. When producing electricity, the solar modules give off heat. Ventilation is a key factor for the solar module to keep low temperatures. How the module is installed, the type of module and surrounding air conditions have to be considered to achieve optimum conditions. [33]

2.5 Solar Energy System Components

A solar module is a combination of multiple solar cells connected in either series or parallel. Additional components are necessary to successfully wire together a power generating system. These components can be observed in Figure 2.6. Like most electrical equipment, performance losses will naturally occur in the components. These need to be taken into consideration when determining the system power output.

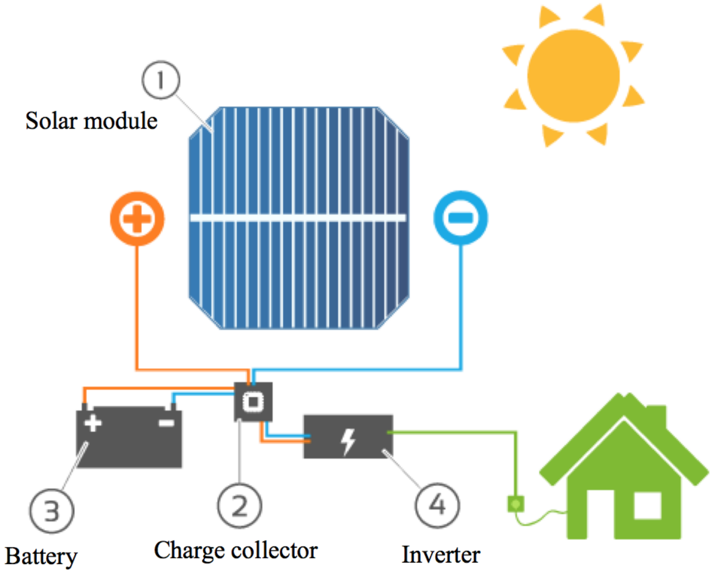

Figure 2.6: The basic components that build up a solar energy system. The figure has been edited from its orignial form. [36]

Inverters

Inverters in a solar energy system collect produced DC current from the solar modules and converts it to AC current. Only AC current can be used in other parts of the building or be transported to the electrical grid. The amount of light hitting the solar modules vary, resulting in fluctuating electricity production. The inverter modifies the electrical power that is further supplied to a battery or the grid. Inverters also assure that voltage levels are kept stable. [28]

The geography of the solar energy system is a factor when determining the correct inverter. Inverters in locations with high solar irradiance must be able to endure the maximum power from the modules. The inverter operates most efficiently when it is running close to its maximum capacity. By slightly undersizing the inverter, the inverter will run closer to its optimal conditions. Having an undersized inverter in regards to the solar arrays will additionally be economically beneficial since lower power inverters have a lower cost. If there is a chance that the consumer will expand their solar energy system in the future, undersizing the inverter is not recommended. [37]

The array-to-inverter ratio determines the combined Wp from modules divided by the inverters power output. Many installations have ratios between 1.15 and 1.25, and it is recommended that the ratio does not exceed 1.55. [37]

Three inverter types include string-, central- and micro inverters. A visualization of all three types is shown in Figure 2.7. **String inverters** are interconnected with wires between each module. Only one string inverter is needed for a small solar energy system, but several can be used when connecting a larger system. When one module is shaded, the performance of the others are affected. These inverters are usually easy to maintain because of the accessibility, and are generally inexpensive. **Central inverters** are often used for utility scaled sites. The modules are connected as strings in parallel to one single inverter. **Micro inverters** are placed behind each module, allowing energy to be produced independently from neighboring modules. Independent operation is an advantage if partial shading is a concern. [28, 38]

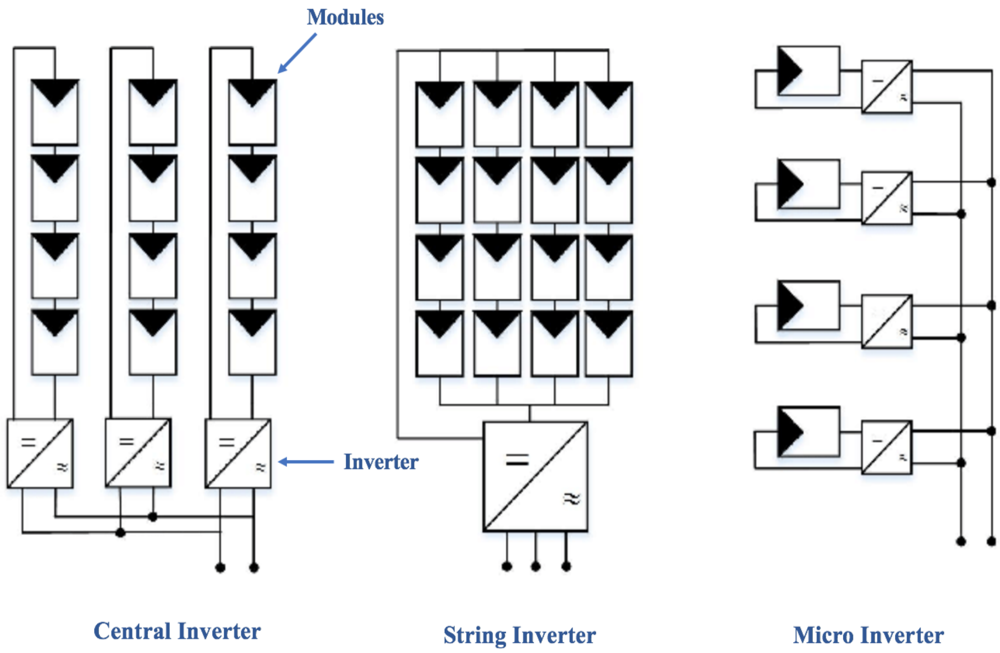

Figure 2.7: String-, central- and micro inverters. The figure is edited from its original form. [39]

The **maximum power point tracker** is a function embedded in inverters to optimize the connection between the solar module and a battery or the grid. This is done by converting down the voltage to the most efficient voltage for the battery or the grid. Figure 2.8 illustrates the additional effect the tracker has on the power extraction compared to a regular system. Certain inverters have dual MPPTs. This allows arrays with varying module types, azimuth, tilt angles and different string lengths to be connected. Having a dual MPPT function provides greater flexibility when designing a solar energy system. [40]

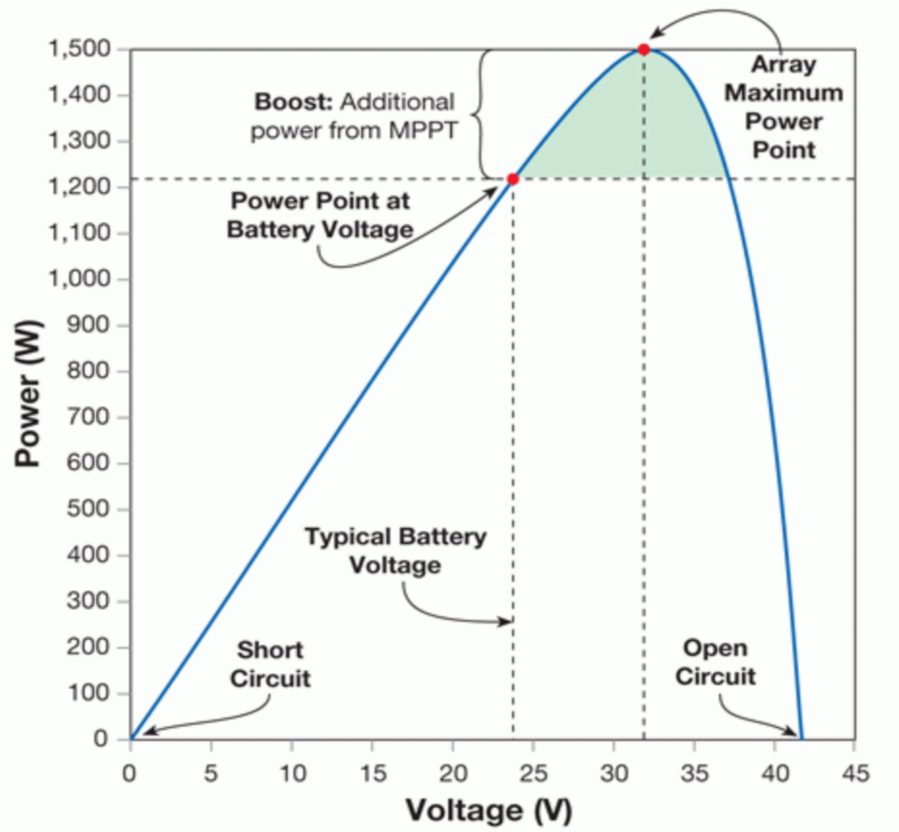

Figure 2.8: Additional power when including MPPT. [41]

String

The concept of string sizing is a critical factor when designing the array layout. The definition of a string is the connection of modules in series that eventually are fed into an inverter. The outside temperature, the type of module and type of inverter are all factors when choosing the number of modules in a string. [42]

For the inverter to run at optimum conditions, the optimal number of modules in a string needs to be calculated. All inverters acquire an operating voltage range. If the string fail to provide voltage within this range, the inverter will not be able to operate. If the string of modules exceed the maximum voltage, severe damage can be done to the inverter. This can be observed as the maximum DC input voltage in the equipment's spec sheet. Even if the voltage is within the range, the inverter might not work optimally. On the inverter's spec sheet, information about the V_{MPP} can be found. This specific voltage optimizes the performance of the inverter. [42]

Battery

A battery provides the opportunity to store generated electricity for later usage, and can be applied for both off-grid and hybrid systems. Batteries are not a necessity in solar energy systems, but a great way to store energy at times when energy is not needed. Another way to store energy is heat storage in a water tank. When energy is not momentarily needed, it can instead be used to heat water. [38, 43]

Charge collectors regulate the pace of which electrical power is supplemented and withdrawn from batteries. The collectors work to control the voltage and power from the solar modules. Over-charging and fluctuating voltage can over time result in problems with the battery. [38]

Racking and Wiring

Other important features for a solar energy system are racking and wiring. The correct racking is required to ensure that the solar modules are securely fastened to the chosen surface. Both roof and ground mounted arrays need to be set on reliable structure to maintain principle functions and operate for an extensive amount of years. Wiring is a necessity to connect the components. The amounts and types of wiring needed will vary between solar energy systems. [38]

Monitoring Equipment

Monitoring equipment displays energy information to and from the solar modules. The device can control real time- or system lifespan data, detect faults, and monitor the energy yield over a certain time period. Monitoring equipment gives the operator a better understanding of how the solar energy system is operating. [38]

Every household contains a power meter which registers load profiles. By January 1st 2019, all power meters in Norway were replaced with an advanced measurement and control system (AMS). An AMS is a digital power meter that automatically registers the consumption, which results in more accurate measurements. The installment was necessary due to future electrical grid changes, as accurate load profiles will be required. It has additionally expanded the possibilities of creating smart and flexible energy systems. [44]

Maintenance and Cleaning

The required maintenance of a PV system is minimal and will not contribute to a major cost. Scratches on the protective layer happens occasionally, but will only slightly reduce the performance of the module. If the layer incurs cracks, water will seep through and cause a short circuit. [45]

Snow is a concern regarding solar energy systems in Nordic climates. Light snow will easily be blown off the module. Only accumulation of heavy snow that fully cover the PV solar cell will cause no generation of electricity. When projecting a PV system, a frameless module can be chosen. This will allow heavy snow to easier slide off the module and increase the electricity generation during the winter season. Snow load above 2.5 kN/m^2 will require solid installation gear to tolerate the heavier weight, resulting in an increased installation cost. In areas where the snow load is between 2.6 kN/m^2 and 3.5 kN/m^2 the cost of installation gear will be approximately 50 % higher. The price will double when the snow load is greater than 3.5 kN/m^2 [46]. Snow loads in Trondheim at different metres above sea level is presented in Table 2.1.

Table 2.1: Snow load in Trondheim, Trøndelag. [47]

Metres above sea level [m]	< 150	150-250	250-350	350-450	> 450
Measurements $[kN/m^2]$	3.5	4.5	5.5	6.5	7.5

Cleaning is especially important in periods without rain, as dirt will cling to the modules and decrease the performance. Cleaning will happen naturally if snow is allowed to melt on the modules. [48]

2.6 The Electrical Grid

The successful operation of an electrical grid is essential for any modern society to function. The grid must endure variations in production and consumption. During the winter months, the Norwegian grid is aimed to cope with high consumption levels. In the summer months, overproduction of electricity occurs resulting in sales with nearby European nations. Sufficient transmission capacity is, therefore, both domestically and internationally. [49]

Nord Pool is a joint-stock company that runs the leading power market in Europe. Both day-ahead prices and historical data can be collected from Nord Pool. The day-ahead market is necessary to secure balance between supply and demand. [10]

2.6.1 The Norwegian Grid

The Norwegian electrical grid is partitioned into three segments consisting of the transmission-, regional- and distribution grid. A simple sketch of the grid can be observed in Figure 2.9. Statnett, a state-owned company, is the administrator for the transmission lines in Norway. The **transmission grid** is the main grid and stretches out approximately 11 000 km. The voltage level is between 132 and 420 kV. The **regional grid** often interconnects the transmission and distribution line. It has a total length of 19 000 km and carries voltages between 33 and 132 kV. Sizable consumers are connected to the main- or regional grid, while smaller consumers are connected with the regional- or distribution grid. [49]

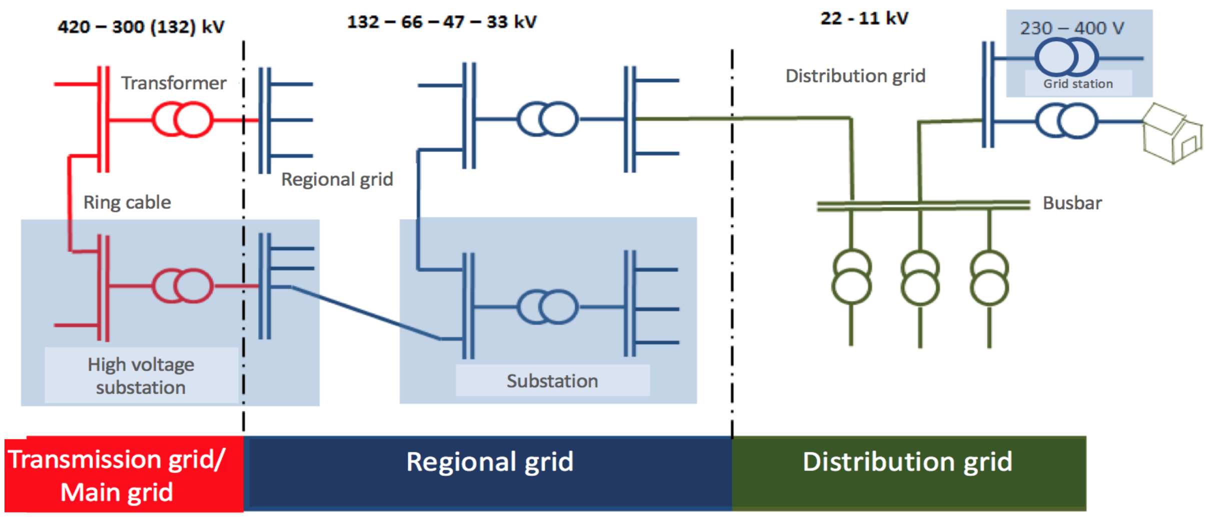

Figure 2.9: The Norwegian grid system. The figure is edited from its original form. [50]

The **distribution grid** is the local electrical grid that provides electricity for end users. It is common to separate between a high- and low voltage distribution grid. The length of the high-voltage grid is roughly 100 000 km. The rated voltage is between 11 and 22 kV. For businesses and industries it is normal that the voltage carried is 400 V. For households the voltage is 230 V. This grid can consist of air- and underground cables. [49]

2.6.2 IT- and TN Systems

The low voltage distribution grid in Norway can be built up of three different systems, IT-, TT- and TN system. IT is an abbreviation for “Insulated Terra”. The connected consumers only have access to 230 V. The transformer’s neutral point is isolated from the ground, therefore, residual current has a more complicated route to travel in occurrence of system failure. Most systems have a protective function that activates when for example lightening strikes. Residual current detectors are often used or even mandatory. Previously in Norway, IT systems were almost unanimously used in households. [51, 52]

There are several variants of the TN system, including the TN-S system. There are several variants of the TN system, including the TN-S system. TN is an abbreviation for “Terra Neutral”. Larger electrical installations need to be connected to a TN grid. The transformer’s neutral point is close to the consumer. The consumers have access to 230 V and 400 V. All new electrical installations in Norway are built with TN grids. [51, 52]

2.6.3 Regulation of Grid Operations

Both the production and sale of electricity are competitive businesses, but the electrical grid itself is operated under a monopoly. Having competing grid companies would be unreasonable as construction and further expansion of the grid is expensive. Strict regulations are incorporated to prevent grid companies from taking advantage of this monopoly. Companies are required to do necessary investments to maintain the grid at a satisfactory degree. This investment is autonomous to the business profitability. NVE determines a maximum annual earning that each grid company collects. These regulations are set to endure financial conditions for the companies, and also safeguard the customers through reasonably priced grid tariffs. [53, 54]

A consumer has to pay two fees to be connected to the grid. The first fee is the electricity the customer consumes over a time period, and is measured as the energy used in kWh. The second fee is called tariffs. Customers pay for the service of transmission and distribution, and tariffs contribute to the costs of keeping the grid operational. Tariffs are meant to be spent in a way that provides long term effective developments and investments to the grid. The charge of these tariffs are dependent on which grid the customer has an agreement with. Consumers connected to lower grid levels pay for both the higher and lower levels of the grid. The tariffs vary between grid companies and where the household is located. Challenging landscape and long distances may contribute to higher transmission costs, which leads to higher tariffs. Today’s grid tariffs are separated into an energy-fee and constant-fee. The first mentioned, represents the electricity loss during transportation. The second mentioned, covers all fixed expenses including measurement costs, settlements and invoices. [53, 54]

2.6.4 The Future Grid

The load on the distribution system has increased with the rise of power demanding equipment. In addition, sale of self-produced electricity back to the grid contributes to the load. Today costumers are mainly charged based on the amount of kWh that is consumed over a period. Consumers are not charged for using large amounts of electricity over a short period of time. The grid today has to endure high levels of power fluctuations which leads to uneven burdening on the network. Grid companies will eventually be forced to expand the electrical grid because of the society's electrification. Before this happens, a plan how to utilize the grid in a more efficient way is under construction. [54, 55]

Grid tariff payments are about to undergo a drastic change. Exactly how the tariffs will be paid in the future is hard to predict. In NVE's latest consultation document from 2020, three specific suggestions that include moving from energy to power based tariffs have been proposed. NVE suggests that for individual consumers, the changes will essentially take effect in 2022. From 2022 to 2026 there will be a transition phase, and by the beginning of 2027 the new tariff system will be finalized. The transition phase is to avoid abrupt economic changes for customers. The electrical companies will design tariffs for customers within the regulation limits. The companies can choose different tariff models for different customers, based on objective and verifiable criteria. The three new tariff proposals can be observed in Figure 2.10. [8]

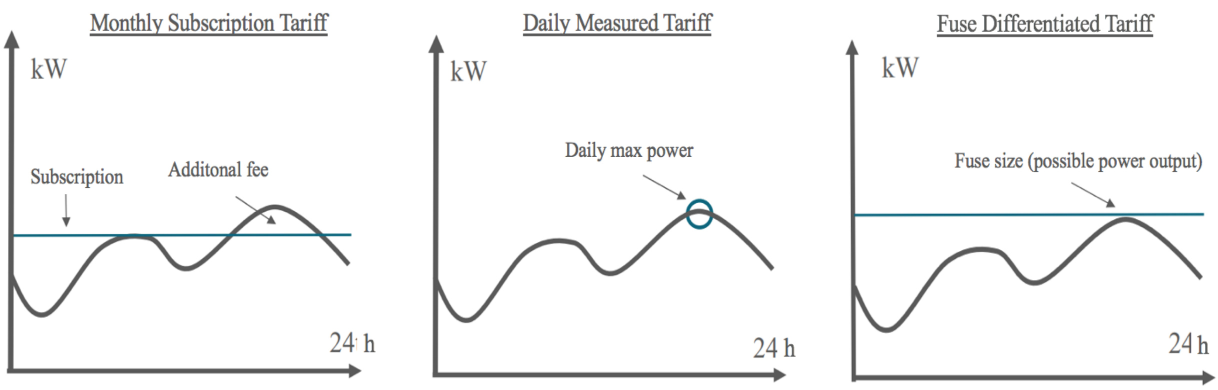

Figure 2.10: The three tariff proposals from NVE. The figure is edited from its original form. [8]

The *monthly subscription tariff* will consist of a yearly-, energy- and pre-subscribed power output fee. Consumers will pay for the planned power output. This payment will increase if the planned power output is exceeded. The *daily measured tariff* proposal will include a yearly-, energy-, and daily maximum power output fee. The *fuse differentiated tariff* consists of a yearly-, energy-, and yearly peak load fee. This tariff will reflect the capacity of the consumer's fuse box. [8]

NVE states that the new tariffs will help flatten the occurrence of peak loads. Power-based tariffs will be a economic motivator to avoid peak loads, and at the same time give consumers the opportunity to be aware of their consumption. NVE has stated that simple adjustments for households like avoiding charging of electric cars, turning off water and floor heating at peak hours will decrease the burden on the grid. This will additionally be economic beneficial for the consumer. [56]

2.7 Economy

A dominant factor in solar technology development is the cost. Prices have fallen rapidly in recent years, and there is reason to believe the price of PV solar cells will drop with 60 % by mid-century. [57] This development is shown in the Figure 2.11 with the reference point being 2016. Some factors that are declining the production costs is higher efficiency performance, price reduction of the raw material and an increase in international penetration from low-cost manufactures. By increasing the efficiency of solar modules, the cost of electricity per Wp decreases. With international penetration, especially from low-cost manufactures in China, the prices are in general being pushed down. This gives companies the opportunity to compete on the market. However, the largest contributor to price reduction of PV solar cell is the decline in the price of silicon. [58]

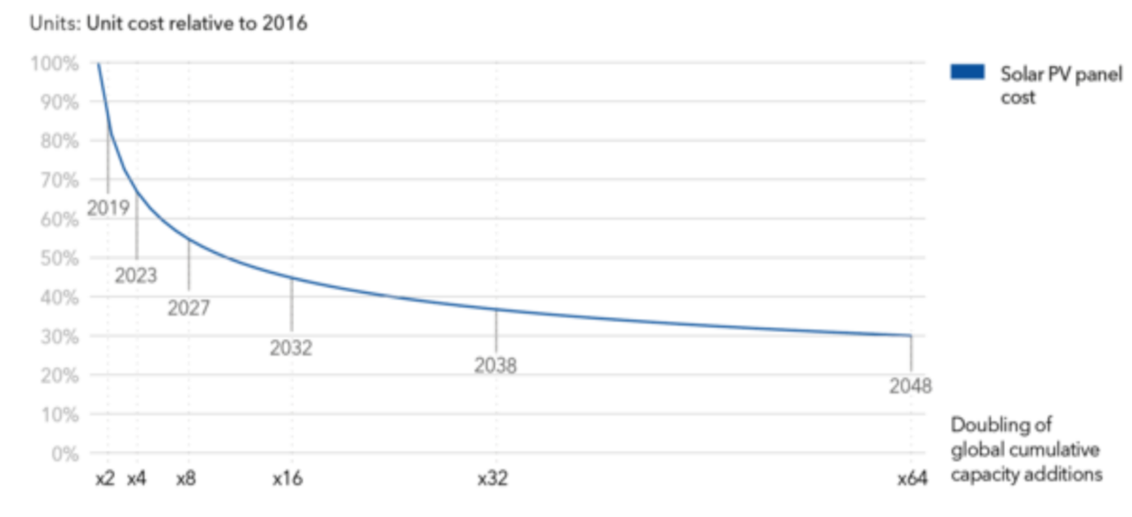

Figure 2.11: A future prediction of solar price reduction. [59]

2.7.1 The Norwegian Solar Industry

Norway is closely connected to the European Union (EU), despite a direct partnership. EU has decided to increase the share of renewable energy from 16 to 27 % by 2030. Norway is directly affected by EU's decisions as the country now needs to compete more aggressively against the European power market. This might negatively affect the demand of Norwegian natural gas and hydropower. Today these factors push the electricity prices down, so that Norway can stay competitive within the European power market. International penetration is not alone being experienced from Asian countries, but also from the neighboring European market. [60]

In the early dawn of Norwegian solar development, it was said that Nordic climates were not suitable for solar power generation. This was mainly because of the northern location creating a short summer period resulting in lower irradiation levels than desired [61]. This assumption resulted in a fairly slow engagement in the development of solar energy in Norway, especially considering large-scale systems. As illustrated in Figure 2.12, the development of solar power before 2014 consisted mainly of stand-alone systems, often within the leisure market.

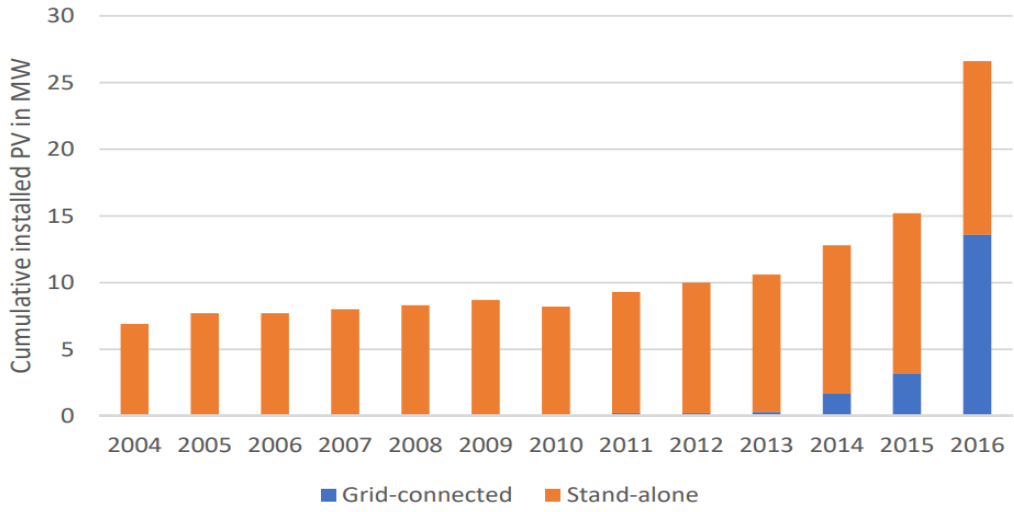

Figure 2.12: Accumulated solar capacity in Norway. [62]

Since Norway has a limited PV market, applicable companies often withhold market data for competitive reasons. Accurate and trustworthy data from recent years might be challenging to find. The international energy agency, IEA PVPS, has released data stating that the installed capacity in 2016 was 11.4 MW compared to 23.4 MW installed capacity in 2018. This capacity increase was equivalent to 200 million NOK [63]. The Norwegian PV market is expected to grow, as long as the growth can bear a possible expansion of the electrical grid and changes in future grid tariffs.

2.7.2 Financial Support

The installation of a solar energy system will give the support of 7500 NOK from Enova. Further support is dependent on the installed system capacity. A consumer will receive 1250 NOK per installed kW, up to a maximum of 15 kW. From April 1st 2020 the fixed support rate was reduced from 10 000 NOK to 7500 NOK. Justification for the support reduction is due to the recent growth of the Norwegian solar market. The financial support is funded from public tariff fees. After the new tariff agreements have been introduced, the support will gradually phase out up until 2027. [8, 64, 65]

Financial grants from the government may vary, depending on which county the solar energy system will be located in. The grants vary from year to year, and are also dependent on the applicant. Each project is evaluated from an individual perspective. There is no specific amount of support a self-power producer in Trondheim county would receive. [66]

2.7.3 Prosumer Agreement

NVE has established the prosumer agreement for customers producing and selling overproduced electricity. The customer needs to make an arrangement with a power company that manages both electricity production and consumption. The customers are in principle obligated to sell excess energy back to the power supplier. This implies that electricity can not be resold to other end users. The input power from the customer can not exceed 100 kW. [9, 67]

When selling back to the grid, the customer needs to pay a marginal loss fee for electricity transportation. These fees are divided into summer and winter periods, as there is a great difference between the electricity prices in the respective periods. The fees vary between electricity companies. For the company Tensio AS, the winter period is defined from November 1st to March 31st. The rest is defined as summer. The loss rate is set to 5 % during the summer period, 6.5 % during a winter day and 6.0 % during a winter night. [67]

2.7.4 Net Present Value Method

The net present value (NPV) method is often used while performing investment planning and analyzing the profitability of a project. This is completed by discounting future cash flows to present values. It is the difference between the present value in cash inflows and outflows, over a chosen time period. It is expected that a positive NPV will be profitable, and a negative NPV will not profit the project. [68, 69]

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} - R_0 \tag{5}$$

A numerical representation of the NPV method can be observed in Equation 5, where n is the operative period of the solar energy system given in years. t represents the present year. R_t is the proceeds surplus in year t. For a solar energy system, the R_t will be dependent on the solar irradiation and the electricity prices. i is the discount rate. This value includes inflation and risks related to the project. R_0 is the investment cost of the project.

The internal rate of return (IRR) for a project, is the percentage when the NPV is equal to zero. When the NPV is calculated to be lower than zero, the project usually is discarded. The discount rate has to be lower than the IRR for the project to be profitable. The correct discount rate may be a challenge to determine. Similar completed projects should be analyzed. [69]

2.7.5 Statistical Expressions

Statistics is often used in research and makes it possible to examine samples to draw comprehensive conclusions regarding the entire study [70]. It is of frequent interest to examine the correlation of data. This can be done by calculating Pearson's correlation coefficient using Equation 6. This is often completed digitally with built-in statistical functions. The coefficient is a number between -1 and 1. The coefficient will be close to 1 if the correlation between two data sets is strongly positive, and close to -1 if the correlation is strongly negative. If the correlation equals 0, there is no relationship. These three scenarios are illustrated in Figure 2.13. [71]

$$R = \frac{z(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[z\Sigma x^2 - (\Sigma x)^2][z\Sigma y^2 - (\Sigma y)^2]}} \quad (6)$$

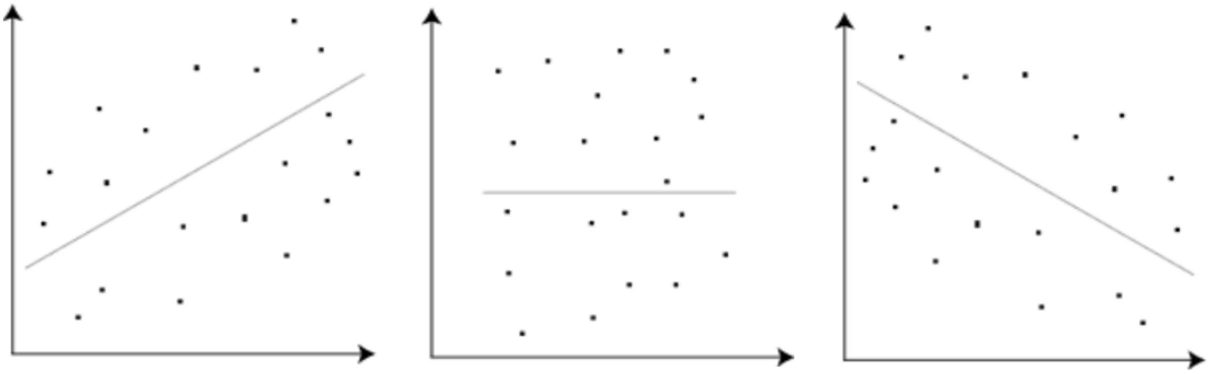

Figure 2.13: Linear regression. From the left: R=0.3, R=0 and R=-0.3. [72]

R is the Pearson's correlation coefficient, z is the number of data set pairs, Σxy is sum of products of the paired data, Σx and Σy are the sum of each data set, and Σx^2 and Σy^2 are the square sum of each data set.

Regression is often mentioned when talking about correlation, as there is a close connection between the two statistical expressions. The aim with a regression analysis is to understand the association between one independent variable and one dependent variable. The determination coefficient, R^2, is found when completing a regression analysis. Regression can both have a linear, curvilinear or exponential relationship. A linear regression is shown in Figure 2.13. [73]

3 Preliminary Work

The barn investigated in this project is located at Byneset in a county called Trøndelag in Norway, and is shown in Figure 3.1. An excursion to the poultry farm took place in March 2020. The purpose of the visit was to obtain information regarding the solar path, building layouts and the poultry industry. Further information is provided by the farmer Eli Stenstad, power suppliers, meteorologic services, Nord Pool AS, consulting- and engineering firms.

Figure 3.1: The poultry barn. [3]

3.1 The Poultry Farm

The barn was built in 2014 with the dimensions listed in Table 3.1. The construction drawings with given dimensions can be observed in Figure 3.2 and 3.3. Heating of the barn is accomplished through the usage of two propane furnaces. The furnaces are located in the ceiling at each end of the barn and can be observed in Figure 3.2. The heating is distributed evenly throughout the whole barn with electrical fans. These fans contribute to the majority of the electricity consumption.

Table 3.1: Dimensions of the barn. [5]

Dimensions	**Measurements**
Width of Front Wall	20 m
Length of Side Wall	60 m
Height of Roof Ridge	6.4 m
Height of the Outermost Point of Roof	3.6 m
Area	1200 m^2
Gross Area	1232 m^2
Tilted Roof Angle	20.68 $^\circ$
Area of Roof	641 m^2

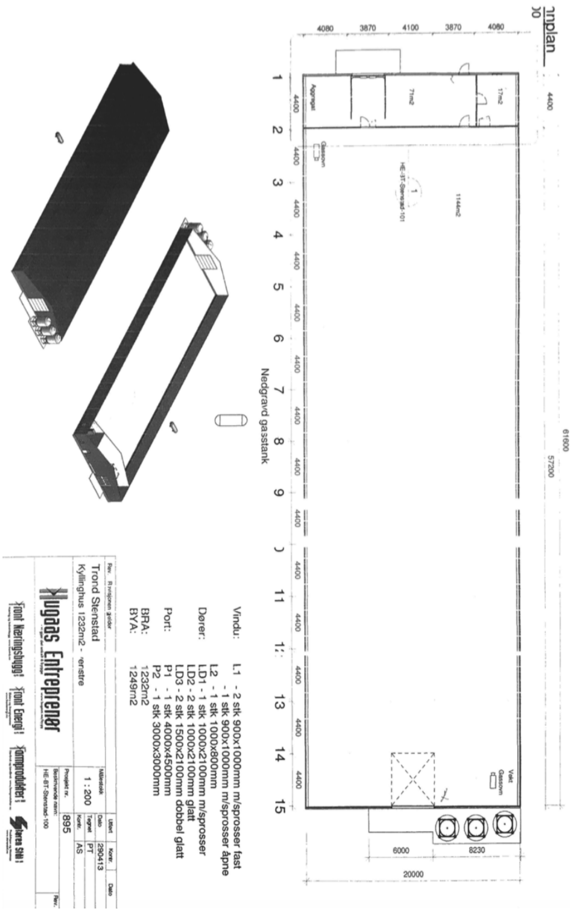

Figure 3.2: View from above. [5]

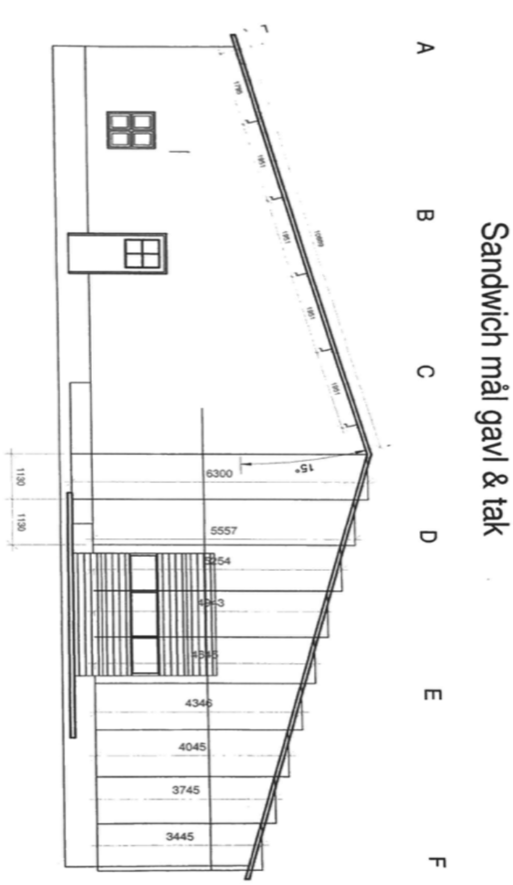

Figure 3.3: View from the front. [5]

There are in total 16 pipes constructed on the roof. Ten ventilation pipes are for collecting fresh air into the barn to preserve the air quality. The six remaining pipes are for exhaust. The ventilation pipes are 1.50 m tall, and are placed 4 m from the roof ridge. The exhaust pipes are 0.90 m tall and are placed on the ridge.

One group of broilers live in the barn for approximately 47 days. Between each group, there is a 8-12 day period where hygiene regulations take place. The barn consumes less electricity in this cleaning period. There are 16 000 birds in one group, and annually a total of 104 000 birds live in the barn. An internal view of the poultry barn is showed in Figure 3.4.

As the tilted roof angle is not presented on the construction drawings or other documents given by Eli Stenstad, a calculation using the dimensions presented in the Table 3.1 is made. The azimuth of the barn was measured with a digital compass during the excursion. Possibilities for shading were also investigated, and no trees nor buildings were detected to cause shade on the roof.

Figure 3.4: Internal view of the barn. [3]

An estimation of the theoretical maximum number of solar modules on the roof is calculated. The five ventilation pipes need to be included to obtain a realistic number. An assumption that the pipes have the dimension 1 x 1 m and are equally positioned on the roof is made. A graphic illustration of the roof can be observed in Figure 3.5. The figure is not correctly scaled. The photo of the poultry farm in Figure 3.6 is taken from an aerial perspective, where the 16 pipes are visible.

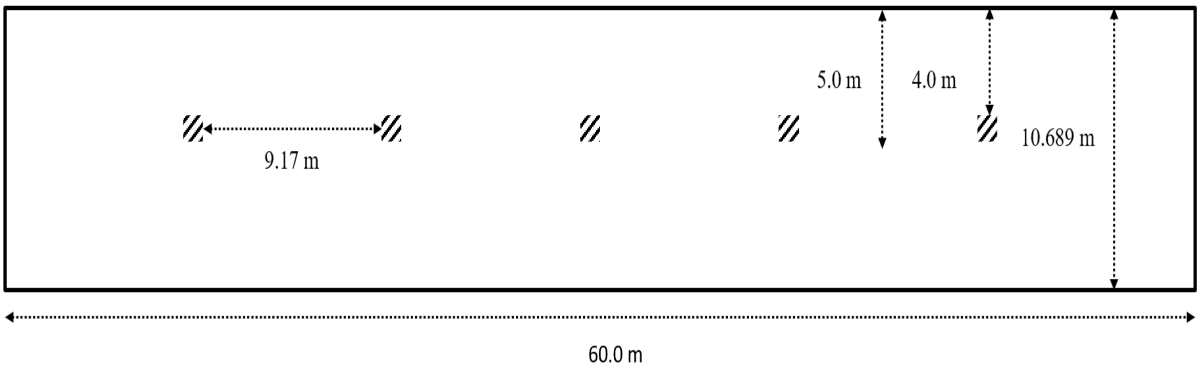

Figure 3.5: Graphic illustration of roof with pipes. [3]

Figure 3.6: Aerial view of the farm. [74]

3.2 Simulation Parameters

The simulation program used in this project is called PVsyst. The program offers various functions where the user can create a highly detailed system. A simulation can be constructed with specifications according to weather, geography, manufacturers, specific technology and economy. A simplified schema of the solar energy system in PVsyst can be observed in Figure 3.7. E represents electricity, and U represents voltage.

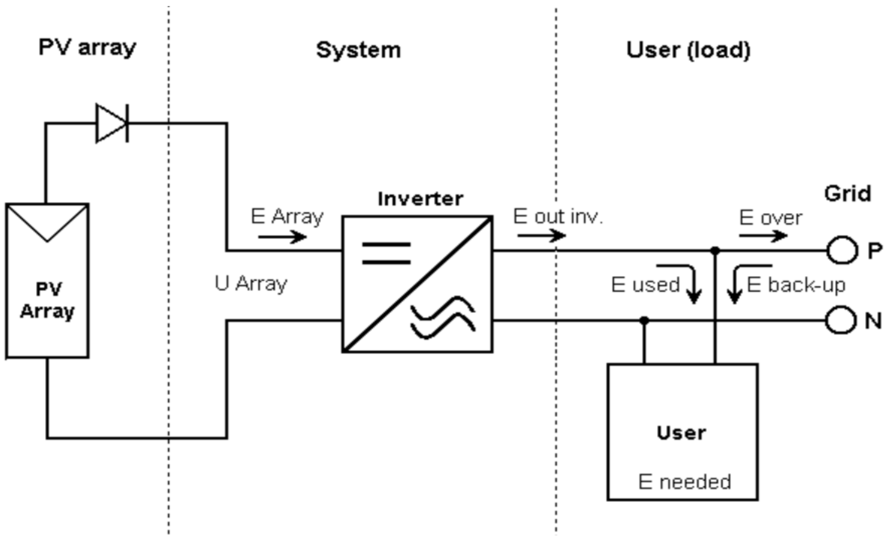

Figure 3.7: Simplified schema of the solar energy system from PVsyst. [75]

The **solar module** applied in this project is chosen according to the technology that provides the highest Wp relative to the price. In addition, availability on the Norwegian energy market is considered. The module has a linear performance degradation in the first 25 years. This can be observed in Appendix E.

In similarity to the chosen solar module, the **inverter** is chosen according to what is available on the market, or easily can be imported. The inverter naturally has to be suited for the Norwegian grid conditions at 60 Hz and 230 V. PVsyst provides inverters ranging from 0.11 kW to 3154 kW. Since the inverter needs to be selected according to the selected module, the first step is to observe the total nominal power of the modules. Heavily undersizing the inverter is not considered in this project.

The modules are arranged in **strings** which are connected in parallel to the inverter. The number of modules per string is calculated by observing the upper and lower end of the inverter's voltage range. The minimum and maximum number of modules per string are then accordingly established. The optimal amount of modules in series is found from the nominal MPP voltage. Limitations on the roof such as pipes, must be taken into consideration when choosing the number of strings. Certain inverters only have a specific number of strings that may be applied.

3.3 Solar Irradiation Data

The solar irradiation data is collected through PVsyst on a hourly basis. PVsyst provides the option of choosing a specific geographic location. Data from the two meteorologic sources, Meteonorm and NASA, are available. Meteonorm collects data from worldwide weather stations. This data does not include the effects from far away shading, meaning Meteonorm is not suitable for high mountainous regions. NASA creates an average data set from an area of 111 km x 111 km, and is mainly applied when weather stations are not present. [76, 77]

The data set from Meteonorm 7.1 station is chosen for the project since the area at Byneset is not particularly mountainous. This data set is an average between years 1991-2010. The respective sun path for each month can be observed in Figure 3.8. When simulating in PVsyst, the weather data produced is synthetic. This means that an average amount of real life distractions are included, for example passing clouds or rainfall.

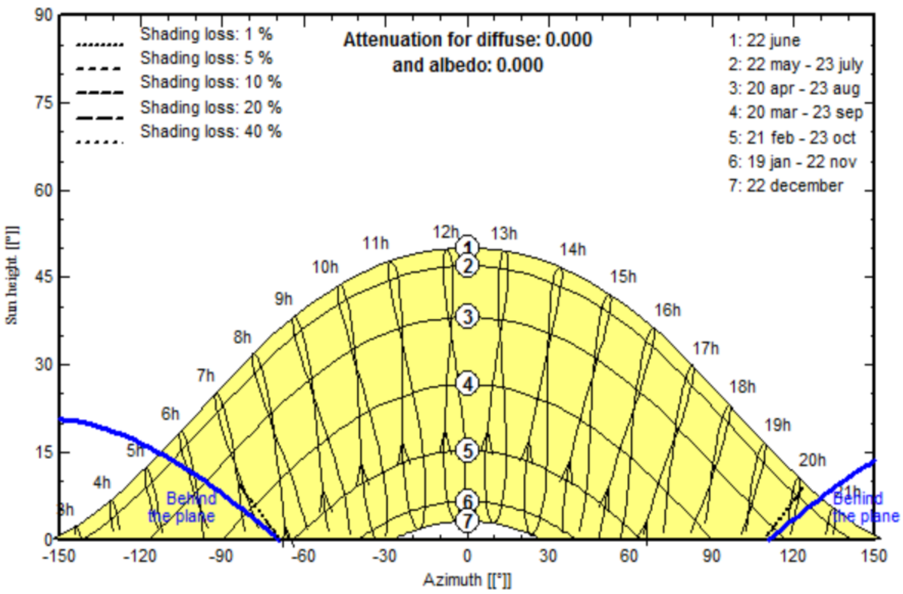

Figure 3.8: Solar irradiation path with data from Meteonorm 7.1 station. [75]

3.4 Investment Cost

The prices for installed solar energy systems on the market vary greatly. Companies provide varying deals, depending on system size, equipment, customers and location. Information regarding installation prices were extracted from a report written by the consulting firms Multiconsult and Asplan Viak for the Norwegian industry cluster Solenergiklyngen. The solar engineering firm, Solbes AS, also provided information regarding installation costs. Prices per installed Wp can be observed in Table 3.2.

Prices from Eidsiva Energi, a Norwegian power producer and supplier, have also been used as a comparison in Scenario 1 and 2. This can be observed in the results section of this report. Other additional segments of the investment cost such as the type of grid system and snow load requirements are taken into consideration. The possibilities for economic subsidies are investigated, but possible tax reductions are excluded from this project.

Table 3.2: Obtained solar energy system prices. [78, 79]

Solar Energy System Prices [NOK/Wp]		
Solenergiklyngen		**Solbes AS**
Small >10 kW	14	8-15
Industry 10-100 kW	13	
Large <100 kW	10	

3.5 Temperature Analysis Data

Solar irradiation data applied in Scenario 3 is a separate set of data than used in Scenario 1 and 2. The data set in Scenario 3 is actual irradiation measurements from an operating solar farm at Rye. Power output values are also collected from Rye. Historic data only back to April 2019 can be collected as the solar farm at Rye is fairly new. Data from April to December is from 2019, and data from January to March is from 2020. The solar farm is operated by TrønderEnergi and Solbes AS. The solar farm at Rye is located approximately 5.2 km from the poultry farm at Byneset. Further information about the operating solar farm, can be found in Appendix F.

The air temperature is collected from the Norwegian website *Klima Service Senter* on an hourly basis [12]. The air temperature is measured 2 m above ground level. The closest weather station to Rye is Høvringen. The station is located 11.7 km from Rye. Høvringen is at 41.5 m above sea level, while Rye is 101 m above sea level. This data is obtained from the application called *Above - Høyde over havet* [80]. A map of Trondheim is shown in Figure 3.9. The solar energy system at Rye and the weather station at Høvringen are marked with a red circle, respectively from left to the right. The blue circle is the location of the poultry farm at Byneset. The green pin points are other available weather stations.

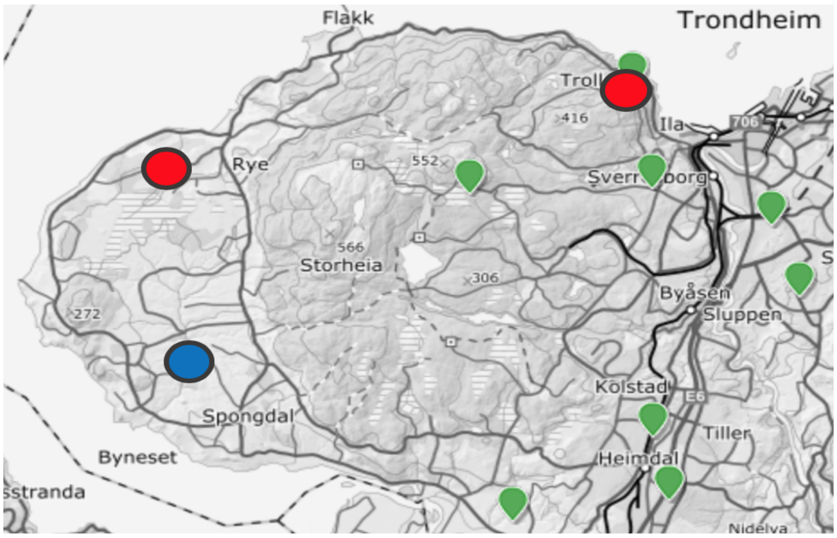

Figure 3.9: The red circles represent Rye and Høvringen from left to right. The blue circle represents the poultry farm. [12]

4 Spreadsheet Construction

Historical data from 2019 is used to construct a model of the solar energy system's operations and the economic profitability. This model is created from the beginning of 2020 til the end of 2044. The method to create the Excel spreadsheet on a hourly basis is described in this chapter.

4.1 Scenario 1

System Optimization

Firstly, the solar irradiation yield is calculated from the solar irradiation and the module's theoretical efficiency. The area of the selected solar module needs to be multiplied with the irradiation yield, to create the power output per module. To calculate the entire system power output, the power output per module is multiplied with the chosen number of modules.

As both Scenario 1 and 2 examine the profitability of installing a solar energy system, it is interesting to determine how much kW yet needs to be purchased and at which times. Using this method, the hours with overproduction are also determined. When electricity is purchased from Tensio AS, an additional fee of 0.25 NOK is added to the Nord Pool spot price [67]. Tensio AS is the largest operating grid company in the region of Trondheim.

When determining the actual electricity sales price of overproduced electricity, an input marginal loss fee is added. This fee is divided into summer and winter periods. The summer period is defined from March to October and has a fee of 5 %. The winter period is defined from November to February and has a fee of 6.5 %. The additional fee for the winter period is originally divided into day- and night fees with respectively 6.5 % and 6.0 %. However, the decision to use 6.5 % as the marginal loss fee is made to simplify the Excel spreadsheet. [67]

The last section of the Scenario 1 includes the calculation of purchased and sold electricity in NOK. This is done by multiplying the column with profits and deficits of kW with the appropriate electricity price. All the detailed calculations and the final spreadsheet can be observed in Appendix I.1.

Calculating the Net Present Value

The profitability of the project is calculated by applying the net present value (NPV) method in Excel. All cash flow values are presented in Norwegian Kroners. Negative numbers in the spreadsheet represent cash-out values. The discount rate for this project is likely to be between 5-8 % [26]. Four different discount rates within this range is examined to illustrate how the profitability varies with changes in the discount rate.

The relevant year's total bill, including both tariff and electricity bills, is compared to the total bill in 2019. This saved cash value is considered to be the yearly cash flow. The cash flow is calculated by comparing the hourly system power outputs with the hourly load profiles. The load profiles represents the hourly power consumption from 2019. The comparison between the system power outputs and the load profiles illustrates how much electricity can be bought and sold per hour. These profits and deficits are linked up with historical electricity prices from Nord Pool.

The time period for the NPV method is set to 25 years. The modules will according to Luxor most likely have a linear degradation to 85 % of its original performance after 25 years. The possibilities to examine the profitability over a longer time period than 25 years are strong, but is not further researched in this project. The cost of uninstalling the solar energy system should to be part of the NPV calculations to obtain accurate results. This cost is, however, not included in this project.

Spot Price Evaluation

As part of Scenario 1, a spot price evaluation is completed on the behalf of the historical Nord Pool prices. An average price reduction is calculated by using spot prices from 2019 and comparing them with the prices from 2020. January, February and March are the months investigated. The net present value method is completed again with the average price reduction included in the spot prices.

4.2 Scenario 2

Scenario 2 has the same construction method as the spreadsheet in Scenario 1. The same accounts for the net present value method. The singular difference in the Scenario 2, will be a different way of calculating the yearly tariff. Data regarding the future tariff prices have been collected from NVE, and present tariffs are taken from Tensio AS. The original data from NVE and scaled up prices for this project, can be found in Appendix C. Detailed calculations regarding Scenario 2 can be found in Appendix I.2.

Monthly Subscription Tariff

The monthly subscription tariff is divided into four segments. These include a constant yearly fee, an energy fee, a subscription fee, and additional fee for kW exceeding the subscription.

The constant yearly fee is calculated from data provided by NVE which are scaled up linearly. The energy fee is calculated by looking at this linearly scaled energy price and multiplying it with the yearly electricity production. The subscription fee is calculated from the mean value of the maximum power output from the grid on a monthly basis. The mean value is linked with the fixed price per kW. On an hourly basis throughout the year, the subscription fee is subtracted from the power output. This difference provides information regarding which hours the subscription is exceeded and how much kW is exceeded. The summation of this row is then linked with the fee for exceeding the subscription.

The solar energy system is planned to be operational between 2020-2044. The tariff calculated from 2020 is the starting value. Between 2020-2021, CPI is included. A transition phase occurs between 2022-2026. From 2027-2044, CPI is included. The CPI used for this project is constant at 0.9 %.

Daily Maximum Tariff

The *daily maximum tariff* is divided into three segments. These include a constant yearly fee, an energy fee, and a fee reflecting the highest daily power output from the grid.

The constant yearly fee and energy fee are calculated using the same method as for the *monthly subscription tariff*. For each day, the maximum power is measured. This maximum daily power is linked up with the price per kW reflecting the summer or winter months. For this tariff, summer is defined from April 1st till October 31st, and winter is defined from November 1st till March 31st. The summation of each daily maximum fee for the entire year is defined as the highest daily power output fee.

Fuse Differentiated Tariff

The *fuse differentiated tariff* is divided three segments. This are a constant yearly fee, an energy fee, and a fee reflecting the highest yearly power output from the grid.

The constant yearly fee and energy fee are calculated with the same method as for the *monthly subscription tariff* and the *daily maximum tariff*. The highest yearly power output fee is found by observing the power output on an hourly basis through the entire year. The peak load is linked up with the appropriate price per kW.

4.3 Scenario 3

The objective in Sceanrio 3 is to examine if there is a correlation between the air temperature and the module's actual efficiency. Observe Appendix I.3 for detailed method description. It is essential to separate this part of the project from the previous research regarding the implementation of a solar energy system at Byneset. The temperature analysis is not directly linked with the poultry farm previously described, as the observed building is an operative solar energy system at Rye. As the solar energy system contains two types of modules, an new efficiency is calculated to reflect an average.

System power output and solar irradiation is applied in the Equation 4 to calculate the actual efficiency. The performance ratio of the solar modules is found from the actual efficiency and the theoretical efficiency. Statistical analysis tools in Excel are used to calculate the correlation- and determination coefficients. The results of the coefficients are confirmed using Equation 6. The comparisons are firstly made in the time period February 8th to April 8th, as the objective is to examine how cold temperatures affect the solar module's efficiency. Comparisons are secondly made in the time period June 1st to June 30th to briefly examine the correlation in a warmer month.

5 Results

Results from Scenario 1, 2 and 3 will be presented in this chapter. In addition, the results regarding the effects of varying solar energy system prices and a general overview of all analyses are presented in the NPV overview. Obtained results such as measurements from the excursion and the selection of solar irradiation data are presented in the chapter preliminary work.

5.1 Preliminary Work

Comparing Meteonorm and NASA

In PVsyst, the user is able to retrieve a comparison of the two data sets. Since PVsyst uses a synthetic weather function while simulating, the comparison is given through a Gaussian distribution curve. It can be observed in Figure 5.1.

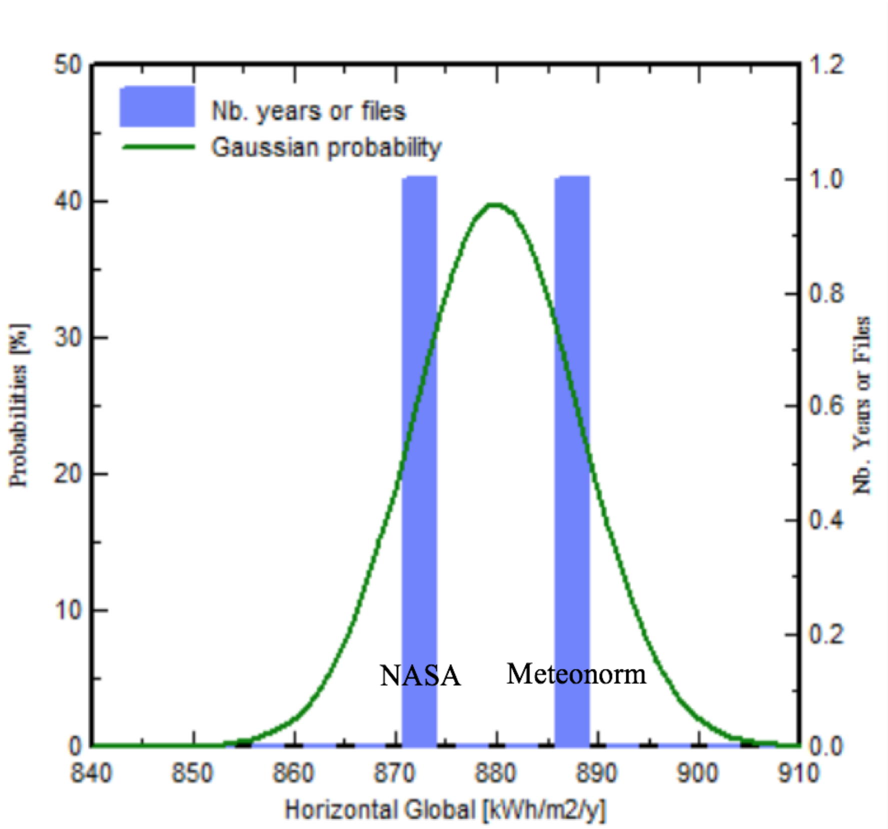

Figure 5.1: Comparison of Meteonorm and NASA irradiation data from PVsyst.

The horizontal axis represents the global horizontal irradiance for one year, given in $kWh/m^2\ year$. The right side of the vertical axis represents the number of years, and the left side represents the probability in %. The blue pillars represent the two sets of data, NASA to the left and Meteonorm to the right. The NASA data falls between a span of approximately 871 to 874 $kWh/m^2\ year$, while the Meteonorm data ranges from approximately 886 to 889 $kWh/m^2\ year$. The year to year variability lies at 0.9 % for the data sets. It is clear from the graphs that the two data sets do not fall far from each other.

Simulation Parameters

Table 5.1: PVsyst parameters.

Parameters	Description
Module Name	Eco-Line Full Black M60
Module Height	1.665 m
Module Width	1.002 m
Inverter	Solectria
Azimuth	21 ^{o}

The chosen solar module is Eco-Line Full Black M60 from the German manufacturer Luxor. This solar module is sold on the European market. The solar module dimensions gives an area of 1.67 m^2. More information about the chosen module and inverter can be found in Appendix B.1.

V_{MPP} for the module is 32.6 V, and the I_{MPP} is 9.51 A. Using Equation 2, P_{max} for the module is 310.026 W. Given Wp from the manufacturer is 310 Wp. V_{OC} for the module is 39.3 V, and the I_{SC} is 9.98 A. Using Equation 3, FF for the module is calculated to be 0.79.

The installations of the solar modules are made with the same angle as the roof, which is calculated to 21.63 ^{o}. Other simulation parameters can be observed in Table 5.1.

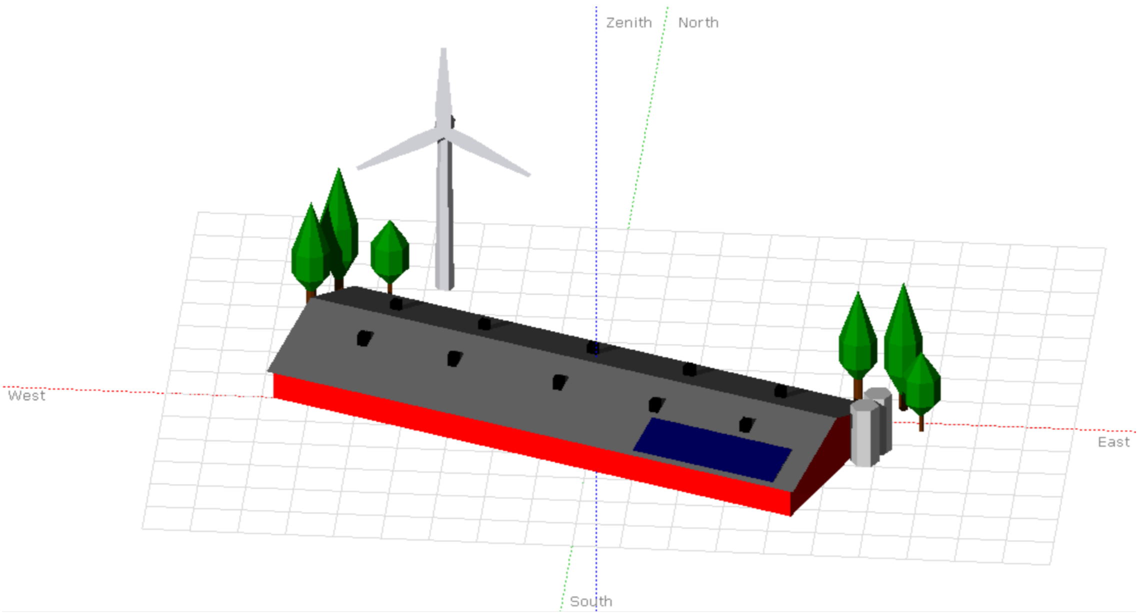

Figure 5.2: Module layout for Scenario 1.

A visualization of the projected solar energy system can be observed in Figure 5.2. The figure is created in PVsyst. The trees and wind turbine are only added for visual purposes and are outside the bounds of the system. The system in this figure consists of 48 solar modules and illustrates the area of the roof that will be covered.

The estimation of the theoretical maximum number of solar modules is calculated to 339. Calculations regarding this estimation can be observed in Appendix B.3. With 339 installed solar modules, the maximum system power output 95.68 kW.

5.2 Scenario 1

5.2.1 System Optimization

The applied discount rate is 5 % and the solar energy system price is 10 NOK/Wp. As shown in Table 5.2, the optimum number of solar modules is 48 for the chosen parameters. By installing 91 solar modules, the project will be green profitable if the discount rate is constant at 5 %. Green profitable means the payback time equals the life time of the solar modules. Discount rates at 6, 7 and 8 % can respectively be observed in Tables 5.3, 5.4 and 5.5. The total investment cost with 48 solar modules is calculated to equal 122 700 NOK in the Excel spreadsheet. An investment cost of 208 890 NOK is collected from Eidsiva Energi.

Table 5.2: Discount rate of 5 %.

	Number of Modules
Minimum	20
Optimum	48
Green Profitable	91
Maximum	339

Table 5.3: Discount rate of 6 %.

	Number of Modules
Minimum	20
Optimum	46
Green Profitable	68
Maximum	339

Table 5.4: Discount rate of 7 %.

	Number of Modules
Minimum	20
Optimum	36
Green Profitable	51
Maximum	339

Table 5.5: Discount rate of 8 %.

	Number of Modules
Minimum	20
Optimum	>20
Green Profitable	>20
Maximum	339

Figure 5.3 shows the calculated NPV results at year 25 for an increasing number of solar modules. The graph does not start in the origin since the minimum number of modules is set to 20. Less than 20 modules give an unrealistic NPV result. The graph peaks at 48 modules, which indicates the optimum number of solar modules. This is applicable when the solar energy system price is 10 NOK/Wp. The NPV after 25 years is then 26 846 NOK. The IRR is 7.19 %. The yearly cash flow is 10 706 NOK. Further information about the NPV analysis can be observed in Appendix A.1.

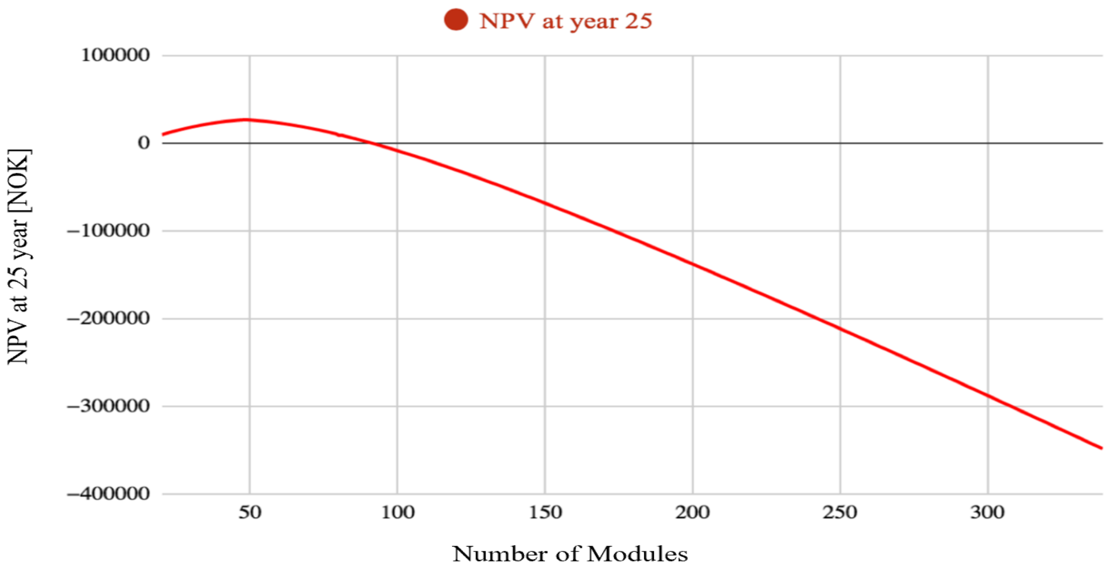

Figure 5.3: NPV at year 25 with a discount rate at 5 %.

The system nominal power output is 14 880 Wp. This value equals the maximum power the inverter must manage. The simulation in PVsyst contains a string inverter with a power of 14 kW. The manufacturer is Yaskawa Solectrica Solar. It is a triphased inverter. The voltage range is 260-550 V. This gives the system an array-to-inverter ratio of 1.06. The inverter has a dual MPPT feature, which optimizes the inverter's performance.

The yearly system electricity production from PVsyst is 13 565 $kWh/year$. The performance ratio is 0.875. When the inverter's dual MPPT feature is applied, the electricity production from PVsyst is 13 844 $kWh/year$. The performance ratio is then 0.879.

The layout in PVsyst has three rows and 16 solar modules per row. The minimum and maximum number of modules per string is calculated to be respectively 10 and 19. The module layout from PVsyst can be view in Appendix B.2. The optimum number of modules per string should be available in PVsyst as the nominal MPP voltage, but is not available. The modules are connected in four strings to one inverter. The number of modules per string is 12. Detailed calculations can be observed in Appendix B.3.

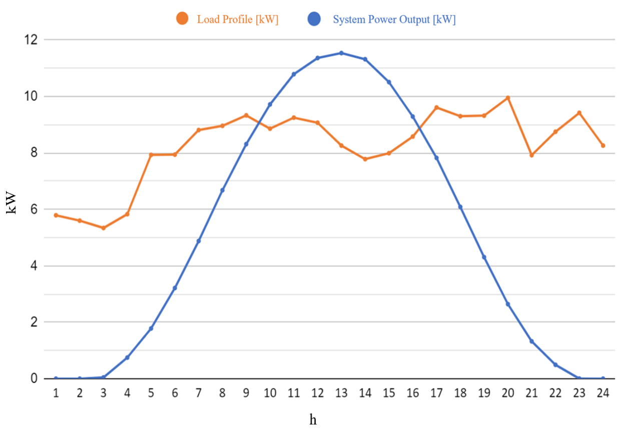

Figure 5.4: June 15th 2019.

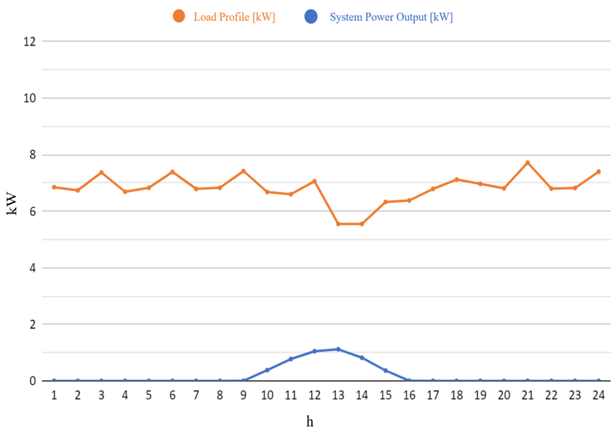

Figure 5.5: November 15th 2019.

Figure 5.4 and 5.5 shows the load profile and the system power output for a day in June and November 2019. The electricity consumption will be completely covered between 10:00 - 16:00 this day in June, meaning the barn does not need to purchase additional electricity from the grid at that time. However, in November the barn is highly dependant on the grid as minimal solar irradiation is present. In Table 5.6 the system power output is presented with the load profile from 2019. The average solar irradiation presented in Table A.2 is valid for the Scenario 1 and 2.

Table 5.6: System power output versus load profile.

	Load Profile [kW]	**System Power Output [kW]**	**Solar Irradiation [W/m^2]**
January	2.96	0.119	7.84
February	6.6	0.497	32.74
March	4.34	1.311	86.31
April	7.48	2.330	153.38
May	3.66	3.128	205.93
June	7.53	3.323	218.73
July	5.67	3.141	206.79
August	8.88	2.295	151.08
September	5.25	1.396	91.88
October	6.87	0.605	39.80
November	4.71	0.169	11.13
December	6.17	0.057	3.74

The total yearly electricity production calculated from the Excel spreadsheet is 13 471 kWh. This covers 25.9 % of the yearly electricity consumption. The system power output and the barn's load profile is plotted against every hour through one year in Figure 5.6. The load profile peak is at 16.5 kW. The six load profile peaks occur for each intake of broilers. The electricity consumption gradually increases during each intake, because the ventilation requirements increase as the broilers grow. Further information regarding data from the poultry barn can be viewed in Appendix F.

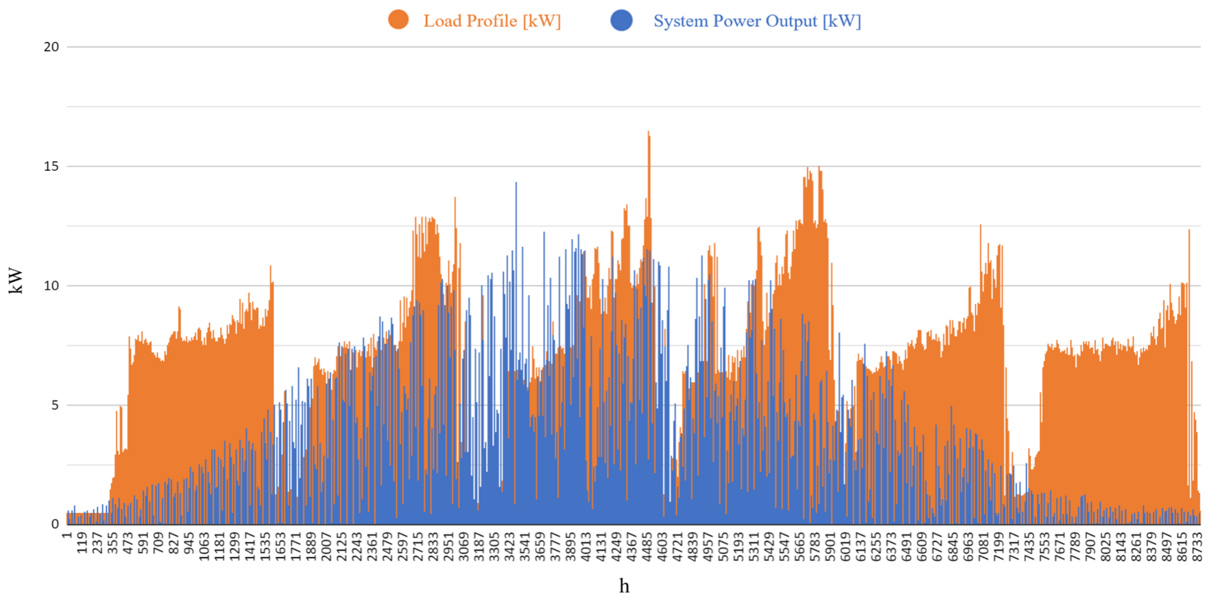

Figure 5.6: Load profile and system power output from 2019.

5.2.2 Evaluating the Spot Prices

Figure 5.7 shows the difference in spot prices from January 2017 till March 2020. The electricity prices in 2020 are exceptionally low compared the previous three years. It is important to notice that the spot prices do not include additional tariff fees from grid companies. Monthly spot prices from Nord pool between 2017-2020 can viewed in Appendix D.

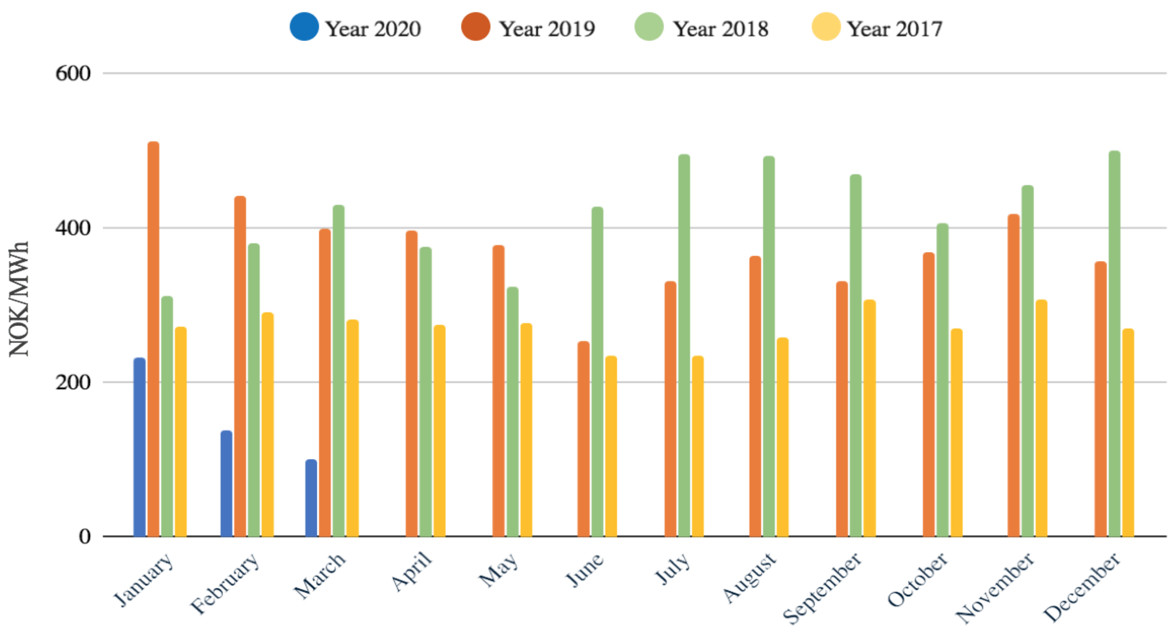

Figure 5.7: Nord Pool spot prices from the past four years. [10]

A comparison of spot prices between 2020 and 2019 is made. The reduction in January, February and March is 45.4 %, 31.6 % and 25.1 % respectively. The mean value of these reduction percentages is 34.03 %. A new NPV analysis was completed using the mean value as a constant reduction of the hourly spot prices from Nord Pool. The NPV after 25 years including the reduction is 91 659 NOK. The discount rate is still at 5 %, and the new IRR is 10.68 %. The yearly cash flow is 14 228 NOK.

It is now possible to install higher quantity of solar modules and still be profitable. The number of modules for green profitability is 106 solar modules. This is 15 more modules than previously calculated. The optimal number of modules is 39, which is an unexpected decrease.

5.3 Scenario 2

The application of 48 solar modules as the optimal number from Scenario 1, is brought into Scenario 2. The discount rate is still 5 %. The electrical grid tariffs are not constant in this scenario, as it is desired to examine how various grid tariff proposals affect the economic profitability of the solar energy system.

Table 5.7: Estimated future tariff prices.

	Energy Fee [NOK/kWh]	**Additional Fee [NOK/kW]**	**Constant Fee [NOK/year]**
Present Tariff	0.429125	–	2187.50
Subscription	0.115418	1.00	1443.37 + 721.683 per kW
Measured	0.115418	1.49 and 2.25	1977.94
Fuse	0.115418	–	1871.03 + 366.72 per kW

Table 5.7 contains scaled up values from a report written by NVE matching the present tariff prices from Tensio AS. The values give a rough estimation of how tariff prices might look in the future. The additional fees for the *measured grid tariff* are 1.49 NOK/kW for the summer period and 2.25 NOK/kW for the winter period. The additional fee of 1.00 NOK/kW for the *monthly subscription tariff* is valid through the entire year. The calculations regarding the linear scaling can be observed in Appendix C. Due to the transition phase between 2022-2026, the cash flow between these years will vary for the three tariff models.

Monthly Subscription Tariff

The total grid tariff in 2027 is 14 679.22 NOK. The linear degradation during the transition period between 2022-2026 is 1010.13 NOK. The average monthly power maximum in the duration of 2019 is 11.69 kW, and is selected as the monthly subscribed kW. A total of 126.18 kW exceeds the monthly subscription throughout the year. The NPV after 25 years is 77 773 NOK. The IRR is 10.45 %.

Daily Measured Tariff

The total grid tariff in 2027 is 11 591.03 NOK. This tariff is estimated after completing the expected linear growth during the transition period. The linear degradation is 1627.77 NOK, meaning the grid tariff decreases every year with this amount. The NPV after 25 years for this case is 108 911 NOK. The IRR is 12.10 %.

Fuse Differentiated Tariff

The total grid tariff in 2027 is 12 024.39 NOK. The linear degradation is 1541 NOK. The maximum purchase of electricity with this grid tariff adjustment, is 14.95 kW. The NPV after 25 years is 104 542 NOK. The IRR is 11.88 %. Further information about the NPV results in Scenario 2, can be observed in Appendix A.2.

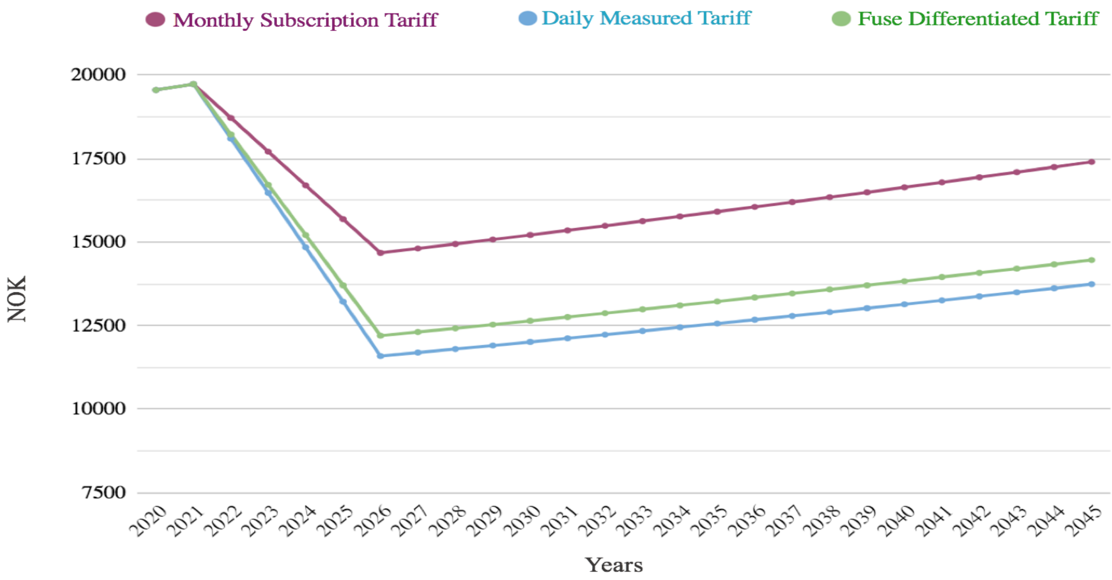

Figure 5.8: The cost of the three tariff proposals between 2020-2044.

Figure 5.8 shows that an implementation of the three tariff proposals will lead to a decrease in the yearly tariff for the system. The CPI is included between 2020-2022, and 2027-2045. A linear reduction occurs in five stages between 2022 and 2026. This is the transition phase between the present and possible new tariff models.

5.4 Net Present Value Overview

Figure 5.9 shows the NPV on the y-axis and the discount rates on the x-axis. The four curves represent Scenario 1 and the three tariff proposals in Scenario 2. The IRR can be observed where the curves cross the x-axis and y=0. All four curves illustrate an economic profitable project, since the discount rate is lower than the IRR.

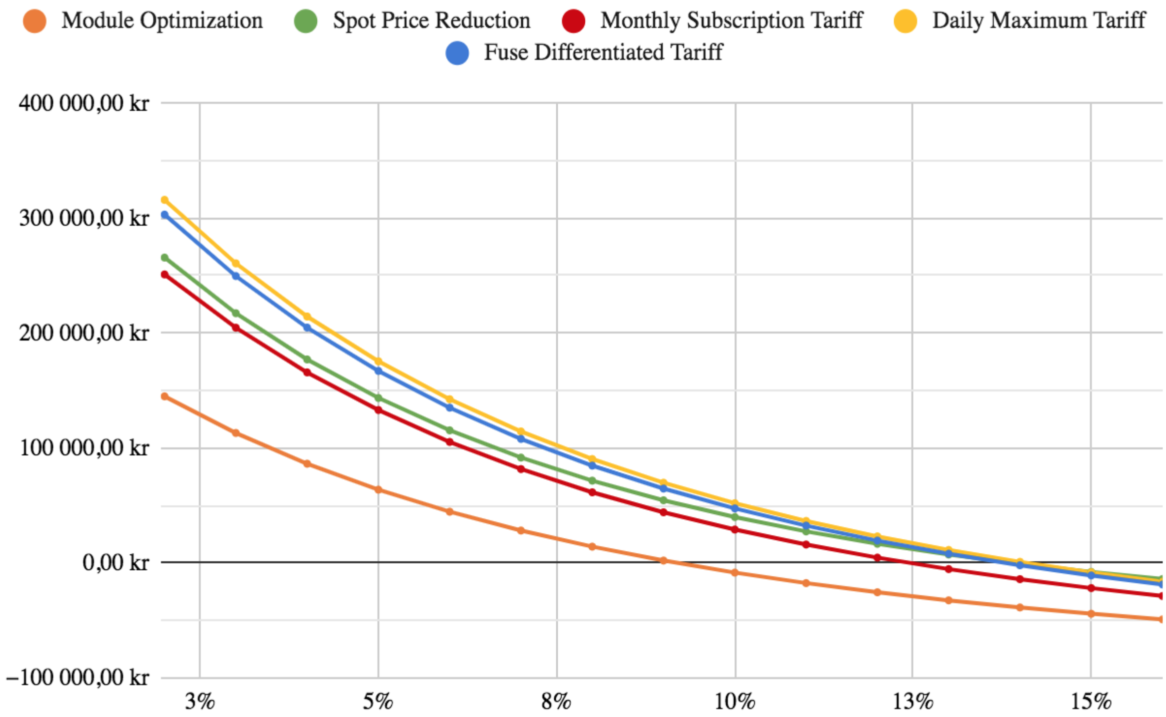

Figure 5.9: NPV plotted against discount rates.

An overview of the NPV related results can be viewed in Table 5.8. The cash flow for the tariff estimations are not presented due to yearly variations.

Table 5.8: Results overview.

	NPV [NOK]	IRR [%]	Cash Flow [NOK]	Payback Time [years]
System Optimizing	26 846	7.19	10 706	18
Spot Price Evaluation	91 659	10.68	14 228	11
Monthly Subscription Tariff	77 773	10.45	–	13
Daily Maximum Tariff	108 911	12.10	–	11
Fuse Differentiated Tariff	104 542	11.88	–	11

5.4.1 Solar Energy System Price Effect

The optimal number of modules for 8, 9, 10 and 11 NOK/Wp is respectively 66, 53, 48 and 45 modules. These results are obtained from the value of the peaks in Figure 5.10. This is the equivalent method as in Scenario 1. Figure 5.11 is a zoomed-in version of Figure 5.10 to more clearly illustrate the peaks.

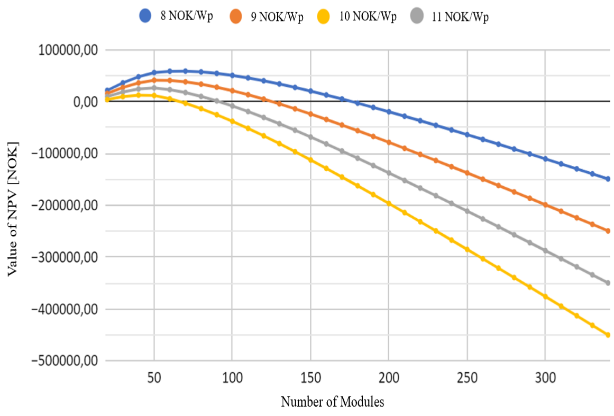

Figure 5.10: NPV for 20-340 modules.

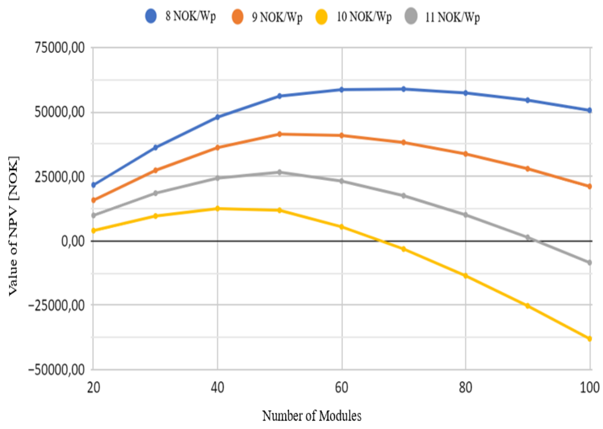

Figure 5.11: Zoomed-in graph.

5.5 Scenario 3

Figures 5.12 and 5.13 illustrate the relation between the actual efficiency and air temperature in duration of two months. The figures are divided into the time periods February 8th to March 8th, and March 9th to April 8th. A direct relation is not obtained simply from observing these figures. The highest actual efficiency obtained during these two months is 17.51 % and occurs on March 27th at 11:00. This efficiency is marked with a circle on Figure 5.13. The air temperature at this time is respectively 5.4 °C. The solar irradiation applied in Scenario 3 lacked data at certain hours, and assumptions regarding this shortage can be viewed in Appendix H.

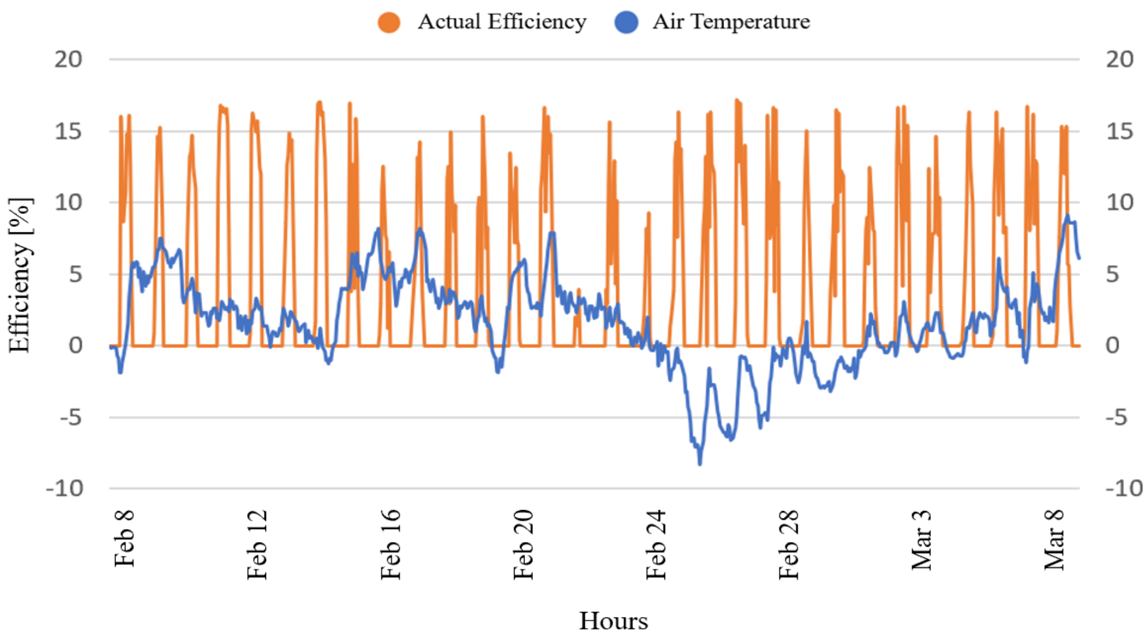

Figure 5.12: A comparison in the time period February 8th - March 8th.

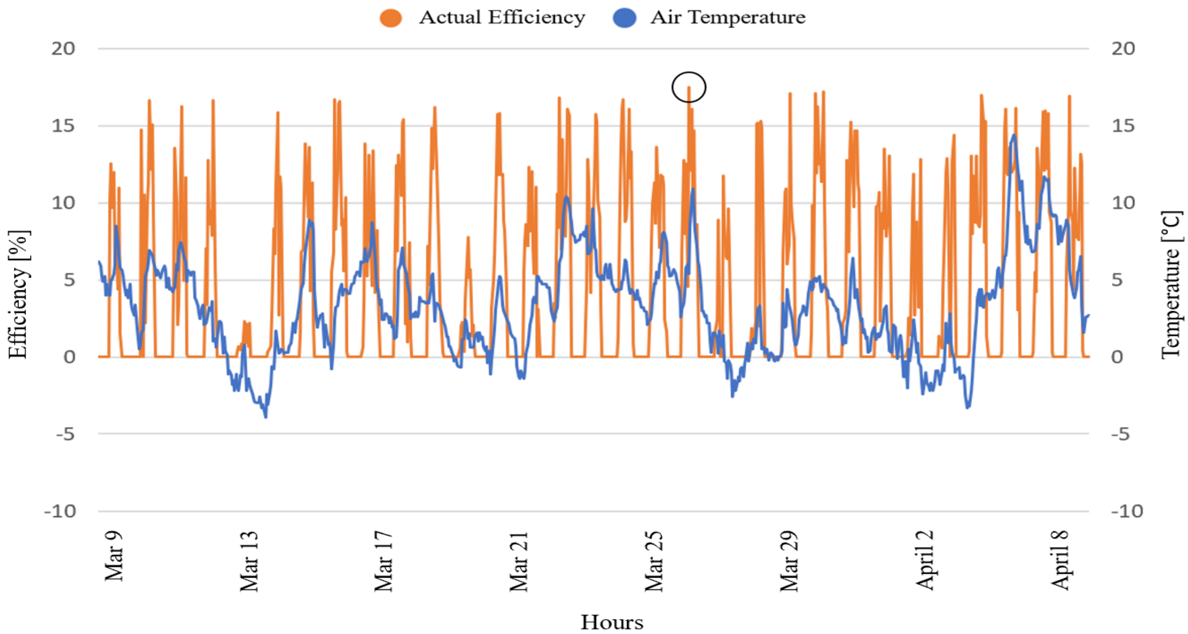

Figure 5.13: A comparison in the time period March 9th - April 8th.

It is observed from figure 5.12 and 5.13 that nearly all peaks are above 15 % efficiency, which is a fairly good performance considering the average theoretical efficiency is 18 %. The calculation of the average theoretical efficiency is presented in Appendix F. Table 5.9 and 5.10 are created to examine the calculated actual efficiency, and the deviation from the theoretical efficiency of the solar modules. The efficiency deviation represents the solar module's real operating value relative to the theoretical efficiency.

Table 5.9: Actual efficiency and efficiency deviation at 12:00 for February 24th-March 8th.

Date	Actual Efficiency [%]	Efficiency Performance [%]
February 24	2.153	11.96
February 25	14.27	79.28
February 26	16.17	89.82
February 27	16.96	94.21
February 28	16.62	92.33
February 29	12.82	71.20
March 1	7.945	44.14
March 2	9.010	50.06
March 3	4.172	23.18
March 4	7.947	44.15
March 5	9.934	55.19
March 6	9.154	50.85
March 7	12.10	67.20
March 8	15.06	83.66

The highest obtained actual efficiency during the chosen time period in Table 5.9 is February 27th with an actual efficiency of 16.96 %. At noon this specific day the solar modules were operating at 94.21 %.

Table 5.10: Actual efficiency and efficiency deviation at 12:00 for March 26th-April 8th.

Date	**Actual Efficiency [%]**	**Efficiency Performance [%]**
March 26	9.398	52.21
March 27	12.10	67.24
March 28	0	0
March 29	1.275	7.083
March 30	10.92	60.69
March 31	16.24	90.22
April 1	13.33	74.04
April 2	9.348	51.93
April 3	11.84	65.76
April 4	12.01	66.72
April 5	8.733	48.52
April 6	13.57	75.41
April 7	12.09	67.16
April 8	4.402	24.45

The highest obtained actual efficiency is surprisingly not obtained at 12:00, even though this is when the sun provides the most direct normal irradiation as the sun is located in the zenith position. All calculated actual efficiencies at Rye are presented in Appendix I.3.

A statistical analysis was completed in Excel to further investigate the temperature impact on the efficiency. The selected approach was linear regression. The correlation coefficient, R=0.597 when solar irradiation and actual efficiency is compared. This can be observed in Figure 5.14. This results in a determination coefficient, R^2=0.357. When air temperature and actual efficiency is compared in Figure 5.15, R=0.235 resulting in R^2 =0.055.

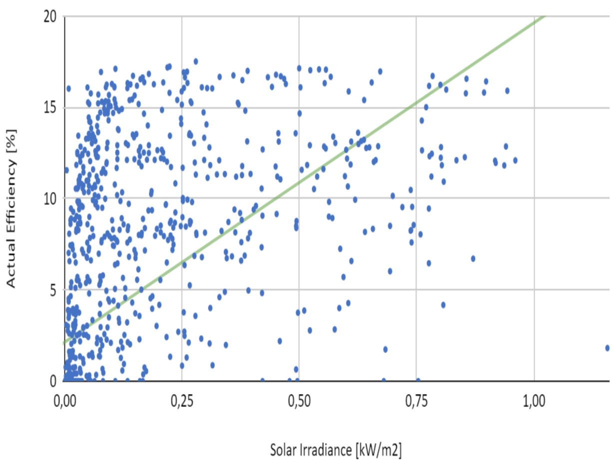

Figure 5.14: Plot of actual efficiency against solar irradiance for February 8th-April 8th.

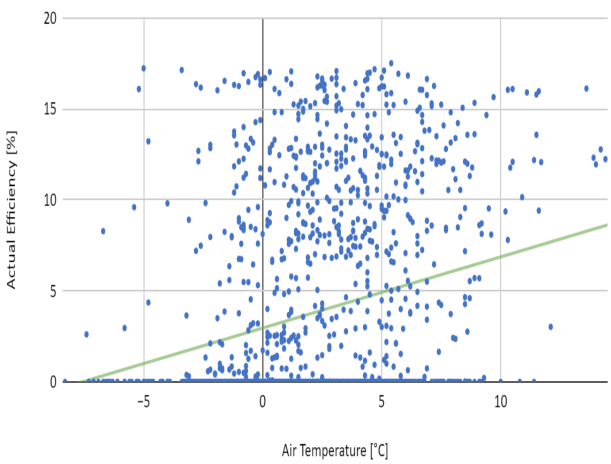

Figure 5.15: Plot of actual efficiency against air temperature for February 8th-April 8th.

In Figures 5.16, 5.17, 5.18 and 5.19 the correlation between the air temperature and actual efficiency is presented. The solar irradiation is estimated to be a constant factor when comparing the air temperature and the actual efficiency. In reality the estimation is an interval of 5 W/m^2. The intervals were selected as the most data was found in these specific intervals. There is no obvious correlation between the graphs from a visual perspective.

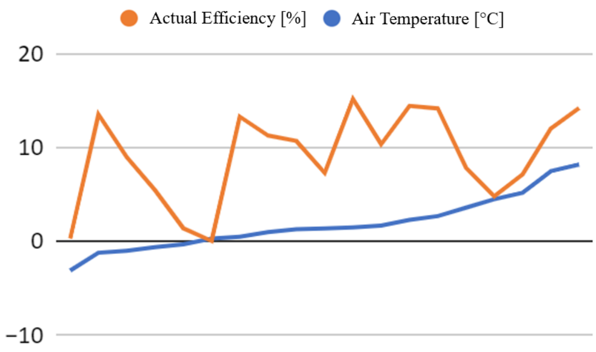

Figure 5.16: Range: 50-55 W/m^2.

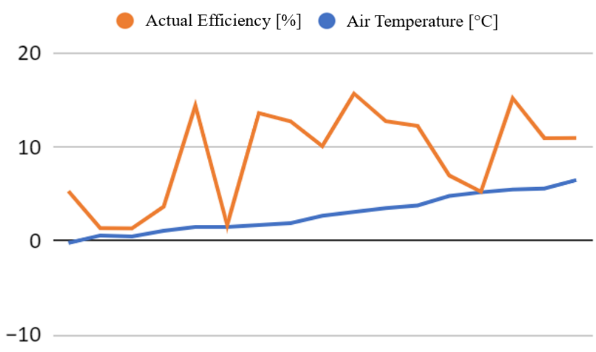

Figure 5.17: Range: 70-75 W/m^2.

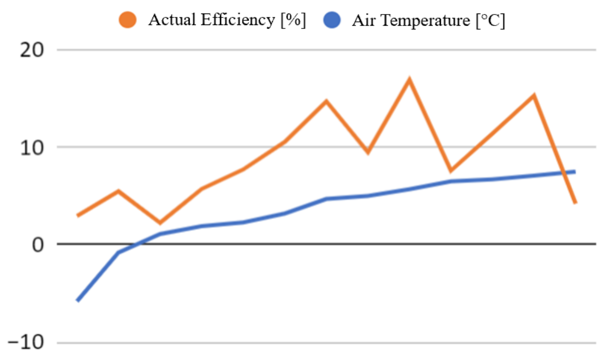

Figure 5.18: Range: 75-80 W/m^2.

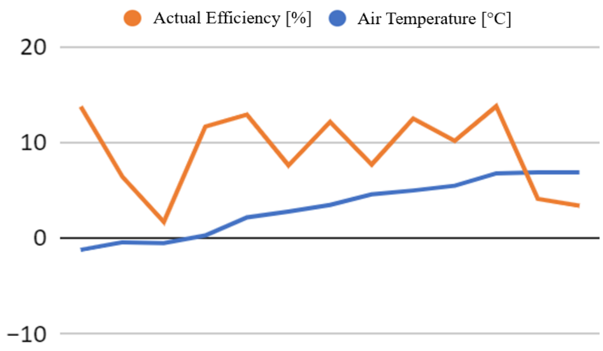

Figure 5.19: Range: 110-115 W/m^2.

The month of June was then examined. Figure 5.14 shows the actual efficiency plotted against the solar irradiation. Figure 5.15 shows the actual efficiency and air temperature. The graphs show an absence of correlation. This month was chosen to examine if a broader temperature variation will effect the results. June has a temperature variation from 5.1 to 28.8 ^oC, whilst the figure illustrating February and March has a temperature variation from -8.3 to 14.4 ^oC.

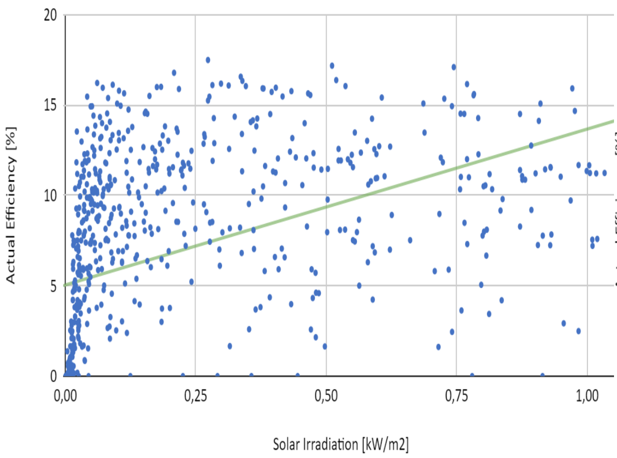

Figure 5.20: Plot of actual efficiency against solar irradiation for June 1st-June 30th.

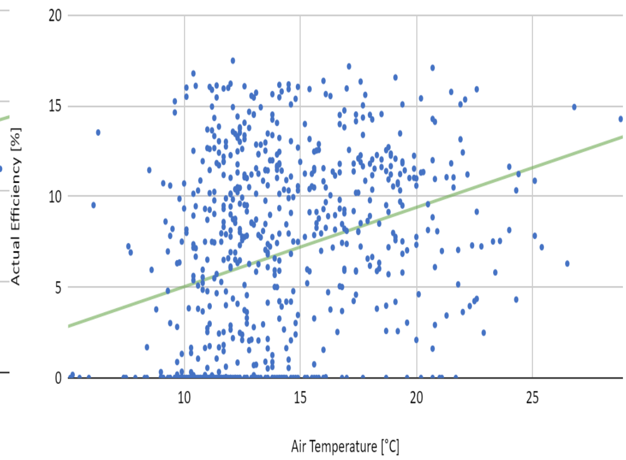

Figure 5.21: Plot of actual efficiency against air temperature for June 1st-June 30th.

The correlation coefficient, R=0.447 when solar irradiation and actual efficiency is compared in Figure 5.20. This results in a determination coefficient, R^2=0.200. When air temperature and actual efficiency is compared in Figure 5.21, R=0.311 resulting in R^2=0.097.

6 Discussion

6.1 Investment Cost Estimation

In a report written by Multiconsult and Asplan Viak for Solenergiklyngen, information regarding the total solar energy system prices for projects of various sizes is provided. These prices were used when considering the price for the solar energy system in this project. According to Solbes AS, the solar energy system price is in the range 8-15 NOK/Wp. An assumption that 8 NOK/Wp will apply for larger projects is made. The same applies to 15 NOK/Wp for smaller projects. A small and large project is defined as < 10 kW and > 100 kW respectively. The project at Byneset is treated as an industry since it is projected that the supply will be 13.47 kW with 48 solar modules as the optimum.

An essential factor to keep in mind regarding the report from Solenergiklyngen, is that it was written in 2018. As mentioned, the solar industry has had a remarkable price reduction in recent years. The Energy Transition Outlook written in 2019 by DNV GL, predicts a continuation of this reduction and considers a price drop less than 60 $\%$ by mid-century achievable. Consequently, it is likely that the price per Wp in 2020 is lower than 13 NOK/Wp for an industry-scaled installation. By comparing the information given by Solbes AS with the information given by Multiconsult and Asplan Viak, 10 NOK/Wp was the chosen system price for this project. Figures 5.10 and 5.11 are illustrating the net present value after 25 years with various system prices. The chosen system price is illustrated in yellow.

A linear price progression for a solar energy system is considered a simplified estimation. It would be ideal if the investment cost was divided into its constituent segments such as equipment costs, installation costs, and maintenance costs. Separating the investment cost was not considered due to the variation in prices regarding these segments. Suppliers provide various deals considering the location, size, equipment quality and the customer or company requesting the solar energy system.

A comparison of the investment cost was made with information gathered from Eidsiva Energi. Eidsiva Energi calculated a total investment cost of 208 890 NOK when 48 solar modules was installed. The calculated total investment cost in the Excel spreadsheet was 122 700 NOK. It was expected for some deviation to occur when using two different sources. However, a deviation of 86 190 NOK is significant and highlights the fact that not all factors were included in the linear price progression. There is reason to believe a more accurate economic profitability analysis would be achieved if the investment cost was divided into segments.

Factors such as the economic support given from Enova affects the total investment cost and was included in both estimations of the investment cost. However, when the tariff changes are pursued, the Enova support will eventually disappear. There might be governmental support available from both the municipality and county, but these were not investigated. A reason for not further investigating these possibilities, is because the support is much dependent on the specific solar energy system. Additionally, government subsidies are not fixed and might vary from year to year.

The type of distribution grid is a factor that needs to be considered when estimating the investment cost. The grid system at the farm is of the type IT, while a TN-S grid is required. A full reconstruction of the electric system will result in an additional cost. The investment cost will also increase due to the snow load requirements. Racking equipment will increase with an additional 50 % when the snow load requirements reaches 3.5 kN/m^2. This level is reached for the poultry barn at Byneset due to the location and altitude, as shown in Table 2.1. Neither of these additional installation costs are investigated in this project, as a linear price progression is the chosen approach for investment cost calculation.

6.2 Spot Price Uncertainties

As the domestic electricity production comes mainly from hydro power, Norway is forced to import electricity from neighboring countries when the water reservoirs go empty due to rainfall shortage. This results in an increase in spot prices. Spot prices from Nord Pool were exceptionally high in 2019, compared to 2017, 2018 and 2020. This can be viewed in Figure 5.7. There are several reasons for this occurrence. Two of them being the high temperatures and minimal rain fall in 2018. The spot prices started escalating in the second half of 2018, and remained high throughout 2019, as a result of these weather conditions.

The economic profitability analysis naturally centers around the spot prices. The spot prices from 2019 are applied when the building's load profile exceeds the system power output. The same is applied when the system produces more electricity than it consumes. As a prosumer, you are able to sell excess electricity back to the grid equal to the spot prices (with an additional transportation fee at 5-6 %). Since the spot prices have been fluctuating drastically over the past four years, it is clear that the results from the economic profitability analysis would have been different if another year had been examined in this analysis.

As part of Scenario 1, an evaluation of the spot prices was completed. The reduction of 34.03 % was calculated from the average of January, February and March's spot price reduction between 2019 and 2020. The ideal situation would be to look at the reduction on an hourly basis, however a simplification was made. All spot prices from 2019 were reduced with 34.03 %.

The projected solar energy system in Scenario 1 is highly dependent on the electrical grid due to its size. The system will only cover 25.9 % of the yearly electricity consumption, resulting in the need to still purchase 38 613 $kWh/year$ from the grid. The reduction in spot price will, therefore, have a positive impact on NPV as the cash flow increases. The NPV after 25 years increased from 26 847 NOK to 91 659 NOK. This shows that the economic profitability of the solar energy system is significantly dependent on factors that are challenging to predict. If the projected solar energy system had a higher installed Wp, electricity production would be higher, resulting in more independence from the grid. A reduction in spot price would then have minimal effect on the cash flow. This because the majority of the electricity demand would be self-produced.

The optimum number of solar modules was also affected when the spot price reduction was applied. The number unexpectedly decreased to less than 48 modules, while the number of modules to obtain green probability simultaneously increased by 15 modules. A reasoning for the decrease in number of optimum modules might be a negative effect of linearizing the installation price. This strengthens the argumentation of dividing the investment cost into segments.

6.3 PVsyst Simulation

Inverter Selection

The selection of the inverter was done purely with the intention to complete a successful simulation in PVsyst. PVsyst operated independently from the economic profitability analysis in this project. Specific optimizers improving the electricity production were, therefore, not prioritised. However, the chosen inverter had a dual MPPT feature, and when applied, the system electricity production increased with 188 $kWh/year$. This will result in less purchased electricity from the grid and increase the NPV. Having an inverter with a dual MPPT feature may be an advantage, if future expansion of the solar energy system is considered. The inverter's dual MPPT feature gives the opportunity to connect arrays with different azimuths, tilt angles, and module types. If both sides of the roof are enforced, the dual MPPT function inverter becomes useful.

Undersizing the inverter is an option, but not heavily considered in this project. Inverters with lower power labels are generally cheaper, resulting in a minor reduction in installation cost if this decision is made. This decision should only be pursued if it is absolutely certain that the Wp for all modules in the system will not be reached. If the system power out exceeds the inverter power, serious equipment damage may occur. A negative consequence of undersizing an inverter is the limited possibilities regarding expansion of the solar energy system. The array-to-inverter ratio for the projected solar energy system was 1.06. As mentioned in the theory section, a typical array-to-inverter ratio is between 1.15 and 1.25 [37].

Module Selection

Monocrystalline silicon solar modules are used in this project. Prices of monocrystalline cells have become highly competitive against polycrystalline cells. When comparing modules at Tier-1, the prices are similar. Additionally, monocrystalline cells have a higher theoretical efficiency which again justifies the choice.

For Scenario 1 and 2, the module efficiency and Wp were actively part of the investigation. However, similar to the inverter choice, the type of module was mainly used for the simulation in PVsyst. The FF for the module is calculated to be 0.79. A typical commercial solar module today has a FF-value of 0.83. This illustrates that the chosen module may not be of the highest quality, in comparison to what is available on the market. Since the installation price for the solar energy system was scaled linearly, the module price was not considered.

Performance Ratio

The performance ratio from PVsyst with the regular inverter was 87.5 %. The performance ratio with the dual MPPT function activated was 87.9 %. With the regular inverter, 12.5 % of the produced electricity has been lost. This loss may partially be explained by weather related issues. The weather data used in PVsyst was created synthetically, meaning that temperature fluctuations, clouds and snow effects were considered. In a real life situation, dirt on the solar modules will also have an effect on the performance. Another part of this loss can be explained as thermal or conduction losses in the electrical equipment. A performance ratio above 80 % is considered high and it is, therefore, clear that the simulation in PVsyst had a successful outcome in regards to the consumer.

6.4 Excel versus PVsyst

The reason for calculating results in the Excel spreadsheet and completing simulations in PVsyst was to increase the credibility of the results. Results from Scenario 1 were similar when collected from Excel and PVsyst. In both Excel and PVsyst the solar irradiation was collected on an hourly basis. This data was collected through Meteonorm, where satellites only register the solar irradiation a few times per day. Neither losses, optimization tools, the azimuth, the solar path, and the tilt angle are considered in Excel. All these factors are however considered in PVsyst. The electricity production from Excel was 13 471 $kWh/year$ and the yearly electricity production from PVsyst was 13 565 $kWh/year$. The deviation between these two is 94 $kWh/year$.

PVsyst collects parameters such as temperature and wind velocity. The temperature can significantly affect the efficiency of a solar module [32]. The Excel spreadsheet does not consider losses or weather conditions in its calculations. Therefore, it would be natural to assume that the system results from PVsyst would be less satisfactory than the system results from Excel. However, the results turned out opposite. A reason for this may be unconsidered optimization features embedded in the modules and inverter, not included in the Excel spreadsheet. Another reason might be that the synthetic weather conditions in PVsyst worked in favour for the electricity production. However, the difference between the Excel and PVsyst results were not remarkably large.

6.5 Module Efficiency

Linear Degradation

The project is examined over a 25-year period. In this duration, the efficiency of the solar modules will decrease. The calculation of the economic profitability in Excel is performed with the theoretical efficiency at 18.97 %. The efficiency reduction is not included during Scenario 1 and hence the results will represent the ideal system power output. The degradation for the Luxor module used in this project is considered to be linear. The power guarantee starts at 97 % and decreases down to 85 % after 25 years. It is clear that if the yearly linear degradation was considered, the NPV after 25 years in Scenario 1 and 2 would have decreased.

Calculating the Actual Efficiency

The actual efficiency of the solar modules was calculated on an hourly basis between February 8th and April 8th, and between June 1st and June 30th. A noticeable observation from this analysis was that the solar modules do not operate with the efficiency provided by the manufacturer at all times. Table 5.9 presents the efficiency deviations from two weeks in February, measured at 12:00 PM. Taking February 24th as an example, the efficiency is only operative 11.96 % of what is provided by the manufacturer. Meaning that the solar modules used in Scenario 3 only have an efficiency of 2.153 % during this specific hour.

If the results from Scenario 3 were implemented into Scenario 1 and 2, the NPV would change drastically. Since Byneset and Rye are 11.7 km apart, the weather conditions are assumed to be similar, hence data from Rye is applicable for Byneset. In Scenario 1 and 2, it was assumed that the efficiency for the solar module would be 18.97 % at all hours of the year. If the actual efficiency was used instead and the number of modules remained constant, the amount of electricity purchased from the grid would increase. This would further result in a decrease in the yearly cash flow, which would affect the NPV for the installed solar energy system.

6.6 Load Profile versus System Power Output

One of the first steps when installing a solar energy system, is evaluating if the system should be optimized on behalf of summer or winter months. The number of modules will vary greatly according to which optimization is chosen. The tilt angle is also a parameter that will vary depending on the season, due to the suns position in the sky. As Nordic regions have long summer days and short winter days, it is challenging to scale a solar energy system that will cover the full power demand while being economically profitable. From Figure 5.6, it is clear that the results from this project reflect a solar energy system located in a Nordic region. The system power output is substantially higher during the summer period, and close to negligible towards the end of December. Since minimal irradiation is present at this time, an excessive amount of modules would be necessary to cover the load profile. Therefore, a system to reflect the power demand during summer was created in this project.

As the electricity production from a solar energy system also varies greatly in the span of one day, there will be a need to buy electricity from the grid at certain times. However, what separates the poultry industry from a regular Norwegian household, is the shape of the building's load profile. This is clear from both a yearly perspective in Figure 5.6 and a daily perspective in Figure 5.4. It is more profitable to use self produced electricity, rather than selling it back to the grid. When selling electricity, the consumer needs to pay a marginal loss fee. In the poultry industry there are strict ventilation and temperature requirements, which increases the load profile as outside air temperatures rise. A typical Norwegian household on the other hand, will most likely decrease its electricity bill as temperatures rise and the days become brighter. It is crucial that the load profile and system power output corresponds for full optimization.

6.7 Tariff Analysis

Today, a customer's tariff bill mostly reflects the amount of electricity consumed per month. Peak loads regarding the electrical grid are in the morning and late afternoon/evening. Implementing a solar energy system with today's tariff system will be economically beneficial for the consumer that is installing the system, but will probably not reduce the burden on the electrical grid. For most situations it seems that a solar energy system will produce the most electricity while the power capacity on the grid is satisfactory. The solar energy system has highest production while the load profile for a typical Norwegian household is low. For the poultry industry, the daily load profile is quite evenly distributed throughout the day. However, there is still a need for electricity when solar irradiation is unavailable. The intention concerning the new tariff system is to more evenly distribute payments between consumers and grid companies. Before grid expansion is strictly necessary, an attempt to operate the grid in a more efficient way will be proceeded.

General Reasoning For The Results

Figure 5.8 shows how an implementation of the three tariff models will change the yearly grid tariff. The tariff is affected by the CPI before 2022 and after 2027. This CPI is set constant to 0.9 % in this project, even though the inflation varies over time. If the graph was presenting a real case, the years before 2022 and after 2027 would still have an upward inclination, but would not be linear.

The transition phase of the tariff changes occurs in the time period 2022 to 2027. The reason for this transition period is to avoid abrupt changes for the consumers. The changes in tariffs will lead to a price increase for some, reduction for others, and many will not notice a difference. The estimated tariff in 2027 for the *monthly subscription*, *daily measured* and *fuse differentiation*, has a price reduction of respectively 25 %, 41 % and 39 % compared to year 2022. From the results obtained in this report, the three tariff models can be interpreted as positive impacts on the NPV. These positive results are only applicable for this specific project.

A reason for the declining yearly tariffs might be the structure difference of the present grid tariff compared to the three new tariff models. The grid tariff today is mainly dependent on how much electricity is consumed during the billing period. All three future tariff models are mainly based on how much power is consumed from the grid. For this project, it is clear that the power tariffs work in favour of the solar energy system.

Fuse Differentiated Tariff

In 2019 there were six flocks of broilers throughout the year. As each group of broilers live in the barn for approximately 47 days, there will be a 8-12 day period between each flock where cleaning takes place. In this cleaning period, the load profile drops quite drastically. There are six cleaning periods in one year. Meaning that there is between 13-20 % of the year where the need for electricity is almost negligible.

In the tariff calculations in Section 5.3, the price of the withdrawn power output from the grid is based on the yearly maximum power output from 2019. Meaning, if there is one high power peak throughout the year, the tariff bill will reflect this peak. This results in an opportunity to extract power up to this limit as long as it is not exceeded. A regular Norwegian household will be able to reduce costs quite easily by cutting the exceptionally high power peaks. This is however not considered in this project, since the poultry industry has ventilation requirements depending on uncontrollable factors like weather and broiler growth.

The highest necessary power output from the grid with the installed solar energy system is 14.95 kW. The barn's highest load peak is 16.5 kW. The highest yearly load peak is cut with approximately 1.5 kW, which is not considered much. The price per kW regarding the *fuse differentiated tariff* is 366.72 NOK, meaning that the yearly amount saved would be 550.08 NOK.

By analysing the *fuse differentiated tariff* model, it suggests to be more suitable for a building with a steady yearly load profile. The load profile varies considerably from 0.5 kW in January to 16.5 kW in July, when examining the same hour of a day. However, from the calculations completed in this report, the implementation of the *fuse differentiated tariff* had a positive impact compared to the present tariff system.

Daily Maximum Tariff

Similarly to the *fuse differentiated tariff*, the price of the power output is based on a power peak. Instead of looking at the yearly power peak, the daily power peak is now observed. Equal challenges apply for both tariff models, considering determination of the tariff bill based on singular high peak loads. With help from AMS, the intention is for the consumer to easily stay updated with real time data regarding power consumption. This will avoid unnecessary peaks, particularly for a regular Norwegian household. Like mentioned earlier, the poultry industry has strict regulations regarding ventilation. Shifting peak loads is, therefore, not considered.

The load profile, illustrated in Figure 5.6, shows a few high power peaks towards the end of each flock period. It is also noticeable that the highest peaks are when the system power output is high. On the other hand, the load peak at the end of December when the flock is reaching its 47th day, is still considerably high. At the same time, solar irradiation is almost negligible, resulting in no cuts of peak loads. The load profiles will, therefore, correspond directly to the tariff bill at days with no solar irradiation.

The load profile does not have many peak loads through the year. By observing Figure 5.6, the load profile peaks overlaps with periods where the system power output is high. Since the load peaks are few and paid on a daily basis, these do not affect the rest of the year. The *daily maximum tariff* is, therefore, considered as a more suitable model than the *fuse differentiated tariff* for the poultry farmer.

Monthly Subscription Tariff

The *monthly subscription tariff* consists of a specific kW subscription per month, and power exceeding this amount will be supplemented as an additional fee. The subscription is estimated using historical data, so the kW will vary each month. As each flock of broilers is present for approximately 47 days, the load profile of the barn will never correspond exactly with the monthly kW subscription. However, with help from AMS, finding the optimal subscription is possible. When observing the load profile data from 2019, certain months have the broilers always present, while other months include the full 8-12 day hygiene period. Therefore, the regulation of the monthly subscription is crucial. If the load profile is rather constant, the regulation of the monthly subscription should easily be completed.

Deficiencies With The Method

The due date for submission of suggestions and complaints to NVE's latest consultation document was May 4th 2020. The information in the document was hence just a temporary proposal. Information treated in this project was extracted before this date. However, it was still relevant to create a model using current information, even though the tariff models might change in the next consultation document. The grid companies can individually design the layout of the grid tariff as desired. The three mentioned tariff models can also be combined, as long as the companies stay within the rules of regulation. Different models will be valid for consumers depending on the power consumption.

A set of proposed data from the consultation document was used in Scenario 2. The data set is based on an evaluation from Ringerikskraft Nett including 383 households. Ringerikskraft Nett is located in the south-east of Norway. The data was scaled up linearly to correspond with the present tariff prices from Tensio AS. Using data from another power supplier, lowers the credibility of the results. The estimation regarding the scaling of prices, also creates room for uncertainties. The aim for the tariff analysis was, however, not to obtain accurate results, but more to get an idea of how the new tariffs might look.

6.8 Net Present Value

Figure 5.2 shows the solar modules arranged on the barn's roof in a model created in PVsyst. It is clear that 48 modules do not cover extensive space on the roof when compared to the available area. When installing a solar energy system, the user may have other intentions than pure economic profitability. Installing between 20-91 panels will not lead to a negative NPV value. However, 48 was the number of modules that resulted in the highest NPV value after 25 years. The three determining factors that reflects this result, is the project's discount rate, linear price installation, and cash flow.

As discussed in Section 6.1, linearising the installation price for a solar energy system is a simplification, and leads to some limitations when choosing parameter sizes. This was clear when creating Figure 5.3. If one module was installed (310 Wp · 10 NOK/Wp), an installation price would be higher than 3100 NOK, due to costs such as the inverter, racking, and installation. 20 modules was set as the lower limit and values below were considered unrealistic in regards to the NPV after 25 years. In Figure 5.10, various NOK/Wp values are plotted. A system price equal to or greater than 12 NOK/Wp resulted in peaks occurring before 20 modules. 12 NOK/Wp was set as the highest installation price that could be applied, as anything below 20 modules was not considered in this project.

The discount rate is determined by observing similar projects that have been previously completed. It is clear from Figure 5.9, that a change in the the discount rate has an impact on the NPV. Escalating from 5 % to 10 % changes the NPV from a positive to a negative value, in Scenario 1. A constant cash flow is applied in Scenario 1. This is unrealistic, as cash flow is dependent on solar irradiation, load profile, spot prices and the amount of electricity purchased from the grid. Meaning that in a real situation, the yearly cash flow may vary greatly throughout the lifetime of the solar modules.

6.9 Temperature Analysis

Temperature Data

The temperatures used in the efficiency calculations were air temperatures from a location 11.7 km from Rye. The ideal data set would be to use the temperature measured inside the solar modules at Rye. However, this data was not available. The air temperature will not necessarily reflect the same temperature that is within the module. Especially since the air temperature is measured 2 m above ground level, while the height of the poultry barn is measured at 3.6 m. Nevertheless, an assumption was made that the data set could still be used in the analysis.

Correlation Between Temperature and Efficiency

TrønderEnergi has observed surprisingly high efficiencies during the winter period at Rye. A time period February 8th to April 8th was, therefore, closer examined. The efficiencies in Figure 5.12 and 5.13 show promising performance. However, it is difficult to detect if there is a relation between the efficiency and temperature based on these Figures. The efficiency peaks could simply reflect a bright and sunny day.

A statistical analysis was completed to mathematically prove the possible validity of the relation between air temperature and actual efficiency. As the Pearson's correlation coefficient in Figure 5.15 equals R=0.235, it is clear that no relation is found purely from plotting air temperature against the actual efficiency.

Further, a last attempt to examine the correlation was completed with the solar irradiation as a constant factor. The solar irradiation from February 8th to April 8th was arranged into intervals of 5 W/m^2. The values within these intervals were, therefore, theoretically set to be constant even though in reality there was a range of 5 W/m^2. These intervals can be observed in Figures 5.16, 5.17, 5.18 and 5.19. The efficiency curve would ideally have consisted of a downward incline as the temperature had a rising incline. The graph would not be completely linear, but should have a decreasing tendency. This is, however, not occurring in the graphs previously mentioned. The ideal situation would be to have several temperature and efficiency values, with a constant solar irradiation. However, because of the weak R^2-value there is reason to believe the tendency of increasing actual efficiency with decreasing air temperature would not occur even with smaller intervals.

Colder temperatures have been observed to increase the module efficiency. A study completed by SINTEF in Trondheim, shows that a correlation between temperature and efficiency is present [34]. This study was completed in a climate laboratory where parameters were closely regulated. The analysis completed in Scenario 3 was based on actual power output measurements from the solar farm at Rye, and air temperatures from a nearby location. The weak R^2-value from Scenario 3 does not necessarily reflects the absence of correlation between the data sets. It might simply mean that there are numerous factors that need to be kept constant and regulated, to observe a possible correlation.

It is clear the a solar energy system is complex, with several parameters affecting the results. A source of error could be that only three months were examined, and the variation of temperature was too narrow. There is little that indicates that examining further months would give more satisfactory results. Unregulated meteorological factors such as wind velocity and humidity could have affected the correlation, but was not considered in this project.

7 Conclusion

When installing a solar energy system, it is an advantage that the system power output progressively corresponds with building's load profile. This is true for the poultry barn at Byneset from a daily and yearly perspective. The barn's peak loads are cut, due to electricity production from the solar modules at appropriate hours. The conclusion for Scenario 1 is that the installation of 48 solar modules is calculated to be the optimal quantity. The payback time is 18 years and the achieved NPV after 25 years is 26 847 NOK. As the solar energy system is highly dependant on the grid with only 25.9 % electricity coverage, a reduction in spot prices leads to an increase in NPV.

The solar energy system is aimed to be operational between years 2020-2045. Changes in electrical tariff system will happen in this period, and will affect the economic profitability of the solar energy system. In Scenario 2, a reduction in the yearly tariff bill occurs for all three models. The NPV for the monthly-, daily-, and fuse tariff is 77 773 NOK, 108 911 NOK and 104 542 NOK respectively after 25 years.

In Scenario 3, the correlation between air temperature and actual efficiency at a nearby operating solar farm was examined. In the time period February 8th to April 8th, the coefficient R^2=0.055 is calculated. A conclusion is drawn that no correlation is found for this specific scenario since the coefficients are considered to be severely weak. A second attempt was completed for June, but no correlation is detected for this month either as R^2=0.097.

It is important to acknowledge that the results obtained in this thesis is only applicable for this specific project considering assumptions and estimations made. It is clear that the economic profitability of a solar energy system is complex, and small changes in variables have a great impact on the results. This is especially true for the installation price. Overall, it is concluded that installing a solar energy system as projected in Scenario 1 will be profitable for the poultry barn at Byneset, regardless of possible grid tariff changes.

8 Future Work

This chapter will present suggestions regarding future work, as there are multiple approaches when projecting a solar energy system and only a few are investigated in this report. Completing some or all of the suggestions will provide a better insight in the complexity of a solar energy system and could lead to the selection of a more suitable solution.

Electricity to the Remaining Equipment

From an overall perspective, overproduction of electricity will not occur with installation of 48 solar modules. However, if the number of modules is increased, overproduction will occur especially in the summer months when solar irradiation is at its highest. It is projected for the solar energy system to sell the overproduction back to the grid for a price equal to the spot price. However, the sales price might not always be equal to the spot price, especially if the prosumer arrangement is not considered. Instead of selling the overproduced electricity back to the grid, a suggestion to expand the electricity distribution to the rest of the farm is made. In addition to the poultry barn, the farm has production of grain and, therefore, a grain dryer that requires electricity. A significant increase in the number of solar modules would be necessary to provide electricity for the entire poultry farm.

Renting Solar Modules

As observed in the results section, the investment cost of 48 solar modules at 122 700 NOK has a payback time of 18 years. This might be a large investment for many costumers, considering the absence of direct income for almost two decades. The idea behind renting solar modules is for costumers to install a solar energy system over a shorter time period. A regular fee will be paid instead of a full investment cost. For future work, it might be interesting to contact engineering firms such as TrønderEnergi and Solbes AS to investigate the actual possibilities of implementing this idea into projects.

Replacing Propane With Electricity

The two heating furnaces in the barn contribute to greenhouse gas emissions. Installing electric furnaces and replacing the propane fuel with green electricity from either the installed solar energy system or purchased from the grid, will cut these emissions. This change has strong environmental benefits, but not necessarily economic as fossil fuels are still often today less expensive than electricity.

A suggestion for future work is, therefore, to look at the possibilities of electrifying the remaining parts of the barn. It might also be interesting to research the economic prospects of electrifying the entire poultry farm, such as the grain dryer. To ensure that the consumed electricity originates from renewable energy sources, an expansion of the solar energy system can be made. This solution avoids the uncertainty of purchasing imported electricity originating from fossil sources.

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[83] Inc. (2020) Solar Electric Supply. Rec twinpeak 2 rec295tp2 295w solar panel. *https://www.solarelectricsupply.com/rec-twinpeak-2-rec295tp2-295w-solar-panel*, Retrieved 24.04.2020.

A Net Present Value Results From All Scenarios

All NPV with respective cash flows are systematically presented in this chapter.

A.1 Scenario 1

System Optimization

Table A.1: Scenario 1 - System Optimization: NPV results.

Time Period	Cash Flow [NOK]	Net Present Value [NOK]
Year 0	-122 700	-122 700
Year 1	10 705.95	-107 146.53
Year 2	10 705.95	-97 898.33
Year 3	10 705.95	-89 090.52
Year 4	10 705.95	-80 702.12
Year 5	10 705.95	-72 713.18
Year 6	10 705.95	-65 104.66
Year 7	10 705.95	-57 858.45
Year 8	10 705.95	-50 957.30
Year 9	10 705.95	-44 384.78
Year 10	10 705.95	-38 125.23
Year 11	10 705.95	-32 163.76
Year 12	10 705.95	-26 486.16
Year 13	10 705.95	-21 078.93
Year 14	10 705.95	-15 929.19
Year 15	10 705.95	-11 024.67
Year 16	10 705.95	-6 353.70
Year 17	10 705.95	-1 905.15
Year 18	10 705.95	2 331.56
Year 19	10 705.95	6366.52
Year 20	10 705.95	10 209.33
Year 21	10 705.95	13 869.16
Year 22	10 705.95	17 354.71
Year 23	10 705.95	20 674.28
Year 24	10 705.95	23 835.78
Year 25	10 705.95	26 846.73

Evaluating the Spot Price

Table A.2: Scenario 1 - Evaluating the Spot Price: NPV results.

Time Period	Cash Flow [NOK]	Net Present Value [NOK]
Year 0	-122 700	-122 700
Year 1	15 534.44	-102 766.95
Year 2	15 534.44	-89 347.71
Year 3	15 534.44	-76 567.49
Year 4	15 534.44	-64 395.85
Year 5	15 534.44	-52 803.81
Year 6	15 534.44	-41 763.77
Year 7	15 534.44	-31 249.45
Year 8	15 534.44	-21 235.81
Year 9	15 534.44	-11 699.01
Year 10	15 534.44	-2 616.34
Year 11	15 534.44	6 033.82
Year 12	15 534.44	14 272.02
Year 13	15 534.44	22 118.01
Year 14	15 534.44	29 590.35
Year 15	15 534.44	36 706.85
Year 16	15 534.44	43 484.48
Year 17	15 534.44	49 939.36
Year 18	15 534.44	56 086.87
Year 19	15 534.44	61 941.63
Year 20	15 534.44	67 517.60
Year 21	15 534.44	72 828.05
Year 22	15 534.44	77 885.62
Year 23	15 534.44	82 702.35
Year 24	15 534.44	87 289.72
Year 25	15 534.44	91 658.63

A.2 Scenario 2

Monthly Subscription Tariff

Table A.3: Scenario 2 - Monthly Subscription Tariff: NPV results.

Time Period	Cash Flow [NOK]	Net Present Value [NOK]
Year 0	-122 700	-122 700
Year 1	10 705.95	-107 146.53
Year 2	10 705.95	-97 898.33
Year 3	11 716.08	-88 259.48
Year 4	12 726.22	-78 288.15
Year 5	13 736.35	-68 037.87
Year 6	14 746.49	-57 557.82
Year 7	15 756.62	-46 893.12
Year 8	15 756.62	-36 736.26
Year 9	15 756.62	-27 063.06
Year 10	15 756.62	-17 850.49
Year 11	15 756.62	-9 076.61
Year 12	15 756.62	-720.54
Year 13	15 756.62	7 237.63
Year 14	15 756.62	14 816.83
Year 15	15 756.62	22 035.12
Year 16	15 756.62	28 909.69
Year 17	15 756.62	35 456.89
Year 18	15 756.62	41 692.32
Year 19	15 756.62	47 630.82
Year 20	15 756.62	53 286.54
Year 21	15 756.62	58 672.94
Year 22	15 756.62	63 802.85
Year 23	15 756.62	68 688.47
Year 24	15 756.62	73 341.44
Year 25	15 756.62	77 772.85

Daily Measured Tariff

Table A.4: Scenario 2 - Daily Measured Tariff: NPV results.

Time Period	Cash Flow [NOK]	Net Present Value [NOK]
Year 0	-122 700	-122 700
Year 1	10 705.95	-107 146,53
Year 2	10 705.95	-97 898.33
Year 3	12 333.72	-87 751.34
Year 4	13 961.49	-76 812.15
Year 5	15 589.27	-65 179.20
Year 6	17 217.04	-52 943.37
Year 7	18 844.81	-40 188.46
Year 8	18 844.81	-28 040.93
Year 9	18 844.81	-16 471.85
Year 10	18 844.81	-5 453.68
Year 11	18 844.81	5 039.82
Year 12	18 844.81	15 033.62
Year 13	18 844.81	24 551.53
Year 14	18 844.81	33 616.21
Year 15	18 844.81	42 249.23
Year 16	18 844.81	50 471.16
Year 17	18 844.81	58 301.57
Year 18	18 844.81	65 759.10
Year 19	18 844.81	72 861.51
Year 20	18 844.81	79 625.71
Year 21	18 844.81	86 067.81
Year 22	18 844.81	92 203.14
Year 23	18 844.81	98 046.31
Year 24	18 844.81	103 611.24
Year 25	18 844.81	108 911.16

Fuse Differentiated Tariff

Table A.5: Scenario 2 - Fuse Differentiated Tariff: NPV results.

Time Period	Cash Flow [NOK]	Net Present Value [NOK]
Year 0	-12 2700	-122 700
Year 1	10 705.95	-107 146.53
Year 2	10 705.95	-97 898.33
Year 3	12 247.05	-87 822.65
Year 4	13 788.15	-77 019.27
Year 5	15 329.26	-65 580.34
Year 6	16 870.36	-53 590.89
Year 7	18 411.46	-41 129.29
Year 8	18 411.46	-29 261.10
Year 9	18 411.46	-17 958.06
Year 10	18 411.46	-7 193.26
Year 11	18 411.46	3 058.93
Year 12	18 411.46	12 822.92
Year 13	18 411.46	22 121.95
Year 14	18 411.46	30 978.18
Year 15	18 411.46	39 412.68
Year 16	18 411.46	47 445.54
Year 17	18 411.46	55 095.88
Year 18	18 411.46	62 381.92
Year 19	18 411.46	69 321.01
Year 20	18 411.46	75 929.66
Year 21	18 411.46	82 223.62
Year 22	18 411.46	88 217.86
Year 23	18 411.46	93 926.66
Year 24	18 411.46	99 363.62
Year 25	18 411.46	104 541.67

B Complete Calculations

Complete calculations and relevant additional information from the results are presented in this chapter.

B.1 Construction in PVsyst for 48 Modules

The operating voltage for this inverter is 260-550 V. 27.3 V is the nominal MPP for the module. Minimum number of modules per string:

$$\frac{260\ V}{27.3\ V} = 9.42 \approx \underline{\underline{10\ modules}}$$

Maximum number of modules per string:

$$\frac{550\ V}{27.3\ V} = 19.93 \approx \underline{\underline{19\ modules}}$$

The nominal MPP voltage for this inverter is not available in PVsyst. It is, therefore, assumed that the nominal MPP voltage for the inverter is $\approx$ 340 V. This assumption is made by observing similar inverters.

$$\frac{340\ V}{27.6\ V} = 12.45 \approx \underline{\underline{12\ modules}}$$

B.2 Module Layout

Figure B.1 shows how the 48 modules are placed on the roof in PVsyst. Each of the four colors represent one string.

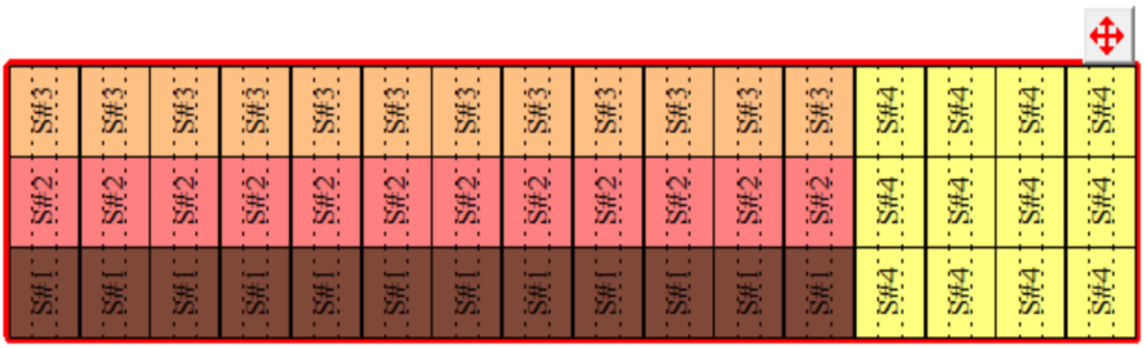


Figure B.1: Module layout on the roof of the poultry barn.

B.3 Estimation of the Theoretical Maximum Number of Modules

The length- and height dimensions of the crystalline silicon solar module Eco-line full black M60 from Luxor are 1.665 m x 1.002 m respectively. The estimation is completed on both a portrait and a landscape layout to determine when the theoretical maximum number of modules occurs.

Portrait Layout

Number of modules below the pipes:

$$Width : \frac{60\ m}{1.002\ m} = 59.88 \approx 59\ modules$$

$$Height : \frac{5.689\ m}{1.665\ m} = 3.417 \approx 3\ modules$$

$$Total : 59 \cdot 3 = \underline{177\ modules}$$

Number of modules between the pipes:

$$Width : \frac{9.167\ m}{1.002\ m} = 9.148 \approx 9\ modules$$

$$Height : \frac{5\ m}{1.665\ m} = 3.003 \approx 3\ modules$$

$$Total : 9 \cdot 3 = \underline{27\ modules}$$

Number of modules in total:

$$177 + (6 \cdot 27) = \underline{\underline{399\ modules}}$$

Landscape Layout

Number of modules below the pipes:

$$Width : \frac{60\ m}{1.665\ m} = 36.04 \approx 36\ modules$$

$$Height : \frac{5.689\ m}{1.002\ m} = 5.678 \approx 5\ modules$$

$$Total : 36 \cdot 5 = \underline{180\ modules}$$

Number of modules between the pipes:

$$Width : \frac{9.167\ m}{1.665\ m} = 5.506 \approx 5\ modules$$

$$Height : \frac{5\ m}{1.002\ m} = 4.990 \approx 4\ modules$$

$$Total : 5 \cdot 4 = \underline{20\ modules}$$

Number of modules in total:

$$180 + (6 \cdot 20) = \underline{\underline{300\ modules}}$$

C Tariff Prices From NVE

The data in Table C.1 is collected from NVE's most recent consultation document. These prices are based on a data set from Ringerrikskraft Nett with 383 costumers. The numbers in each column have been scaled linearly to fit the current grid tariffs from Tensio AS.

Table C.1: Data form NVE's consultation document. [8]

	Energy Fee [NOK/kWh]	Addition To Energy Fee [NOK/kW]	Constant Fee [NOK/year]
Present Tariff	0.1859	–	2046
Monthly Subscription	0.05	1.00	1350 + 675 per kW
Daily Measured	0.05	1.49 per kW (summer) 2.49 per kW (winter)	1850
Fuse Differentiated	0.05	–	1750 + 343 per kW

Energy Fee (Scaled Up)

The present energy fee from Tensio AS is 0.429125 NOK/kWh

0.429125/0.18590 = 2.308365

0.05 $[NOK/kWh]\cdot$ 2.308365 = 0.115418 $[NOK/kW]$

The scaled up Energy Fee for the 3 tariff models is 0.115418 NOK/kW

Addition to Energy Fee (Scaled Up)

The addition to the energy fee is the same from NVE's consultation document, as used in this project.

Constant Fees (Scaled Up)

The present constant fee from Tensio AS is 2187.50 $NOK/year$

2187.50/2046 = 1.069159

1350 $[NOK/year]\cdot$ 1.069159 = 1443.37 $[NOK/year]$

675 $[NOK/kW]\cdot$ 1.069159 = 721.68 $[NOK/year]$

The scaled up constant fee for the *monthly subscription tariff* is: 1443.37 NOK + 721.68 NOK/kW

1850 $[NOK/year]\cdot$ 1.069159 = 1977.94 $[NOK/year]$

The scaled up constant fee for the *daily measured tariff* is: 1977.94 $NOK/year$

1750 $[NOK/year]$ · 1.069159 = 1871.03 $[NOK/year]$

343 $[NOK/kW]$ · 1.069159 = 366.72 $[NOK/kW]$

The scaled up constant fee for the *fuse differentiated tariff* is: 1871.03 $NOK/year$ + 366.72 NOK/kW

D Nordpool Spot Prices

Electricity prices have fluctuated drastically over the past years. Table D.1 shows the spot prices in the Trondheim region from 2017-2020 given in NOK/MWh. Consumers will experience a higher price on their electricity bills due to transportation fees.

Table D.1: The spot electricity prices from the Trondheim region. The values are given in NOK/MWh. [10]

	2020	**2019**	**2018**	**2017**
January	232.93	512.96	311.77	271.76
February	139.44	441.33	380.33	290.56
March	100.23	399.76	430.38	283.07
April	-	397.61	376.98	273.92
May	-	378.09	325.17	277.81
June	-	253.30	428.59	235.15
July	-	332.50	496.18	235.39
August	-	365.00	494.40	257.98
September	-	331.04	470.19	308.35
October	-	369.99	407.00	269.08
November	-	417.72	455.77	307.08
December	-	357.54	501.58	269.89

E Module Spec Sheet

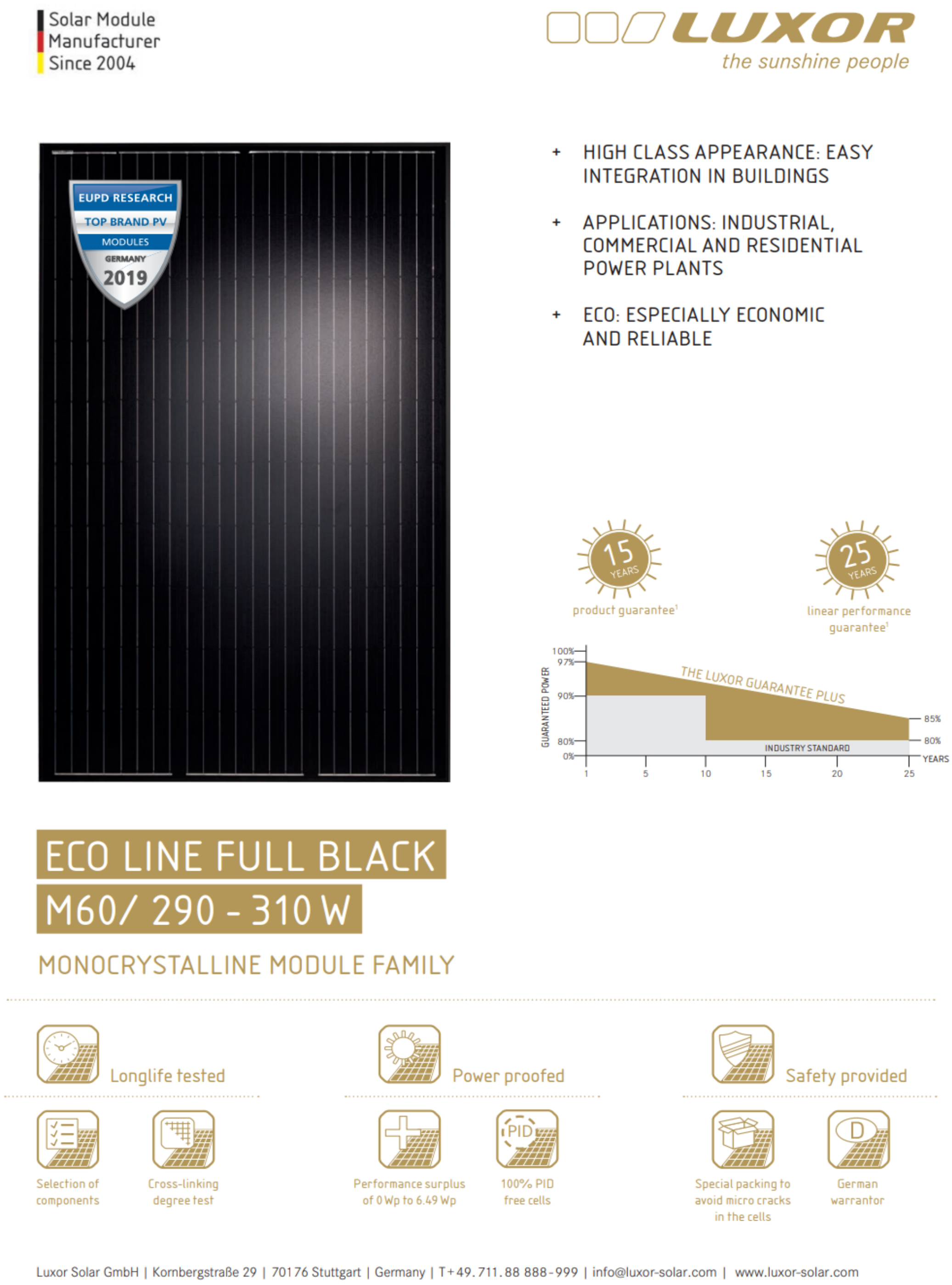


Figure E.1: Detailed information about the selected solar module in Scenario 1 and 2. [81]

ECO LINE FULL BLACK M60/290 - 310 W

Monocrystalline module family | Module type LX - XXXM/156-60+ | XXX = Rated power Pmpp

Electrical data at STC					
Rated power Pmpp [Wp]	290.00	295.00	300.00	305.00	310.00
Pmpp range to	296.49	301.49	306.49	311.49	316.49
Rated current Impp [A]	9.26	9.32	9.38	9.44	9.50
Rated voltage Vmpp [V]	31.37	31.68	32.02	32.33	32.68
Short-circuit current Isc [A]	9.78	9.83	9.88	9.93	9.98
Open-circuit voltage Uoc [V]	38.50	38.70	38.89	39.08	39.28
Efficiency at STC up to	18.22%	18.53%	18.84%	19.15%	19.45%
Efficiency at 200 W/m²	17.25%	17.51%	17.78%	18,06%	18.34%

Electrical data at NOCT					
Power at Pmpp [Wp]	214.58	217.95	221.68	225.18	228.89
Rated current Impp [A]	7.38	7.43	7.48	7.53	7.58
Rated voltage Vmpp [V]	29.06	29.33	29.64	29.91	30.21
Short-circuit current Isc [A]	7.80	7.84	7.88	7.92	7.96
Open-circuit voltage Uoc [V]	35.47	35.63	35.76 V	35.92	36.07

Specification as per STC (Standard test conditions): irradiance 1000 W/m² | module temperature 25°C | Air Mass = 1.5
NOCT (nominal operating cell temperature): irradiance 800 W/m² | wind speed 1 m/sec | ambient temperature 20°C | cell operating temperature 45 +/-2°C | Air Mass = 1.5

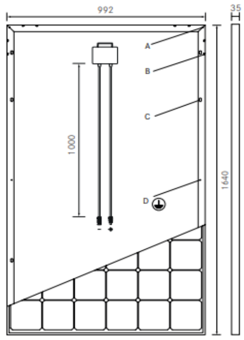
Limiting values	
Max. system voltage [V]	1000 V or 1500 V
Max. return current [I]	15 A
Operating Temperature	-40 to 85°C
Safety class	II
Max. tested pressure load [Pa][2]	5400
Max. tested tensile load [Pa][2]	2400

Temperature coefficient	
Temperature coefficient [V] | [I] | [P]	-0.30% /°C | 0.06% /°C | -0.40% /°C

Specifications	
Number of cells (matrix)	60 (6 x 10), three strings in a row I 156 mm x 156 mm
Module dimensions (LxWxH)[3] | Weight	1640 mm x 992 mm x 35 mm | 18.5 kg
Front-side glass	3.2 mm tempered highly transparent, anti-reflection solar glass
Frame	stable, anodised aluminium frame
Junction Box	At least IP65
Cable	4 mm² solar cable, cable length 1.0 m
Diodes	3 Schottky Diodes 15A/45V
Plug-in connection	MC4 or equivalent with IP67
Hail test (max. hailstorm)	ø 45 mm | impact velocity 23 m/s ≙ 83 km/h

The specifications and average values can vary slightly. Relevant is the corresponding data of the individual measurement. Specifications are subject to change without notice. Measurement tolerance depending on equipment: rated power +/- 3%, other values +/- 10%. All information given in this data sheet correspondes to DIN EN 50380. A potential light-induced degradation of the power after commissioning is not considered here. Further information in the installation manuals.
1 The specific warranty conditions are given under www.luxor-solar.com/download.htm
2 Horizontal mounted
3 Tolerance L/W = +/- 3 mm. H +/-2mm, the dimensions given in the order confirmation will be decisive
4 Location and dimensions of holes on request

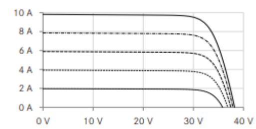
Back - / Front -/ Side view[3]



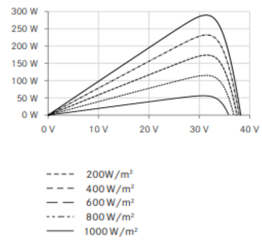
Drilled holes[4] A: 4 x drainage
B: 16 x ventilation
C: 8 x mounting
D: 2 x earthing

Electrical characteristics

UI-diagram e.g. LX-290M/156-60+



UP-diagram e.g. LX-290M/156-60+



Luxor, your specialised company

IEC 61215
IEC 61730

Guidelines:
93/68/EEC
2014/35/EU, (LVD)
2014/30/EU, (EMC)

The validity of the certificates/listings for a specific country has to be examined under: www.luxor-solar.com/download.htm

Eco Line Full Black M60/290-310W_05/2019

Figure E.2: Detailed information about the selected solar module in Scenario 1 and 2. [81]

F Solar Energy System at Rye

Information regarding the operative solar energy system at Rye in Trondheim is presented in this chapter. The solar energy system has in total 288 ground mounted solar modules installed on an area of 481 m^2. The layout is illustrated in Figure F.1. The performance ratio of the solar energy system is 81.28 %.

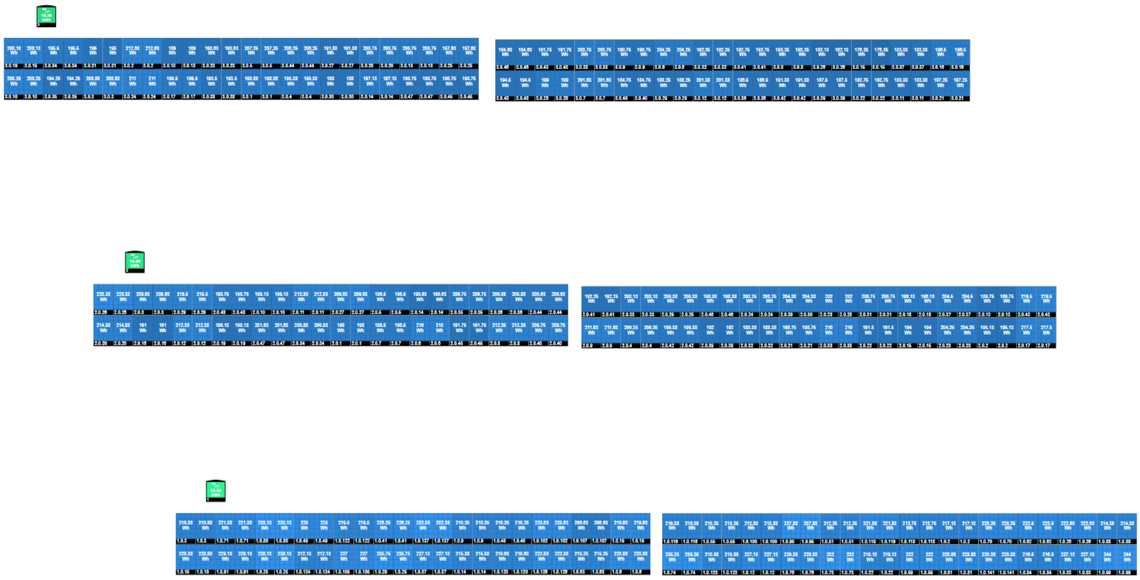


Figure F.1: The layout of the solar energy system at Rye. [26]

The solar energy system has two different solar modules. The system has 192 solar modules of the type REC 295TP2, which is a polycrystalline silicon module with 17.7 % efficiency and 295 Wp. The rest 96 solar modules are of the type REC 310NP, which is a monocrystalline silicon module with 18.6 % efficiency and 310 Wp. The monocrystalline modules are arranged in the front row. More detailed information about the solar modules can be find in Figure F.2, F.3, F.4 and F.5.

An average efficiency is calculated to easier compare the efficiencies and obtain the deviation between the theoretical and actual efficiency at Rye. The average efficiency is used in Scenario 3 for the temperature analysis.

$$\left(0.186 \cdot \frac{1}{3}\right) + \left(0.177 \cdot \frac{2}{3}\right) = 0.18 = 18\ \%$$

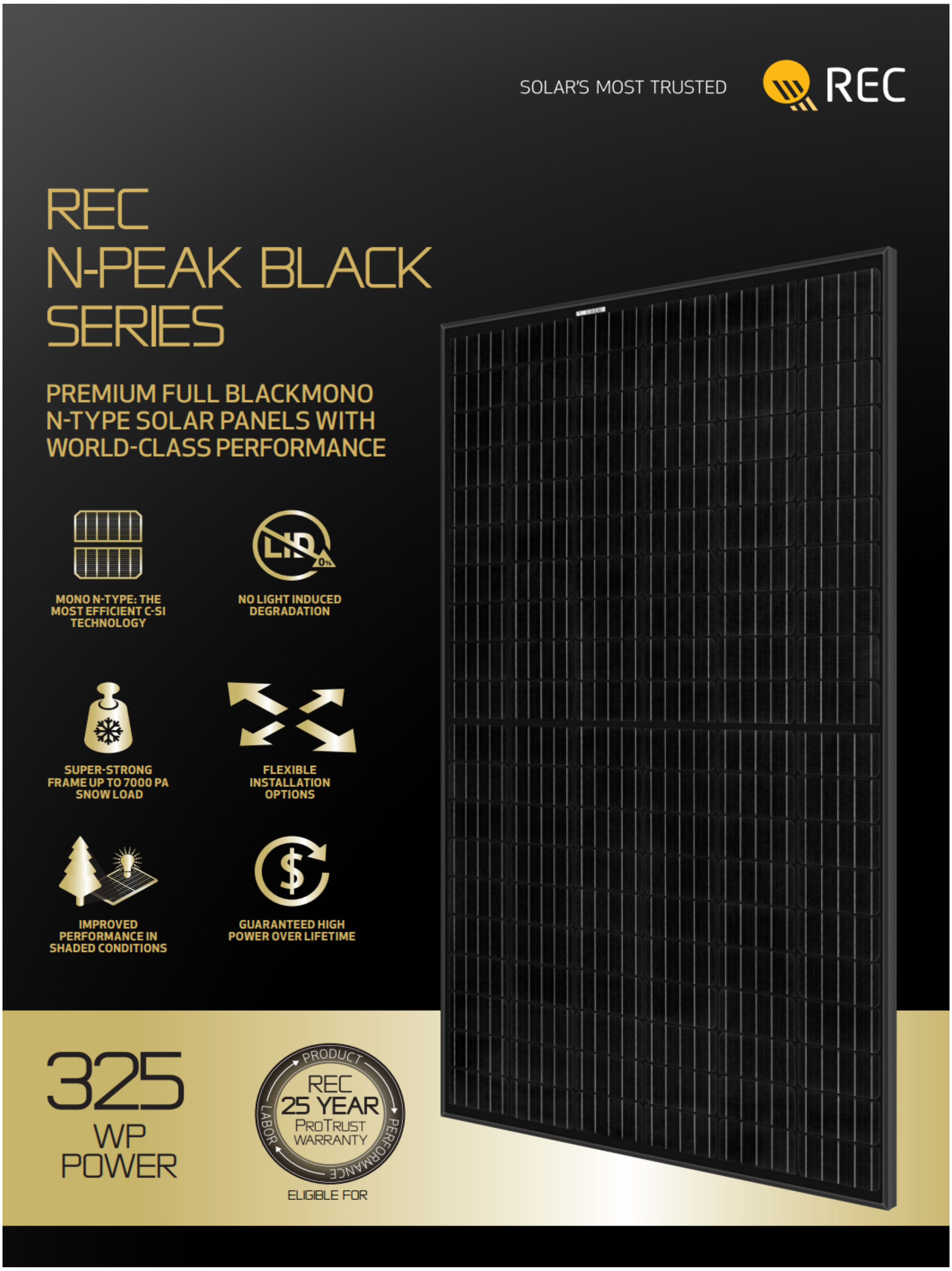
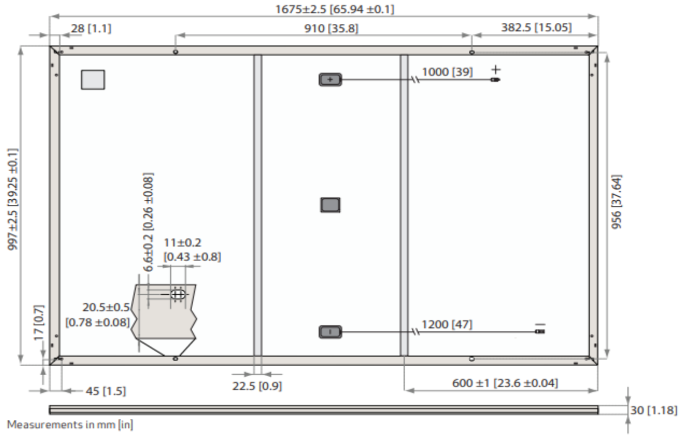


Figure F.2: Detailed information about one of the solar module at Rye. [82]

REC N-PEAK BLACK SERIES



Measurements in mm [in]

GENERAL DATA

Cell type:	120 half-cut mono c-Si n-type cells 6 strings of 20 cells in series
Glass:	3.2 mm solar glass with anti-reflection surface treatment
Backsheet:	Highly reflective and resistant polymeric construction (black)
Frame:	Anodized aluminum (black)
Junction box:	3-part, 3 bypass diodes, IP67 rated in accordance with IEC 62790
Cable:	4 mm² solar cable, 1.0 m + 1.2 m in accordance with EN 50618
Connectors:	Stäubli MC4 PV-KBT4/KST4 (4 mm²) in accordance with IEC 62852 IP68 only when connected
Origin:	Made in Singapore

MECHANICAL DATA

Dimensions:	1675 x 997 x 30 mm
Area:	1.67 m²
Weight:	18 kg

ELECTRICAL DATA @ STC — Product code*: RECxxxNP Black

Nominal Power - P_{MAX} (Wp)	305	310	315	320	325
Watt Class Sorting - (W)	0/+5	0/+5	0/+5	0/+5	0/+5
Nominal Power Voltage - V_{MPP} (V)	33.3	33.6	33.9	34.2	34.4
Nominal Power Current - I_{MPP} (A)	9.17	9.24	9.31	9.37	9.46
Open Circuit Voltage - V_{OC} (V)	39.3	39.7	40.0	40.3	40.7
Short Circuit Current - I_{SC} (A)	10.06	10.12	10.17	10.22	10.28
Panel Efficiency (%)	18.3	18.6	18.9	19.2	19.5

Values at standard test conditions (STC: air mass AM 1.5, irradiance 1000 W/m², temperature 25°C), based on a production spread with a tolerance of P_{MAX}, V_{OC} & I_{SC} ±3% within one watt class. * Where xxx indicates the nominal power class (P_{MAX}) at STC above.

MAXIMUM RATINGS

Operational temperature:	-40 ... +85°C
Maximum system voltage:	1000 V
Design load (+): snow	4666 Pa (475 kg/m²)*
Maximum test load (+):	7000 Pa (713 kg/m²)*
Design load (-): wind	1600 Pa (163 kg/m²)*
Maximum test load (-):	2400 Pa (245 kg/m²)*
Max series fuse rating:	25 A
Max reverse current:	25 A

* Calculated using a safety factor of 1.5
* See installation manual for mounting instructions

ELECTRICAL DATA @ NMOT — Product code*: RECxxxNP Black

Nominal Power - P_{MAX} (Wp)	214	217	221	224	228
Nominal Power Voltage - V_{MPP} (V)	31.1	31.4	31.7	32.0	32.2
Nominal Power Current - I_{MPP} (A)	6.86	6.91	6.97	7.01	7.08
Open Circuit Voltage - V_{OC} (V)	36.7	37.1	37.4	37.7	38.0
Short Circuit Current - I_{SC} (A)	7.53	7.57	7.61	7.65	7.69

Nominal module operating temperature (NMOT: air mass AM 1.5, irradiance 800 W/m², temperature 20°C, windspeed 1 m/s).
* Where xxx indicates the nominal power class (P_{MAX}) at STC above.

TEMPERATURE RATINGS*

Nominal Module Operating Temperature:	44°C (±2°C)
Temperature coefficient of P_{MAX}:	-0.35 %/°C
Temperature coefficient of V_{OC}:	-0.27 %/°C
Temperature coefficient of I_{SC}:	0.04 %/°C

* The temperature coefficients stated are linear values

CERTIFICATIONS

IEC 61215, IEC 61730 & UL 1703; UL 61730, MCS 005, IEC 62804, IEC 61701, IEC 62716, IEC 62782
ISO 9001: 2015, ISO 14001: 2004, OHSAS 18001: 2007

take e-way take-e-way WEEE-compliant recycling scheme

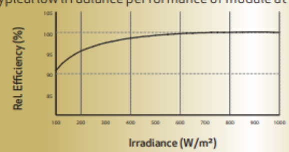
WARRANTY

	Standard	REC ProTrust	
Installed by an REC Certified Solar Professional	No	Yes	Yes
System Size	Any	≤25 kW	25-500 kW
Product Warranty (yrs)	20	25	25
Power Warranty (yrs)	25	25	25
Labor Warranty (yrs)	0	25	10
Power in Year 1	98%	98%	98%
Annual Degradation	0.5%	0.5%	0.5%
Power in Year 25	86%	86%	86%

See warranty documents for details. Some conditions apply.

LOW LIGHT BEHAVIOUR

Typical low irradiance performance of module at STC:



Specifications subject to change without notice.

Ref: PM-DS-11-03-Rev-D 01.20

Founded in Norway in 1996, REC is a leading vertically integrated solar energy company. Through integrated manufacturing from silicon to wafers, cells, high-quality panels and extending to solar solutions, REC provides the world with a reliable source of clean energy. REC's renowned product quality is supported by the lowest warranty claims rate in the industry. REC is a Bluestar Elkem company with headquarters in Norway and operational headquarters in Singapore. REC employs around 2,000 people worldwide, producing 1.5 GW of solar panels annually.

REC
www.recgroup.com

Figure F.3: Detailed information about one of the solar module at Rye. [82]

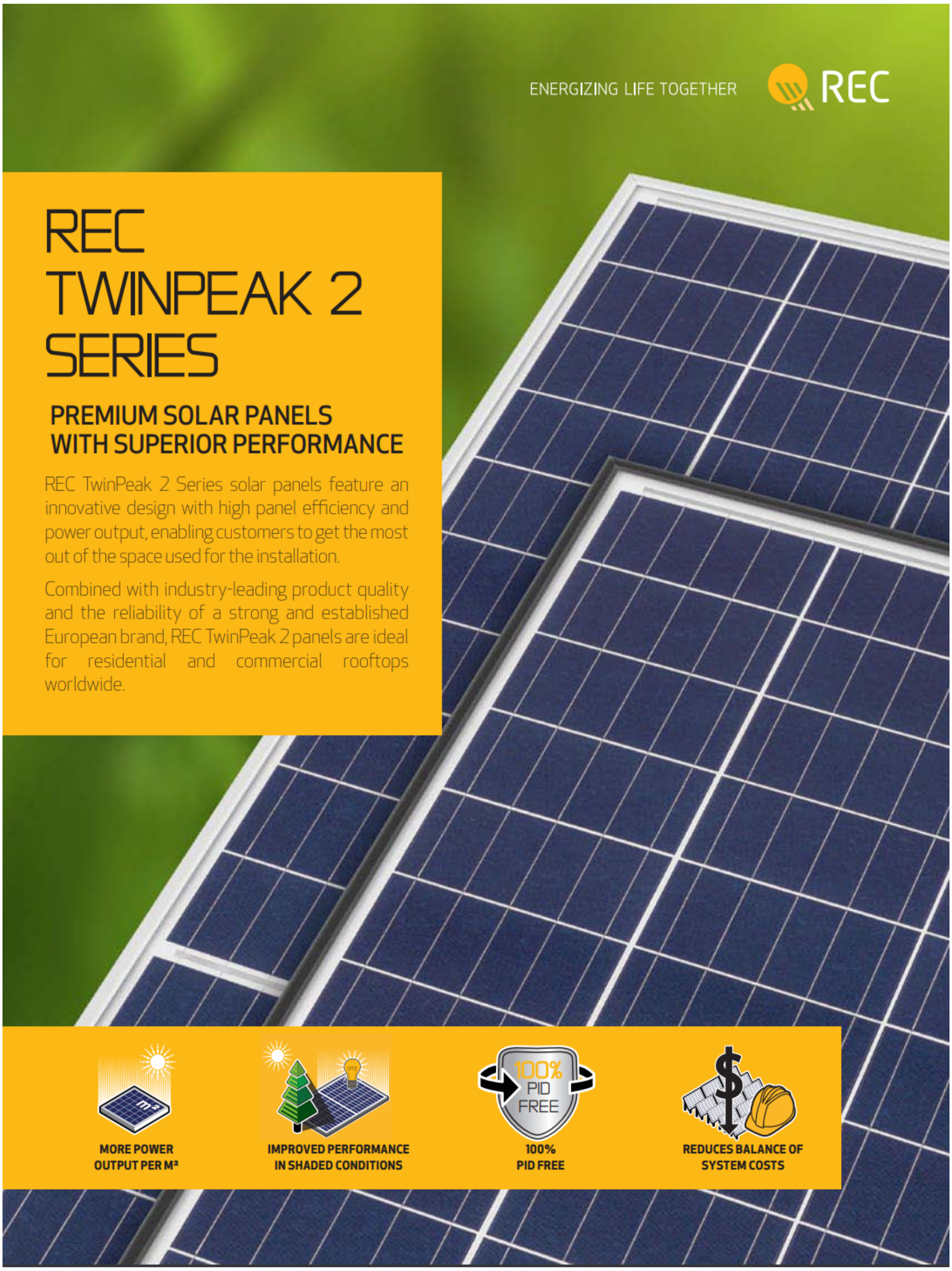
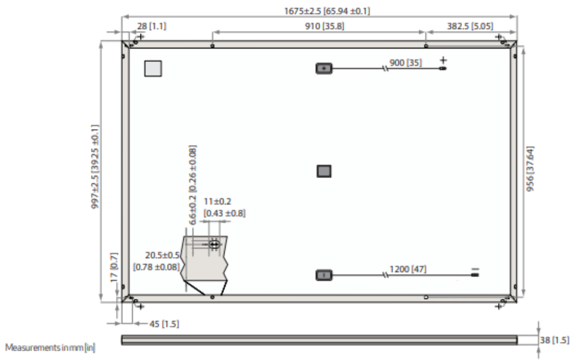


Figure F.4: Detailed information about one of the solar module at Rye. [83]

REC TWINPEAK 2 SERIES



17.7%	EFFICIENCY
10	YEAR PRODUCT WARRANTY
25	YEAR LINEAR POWER OUTPUT WARRANTY
DUTY FREE	US IMPORT DUTY FREE

ELECTRICAL DATA @ STC*	Product Code*: RECxxxTP2				
Nominal Power - P_{MPP} (Wp)	275	280	285	290	295
Watt Class Sorting - (W)	0/+5	0/+5	0/+5	0/+5	0/+5
Nominal Power Voltage - V_{MPP} (V)	31.5	31.7	31.9	32.1	32.3
Nominal Power Current - I_{MPP} (A)	8.74	8.84	8.95	9.05	9.14
Open Circuit Voltage - V_{OC} (V)	38.2	38.4	38.6	38.8	39.0
Short Circuit Current - I_{SC} (A)	9.30	9.39	9.49	9.58	9.65
Panel Efficiency (%)	16.5	16.8	17.1	17.4	17.7

Values at standard test conditions STC (airmass AM 1.5, irradiance 1000 W/m², cell temperature 25°C).
At low irradiance of 200 W/m² (AM 1.5 and cell temperature 25°C) at least 94% of the STC module efficiency will be achieved.
*Where xxx indicates the nominal power class (P_{MPP}) at STC indicated above, and can be followed by the suffix BLK for black framed modules.

ELECTRICAL DATA @ NOCT	Product Code*: RECxxxTP2				
Nominal Power - P_{MPP} (Wp)	206	210	214	218	223
Nominal Power Voltage - V_{MPP} (V)	29.2	29.4	29.6	29.8	30.0
Nominal Power Current - I_{MPP} (A)	7.07	7.15	7.24	7.32	7.43
Open Circuit Voltage - V_{OC} (V)	35.4	35.6	35.8	36.0	36.2
Short Circuit Current - I_{SC} (A)	7.52	7.59	7.68	7.75	7.85

Nominal operating cell temperature NOCT (800 W/m², AM 1.5, windspeed 1 m/s, ambient temperature 20°C).
*Where xxx indicates the nominal power class (P_{MPP}) at STC indicated above, and can be followed by the suffix BLK for black framed modules.

CERTIFICATIONS

UL 1703, Fire classification Type 2; IEC 61215, IEC 61730, IEC 61701 (Salt Mist - severity level 6), IEC 62804 (PID Free), IEC 62716 (Ammonia Resistance), ISO 11925-2 (Ignitability Class 1), UNI 8457/9174 (Class A), ISO 9001:2015, ISO 14001, OHSAS 18001

WARRANTY

10 year product warranty
25 year linear power output warranty
(max. degression in performance of 0.7% p.a. from 97% after the first year)
See warranty conditions for further details.

TEMPERATURE RATINGS	
Nominal operating cell temperature (NOCT)	44.6°C (±2°C)
Temperature coefficient of P_{MPP}	-0.39 %/°C
Temperature coefficient of V_{OC}	-0.31 %/°C
Temperature coefficient of I_{SC}	0.045 %/°C

GENERAL DATA	
Cell type:	120 REC HC multicrystalline 6 strings of 20 cells
Glass:	0.13" (3.2 mm) solar glass with anti-reflective surface treatment
Back sheet:	Highly resistant polyester polyolefin construction
Frame:	Anodized aluminum* *(available in silver or black)
Junction box:	IP67 rated, 3-part with bypass diodes 12 AWG (4 mm²) PV wire, 35" + 47" (0.9 m + 1.2 m)
Connectors:	Multi-Contact MC4 PV-KBT4/PV-KST4 12 AWG (4 mm²)

MAXIMUM RATINGS	
Operational temperature:	-40 ... +185°F (-40 ... +85°C)
Maximum system voltage:	1000 V
Design Loads:	(+) 75.2 lbs/ft² (3600 Pa) (-) 33.4 lbs/ft² (1600 Pa) Refer to installation manual
Max series fuse rating:	20 A
Max reverse current:	20 A

MECHANICAL DATA	
Dimensions:	65.9 x 39.25 x 1.5 (1675 x 997 x 38 mm)
Area:	17.98 ft² (1.67 m²)
Weight:	40.8 lbs (18.5 kg)

Note! Specifications subject to change without notice.

Ref: NE-05-07-07 Rev- C2 12.16

Founded in Norway in 1996, REC is a leading vertically integrated solar energy company. Through integrated manufacturing from silicon to wafers, cells, high-quality panels and extending to solar solutions, REC provides the world with a reliable source of clean energy. REC's renowned product quality is supported by the lowest warranty claims rate in the industry. REC is a Bluestar Elkem company with headquarters in Norway and operational headquarters in Singapore. REC employs more than 2,000 people worldwide, producing 1.4 GW of solar panels annually.

REC
www.recgroup.com

Figure F.5: Detailed information about one of the solar module at Rye. [83]

G Data Obtained From the Poultry Barn

Table G.1 provides information about electricity consumption and prices on a monthly basis from 2019.

Table G.1: Raw data from 2019.

	Electricity Consumption [kWh]	Electricity Bill [NOK]	Grid Tariff Bill [NOK]	Total Bill [NOK]
January	2631	1953	1439	3392
February	4591	2932	2157	5089
March	3228	1918	1616	3534
April	5379	3115	2503	5619
May	2721	1539	1404	2944
June	5420	2181	2520	4701
July	4216	2143	2027	4170
August	6609	3623	3024	6647
September	3777	1959	1836	3795
October	5121	2854	2404	5258
November	3391	2131	1675	3805
December	5000	3142	2470	5612
Sum	52084	29490	25075	54566

H Estimations Regarding Lack of Data

Load Profile Data 2019

Load profile data is missing from January 1st to January 14th and is, therefore, set to 0.5 kW for all hours in this time period.

Certain data from December was not available. Excel extrapolated the data from November, and the data was estimated as an average from earlier months. This affects the grid tariff and electricity bill for December, which further affects the yearly grid tariff and electricity bill. The yearly grid tariff and electricity bill was used in the economic profitability analysis to calculate the yearly cash flow in the NPV method.

Solar Irradiation Data from Rye

Measured data obtained from Rye lacked certain hours. These were linearly interpolated between available the data to appropriately correspond to the existing graph. The hours that were linearly interpolated can be observed in the list below:

- Feburary 22nd between 13:00-18:00. A visualization of the linear interpolation can be observed in Figure H.1.
- March 28th at 11:00
- March 29th at 02:00

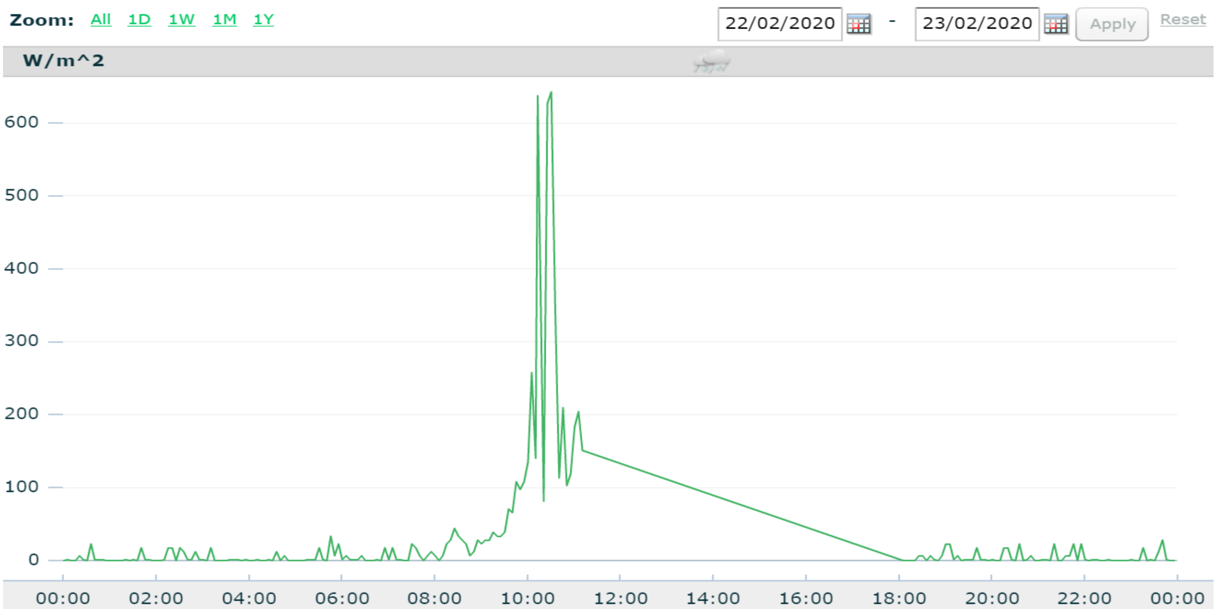


Figure H.1: Hourly solar irradiation data from February 22nd.

I Guidelines for Recreating The Spreadsheet

I.1 Scenario 1

A step-by-step method for creating the Excel spreadsheet shown in Table I.8 is described. Firstly, the solar irradiation yield is calculated by multiplying the solar irradiation with the theoretical efficiency.

$$\text{Irradiation } [kW/m^2] \cdot \text{Theoretical Efficiency } [\%] = \text{Irradiation Yield } [kW/m^2]$$

The area of the selected solar modules is then multiplied with the irradiation yield, so the power output per module can be described without the unit m^2. To calculate the entire system power output, the power output per module is multiplied with the chosen number of modules.

$$\text{Irradiation Yield } [kW/m^2] \cdot \text{Solar Module Area } [m^2] = \text{Power Output per Module } [kW]$$

$$\text{Power Output per Module } [kW] \cdot 48 \text{ Solar Modules} = \text{System Power Output } [kW]$$

As both Scenario 1 and 2 examine the profitability of installing a solar energy system, it is interesting to determine how much kW still needs to be purchased and at which time. Using this method, the hours with overproduction is also determined.

$$\text{System Power Output } [kW] - \text{Load Profile } [kW] = \text{Profit / Deficit } [kW]$$

As some fees are added to the electricity price when purchasing the electricity through a company, a column is made to better illustrate the actual electricity price both when purchasing. A purchasing fee of 0.25 NOK is added to the collected electricity prices from Nord Pool.

$$\text{Nordpool Electricity Price } \left[\frac{NOK}{kW}\right] + \text{ Additional Fee } [NOK]$$

$$= \text{Purching Electricity Price } \left[\frac{NOK}{kW}\right]$$

When determining the actual electricity price when selling the overproduction, an input marginal loss fee is added. This fee is divided into summer and winter periods. The summer period is defined from March to October and has a fee of 5 %. The winter period is defined from November to February and has a fee of 6.5 %.

$$\text{Electricity Price from Nordpool } [NOK/kW] \cdot \text{ Marginal Loss Fee } [NOK]$$

$$= \text{Selling Electricity Price } [NOK/kW]$$

Lastly, the interesting section of this first scenario is to calculate the amount of purchased and sold electricity in NOK. This is done by multiplying the column with profits and deficits of kW with the electricity price for respectively purchasing or selling.

$$\text{Profits } [kW] \cdot \text{Selling Electricity Price } [NOK/kW] = \text{Sold Electricity } [NOK]$$

$$\text{Deficits } [kW] \cdot \text{Purchasing Electricity Price } [NOK/kW] = \text{Purchased Electricity } [NOK]$$

Table I.1: Part two: Data for the profitability analysis - June 15th.

Hour	**Electrical Price Nord Pool (NOK/kW)**	**Real Electricity Price: Purchasing (NOK/kW)**	**Real Electricity Price: Selling (NOK/kW)**	**Purchased Electricity (NOK)**	**Sold Electricity (NOK)**
00:00	0.27527	0.52527	0.2615065	-3.041313300	0
01:00	0.26783	0.51783	0.2544385	-2.899848000	0
02:00	0.22478	0.47478	0.2135410	-2.514409089	0
03:00	0.19581	0.44581	0.1860195	-2.265871960	0
04:00	0.17692	0.42692	0.1680740	-2.626034803	0
05:00	0.19483	0.44483	0.1850885	-2.102743747	0
06:00	0.20990	0.45990	0.1994050	-1.808383429	0
07:00	0.24063	0.49063	0.2285985	-1.119604105	0
08:00	0.27899	0.52899	0.2650405	-0.539000721	0
09:00	0.28926	0.53926	0.2747970	0	0.236131684
10:00	0.28779	0.53779	0.2734005	0	0.420695468
11:00	0.26881	0.51881	0.2553695	0	0.585556376
12:00	0.24836	0.49836	0.2359420	0	0.773341223
13:00	0.24396	0.49396	0.2317620	0	0.820187785
14:00	0.23035	0.48035	0.2188325	0	0.551290397
15:00	0.23133	0.48133	0.2197635	0	0.155563208
16:00	0.23799	0.48799	0.2260905	-0.871823410	0
17:00	0.27664	0.52664	0.2628080	-1.692045837	0
18:00	0.27928	0.52928	0.2653160	-2.653444827	0
19:00	0.26724	0.51724	0.2538780	-3.780910031	0
20:00	0.23417	0.48417	0.2224615	-3.193997452	0
21:00	0.22125	0.47125	0.2101875	-3.891491493	0
22:00	0.18808	0.43808	0.1786760	-4.125382613	0
23:00	0.15109	0.40109	0.1435355	-3.313003400	0

Table I.2: Part one: Data for the profitability analysis - June 15th.

Hour	**Irradiation (kW/m^2)**	**Irradiation Yield (kW/m^2)**	**Load Profile (kW)**	**Power Output per Module (kW)**	**System Power Output (kW)**	**Profit/Deficit (kW)**
00:00	0	0	5.79	0	0	-5.790000000
01:00	0	0	5.60	0	0	-5.600000000
02:00	0.0029	0.00055013	5.34	0.000917798	0.044054322	-5.295945678
03:00	0.0492	0.00933324	5.83	0.015570924	0.747404366	-5.082595634
04:00	0.1171	0.02221387	7.93	0.037060066	1.778883155	-6.151116845
05:00	0.2115	0.04012155	7.94	0.066935986	3.212927305	-4.727072695
06:00	0.3211	0.06091267	8.81	0.101622435	4.877876868	-3.932123132
07:00	0.4396	0.08339212	8.96	0.139125576	6.678027627	-2.281972373
08:00	0.5471	0.10378487	9.33	0.173147412	8.311075784	-1.018924216
09:00	0.6398	0.12137006	8.86	0.202485312	9.719294986	0.859294986
10:00	0.7102	0.13472494	9.25	0.224765659	10.78875164	1.538751639
11:00	0.7480	0.14189560	9.07	0.236728686	11.36297694	2.292976945
12:00	0.7595	0.14407715	8.26	0.240368232	11.53767512	3.277675120
13:00	0.7451	0.14134547	7.78	0.235810888	11.31892262	3.538922622
14:00	0.6918	0.13123446	7.99	0.218942387	10.50923456	2.519234559
15:00	0.6114	0.11598258	8.58	0.193497218	9.287866449	0.707866449
16:00	0.5150	0.09769550	9.61	0.162988334	7.823440009	-1.786559991
17:00	0.4007	0.07601279	9.30	0.126814418	6.087092061	-3.212907939
18:00	0.2835	0.05377995	9.32	0.089722704	4.306689791	-5.013310209
19:00	0.1738	0.03296986	9.95	0.055004607	2.640221114	-7.309778886
20:00	0.0871	0.01652287	7.92	0.027565600	1.323148786	-6.596851214
21:00	0.0324	0.0614628	8.75	0.010254023	0.492193119	-8.257806881
22:00	0.0002	0.00003794	9.42	0.000063296	0.003038229	-9.216961771
23:00	0	0	8.26	0	0	-8.260000000

I.2 Scenario 2

This chapter contains detailed descriptions of the method proceeded in Section 4.2, and the results presented in Section 5.3. Negative values indicate power out or cash out values.

I.2.1 Monthly Subscription Tariff

Constant yearly fee:
-1443.37 $[NOK]$

Energy fee:
40469.350150 $[kWh/year]$ · (-0.115418 $[NOK/kWh]$) = -4670.85 $[NOK]$

Subscription fee:

Table I.3: Monthly maximum kW - from Excel spreadsheet.

Month	Max [kW]
January	-8.07
February	-9.42
March	-10.85
April	-12.82
May	-11.85
June	-13.13
July	-13.12
August	-14.95
September	-14.48
October	-11.8
November	-7.82
December	-12.02

The mean of the 12 values in the Figure I.3 is -11.69 kW

-11.69 $[kW]$ · 721.68 $[NOK/kW]$ = -8438.78 $[NOK]$

Additional fee for exceeding the subscription:
-126.18 $[kW]$ · 1 $[NOK/kW]$ = -126.18 $[NOK]$

Estimated tariff 2027:
The monthly subscription tariff includes four segments: a constant yearly fee, an energy fee, a subscription fee, and additional fee for any kW exceeding the subscription.

(-1443.37 $[NOK]$) + (-4670.85 $[NOK]$) + (-8438.78 $[NOK]$) + (-126.18 $[NOK]$) = -14679.22 $[NOK]$

Yearly Payed Tariffs From 2020-2044

Table I.4: Yearly tariff (monthly subscription) - from Excel spread sheet.

Year	Tariff [NOK]
2020	-19 553.91
2021	-19 729.90
2022	-18 719.76
2020	-17 709.63
2024	-16 699.49
2025	-15 689.36
2026	-14 679.23
2027	-14 811.34
2028	-14 944.64
2029	-15 079.14
2030	-15 214.82
2031	-15 351.79
2032	-15 489.95
2033	-15 629.36
2034	-15 770.03
2035	-15 911.96
2036	-16 055.16
2037	-16 199.66
2038	-16 345.46
2039	-16 492.57
2040	-16 640.00
2041	-16 790.77
2042	-16 941.88
2043	-17 094.36
2044	-17 248.21

Year 2020: -19553.90988 $[NOK]$ (The same as calculated in the Scenario 1)

The CPI is 0.09 %

Year 2021: -19553.90988 $[NOK] \cdot$ 1.009 = -19729.89507 $[NOK]$

Linear reduction between 2022-2027:
CPI is not considered in this period.

$\frac{-(14679,22256\ NOK - 19729,89507\ NOK)}{5}$ = 1010.134503 $[NOK]$

Year 2022-2026: An addition of 1010.134503 NOK is added between each year. The values can be viewed in Table I.4.

Year 2027-2044: CPI is included between each year. The values can be viewed in Table I.4.

Cash Flows Between 2020-2044

Cash flows are calculated by taking the total bill from 2019, and subtracting it by the tariff + electricity bill for the relevant year. CPI is included in the NPV method, so the cash flow values between 2020-2021, and between 2026-2044 are the same.

The total bill from 2019 was 54 566 NOK. The electricity bill for 2020 is estimated to be -24306.14 NOK

Cash flow year 2020 and 2021:
54 566 [NOK] – 24306.14 [NOK] (electricity bill) – 19553.91 [NOK] (tariff)= 10705.95 [NOK]

Cash flow year 2022:
10705.95 [NOK] + 1010.13 [NOK] = 11716.08 [NOK]

Cash flow year 2023:
11716.08452 [NOK] + 1010.13 [NOK] = 12726.22 [NOK]

Cash flow year 2024:
12726.22 [NOK] + 1010.13 [NOK] = 13736.35 [NOK]

Cash flow year 2025:
13736.35 [NOK] + 1010.13 [NOK] = 14746.49 [NOK]

Cash flow year 2026-2044:
14746.49 [NOK] + 1010.13 [NOK] = 15756.62 [NOK]

I.2.2 Daily Maximum Tariff

Constant yearly fee:
-1977.94 [NOK]

Energy fee:
40469.350150 [$kWh/year$] · (-0.115418) [NOK/kWh] = -4670.85 [NOK]

Highest daily power output fee:
Table I.5 shows the highest daily power output values, with the appropriate tariff . Only May is included as an example month. Notice the change in kW between May 7th and May 8th. The broilers are taken out of the barn at this date, so the building's load profile decreases drastically.

From April 1st till October 31st the price per kW is 1.49 NOK. From November 1st till March 31st the price per kW is 2.49 NOK.

Table I.5: Daily maximum tariff (May 2026) - from Excel spread sheet.

Date	Highest daily power output [kW]	Tariff 2027 [NOK]
May 1st	-11.07	-16.50
May 2nd	-9.25	-13.78
May 3rd	-9.88	-14.72
May 4th	-9.71	-14.47
May 5th	-9.975	-14.85
May 6th	-11.85	-17.65
May 7th	-10.67	-15.90
May 8th	-1.22	-1.82
May 9th	-1.04	-1.55
May 10th	-1.09	-1.62
May 11th	-1.1	-1.64
May 12th	-1.08	-1.61
May 13th	-1.07	-1.59
May 14th	-1.03	-1.53
May 15th	-6.70	-9.99
May 16th	-0.76	-1.13
May 17th	-1.04	-1.55
May 18th	-0.91	-1.36
May 19th	-2.31	-3.44
May 20th	-2.23	-3.32
May 21st	-2.24	-3.34
May 22nd	-2.03	-3.02
May 23rd	-6.95	-10.36
May 24th	-7.26	-10.82
May 25th	-6.64	-9.89
May 26th	-6.68	-9.95
May 27th	-6.58	-9.80
May 28th	-6.08	-9.06
May 29th	-5.87	8.75
May 30th	-6.18	-9.21
May 31st	-5.9	-8.80

The highest daily power output fee for 2027 is equivalent to the summation of the ”Tariff 2027 [NOK]” row in Table I.5. Note that the table only shows May as an example month.

The highest daily power output fee for year 2026 is -4942.202972 NOK

Estimated tariff 2026:
(-1977.94 [NOK]) + (-4670.85 [NOK]) + (-4942.202972 [NOK]) = -11 591.03443 [NOK]

I.2.3 Yearly Payed Tariffs from 2020-2044

Table I.6: Yearly tariff (daily maximum) - from Excel spread sheet.

Year	Payed Tariff [NOK]
2020	-19 553.91
2021	-19 729.90
2022	-18 102.12
2023	-16 474.35
2024	-14 846.58
2025	-13 218.81
2026	-11 591.03
2027	-11 695.35
2028	-11 800.61
2029	-11 906.82
2030	-12 013.98
2031	-12 122.10
2032	-12 231.20
2033	-12 341.28
2034	-12 452.36
2035	-12 564.43
2036	-12 677.51
2037	-12 791.60
2038	-12 906.73
2039	-13 022.89
2040	-13 140.09
2041	-13 258.36
2042	-13 377.69
2043	-13 498.08
2044	-13 619.56

Year 2020: -19553.91 NOK (The same as calculated in Scenario 1)

Year 2021: -19553.91 $[NOK] \cdot 1.009$ = -19729.90 $[NOK]$

Linear reduction:
CPI not considered in this period.
$\frac{-(11591.03\ NOK - 19729.90\ NOK)}{5} = 1627.77\ [NOK]$

Year 2022-2026:
An addition of 1627.77 NOK is completed between each year. The values can be viewed in Table I.6.

Year 2027-2044:
The CPI at 0.09 % included between each year. The values can be viewed in Table I.6.

Cash Flows Between 2020-2044

Cash flows are calculated with the same method as the monthly subscription tariff. See I.2.1.

Cash flow year 2020 and 2021:
54 566 [NOK] (electricity bill 2019) – 24 306.14 [NOK] (electricity bill 2020) = 10 705.95 [NOK]

Cash flow year 2022:
10 705.95 [NOK] + 1627.77 [NOK] = 12 333.72 [NOK]

Cash flow year 2023:
12333.72 [NOK] + 1627.77 [NOK] = 13961.49 [NOK]

Cash flow year 2024:
13 961.49 [NOK] + 1627.77 [NOK] = 15 589.27 [NOK]

Cash flow year 2025:
15589.27 [NOK] + 1627.77 [NOK] = 17217.04 [NOK]

Cash flow year 2026-2044:
17 217.04 [NOK] + 1627.77 [NOK] = 18 844.81 [NOK]

I.2.4 Fuse Differentiated Tariff

Constant yearly fee:
-1871.03 NOK

Energy fee:
40 469.350150 [$kWh/year$] · -0.115418 [NOK/kWh] = -4670.85 [NOK]

Highest yearly power output fee:

(Highest yearly power output: 14.95 kW)

(366.72 [NOK/kW] · 14.95 [kW]) = -5482.46 [NOK]

Estimated tariff 2026:
-1871.03 [NOK] - 4670.85 [NOK]) - 5482.464 [NOK] = -12 024.39 [NOK]

Yearly Payed Tariffs from 2020-2044:

Table I.7: Yearly tariff (fuse differentiated) - from Excel spreadsheet.

Year	Tariff [NOK]
2020	-19 553.91
2021	-19 729.90
2022	-18 188.79
2023	-16 647.69
2024	-15 106.59
2025	-13 565.49
2026	-12 024.39
2027	-12 132.60
2028	-12 241.80
2029	-12 351.97
2030	-12 463.14
2031	-12 575.31
2032	-12 688.49
2033	-12 802.68
2034	-12 917.91
2035	-13 034.17
2036	-13 151.48
2037	-13 269.84
2038	-13 389.27
2039	-13 509.77
2040	-13 631.36
2041	-13 754.04
2042	-13 877.83
2043	-14 002.73
2044	-14 128.75

Year 2020:
-19 553.91 NOK (The same as calculated in Scenario 1)

Year 2021:
-19 553.91 $[NOK]$ · 1.009 = -19 729.90 $[NOK]$

Linear reduction:
CPI not considered in this period. $\frac{-(12024.39NOK-19729.90NOK}{5}$= 1541.10 $[NOK]$

Year 2022-2026:
1541.10 $[NOK]$ is added between each year. Values can be view in table I.7.

Year 2027-2044:
CPI at 0.09 % is included in these years.

I.2.5 Cash Flows between 2020-2044

Cash flows are calculated with the same method as previously described. See Section I.2.1.

Cash flow year 2020 and 2021:
54 566 $[NOK]$ (electricity bill 2019) – 24 306.14 $[NOK]$ (electricity bill 2020) = 10 705.95 $[NOK]$

Cash flow year 2022:
10 705.95 $[NOK]$ + 1541.10 $[NOK]$ = 12 247.05 $[NOK]$

Cash flow year 2023:
12 247.05 $[NOK]$ + 1541.10 $[NOK]$ = 13 788.15 $[NOK]$

Cash flow year 2024:
13 788.15 $[NOK]$ + 1541.10 $[NOK]$ = 15 329.26 $[NOK]$

Cash flow year 2025:
15 329.26 $[NOK]$ + 1541.10 $[NOK]$ = 16 870.36 $[NOK]$

Cash flow year 2026-2044:
16 870.36 $[NOK]$ + 1541.10 $[NOK]$ = 18 411.46 $[NOK]$

I.3 Scenario 3

Both solar irradiation and system power output needs to have the same unit. The system power output is divided by the total area of the solar farm.

$$\frac{\text{System Power Output } [kW]}{\text{Total Area } [m^2]} = \text{System Power Output } [kW/m^2]$$

The system power output is divided by the solar irradiation using Equation 4 to calculate the actual efficiency.

$$\frac{\text{System Power Output } [kW/m^2]}{\text{Solar Irradiation } [kW/m^2]} = \text{Actual Efficiency } [\%]$$

A performance ratio is calculated. This is completed by dividing the actual efficiency by the theoretical efficiency.

$$\frac{\text{Actual Efficiency } [\%]}{\text{Theoretical Efficiency } [\%]} = \text{Performance Ratio}$$

Table I.8: Data for the Temperature Analysis in Scenario 3 - February 15th.

Hour	**Air Temperature [°C]**	**System Power Output [kW]**	**System Power Output [kW/m^2]**	**Solar Irradiation [kW/m^2]**	**Actual Efficiency [%]**	**Performance Ratio [%]**
00:00	1.8	0	0	0.0027812	0	0
01:00	2.2	0	0	0.0065653	0	0
02:00	3.0	0	0	0.0066763	0	0
03:00	3.4	0	0	0.0096808	0	0
04:00	4.0	0	0	0.0041170	0	0
05:00	3.9	0	0	0.0031155	0	0
06:00	4.0	0	0	0.0051185	0	0
07:00	3.9	0	0	0.0047843	0	0
08:00	3.9	0	0	0.0091246	0	0
09:00	4.0	3.2766665	0.006812763016	0.1068578	6.375541154	35.41967308
10:00	4.5	31.8364165	0.06619348075	0.3895949	16.99033554	94.39075299
11:00	5.3	8.961583	0.01863269918	0.4969016	3.749776452	20.8320914
12:00	6.4	36.545749	0.07598500707	0.5997556	12.66932848	70.38515825
13:00	5.8	11.258667	0.02340873877	0.5850622	4.001068395	22.22815775
14:00	5.4	18.99375075	0.0394913314	0.2488941	15.86672059	88.14844765
15:00	6.5	5.704250125	0.01186013416	0.0908283	13.057752	72.54306666
16:00	4.9	0.35166665	0.0007311765012	0.0221480	3.301320666	18.34067037
17:00	5.6	0	0	0.0037828	0	0
18:00	5.0	0	0	0.0071215	0	0
19:00	5.1	0	0	0.0071895	0	0
20:00	3.9	0	0	0.0048952	0	0
21:00	4.8	0	0	0.0013332	0	0
22:00	5.4	0	0	0.0050062	0	0
23:00	6.0	0	0	0.0040047	0	0

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