Building integrated PV system sizing based on techno-economics evaluation: Design study for a Southern Norwegian house

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Abstract

Renewable energy sources are promising to take a significant share in the energy sector as a viable option for integrating with conventional fossil fuel power plants. This thesis contributes to the ongoing studies about building integrated photovoltaic (BIPV) system energy storage. The system comprises the photovoltaic array to capture solar energy, a power converter to change over AC and DC, a grid connection, and a lead-acid battery to store energy. The modeling is also completed by assessing the required load, specifications and choosing the components associated with the system. The geographic area, solar irradiance, and load consumption upon which the whole work depends are considered. It draws attention to the optimal design and sizing considering several techno-economic factors, including net present cost, cost of energy, and PV power output. The techno-economic analysis of the proposed system is performed by using the software Hybrid Optimization Model for Electric Renewable (HOMER). The simulation result found that the grid-only was the optimal system configuration with LCOE equal to 0.168 kr/kWh and the grid-connected PV system with a storage battery and without having no significant difference in LCOE value. The analysis results for techno-economic performance indicate that the PV energy production and grid supply relationship is powerful and helpful for the system. The analysis among the economic performance and technical indicators may be beneficial for BIPV also. A 10 kW PV array and A battery energy storage (Lead-acid) of 24.8 kWh is considered in this thesis. The BIPV systems energy performance with lead-acid battery storage is analyzed for the grid. The project lifetime is 25 years. During the project's lifetime, the battery at least will replace 3 times. This thesis learning outcome is to have a great understanding of the BIPV system with a storage battery and techno-economical performance.

Preface

This thesis is written as part of a two-year master's program in Renewable Energy at the University of Agder.

I would like to thank my supervisor at the University of Agder, professor Mohan Lal Kolhe for his guidance and support throughout the whole time. Furthermore, I would like to thank Dr.Arvind Sharma for helping with the HOMER software and advice.

Islam Yousif Abdulabqi
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List of Abbreviations

DC → Direct current

AC → Alternating current

MPP → Maximum power point

MPPT → Maximum power point tracking

MG → Microgrid

PV → Photovoltaic

DoD → Depth of discharge

TFSC → Thin-Film Solar Cells

SoC → State of charge

BIPV → Building Integrated Photovoltaic

NOK → Norwegian kroner

COE → Cost of energy

NOCT → Nominal operating cell temperature

STC → Standard test conditions

PVB → Photovoltaic battery system

NPC → Net present cost

LCOE → Levelized cost of energy

NREL → National Renewable Energy Laboratory

HOMER → Hybrid Optimization Model for Electric Renewables

NPV → Net present value

List of Symbols

I $\rightarrow$ Current

V $\rightarrow$ Voltage

V_o $\rightarrow$ Output voltage

I_o $\rightarrow$ Output current

D $\rightarrow$ Duty cycle

V_{in} $\rightarrow$ Input voltage

I_{in} $\rightarrow$ Input current

I_d $\rightarrow$ Diode current

I_{ph} $\rightarrow$ Photo current

I_{sh} $\rightarrow$ Leakage current in PV cell

q $\rightarrow$ Electron charge

C $\rightarrow$ Boltzmann constant

R_s $\rightarrow$ Series resistance

A $\rightarrow$ Ideal factor in PN junction

T $\rightarrow$ Thermodynamic temperature

FF $\rightarrow$ Fill factor

V_{oc} $\rightarrow$ Open circuit voltage

I_{sc} $\rightarrow$ Short circuit current

R_{in} $\rightarrow$ Input resistance

1 Introduction

1.1 Background and motivation

Together with the serious environmental problems, the energy crisis accelerates the deployment of renewable energy sources, especially photovoltaic PV, with an average increasing installation rate of 57.6 % during the last five years. The distributed PV production can alleviate the burden on the grid, reducing the household demand. In contrast, the large PV production that fluctuates dramatically may cause transmission and even curtailment problems. The flexible energy storage system for self-consumed PV household systems is of great importance, buffering the mismatch between load and PV production and reducing the interaction between the grid and en-user. The distributed rooftop PV system with utility-scale battery is also emphasized in the major trends that drive the energy transition. According to the report on variable renewable energy from the International Energy, Photovoltaic battery system has received increasing attention in recent years in the academic and industrial sectors under the distributed energy system in smart grid. Nevertheless, more possibilities for reforming the traditional electricity grid and research on the Photovoltaic battery system are under development.

Norway remains one of the few countries where electricity is the primary heating source. The central heating source for about 73% of the households is based on electricity, either by electric space heaters (48%), electric floor heating (7%), air-air heat pumps (21%), or central heating with electricity. The statistics found that 12% that fuelwood as their primary source for heating. It is mainly farming houses that use fuelwood. About half of the farmers use fuelwood as their primary heating source, and their average wood consumption is around 11-12 000 kWh per year [1]. Figure 1.1 presents the solar map of southern Norway.

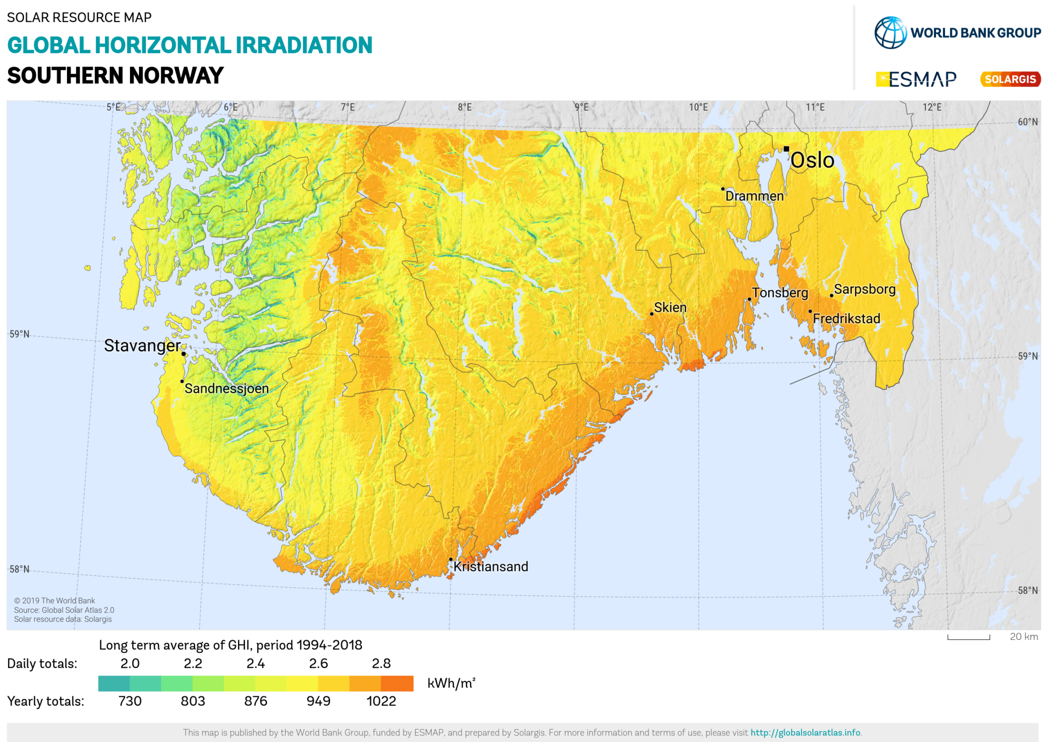


Figure 1.1: Solar map of southern Norway [2]

1.2 Thesis definition

This thesis analyzes the Building Integrated PV system (BIPV) with storage battery for a residential house in Southern Norway (Grimstad). The objective of this is:

- Find the component and sizing for the hybrid renewable energy source
- Collect renewable energy resources
- Conduct sensitivity analysis for the hybrid renewable energy source
- Analyze to find optimal solutions of the system
- Techno-economical performance

1.3 Software tools

HOMER

HOMER is a global standard for optimizing microgrid systems suitable for all sectors ranging from grid level to villages. It is developed by National Renewable Energy Laboratory (NREL), United States. It was developed in 1993 to understand techno-economic trade-offs between energy and economy. It takes several input data, such as demand, resources, components, ETC. Depending upon the inputs, various simulations are performed by HOMER for optimal sizing, LCOE and NPC calculations, renewable fraction and CO2 emission, ETC.

1.4 Thesis outline

The Content in this thesis is based on optimization of grid-connected PV system with storage battery for Southern Norway (Grimstad) to find out if it is a grid-connected PV system with storage battery configurations for the location which can compete with today's solution, the Grid-only.

Section 2 is the theory section which describes all theory used in this thesis. **Section 3** discusses the materials and methodology, data required for the analysis of the system, load profile of site selection, solar resource, and climate data. **Section 4** explains the component used in the system, and it describes the characteristics of the system components such as costs, operation, and maintenance. **section 5** is about system description and strategies.**Section 6** the result and discussion of the optimization and sensitivity analysis. Section 7 is the last section in this thesis and states the conclusions and the further work.

2 Literature Review

2.1 Photovoltaic system description

A solar power system is designed to convert sunlight into electric power. Solar power is produced from concentrated solar plants and photovoltaic solar plants. The main difference between them is the energy extraction process from sunlight. The potent solar plants use solar thermal energy to produce electricity, whereas PV panels use light energy. Solar panels are made of semiconductor materials to converts this light energy into electricity using the photovoltaic effect. The photoelectric effect is an inherent property of some semiconductor materials such as silicon. The semiconductor materials are incorporated with a p-n junction in which electrons are released due to the solar radiation incidence. These freed electrons create an electric field in the connected circuit, and the electricity is produced. Solar electricity depends on the PV cell's efficiency, which relies on the semiconductor materials band-gap, solar series, and mounted on support structure known as a module. The PV array is formed by connecting these modules through electric wires. Solar production depends on the size of the array.

The PV system is divided into two types: grid-connected and standalone. A standalone system is not connected with the local grid. They are widely used for small self-consumption or remote areas power sources where the grid is not feasible. On the other hand, a grid-connected PV system is directly connected to the distribution grid to supply surplus energy into the grid after self-consumption. In this thesis, the grid-connected PV power system is studied.

A grid-connected PV system is designed with several electrical components such as PV modules, inverter, and balance of system equipment. PV module is the essential component that converts natural solar energy into direct current electricity. The inverter converts the DC into AC to make it worthwhile for the end consumer. Balance of the system (BOS) equipment includes mounting, cables, control charger, and other electric accessories to set up a complete system. Solar tracking and battery storage are also included in this system [3].

2.1.1 PV solar modules

Modules are the critical elements in PV technology categorized into two main groups: crystalline silicon (c-Si) and thin-film solar cell (TFSC) based on their manufacturing technology. More than 90% of the installed PV modules are silicon-based on the material's abundance and the low processing cost. Modules based on other semiconductors such as cadmium telluride, gallium arsenide, and copper indium have a low contribution in the PV market due to their lower efficiency and higher cost. Carbon-based semiconductors are also used to manufacture solar cells, which need to improve their efficiency and lifetime. Crystalline silicon (c-Si) solar cells are manufactured from pure silicon, divided into mono-crystalline and multi-crystalline cells.

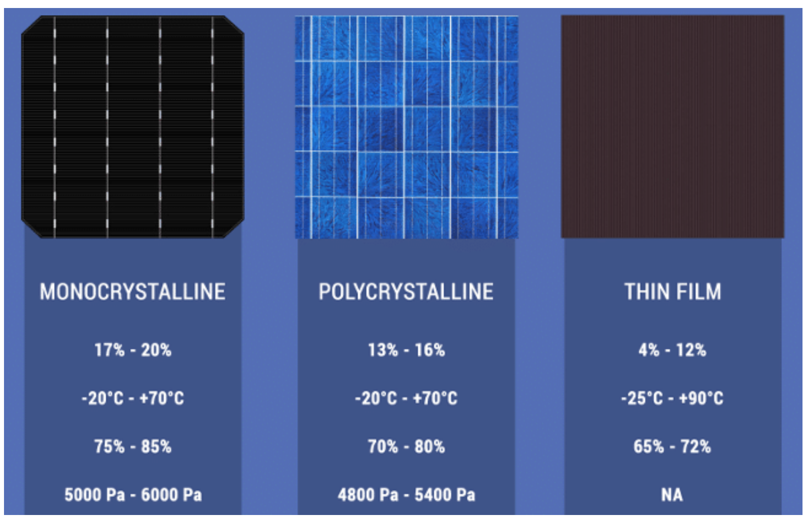


Figure 2.1: PV modules types [4]

Mono-crystalline solar cells are made by cylindrical silicon bars. These silicon bars are cut into four sides to make silicon wafers which improve the module efficiency. At present, mono-crystalline solar panels have 17%-20% efficiency. These cells require less installation area and provide a high lifetime compared to others. Moreover, they can produce more power in low sunlight intensity. The main limitation is the high production cost with a massive wastage of raw silicon in the production process [5]. Figure 2.1 present the three PV module types. Multi-crystalline silicon (mc-Si) based solar panels are manufactured by melting raw silicon and poured into a square mold before cutting into perfectly square wafers. The advantages of these cells are low production cost and that less silicon is wasted. It has lower efficiency around (13%-16%) and required a large area in comparison with mono-crystalline. Moreover, the cell performance is degraded with the increase of outdoor temperature. Thin-Film Solar Cells (TFSC) are made by keeping several thin layers of semiconductor materials on a substrate. The PV market share of this technology type is only 7%-10%, which is very low compared with others due mainly to their lower efficiency (7%-13%). It requires a larger area which increases the balance of system cost and panel degradation rate. The main advantage of TFSC cells is the simple production process at a low cost.

Amorphous Silicon (a-Si) based solar cells have lower efficiency (6%-8%) and used for small-scale applications. Stacking technology is used to improve their efficiency and installing for large systems, which is expensive. Cadmium telluride (Cd-Te) is the most cost-efficient TFSC Compared with crystalline silicon solar panels for a more extensive system, and has an efficiency of around 9%-11%.

2.1.2 The inverter

Inverters are used to convert the PV direct current (DC) output into alternating current (AC), which is the common use of commercial appliances. Therefore, an inverter is a gateway between the photovoltaic (PV) system and the utility load. Standalone and grid-connected types inverters are generally used in the PV system. Batteries are used for DC power sources with a fixed power rating based on the maximum AC load in standalone inverters. In contrast, PV arrays are the primary power source for grid-connected inverters, and power rating depends on array size. Grid-connected inverters can be categorized into micro, string, and central inverters based on their connectivity with the system.

Microinverters are module-level power electronics installed in each module to convert the DC power into AC at the panel level. The usual power output is 200-300 W for a small-sized module and suitable for residential and commercial installations. On the other hand, string inverters are connected to the multiple PV strings where panels are connected. The usual rating of a string inverter is 1 kW to 12 kW, and it is used for single-phase connections with a small number of strings. The main restriction of this inverter is the inability to mitigate the system shading problem, reducing the system output. Power optimizers are module-level power electronics integrated with each module to reduce the shading effect, introducing additional costs. This technology is commonly used for small residential systems and considered less expensive comparing with other solutions [6]. The main functionality of an inverter in a Grid-connected PV system is to convert array DC power into AC. The PV production and system profitability depend on this conversion ratio. Therefore, maximum power point tracking (MPPT) is a critical function of an inverter which states the inverter operation on the maximum power-point of the system. PV modules have a voltage-current (I-V) characteristic curve that includes a short-circuit current value at 0 Volt (DC) and an open-circuit voltage value at 0 A, and the "knee" point known as MPP, which is the maximum power producing point from the highest product of voltage and current. MPP value varies depending on the solar irradiance and cell temperature throughout the day. During the time of higher sunlight, module current becomes higher and vice versa. The inverter can sense the deviation of PV power output from the MPP and act accordingly to keep this MPPT active to limit the power output. Inverter performance is vital for the PV system as the usable AC power is produced from this conversion. Standard specifications for all inverters can be identified from four main parameters: AC power output ratings, conversion efficiency, DC input voltage, and AC output voltage. This efficiency is varied with power level, input voltage, temperature, and other parameters [6]. The parameter that affects inverter efficiency is solar radiation, rated power output, and size of the inverter. First, solar irradiance has a direct impact on efficiency due to the temperature effect. The solar radiation incident below 200 to 300 W/m^2 reduces the efficiency, which can decline up to 70% when the incident radiation ranges between 50-100 W/m^2, and is related to the inverter temperature, which increases when it handles loads with more power. Next, inverter efficiency is impacted by the rated power output, seasonal change, ambient temperature, and system placement. Outdoor systems perform better during winter for low temperatures. An inverter efficiency may decrease by 1% for a 12 C°increase in the ambient temperature. PV system sizing is also equally crucial for inverter performance. The sizing ratio of the array's rated power size to the inverter's rated power should be 1 to get the system's maximum output. The higher sizing ratio will make the system oversize, and excess energy will be dumped due to the lower efficiency of the inverter. Alternatively, an inverter reduces the maximum power point of the PV array for the lower sizing ratio [6].

2.1.3 PV performance parameters

With the antecedent technical performance indicators, the technical performance of the grid-connected PV system can be assessed. These indicators can compare the system's performance with that of any other system with similar installations, regardless of their location and installed capacity. IEC standard-61724 har four distinct parameters, performance ratio (PR), energy yield, reference yield (RY), and capacitor factor (CF), to define the PV system performance based on the site location, energy production, and system losses [7].

Yield factor

The yield factor is the total energy produced by a PV system over one month or year. The yield factor measures the system's productivity because of the various module efficiencies and array designs. Yield factor is measured in kWh/kW_p.The Yield factor is defined as:

$$YF = \frac{E_{Grid}(kWh/year)}{PV_{array}(kWh_{peak})} \tag{2.1}$$

Where YF is the yield factor,E_{Grid} is the system's energy yield, and PV_{Array} is the PV array's nominal power (P_{STC}).

Final energy yield

PV system final energy yield is defined as the annual net AC output of the system divided by the peak power of the installed PV array for a standard test condition (STC) at 100 W/m^2 solar irradiances, 25 C°cell temperature, and 1.5 air mass, which is called as system nameplate capacity.

$$FEY = \frac{Annual\,energy\,output\,E(kWh - AC)}{Nameplate\,power\,capacity\,P(kW - DC)} \tag{2.2}$$

Where is the FEY is the final energy yield.

Reference yield

Reference yield is the ratio between plane solar irradiation and the PV array reference irradiance (1 kW/m2). And that also an hourly measurement of the peak sun solar radiation, which varies with weather data, array orientation, and irradiance losses.

$$RY = \frac{Inplane\, irradiance\, H\; (kWh/m^2)}{PV\, reference\, irradiance\, G\; (kW/m^2)} \tag{2.3}$$

Performance Ratio (PR)

The performance ratio is a metric that defines a PV system's quality regardless of its location and size. Specifically, PR is the ratio f the actual energy output of a PV system to the theoretical standard test conditions output for a given reporting period. The performance ratio is independent of radiation conditions and independent of a specific site and even module orientations. Therefore, the performance ratio can compare different PV system designs, similar system designs but installed at other locations, or for the same system over a specific period. However, the PR's strong temperature dependence implies that in hot climates, the performance ratio will be lower in cold climates.

$$Performance\, ratio\, (PR) = \frac{Final\, energy\, yield(FEY)}{Referenceyield(RY)} \tag{2.4}$$

Capacity factor (CF)

The capacity factor is the ratio of a PV array's actual annual energy yield to the energy it would produce when operating at total capacity over one year. The capacity factor estimates the usable PV array percentage, and the ideal CF is 50% because of the daily sun availability.

$$Capacity\, factor\, (CF) = \frac{Annual\, energy\, production\, (kWh - AC)}{DC\, nameplate\, capacity \cdot time(8760H)} \tag{2.5}$$

The performance ratio (PR) and capacity factor are two main parameters to evaluate the PV system performance. The performance ratio is directly related to system energy loss.

The module loss due to temperature is higher in summer, which decreases the performance ratio. The standard value of the performance ratio is between 0.6 to 0.8. The capacity factor depends on the solar irradiance, weather data, array tracking system, and orientation [8] [7].

2.2 Solar Resource

Energy from the sun can mainly be exploited in two ways, thermal as in passive heating or with the solar collector to heat water, and to produce electricity with either solar PV or concentrated solar power.

There are two metrics used to measure the amount of solar energy resource: irradiance and irradiation. Irradiance is the amount of solar radiation falling on a particular area. And It is a measure of power and does not consider time, and is provided in W/m^2. In the order, irradiation is a measure of solar energy and is presented in kWh/m^2/day. Radiation from the sun that strikes the horizontal surface is divided into a combination of direct radiation (G_d) and diffuse radiation (G_{di}). Direct radiation is the solar radiation that goes directly from the sun without scattering from the atmosphere to the earth's surface. Diffuse radiation has changed direction because of the atmosphere and strikes from all parts of the sky. The sun of the total radiation on a horizontal surface is defined as:

$$G = G_{direct} + G_{diffuse} \tag{2.6}$$

Reflected radiation is defined as:

$$G_r = p \cdot (G_d + G_{di}) \tag{2.7}$$

Total radiation on an inclined surface is defined as:

$$G = G_{direct} + G_{diffuse} + G_r \tag{2.8}$$

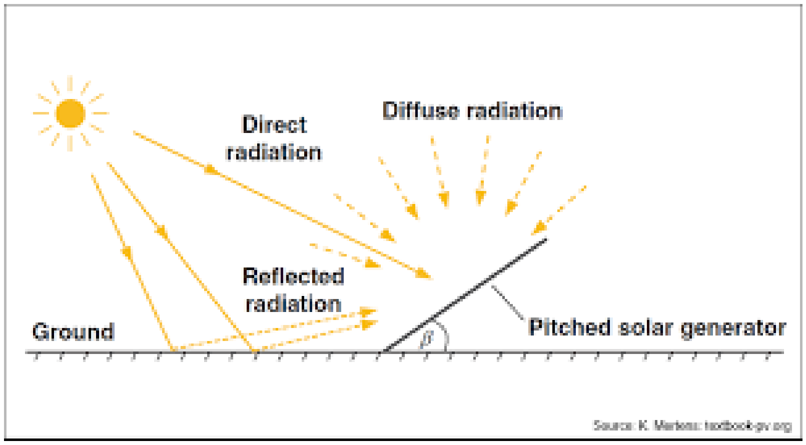


Figure 2.2: Visualization of direct, diffuse, and reflected radiation on an inclined surface [9]

Global horizontal radiation (GHI) is the only radiation input in the model. Since the GHI does not consider its direct and diffuse components, the clearness index calculates the amount of diffuse radiation. The clearness index indicates the fraction of solar radiation striking the top of the atmosphere, making it through the atmosphere and striking the earth's surface [9]. The monthly average clearness index is defined as [10]:

$$K_T = \frac{H_{ave}}{H_{0,ave}} \tag{2.9}$$

Where K_T is the clearness index in month T, H_{ave} is the monthly average radiation on the horizontal surface of the earth (kWh/m^2/day), and $H_{0,ave}$ is the radiation on a horizontal surface at the top of the earth atmosphere, extraterrestrial radiation (kWh/m^2/day).

2.2.1 Altitude and azimuth angle

At any time of the day, the sun's location can be described by altitude angle (β) and azimuth and (ϕ). These angles are depended on latitude, the number of days, and time of day. Figure 2.3 presents altitude and azimuth angle. The altitude angle is the sun's height in the sky at a given time. In contrast, the azimuth angle is the compass direction from where the solar radiation arrives. For the northern hemisphere, the sun is at a position in the southward order. The optimal orientation will therefore be south-facing [11].

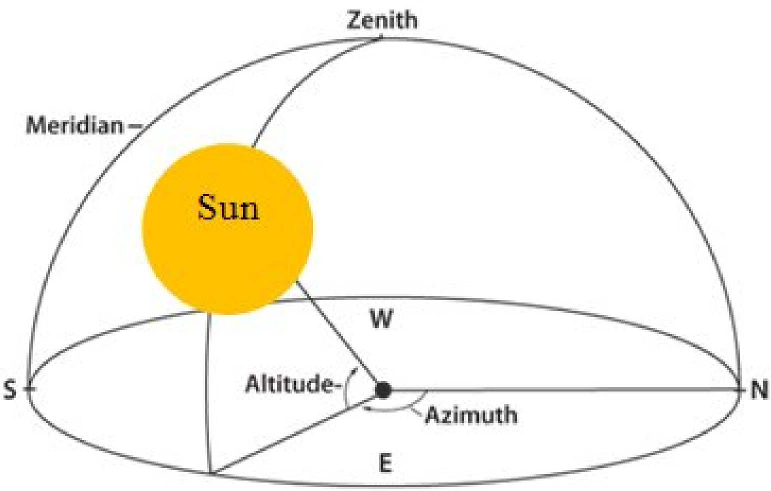


Figure 2.3: Altitude and Azimuth angle [11]

$$\phi + \alpha = \frac{\pi}{2} = 90^{\circ} \tag{2.10}$$

Solar altitude angle is defined as:

$$sin(\alpha) = cos(\phi) = sin(L)sin(\zeta) + cos(L)cos(\zeta)cos(h) \tag{2.11}$$

Where L is the local altitude and defined as the angle between a line from the center of the earth to the interest and equatorial plane site, h is the hour angle, and ζ is the declination angle.

The azimuth angle is defined as:

$$sin(\alpha) = \frac{sin(h)cos(\zeta)}{sin\theta_Z} = \frac{sin(h)cos(\zeta)}{cos(\alpha)} \tag{2.12}$$

The azimuth angle at sunrise (A_{SR}) can be calculated from:

$$sin(SR) = sin(h)cos(\zeta) \tag{2.13}$$

The altitude and azimuth angle defined as:

$$sin\phi_s = \frac{cos(\zeta)sin(h)}{cos\beta} \tag{2.14}$$

$$h = \frac{15^\circ}{hour} \cdot (t_s - 12\,hour) \tag{2.15}$$

Where t_s is the solar time (hour).

2.2.2 Declination angle

The sun's declination is the angle between the equator and a line drawn from the center of the Earth to the sun's center. Figure 2.4 Figure 2 presents the summer solstice in the northern hemisphere and the declination angle (ζ) at its maximum and is 23.45°. Spring equinox in the northern hemisphere and the autumn equinox in the southern hemisphere, the declination angle (ζ) is 0°. Winter solstice in the northern hemisphere and summer solstice in the southern hemisphere, the declination angle is (ζ) is -23.45°[12]. The declination angle can be calculated by the equation:

$$\zeta = 23.45^\circ \cdot sin(\frac{360}{365} \cdot (d + 81)) \tag{2.16}$$

Where is d is the day of a year.

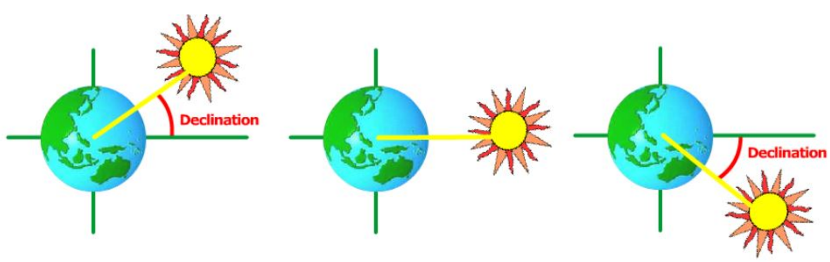


Figure 2.4: Declination angle [12]

2.2.3 Optimum tilt angle

The optimum tilt angle varies between summertime and wintertime. Using a tracking system could increase the amount of solar radiation striking the inclined surface. However, a tracking system has higher investment costs and requires higher maintenance costs than a fixed tilted system. The difference in power output from changing the tilt once every month and a fixed system is less than 4%. The tilt angle (θ) will influence the power output from the solar PV system. To optimize the amount of solar radiation that strikes the solar PV panels, it would be appropriate to orientate the panels at the angle where the sun is at its highest and brightest [12].

2.3 Battery storage technology

A battery's main functionality in a PV system is to store excess energy to use during the hours when no energy is produced. This storage technology allows more renewable integration into the grid. PV production is highly dependent on the weathering profile, like many other renewable sources, and these uncertain power fluctuations create stress on the grid. Battery storage can act as an energy buffer in-between generation and load. The services such as peak shaving, load leveling, frequency, and voltage control for grid stability can be provided from battery storage from both transmission and distribution grid operators.

2.3.1 Lead-acid battery

Lead-acid batteries are the most commonly used type of battery in a PV system. Lead-acid batteries have a low energy density, efficiency, and high maintenance requirement. They also have long lifetimes and costs. The benefit of lead-acid batteries is that they are the most commonly used battery for most renewable battery applications. For most renewable energy systems, the battery lifetime's essential battery characteristics are the depth of discharge and the maintenance requirements of the battery.

A lead-acid battery will experience a gradual reduction in the voltage between the fully discharged and charged states. The voltage level is most used to indicate a battery's state of charge. Figure **??** presents the dependence of the battery on the battery state of charge

[13].

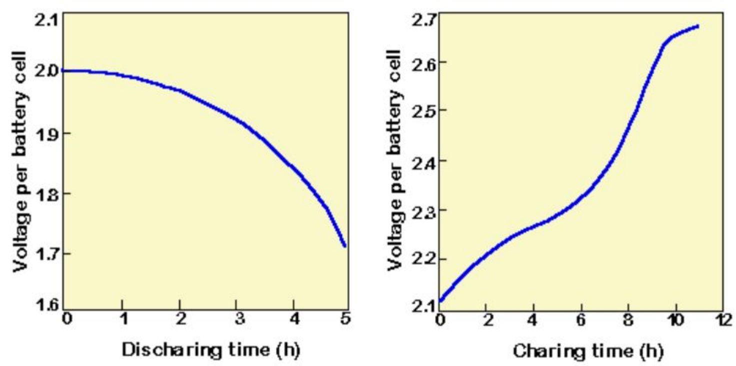


Figure 2.5: Charge and discharge regime [14]

The critical properties of a battery are:

- Its nominal voltage.
- State of Charge (SoC).
- The Minimum State of Charge.
- Round trip efficiency.
- Maximum discharge current.
- Capacity curve.
- Lifetime curve.

State of Charge is the percentage from the maximum possible charge that is present inside the battery. Depending on the renewable sources' energy and the load power requirement, the SoC of a battery can be calculated from the following equations.

Battery charging:

$$SoC(t) = SoC(t-1) \cdot (1-\sigma) + \eta_B (E(t) - \frac{E_L(t)}{\eta_{inv}}) \tag{2.17}$$

Battery discharging:

$$SoC(t) = SoC(t-1) \cdot (1-\sigma) + \eta_B(\frac{E_L(t)}{\eta_{inv}} - E(t)) \tag{2.18}$$

Where:

SoC(t) $\rightarrow$ is the state of charge of the battery bank at the time t

SoC(t-1) $\rightarrow$ is the state of charge of the battery bank at the time t

σ $\rightarrow$ is the hourly discharge rate

E(t) $\rightarrow$ is the total energy generated by the renewable systems

$E_L(t)$ $\rightarrow$ is the load demand at time t

η_{inv} $\rightarrow$ is the inverter efficiency

η_B $\rightarrow$ is the battery bank efficiency

The minimum state of charge is the state of charge below which the battery must not be discharged to avoid permanent damage. The round trip efficiency indicates the percentage of the energy going into the battery that can be width-drawn back out. Some energy is always lost in the discharging process as heat. The maximum discharge current of a battery refers to the maximum current that can be taken from a battery at any one time without significantly shortening the battery life.

Most solar batteries need to hold some charge at all times due to their chemical composition. If using 100 percent of the battery charge, its useful life will be significantly shortened. DoD indicates how much battery capacity is used. Most of the manufacturers will specify the maximum DoD for optimum performance. For example, suppose a 10 kWh battery has 90 percent DoD. In that case, it typically should not use more than 9 kWh of battery before recharging. Generally, the higher the DoD percentage means will be able to use more battery capacity.

In addition to the depth of discharge and rated battery capacity, the instantaneous or available battery capacity is strongly affected by the battery's discharge rate and battery operating temperature. Battery capacity falls by about 1% per degree below about 20°C. However, high temperatures are not ideal for batteries either as these accelerate aging, self-discharge, and electrolyte usage. Figure 2.6 shows the impact of battery temperature and discharge rate on the capacity of the battery. In general, battery capacity degrades due to sulfation of the battery and shedding of active material [13].

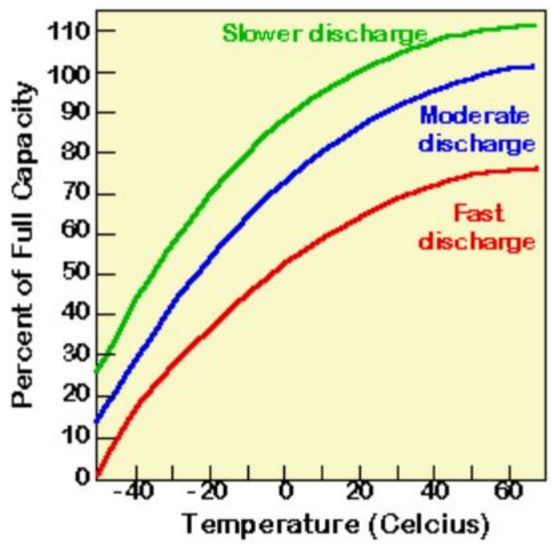


Figure 2.6: The relation between battery capacity, temperature and discharge rate [14]

2.3.2 Lithium-ion battery

The majority of new home energy storage technologies, for example, use some form of lithium-ion chemical composition. Lithium-ion batteries are lighter and more compact than lead-acid batteries. They also have a longer life compared to lead-acid batteries. However, lithium-ion batteries are more expensive than their lead-acid counterparts [15]. Lithium-ion batteries have several benefits over convectional Lead-acid batteries; high energy density, high charge currents, high discharge current, long battery life, high efficiency between charge and discharge, and higher continuous power available.

2.4 Electricity structure

2.4.1 Electricity market overview

As in figure 2.7, Almost all electricity produced in Norway comes from hydropower. The electricity generated from hydropower 93.4% in 2019, while the rest of the electricity came from thermal power and wind power. Hydroelectricity production in Norway amounted to 126 terawatt-hours in 2019.

In 2019, there were more than 1,600 hydropower stations in Norway. Most of these were small or medium-small sized. The most common size was the medium-small plants with a production capacity from one to ten megawatt-hours. The second most common was small-sized plants, with abilities of up to one megawatt-hour [16].

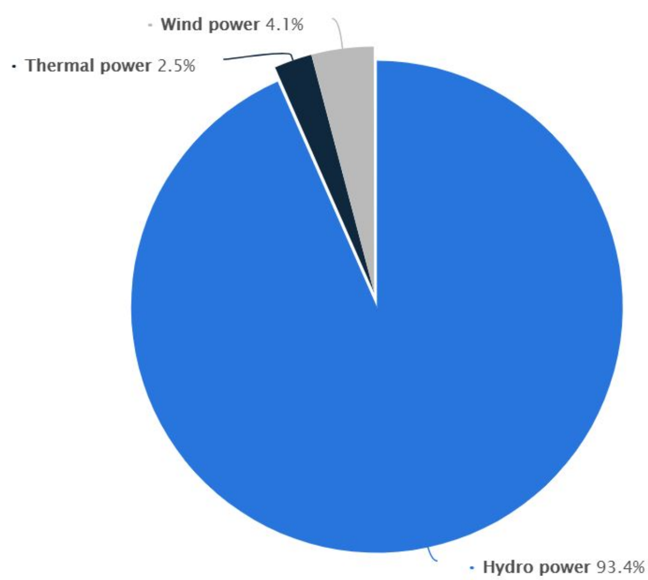


Figure 2.7: Distribution of electricity production in Norway in 2019 [16]

Figure 2.8 shows that electricity is the dominant energy product in households. Electricity has partly replaced heating oil and paraffin, whose use has fallen off considerably since the 1970s. There has also been an increase in district heating and gas use. However, these energy products still constitute a small share of total energy consumption in households. Consumption of biofuels, on the other hand, has risen considerably since 1976. The proportion of wood fuel in households energy consumption rose steadily through the period, although leveling-off since 2005. This may due to heat pumps replacing some wood burning in the household. In 2003 saw a fall in the use of electricity and a rise in other energy products such as wood and heating oil. This may be due to high electricity prices caused by low reservoir levels in the winter of 2002/3002 and increases attention in the media to energy prices and consumption. Since 2003, household consumption of electricity has risen again [17].

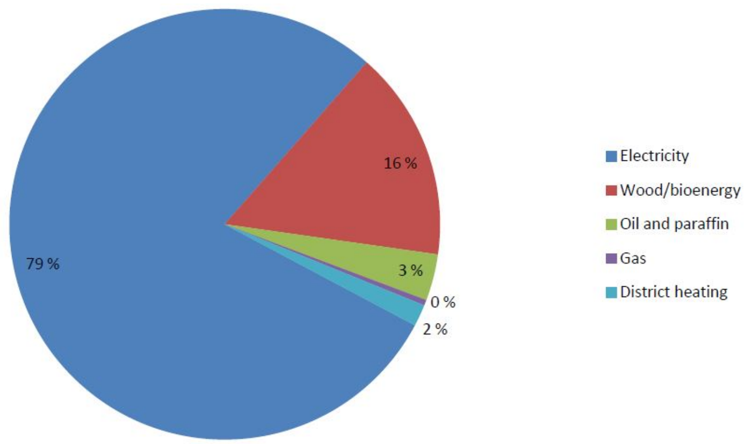


Figure 2.8: Energy consumption in households by energy product [17]

End consumption by purpose is a term used to describe how energy is used for different purposes in Norwegian households, averaged over the housing stock. In general terms, we can distinguish between heating purposes and electricity-specific purposes. End-use changes over time and from housing type to housing type. The distribution between electricity-specific purposes and heating purposes changes over time. White goods and some other electrical devices are replaced relatively frequently, and the number of devices is increasing rapidly. An increasing proportion of electricity is used for the operation of home entertainment equipment, such as flatscreen TVs and PCs. At the same time, technological development is taking place, and each device is becoming increasingly efficient. Some factors are pulling energy consumption upwards, while others are pushing it downwards. Energy for heating is being reduced over time through better insulation in new and existing buildings. More new and more stringent building regulations are likely to reduce the share of energy used for heating. At the same time, higher indoor temperatures and larger houses are helping to increase energy consumption. The net effects of all these factors are uncertain. However, it appears that the relative share of energy for electricity-specific purposes is on the increase, and the share of energy for heating is correspondingly declining. Figure 2.9 shows an estimate of end-use consumption for heating and electricity specific purposes in households [17].

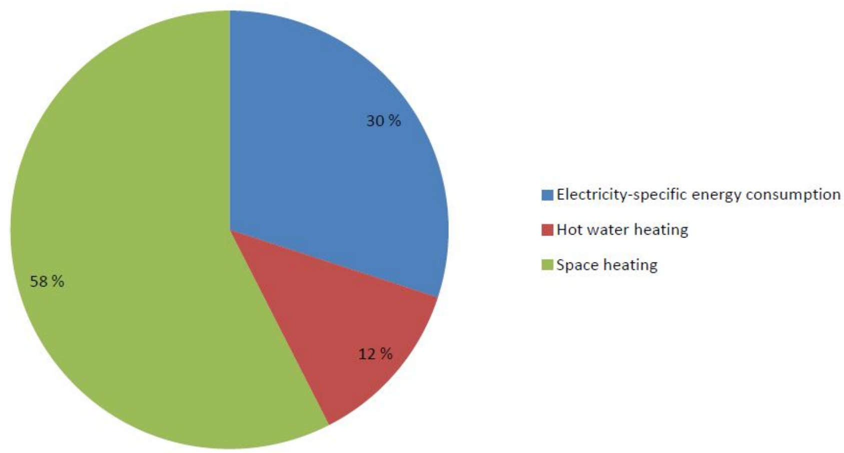


Figure 2.9: End-use consumption of electricity in households, estimated shares [17]

Energy consumption is often divided into consumption for heating purposes and electricity-specific consumption. Electricity-specific energy consumption refers to electrical consumption for devices that can only be powered by electricity, such as lighting, washing machines, refrigerators, TVs, coffee makers, etc. This energy consumption represents about 30 % of the total energy consumption in households. On the other hand, heating purposes can be met by all energy products, including petroleum products, wood fuel, wood pellets, briquettes, solar heating, and heat pumps. Which energy products can be used depends on the heating equipment available in the individual house. Around 55-60% of households' energy consumption is used on space heating and around 10-15 percent on water heating [17].

3 Materials and Method

3.1 Study area and climate

Southern Norway, Grimstad is considered as the study location of this thesis. The latitude and longitudes of the site selected are 58°20.7'N, and 8°35.7'E, figure 3.1 show the map of the geographical site for this study. In this thesis, a typical South Norwegian house (Grimstad) with an area of 140 m^2 with heating 100% electricity. The area calculated of all panels is considered to be 58.2 m^2.

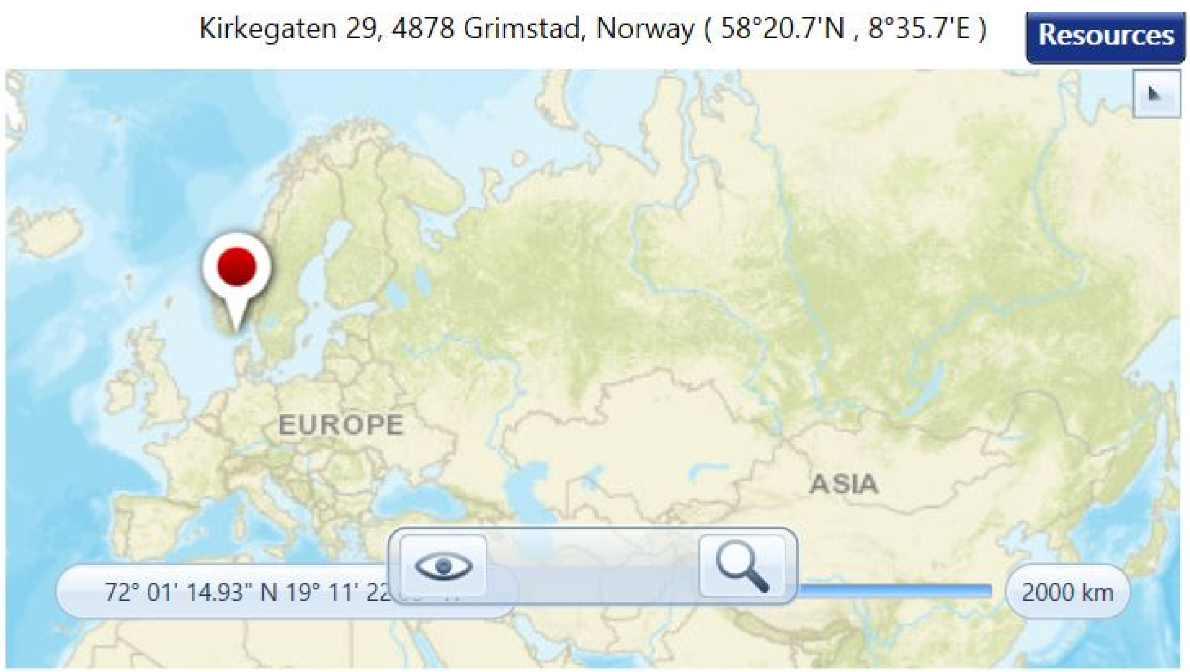


Figure 3.1: The geographical location of the selected location [HOMER]

Figure 3.2 shows the measured hourly air temperature of one year (2016) for Southern Norway site collected from Norges Vassdrags og Energidirektorat (NVE), which the highest temperature in July and August with an average between (20 C° to 25 C°). Furthermore, figure 3.3 show the monthly average air temperature. HOMER uses NASA prediction of Worldwide energy sources to collect their data. The average air temperature is 8.01 C°, and table 3.1 also shows the average monthly temperature data used in HOMER.

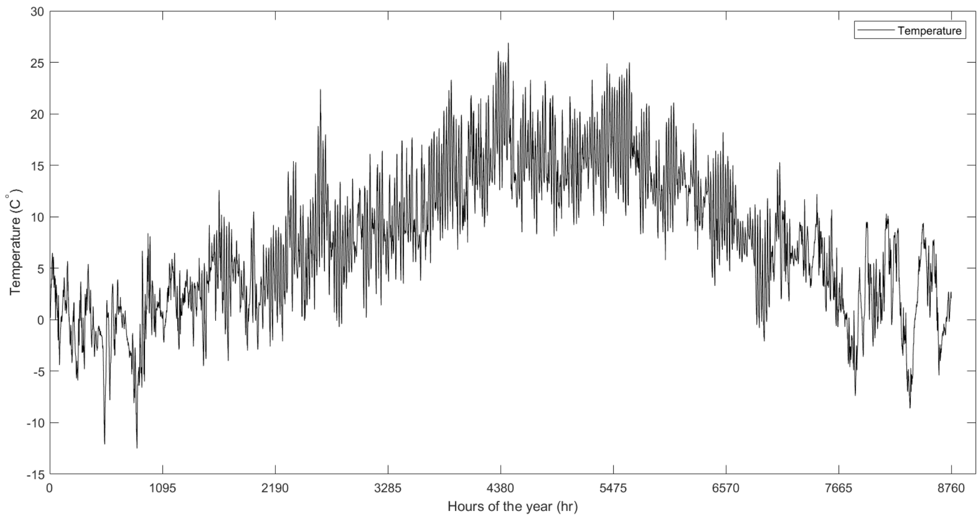


Figure 3.2: Measured hourly air temperature data

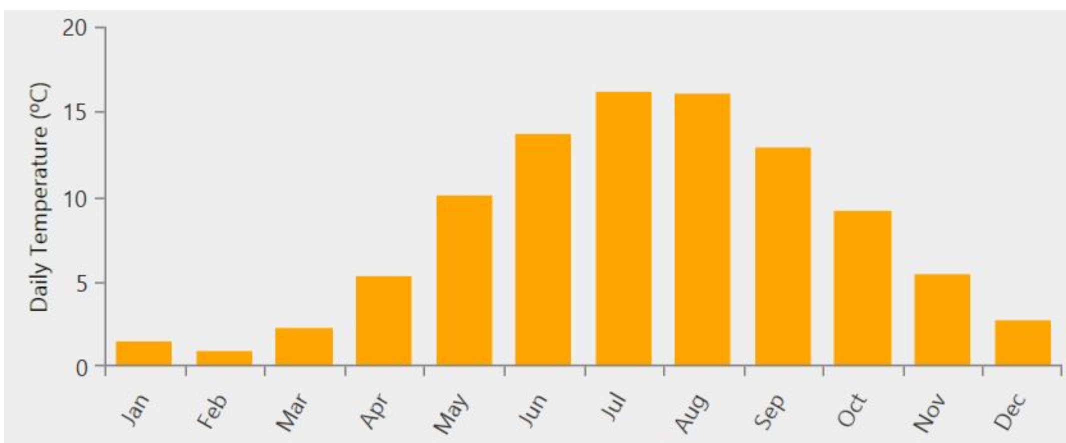


Figure 3.3: Monthly average air temperature (HOMER)

Table 3.1: Monthly average temperature data [HOMER]

Month	Daily Temperature (C°)
Jan	1.440
Feb	0.900
Mar	2.220
Apr	5.350
May	10.080
Jun	13.720
Jul	16.110
Aug	16.020
Sep	12.860
Oct	9.200
Nov	5.480
Dec	2.740
Annual average	**8.010**

3.2 Load and PV power

The load profile is essential for designing a system that meets the requirements for an entity consuming electricity. The analysis conduct in this thesis is sought to make for an average household in Grimstad in south Norway. Also, household consumption depends on many factors, such as temperature, number of residents, and time. The annual measured load profile and PV production of typical South Norwegian (Grimstad) House for 2016 have been studied in this thesis. Figure 3.4, 3.5presents the load profile of year 2016 (8760 hours), PV production of year 2016 (8760 hours).

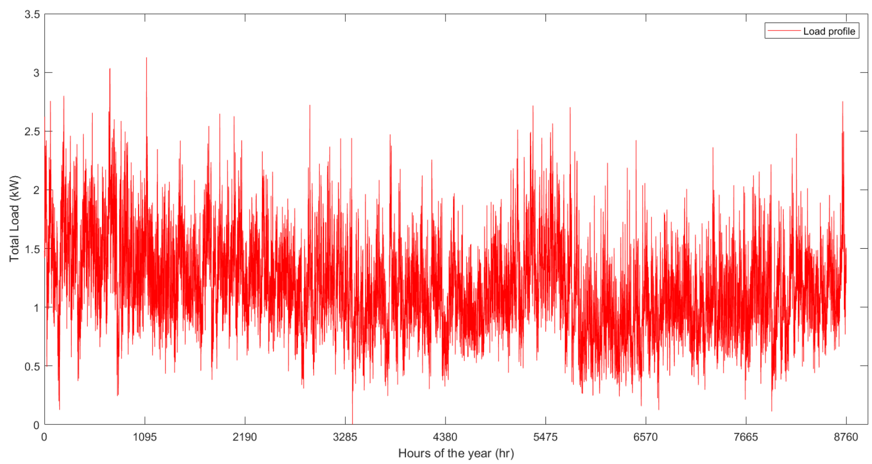


Figure 3.4: Hourly load profile for full year 2016

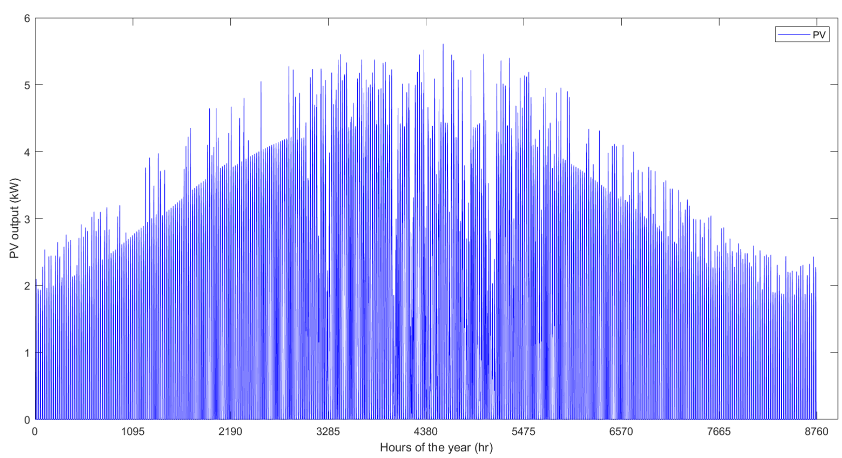


Figure 3.5: Hourly PV Output power for full year 2016

Figure 3.6 presents the monthly average load profiles, as well, the line in the top and bottom show the monthly maximum and minimum values, respectively, the bar at the top and bottom of the blue box shows the average daily maximum and minimum value, the middle line shows the average monthly load based on modeled load values. The daily load curves for each month are presented in figure 3.7.

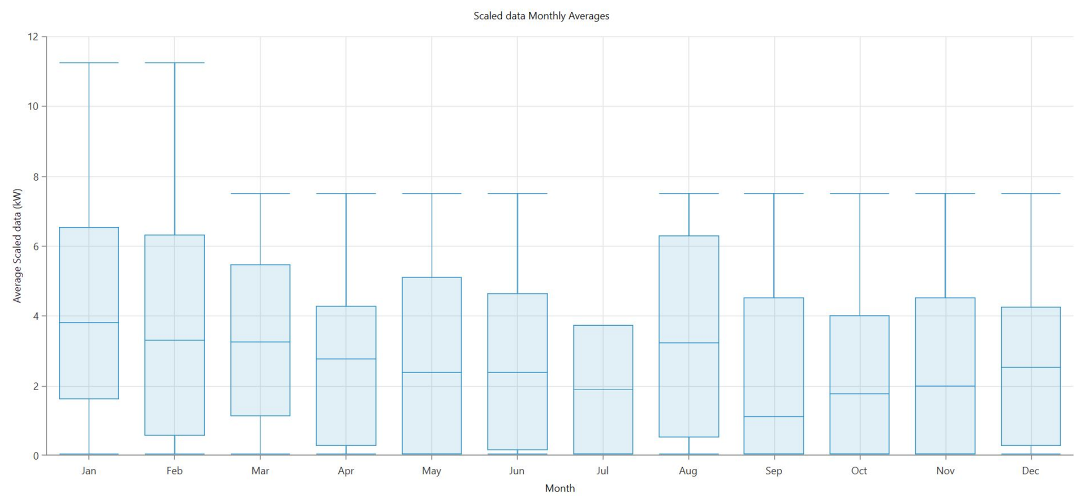


Figure 3.6: Monthly load values created from the load input values [HOMER]

Figure 3.7: Average daily load profile for each month [HOMER]

3.3 Solar Resource

3.3.1 Solar Radiation data

Solar energy can be utilized as an energy carrier in both thermal and electrical energy. Two main metrics can be used for measuring solar radiation:

- irradiance
- irradiation

Irradiance can be defined as the power falling on a specific area at any given time. Irradiation is the energy density of sunlight that hits a specific area in a specified amount of time. Equation eq.2.6 of the sun of the total radiation on a horizontal surface is reported in chapter 2. The clearness index indicates the fraction of solar radiation striking the top of the atmosphere described in chapter 2. The monthly average clearness index is defined in equation eq.2.9.

Global irradiation is the only data that are provided in the model. The clearness index is used to calculate the amount of indirect irradiation the strikes the tilted solar array. monthly values for global irradiance on a horizontal surface and clearness index are in table 3.2 and figure 3.8. Figure 3.9 shows the monthly values for global irradiance on a horizontal surface.

Figure 3.8: The global horizontal irradiance (GHI)

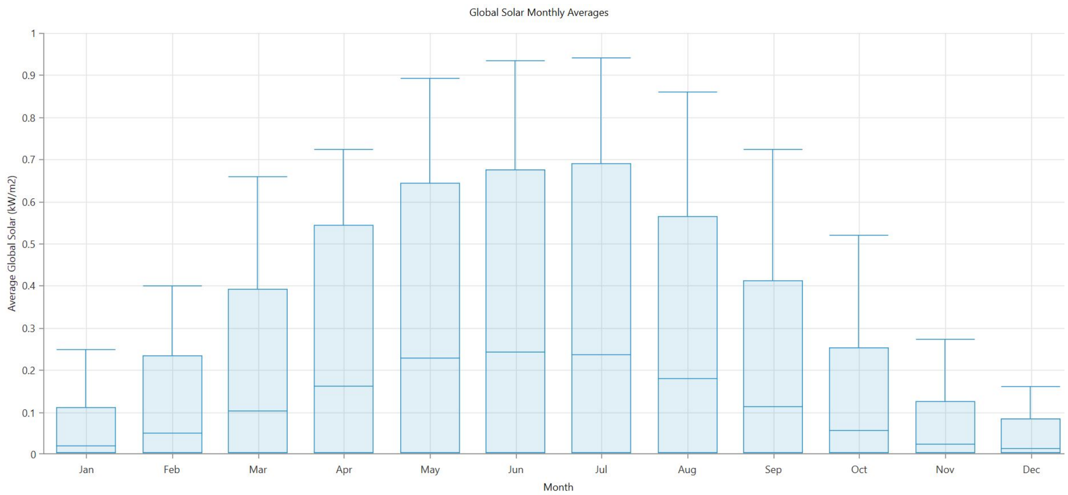


Figure 3.9: Annual monthly solar irradiance in Grimstad

The annual daily average irradiation in Grimstad is **2.837 kWh/m^2/day**. The annual daily average clearness index is 0.457, as presented in the table below.

Table 3.2: Monthly averages for global horizontal radiation [HOMER]

Month	Clearness Index	Daily radiation (kWh/m^2/day)
Jan	0.372	0.450
Feb	0.449	1.160
Mar	0.489	2.430
Apr	0.493	3.870
May	0.532	5.460
Jun	0.507	5.780
Jul	0.521	5.640
Aug	0.492	4.300
Sep	0.453	2.690
Oct	0.410	1.340
Nov	0.406	0.610
Dec	0.363	0.310
Annual average	**0.457**	**2.837**

3.4 Simulation tool-HOMER PRO

The simulation tool used in this thesis is the hybrid Optimization Model for Electric Renewable (HOMER-PRO), originally developed by the National Renewable Energy Laboratory, the United States, which is the worlds leading microgrid simulation model for optimal planning and design of energy systems off-grid or and on-grid modes. HOMER assesses the technical ad economic performances of energy systems. HOMER offers various energy sources and storage such as PV arrays, wind turbines, hydro-power dams, hydro-kinetic turbines, grid, generator, batteries, fuel cell, super-capacitors, etc. The software simulates different system configurations and finds the optimal system combination based on the lowest net present cost. Moreover, a sensitivity analysis can be carried out in HOMER to investigate the impact on the optimization results of changing the input parameters. Figure 3.10 shows the visualization of the primary elements of HOMER. The first step is the simulation of the system with a different configuration. The second step is to use the first step to generate optimization. The third step is optimizations used to conduct one sensitivity analysis [18].

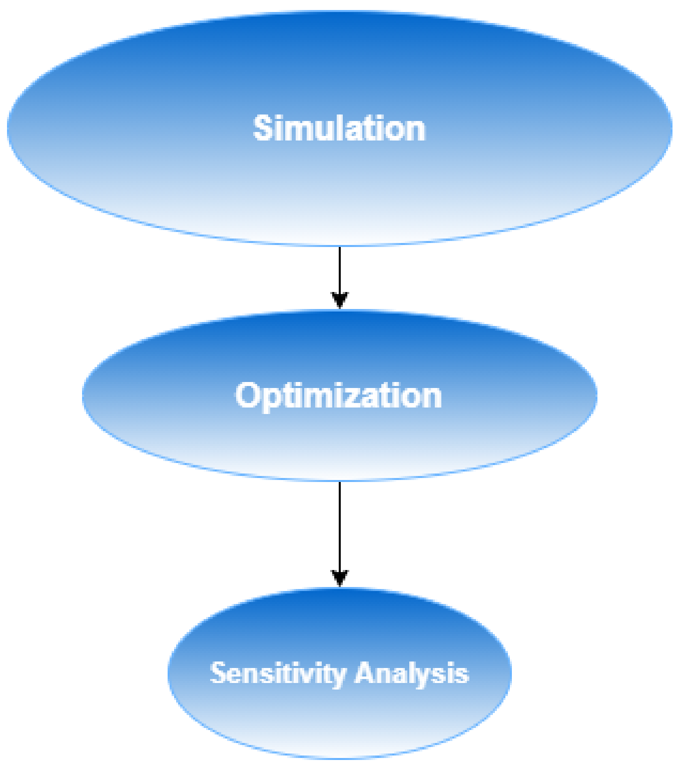


Figure 3.10: HOMER diagram system [HOMER]

The simulation process also determines how certain system configurations, including technologies and their specification, will function over a specified period. Usually, this is done using hourly data essential for the energy system to operate solar irradiation and load demand. For each time step in a year, the energy balance is calculated and summarized. The result makes it possible to determine how much each technology contributes to supplying the load and how much excess deficit energy is generated. Excess energy can either be stored, sold to the grid, or dumped, depending on storage technologies' availability and if the system is grid-connected or autonomous. HOMER uses simulation results to determine if the system is feasible in meeting the modeler's constraints. Optimization uses the simulation results and ranks the different feasible systems based on the NPC. A lower NPC returns in a higher ranking of the system, which means the objective function built into HOMER is to minimize NPC subject to determined constraints. With The objective in mind, HOMER returns different variations of each system configuration, and optimized systems within each configuration are ranked and presented [18].

4 Hybrid system component

4.1 introduction

4.2 PV-panels

The PV effect produces direct electrical current from the radiant energy of the sun using semiconductor cells. Semiconductor cells are large-area p-n diodes and have a minimal power input. The most common semiconductor material using for producing solar cells is Silicon. Other than Silicon, Copper Indium Sidelined (CIS), Cadmium Telluride (CdTe), and Gallium Arsenide (GaAs) is used in the solar cell industry. The power output from a typical solar cell is about 1W. Hence, to generate the required amount of power, many cells are connected in series and parallel on a module [**cite {kouro2015grid}**].

4.2.1 Electrical characteristics of PV cells

The complex of PV cells can be represented by the equivalent electrical circuit as shown in figure 4.1. The corresponding I-V characteristics are described by the following equation:

$$I = I_{ph} - I_0[exp(\frac{V + IR_s}{K_B T/q}) - \frac{V + IR_s}{R_{sh}}] \tag{4.1}$$

Where I_{ph} is the photo-current, and it is related to the photon flux incident on the cell end dependent on the wavelength of the light, I_0 is the diode saturation current (A), K_B is the Boltzmann constant ($1.38 \cdot 10^{-23} m^{-2} kg s^{-2} K{-}1$), R_s is the series resistance, and it represents the internal resistance to the current flow and depends on the n-p junction depth, T is the absolute temperature (K), I is the load current (A), V is the voltage at the terminals of the cell (V), R_{sh} id the shunt resistance and it is inversely related to the leakage current to the ground and g is the electronics charge (C).

Typical I-V characteristics and the power curve are the short circuit current (I_{sc}) and the open-circuit voltage (V_{oc}). The open-circuit voltage is the maximum voltage generated by the cell when no external load is connected. The short circuit current is the maximum current caused by the cell when the cell output is short-circuited.

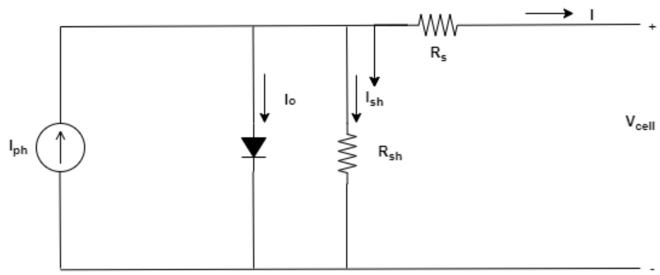


Figure 4.1: PV cell modeled as a diode circuit [19]

The power output of the cell is the product of the output voltage and the current. As shown in figure 4.2, the cell's power output is zero at zero current. The module produces maximum power at a certain point known as Maximum Power Point (MPP). The respective voltage and current at this MPP are denoted as V_{mpp} and I_{mpp}. All these parameters are given in the manufactures datasheet of a solar module.

Small diode and the ground leakage current can be ignored in the equivalent electrical circuit; therefore, the short circuit current I_{sc} equal to the photogenerated current, the open-circuit current defined as:

$$V_{oc} = \frac{K_B T}{q} ln(1 + \frac{I_{ph}}{I_0}) \tag{4.2}$$

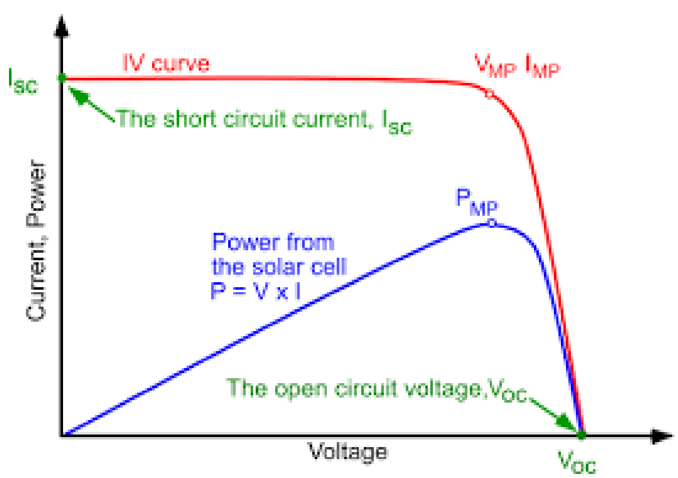


Figure 4.2: Solar cell I-V characteristic curve [19]

4.2.2 Operating temperature of a PV cell

The energy balance of the solar cell is usually used to calculate the operating temperature of the cell. The solar energy absorbed by the PV array is converted into electrical energy and heat energy transferred to the surroundings. The relationship is given by:

$$\tau\alpha G_\tau = \eta_c G_\tau + U_L(T_c - Ta) \tag{4.3}$$

Where:

$\tau =$ is the solar transmittance of the cover the PV array (%)

$\alpha =$ is the solar absorptance of the PV array (%)

$G_T =$ is the solar radiation striking the PV array (kW/m^2)

$\eta_c =$ is the electrical conversion efficiency of the PV array (%)

$U_L =$ is the coefficient of heat transfer to the surroundings (kW/m^2C°)

$T_c =$ is the PV cell temperature (C°)

$T_a =$ is the ambient temperature (C°)

The PV cell temperature is defined as:

$$T_c = T_a + G_T(\frac{\tau\alpha}{U_L})(1 - \frac{\eta_c}{\tau\alpha}) \tag{4.4}$$

It is difficult to measure the value $\frac{\tau\alpha}{U_L}$ in equation 4.4. Still, it can be found by using the nominal operating cell temperature (NOCT), Which is usually mentioned in the manufacturer's datasheet [20]. NOCT is the operating temperature of the cell at an incident irradiance of 0.8 KW/m^2, ambient temperature of 20C°, and no-load operation ($\eta_c = 0$). Substituting these values in equation 4.4:

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \tag{4.5}$$

Where:

$T_{c,NOCT}$ = is the nominal operating cell temperature (C°)

$T_{a,NOCT}$ = is the ambient temperature at which the NOCT is defined (20C°)

$G_{T,NOCT}$ = is the solar radiation at which NOCT is defined (0.8 kW$/m^2$)

Suppose the solar panel is assumed to be operated at its maximum power point all time. In that case, the electrical conversion efficiency of the PV module is the efficiency at MPP.

$$\eta_c = \eta_{mpp} \tag{4.6}$$

The efficiency at MPP is defined as:

$$\eta_{mpp} = \eta_{mpp,STC}[1 + \alpha_p(T_c - T_{c,STC})] \tag{4.7}$$

Where:

$\eta_{mpp,STC}$ = is the maximum power point efficiency under standard test conditions (%)

α_p = is the temperature coefficient (%C°)

$T_{c,STC}$ = is the temperature under standard test conditions (25C°)

Substituting equations, 4.5, 4.6, and 4.7 into the equation 4.4, the final equation is:

$$\begin{gathered} T_c = T_a + G_T(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}})(1 - \frac{\eta_{mpp,STC}[1 + \alpha_p(T_c - T_{c,STC})]}{\tau\alpha}) \\ T_c = \frac{T_a + G_t(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}})[1 - \frac{\eta_{mpp,STC}(1 - \alpha_p T_{c,STC})}{\tau\alpha}]}{1 + (T_{c,NOCT} - T_{a,NOCT})(\frac{G_T}{G_{T,NOCT}})(\frac{\alpha_p \eta_{mpp,STC}}{\tau\alpha})} \end{gathered} \tag{4.8}$$

4.2.3 Energy generation of a PV system

The energy generation of PV cost in this section have been calculated based on the methodology given in the reference [21] [22] [23]. Energy generated from the PV is used to charge the battery, fulfill the load demand, and feed into the grid. Furthermore, while calculating the energy generation cost for PV, it has assumed that the PV module and inverter is part of a PV system, and the battery is an independent energy source.

The PV system generation cost (E_{PV}) has been calculated by equation 4.9.

$$E_{PV} = \frac{NCF_{sys} \cdot CRF_{PV}}{\sum_{m=1}^{12} N_D \cdot M_{PV}} \tag{4.9}$$

Where:

N_D = is the number of days in a month

M_{PV} = is a monthly average per generated by PV system

CRF_{PV} is the capital recovery factor and it is given by:

$$CRF_{PV} = (\frac{b}{1-(1+b)^{-M}}) \tag{4.10}$$

Where:

b = is the discount rate

M = is project lifetime

NCF_{sys} is the total net present cost of a PV system and it is the sum of investment cost of PV (C_{PV}), operation and maintenance cost (OM_{sys}) and replacement (R_{INV} of PV system. NCF_{SYS} is defined as:

$$NCF_{INV} = C_{PV} + OM_{SYS} + R_{SYS} \tag{4.11}$$

PV system maintenance and operation costs

Operation and maintenance cost (OM_{SYS}) includes taxes, insurance, maintenance, recurring costs, etc. Typically, it is specified of initial capital cost. All operating costs are escalated at a rate e_0 and discount rated. The life-cycle maintenance cost for a lifetime of M years is given by:

$$OM_{SYS} = OM_0(\frac{1+e_0}{1-e_0}) \cdot [1 - (\frac{1+e_0}{d-e_0})^M]\, if, b \neq e_0 \tag{4.12}$$

$$OM_{SYS} = OM_0\, if\, b = e_0 \tag{4.13}$$

replacement cost of PV system

The inverter replacement cost R_{NV} is mainly a function of the number of inverter replacements () over the system lifetime, without taking the salvage value of replaced inverter. The equation is given by:

$$R_{INV} = \sum_{j=1}^{w} C_{INV} \cdot (\frac{1+a_0}{1+b})^{\frac{Mj}{u+1}} \tag{4.14}$$

Where v = is the total number of replacements for inverter over a life period of M years.

4.2.4 PV cost

Solar PV technology has seen the sharpest cost decline of any other electricity technology over the last decade. A new report from International Renewable Energy Agency (IRENA) found that between (2010-2019), the cost of solar PV globally dropped by 82%. As well, in 2019, the cost of electricity from solar fell by 13% to just over five pence per kWh [24].

The PV module used in this thesis is the Canadian Solar CS6P-330P poly-crystalline $330W_p$ module with an efficiency of 16.97%. Standard test conditions are specified to ensure those module specifications are comparable between producers, meaning that modules from one producer are tested under the same conditions as other producers. The manufacturer's specification of Canadian Solar CS6P-330P solar module under standard test conditions

(STC) of irradiance 1000W/m^2, spectrum AM1.5 and cell temperature 25$C°$.The standard test conditions is defined in table 4.1.

Table 4.1: STC-data

ELECTRICAL DATA (STC)	**S6U-330**
Peak Power Watts-P$_{MAX}(W_p)^*$	330
Power Tolerance-P$_{MAX}(W)$	0/+5
Maximum Power Voltage-V$_{MPP}(V)$	37.2
Maximum Power Current-I$_{MPP}(A)$	8.88
Open Circuit Voltage-V$_{OC}(V)$	45.6
Short Circuit Current-I$_{SC}(A)$	9.45
Module η m(%) Efficiency	16.97

Manufactures specification of Canadian Solar CS6P-330P solar module under Nominal Operating Cell Temperature (NOCT) of irradiance 800W/m^2, ambient temperature 20$C°$ and wind speed 1m/s has been presented in table 4.2.

Table 4.2: NOCT-data

ELECTRICAL DATA (NOCT)	**S6U-330**
Maximum Power-P$_{MAX}(W_p)$	239
Maximum Power Voltage-V$_{MPP}(V)$	33.9
Maximum Power Current-I$_{MPP}(A)$	7.05
Open Circuit Voltage-V$_{OC}(V)$	41.9
Short Circuit Current-I$_{SC}(A)$	7.66

The cell temperature under normal operating conditions is given in table 4.3.

Table 4.3: Temperature characteristics

$\text{NOCT}_{(NominalOperatingCellTemperature)}$	43°C (±2 K)
Temperature coefficient of P_{MAX}	- 0.41%/K
Temperature coefficient of V_{OC}	- 0.31%/K
Temperature coefficient of I_{SC}	0.053%/K

The cost of the Canadian Solar CS6P-330P in the market around kr.3300. A 10 kW system requires 30 such modules having a worth of kr.100000.Figure 4.4 presents the cost summary of the PV modules chosen in this thesis. The data sheet of the Canadian Solar CS6P-330P can be found in appendix D.

Table 4.4: Summary of the PV modules cost

CS6U-330P	300 W
The average monthly consumption of electricity	1814.50 kWh/month
The average daily consumption of electricity	60.50 kWh/day
The number of panels	30
The PV capacity	10 kW
The average sunshine	6 h
The average cost in $	$10000-$15000
The average cost in NOK	kr.100000-kr.150000

4.3 Battery energy storage

Solar batteries' function is to store the panels' electrical energy while the sun is shining in daylight hours. Moreover, we use this electrical energy stored during the absence of the sun in the evening. Some specifications must consider when evaluating solar battery options, such as how long a solar battery will last or how much energy it can save.

In this thesis, it has been considered the minimum SoC of the battery has been taken as 30% and initial SoC to be 100%. However, 80% of the battery capacity can be used for charging and discharging purpose. In the equation 4.15, power generation from all energy resources and their balance with time (t)

$$P_{PV}(t) + P_{Dis}(t) + P_{Grid}(t) = P_{Load}(t) + P_{chg}(t) + P_{Sell}(t) + P_{Loss}(t) \tag{4.15}$$

Equation 4.15 have been used to calculate energy content in the battery energy storage and has governed by battery energy throughput. Equation 4.16 describes the limits of battery energy contents. Charge and discharge of the battery are described through equations 4.17 and 4.18.

$$SoC_{min} \leq SoC(t) \leq SoC_{max} \tag{4.16}$$

$$SoC(t) = SoC(t + \Delta t) - \eta_{chg} - P_{chg}(t)\Delta t \tag{4.17}$$

$$SoC(t) = SoC(t + \Delta t) - \frac{P_{Dis}(t)\Delta t}{\eta_{Dis}} \tag{4.18}$$

Where η_{chg} and η_{Dis} are representing the charge and discharge efficiency of the battery, and C_{bat} is battery capacity.

The minimum state of charge is the step of an electric battery relative to its capacity. In HOMER, the minimum state of charge is set to 30% to 50% to avoid damaging the storage bank by excessive discharge. The maximum discharge current of a battery refers to the maximum current that can be taken from a battery at any time without significantly shortening the battery life.

In this thesis, the minimum and maximum stat of charge (SoC) set the limits from 30% to 80%, which means that no more energy will be dried when the SoC is $\leq$ 30 %, and no more charging will be done when SoC $\geq$ 80. The battery lifetime is dependent mainly on the depth of charge (DoD) and the state of charge (SoC).

4.3.1 Energy generation cost of battery storage

The battery storage has decided as an independent energy source to meet the load demand. The net cash flow of the battery is defined as:

$$C_{NCF,battery} = C_{cost,sys} + R_{battery,sys} + OM_{battery,sys} + C_{total,energy} \tag{4.19}$$

Where $C_{cost,sys}$ is the total capital investment of battery storage system, ¤ $R_{battery,sys}$ replacement cost of the battery, $OM_{battery,sys}$ is the present value of operation and maintenance cost, and $C_{total,energy}$ is the present value of energy cost.

The battery storage system is mainly charged by the PV module; therefore energy generation cost of PV is considered the input energy cost for the battery energy storage, and its defined by:

$$E_{battery} = \frac{C_{NCF,battery} \cdot CRF}{sum_{m=1}^{12} N_D M_{battery}} \tag{4.20}$$

Where N_D is the number of days in a month, $M_{battery}$ is a monthly average per generated by PV system and CRF is given by:

$$CRF = \frac{d}{1-(1+d)^{-M}} \tag{4.21}$$

operation and maintenance cost of storage battery system

Operation and maintenance cost ($OM_{battery,sys}$) includes taxes, insurance, maintenance, recurring costs, etc. The life-cycle maintenance for lifetime of M years is given by equations 4.22 and 4.23.

$$OM_{battery,sys} = OM_0(\frac{1+e_0}{1-e_0}) \cdot [1-(\frac{1+e_0}{d-e_0})^M]\, if, b \neq e_0 \tag{4.22}$$

$$OM_{SYS} = OM_0\, if\, b = e_0 \tag{4.23}$$

Replacement costs of battery system

The replacement cost of the battery energy storage system ($R_battery, sys$) is mainly a function if the number of battery and power devices replacements over the system lifetime without salvage value. The equation of replacement of battery storage system is given by:

$$R_{battery} = C_{battery} \sum_{j=1}^{w} \cdot (\frac{1+a_0}{1+b})^{\frac{Mj}{u+1}} \tag{4.24}$$

Where v = is the total number of replacements for inverter over a life period of M years.

4.3.2 The cost summary of battery storage

The life of a battery primarily affected by the depth of a discharge and the operating temperature. Depth of discharge is when batteries are discharged in a cycle before they are changed again. Usually, the manufacture specifies the nominal number of complete charge and discharge cycles as a function of the depth of discharge in the product data-sheet.

$$Q_{lifetime,i} = f_i d_i (\frac{q_{max} V_{nom}}{1000}) \tag{4.25}$$

Where:

$Q_{lifetime,i}$ → is the lifetime throughput (kWh)

f_i → is the number of cycles to failure

d_i → is the depth of discharge (%)

q_{max} → is the maximum capacity of the battery (Ah)

V_{nom} → is the nominal voltage of the battery (V)

The depth of discharge, daily cycles and operating temperature battery life is also affected by sulfation and corrosion. When batteries have been in a low state of charge for a long time, sulfate crystals which formed by the chemical reactions of the battery converts o stable crystalline and they deposit on negative plants.Sulfate reduces the battery capacity and increases the battery resistance [25]. The capacity of a battery is defined as the amount of energy that can be withdrawn tarting to fully-charged state and it is measured in Amp-hours. The capacity of a battery depends on the rate at which energy is withdrawn from it. The higher the discharge current, the lower the capacity. Usually, when batteries are left standing without charging, the batteries lose charge slowly by self discharging. This occurs due to the reactions within the cells of a battery. The self discharging rate depends on the temperature, the type of battery and their age. As batteries get older, self discharge rate increases. To avoid self discharge the top surface of the battery and battery terminals must be kept clean [26].

In this study case, I have selected the EnerSys powerSafe SBS 1800 battery, which is cost around NOK 20000, including VAT and its properties, shown in table 4.5. the data sheet of the battery can be found in appendix E.

Table 4.5: Battery storage specification

Brand	EnerSys
Model	EnerSys PowerSafe SBS 1800
Nominal voltage V	12 V
Round trip efficiency [%]	97
Minimum state of charge [%]	30
Maximum capacity [Ah]	2060
Maximum discharge current [A]	2300

Figure 4.3 presents the cost of the battery storage system.

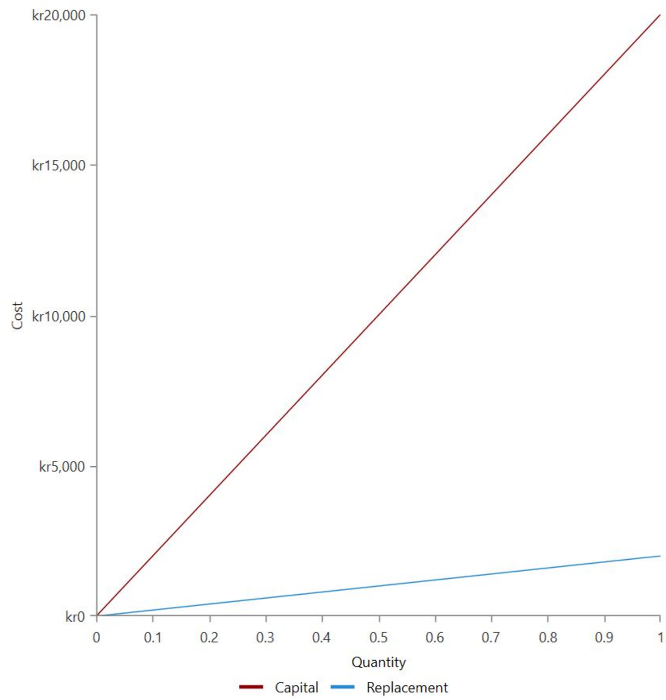


Figure 4.3: Cost curve of the battery [HOMER]

4.4 Solar power Inverter

One of the essential components of solar energy systems is the inverter. Often the size and efficiency of the whole system are about the efficiency and size of the transformer. There are many inexpensive, inferior, and hazardous inverter's on the market with low efficiency. Knowing what inverter is, their working methods, specifications, types, degrees of efficiency, and manufacturing quality are essential. The inverter's main task in the solar energy system is to convert direct current (DC) from the panels or batteries to alternating current (AC). Most power tools and devices operate on alternating current (AC). Figure 4.4 shows the difference between DC and alternating current waves. Several factors need to be considered when selecting an inverter for a specific application. Usually, the inverter used in renewable applications can be divided into two:

1. **Grid-tied inverters**
2. **Off-grid inverters**

Some inverters are specially designed for PV applications and integrated with Maximum Power Point Trackers (MPPT). Some inverters for off-grid PV systems come with integrated charge controllers. Further, some inverters are bidirectional, how can operate in both inverting and rectifying modes.

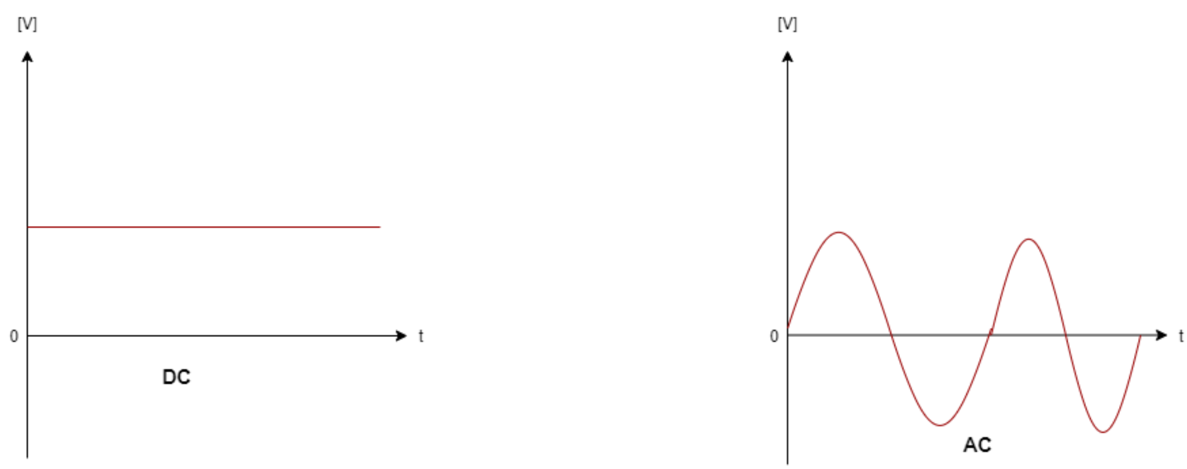


Figure 4.4: DC and AC waves [27]

The inverter can be categorized according to the type of waveform they produce. The three most common waveforms are the square wave, modified square, and sine wave. Square wave inverter is less costly but only suitable for small appliances. They provide little output voltage control, limited surge capacity, and considerable harmonic distortion. The presence of frequency components that are integer multiple of the input signal present in the input signal is known as harmonic distortion. The presence of harmonic distortion distorts the current waveform drawn from the supply. Modified sine wave inverters are better than square wave inverters. They can handle significant surges and produce output with much less harmonic distortion. Sine wave inverter is the most expensive but has a very compact wave shape to the grid voltage; therefore used in grid-connected applications. Figure 4.5 shows the difference between pure waves and modified waves.

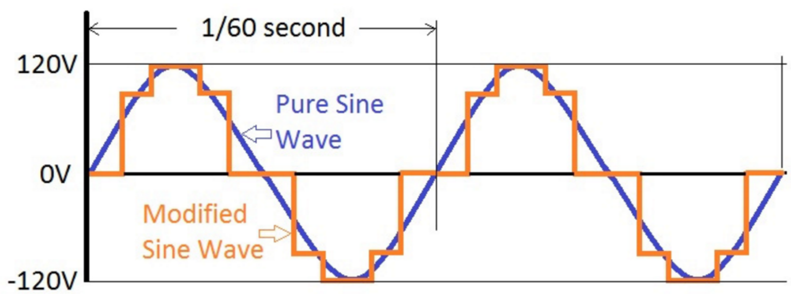


Figure 4.5: Modified and pure sine waves [27]

One of the inverter's necessary specifications is the ratio of its efficiency and effectiveness, which is known as efficiency. What is meant by efficiency is the transformer's ability to convert direct current into alternating current without loss and loss of some current during this process, reaching up to 98%. The inverter's sizing depends on the potential saving or income that the inverter capacity enables, and so different capacities are considered. The input rating of the inverter should not be lower than the total watt of appliances. The inverter must have the same nominal voltage as the battery. The inverter size should be 25-30% bigger than the total of appliances. In the case of appliance type is motor or compressor, the inverter size should be a minimum of three times the capacity of those appliances and added to the inverter capacity to handle surge current during starting. The solar inverter used in this thesis is SolaX X3-hybrid10, as presented in the table 4.6, and the datasheet of the solar inverter can be found in appendix F.

Table 4.6: Solar Inverter Specification

Brand	X Solax power
Model	SolaX X3-hybrid10
Rated Capacity	10kW
Maximum Efficiency	97
DC voltage	370V-1000V
AC voltage	230V, 50Hz
Price	NOK 30000

4.5 Electricity pricing

There are five price areas in Norway, and Nord Pool runs the central marketplace for electrical power. The underlying cause of congestion and different power prices in other regions is that the power situation differs from one area to another and may also vary on an hourly basis and between seasons and years. Some regions may be experiencing a power surplus when others have a power deficit. Grimstad in price is NO2.

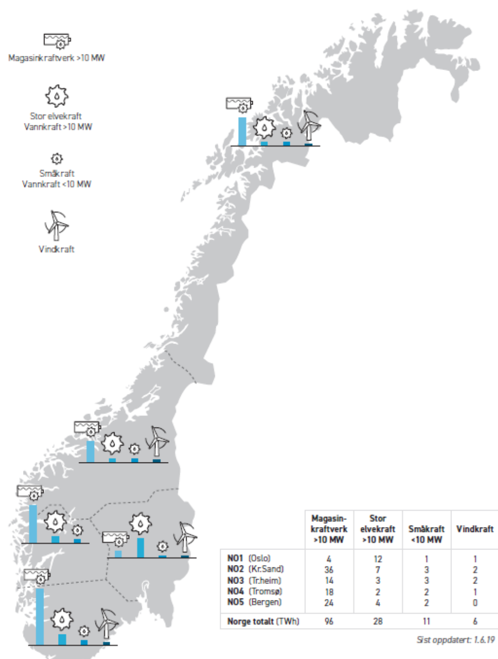


Figure 4.6: Illustration of the five price area in Norway [17]

4.5.1 Grid Power Price

Elspot prices used in this project are collected from the Nord pool and include hourly values from area NO2 from the year 2017-2020 [28]. The data provided by Nord Pool are given in kr/MWh, while HOMER demands the price values to be delivered in NOK/kWh, so the data have been changed correspondingly. Figure 4.7 present the hourly prices for each year.The annual average Elspot price is 0.2921 kr/kWh.

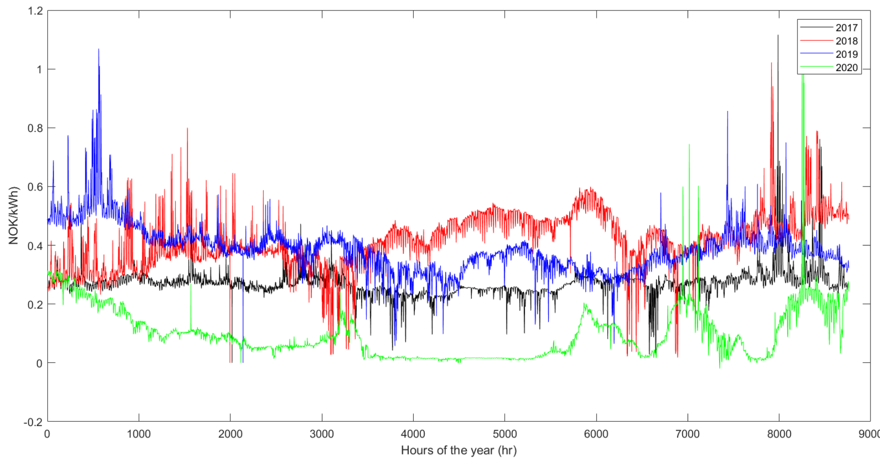


Figure 4.7: Hourly Elspot prices in NO2 from the year 2017-2020

The grid tariff is a part of a grid power price. Grid tariffs are meant to cover the grid supplies cost of transport of electricity, secure, effective operation, exploitation, and development. Grid tariff is collected from 2017-2020 for area NO2, the grid tariff is given in annual values, and like the spot price, the grid price has been calculated to the average value to be used as input value in HOMER [28]. Table 4.7 presents the grid tariff, where both VAT and electricity consumption tax are included.

Electricity tax is also a part of the grid power prices, and is set at an annual frequency, as well, the tax is included in the net tariff as presented in the table 4.7.

Table 4.7: Annual grid tariff for NO2 from 2017-2020

Location	2017	2018	2019	2020	**Average**
NO2	0.576	0.580	0.505	0.480	**0.535**

The electricity certificate of green certificate is a part of a grid power price for consumers and is included as part of the grid power prices. Since 2012 Norway has been a part of a joint el-certificate market with Sweden. The attention of this market is to increase power production from new renewable energy sources. Power producers certified to receive an el-certificate per MWh produced for the next 15 years after being approved. This an extra income for the producers on top of the power price to make projects more profitable. For the consumers, this means a small fee on every kWh consumed.

The grid power prices are input as hourly values into the analysis and consist of prices on Elspot, grid tariff, electricity tax, and green certificates. As well, Elspot, grid tariff, and green certificates include VAT.

4.5.2 Grid sell-back price

Generally, the grid sell-back price is lower than the grid electricity price. The grid sell-back price is equal to the regional spot prices at the current time-step of the production, and some power suppliers give a small sum for marginal loss on the transmission line. Usually, to sell back surplus power, a deal must be done with the power supplier. In Norway, three companies offer a way better deal the surplus electricity than the regular power suppliers. Fredrikstad EnergiSalg and Otovo are two of them, and they offer 1 NOK/kWh for up to 5000 kWh per year. If this 5000 kWh are exceeded, receive the respective spot prices for the surplus electricity for the rest of the year. As well, Otovo is referred to further in this thesis.

$$Sellback = (1NOK - averagespotprice) \cdot 5000\,kWh \tag{4.26}$$

The amount of sellback has been multiplied for the project lifetime and discounted. The amount during the project lifetime has been subtracted from the NPC to show the new NPC and used to calculate a new LOCE. Usually, when calculating the arithmetic mean power price, the hourly values have not been adjusted, this may affect the final LCOE, but will not likely affect the rating of the optimal system configurations. Furthermore, an additional income from the local grid owner because of reduced loss in the distribution network have not been included as an income.

4.6 Economic

4.6.1 Discount rate

The discount rate calculates the future depreciation value of money in the total analysis period. The discount rate is very influential for the energy projects, as is the detailed economic evaluation and presents the investment risk. The real discount rate refers to the value without considering the inflation rate, whereas the nominal discount rate considers inflation. The discount rate for solar PV projects usually varies from 5% to 9%. The nominal discount rate is calculated from real discount and inflation rate using the following equation:

$$\textbf{Nominal Discount Rate} = (1 + \text{Real Discount Rate}) \cdot (1 + Inflation\, Rate) - 1$$

4.6.2 Net present value

The net present value (NPV) is the key economic parameter to evaluate the system investment. It measures the investment profit by calculating the present value of future money by taking the discount rate into account. NV is calculated by summing up all cash outflows and inflows of the investment for an analysis period. The cash flow for each year is discounted with a discount rate. The outflows are calculating as negative values and inflows are considered as positive. The resulting value defines the project net present value. Positive NPV denotes a profitable investment and negative NPC shows the opposite. The following formula is used to calculate the NPV:

$$NPV = -c_0 + \sum_{i=0}^{N} \frac{C}{(1+d)^N} \tag{4.27}$$

Where, C_0 is the capital investment, d is the nominal discount rate and N is the project analysis period.

The operating cost is the annualized value of all costs and revenues other than initial capital costs. The following equation is used to calculate the operating cost [29]:

$$C_{operating} = C_{annt,tot} - C_{ann,cap} \tag{4.28}$$

Where, the $C_{annt,tot}$ is the total annualized cost [$/yr], and the $C_{ann,cap}$ is the total annualized capital cost [$/yr].

4.6.3 Levelized cost of energy

levelized cost of energy (LCOE) estimate the price per unit energy ($kWh) over projects lifetime. LCOE is used to compare the kWh cost different powr system technologies. LCOE is estimates by dividing the life-cycle cost of the project by the expected energy output.

$$LCOE = \frac{LCC}{E_{Grid}} \tag{4.29}$$

Where LCC is the life-cycle cost and E_{Grid} is the system energy yield. The life-cycle cost includes the initial capital cost, operation, and maintenance cost, as well at the replacement cost minus the salvage value, which is the project values at the systems end of life.

$$Lcc = C_{capital} + \sum C_{O\&M} + \sum C_{replacement} - C_{salvage} \tag{4.30}$$

Where $C_{capital}$ is the capital cost,$C_{O\&M}$ is the operation and maintenance, $C_{replacement}$ is the replacement cost, and $C_{salvage}$ is the salvage value or the project vale at end of life.

4.6.4 Internal Rate of Return (IRR)

The internal rate of return refers to the discount rate value at which the net present value of the cash flow of particular investment is zero. This rate is measured to investigate the profitability of a potential investment. The internal rate is defined as:

$$IRR : NPV = \sum_{t=1}^{N} \frac{Revenue_t - Cost_t}{(1+d)^t} \tag{4.31}$$

4.6.5 Payback Period (PBP)

Payback period refer to the time needed for an investment to offset the amount invested in terms of profits or net cash flow. The payback period can be divided into a simple payback period and a discounted payback period. A simple payback period pertains to the period at which the revenue is equal to the investment cost, while a discounted payback period takes into consideration the time value of money. The payback period is given by:

$$Paybackperiod(PBP) = \frac{Net\,capital, cost}{Annual PV revenue - Operationalcost} \tag{4.32}$$

4.6.6 Annual bill saving

The annual electricity bill savings measure the PV system capacity to reduce the annual electricity bill for end consumers. The third-party owners typically use this annual bill saving to shoe the PV system cost reduction potential. The following is used to calculate the bill savings:

$$Annualnetsaving = cost\,without\,PV\ system\ - Cost\,with\,PV\ system \tag{4.33}$$

5 System Model description

5.1 Introduction

The main components of the hybrid system with their technical and relevant cost have been discussed in chapter 4.

HOMER is software that simplifies evaluating design options for both off-grid and on-grid connected power systems for remote, stand-alone, and distributed generation applications. It facilitates a range of renewable energy and conventional technologies, including solar PV, wind turbine, hydro-power, generator, storage battery, and hydrogen. HOMER's optimization analysis algorithm allows the user to evaluate many technology options' economic and technical feasibility. The sensitivity analysis also can be performed in HOMER and allows finding the effect of uncertainty in the input variable on the energy cost and the optimal configuration.

Normally, HOMER hybrid model requires several inputs which basically describe the technology options, component costs, components specifications and resource availability, and it is use the energy balance in optimization calculations. It compare hourly electric and thermal demand to the energy that the system produces in that hour and calculates the flow of energy to and from each component of the system.

5.2 Modeling of the hybrid system in HOMER

This thesis examines the economic performance of a grid-connected PV system composed of the solar array, power converter, storage battery, electric load, and grid as presented in figure 5.1. Simulation studies have been carried out using actual weather data to verify the system performance under various conditions. For evaluating the cost of the system, the following specifications of the system components have been discussed in chapter 4.

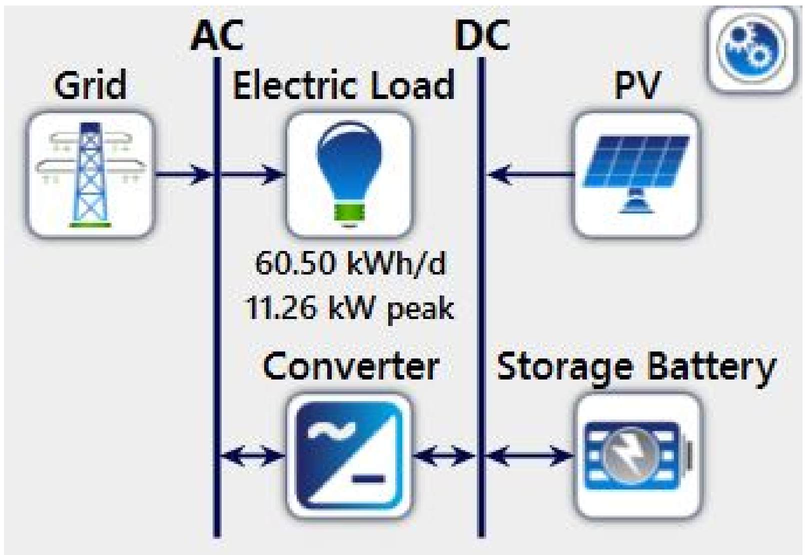


Figure 5.1: Design configuration of PV grid-connected system with battery storage [HOMER]

load

The grid-connected PV system with a battery storage model is made to analyze the residential household load profile. The hourly average load data of 2016 from Norges vassdrags- og energidirektorat (NVE) has been used in this study, and the load profile has been described in chapter 3.2.

Solar resource

Solar resource data is essential for a PV system to estimate the PV electricity generation and proper site selection. HOMER uses NASA weather monthly average solar radiation data, also HOMER can calculate hourly solar radiation data based on the monthly average radiation and clearness index. Solar radiation reaches the PV system, arrays through direct normal irradiance (DNI) beams, and diffuses horizontal irradiance (DHI) beams. A PV array receives DNI radiation directly or perpendicularly from the sky sun position to its surface area. Furthermore, DHI radiation is scattered by molecules and particles in the atmosphere and comes equally from all other directions to the array surface. The global horizontal irradiance (GHI) is the total amount of radiation received by the system array. This is usually used to measure the annual PV production.

5.2.1 Search space

To find the optimal system, here need to consider several combinations of different capacities of the component used in the modeling. As well, it can provide a wide range of abilities to the HOMER. The large number of inputs, the higher, the higher time that HOMER takes to simulate the system. Table 5.1 shows the system component's capacities that have been chosen for the simulation.

Table 5.1: Search Space

Converter Capacity (kW)	**Grid Purchase Capacity (kW)**	**PV Size (kW)**	**Storage Battery string**
0.0	999999	0.0	0
1.7		6.1	3
3.4		12.2	6
5.1		18.3	9
6.8		24.4	12
8.5		30.5	15
10.2		36.6	18
11.9		42.7	21
13.6		48.8	24
15.3		54.9	27
17.0		61.0	30

5.3 Energy management strategy

Figure 5.2 presents the flowchart of the proposed algorithm for the grid-connected system used for energy management of this simulation. In the flowchart below, the model visualising generated PV solar power (P_{PV}),required load (P_{load}) and the SOC of the battery ($SOC_{battery}$). In this simulation, the PV has the primary priority to fulfill the load demand, whatever the grid is available or not. If the PV production (P_PV) is more than the load demand (P_load), the surplus energy will be used to charge the battery ($SOC_{battery}$) or feed into the grid. If the grid supply is not available, the PV and the battery are used to fulfill the total load demand. Furthermore, if the grid is available, the required energy is defined as: $P_{required} = P_{load} - P_{PV}$, this required energy is purchased from the grid. If the $SOC_{battery}$ bigger than 80 %, the surplus or extra energy must sell to the grid. If not, we need to charge the battery. Furthermore, if the $SOC_{battery}$ less than 30 %, there is no option except shedding non-critical and if $SOC_{battery}$ bigger than 30 % need to getting required power to the grid. In this simulation, the PV has the primary priority to fulfill the load demand, whatever the grid is available or not. If the PV production (P_PV) is more than the load demand (P_load), the surplus energy can be used to charge the battery ($SOC_{battery}$) or feed into the grid [30] [31].

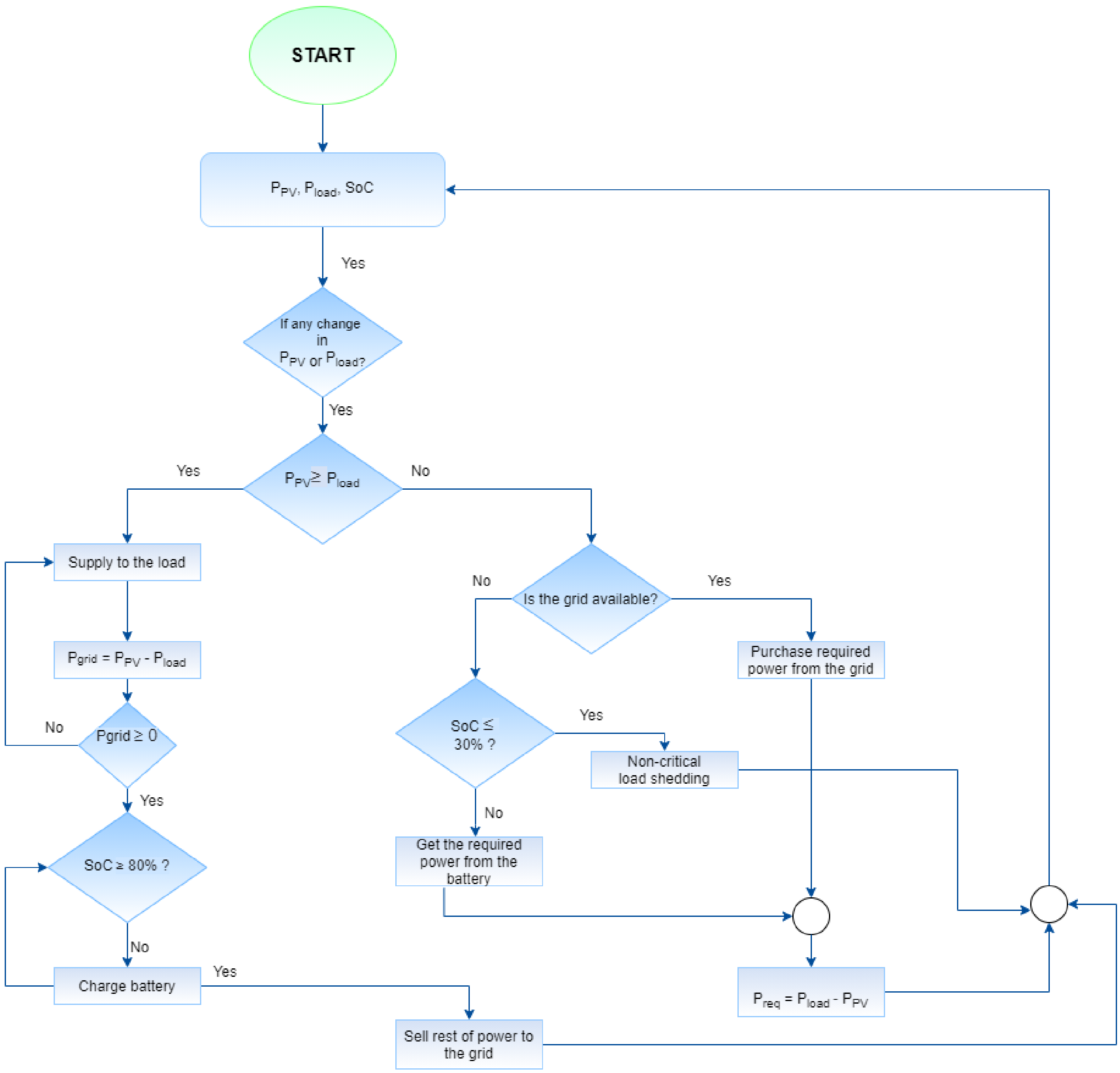


Figure 5.2: Flowchart of the proposed algorithm for the grid connected PV system [30] [31]

6 Result and discussion

This chapter presents the results of the grid-connected PV system with battery storage used to fulfill the needs of residential homes in Grimstad, Norway. The case of operational strategies was examined to investigate the system's performance in terms of sensitivity analysis performed on some essential parameters that affect the performance of an economically optimal system. A project lifetime of 25 years was considered in this thesis.

6.1 Optimization result

In this simulation result, HOMER software optimizes the combination of microgrid system component size to meet the load demand of the case study site. As a result, all system combinations were listed in NPC, COE, and technical performance indicators such as the average renewable fraction, PV production, and emissions. The following results are based on the assumption presented in Table 6.1.

Table 6.1: Project data

PV lifetime	25 Years
Project lifetime	25 years
Nominal discount rate	5.88 %
Expected Inflation rate	2 %
Solar scaled average per year	2.5443 kWh/m^2/day
PV capital cost multiplier	1

Architecture									Cost				PV		Storage Battery		
				PV (kW)	Storage Battery	Grid (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Capital Cost ($)	Production (kWh/yr)	Autonomy (hr)	Annual Throughput (kWh/yr)	Nominal (kW
						999,999		CC	$47,817	$0.168	$3,699	$0.00					
					1	999,999	0.354	LF	$70,113	$0.246	$3,794	$21,063			6.88	17.3	24.8
				10.0		999,999	2.39	CC	$143,983	$0.460	$2,847	$107,172	100,000	11,230			
				10.0	1	999,999	1.77	LF	$160,713	$0.505	$2,738	$125,313	100,000	11,230	6.88	3,120	24.8

Figure 6.1: Optimization result (HOMER)

6.1.1 Grid-only

Only-grid is widely used to supply electricity for household in Norway,table 6.3 presents the grid simulation result. the total NPC and COE of grid-only is kr47,816.54 and kr0.1675. table 6.2 presents the total cost of the grid-only, consumption of electricity (kWh/yr) and production of electricity (kWh/yr) and table 6.3 presents monthly energy purchased (kwh), energy sold (kWh), net energy purchased (kWh), peak load (kW), energy charge (kr) and demand charge (kr).Figure 6.2 presents the cost summary of the grid-only, where the x-axis is the component, and the y-axis is the cost in Norwegian krone.

Table 6.2: The cost of grid-only, Consumption of electricity and production of electricity

The cost of the grid-only (Kr)	
NPC	47,816.54
COE	0.1675
Operating cost	3,698,82
Consumption of electricity (kWh/yr) and %	
AC primary load	22,082 100%
DC load	0 0%
Production of electricity (kWh)	
Grid Purchase	22,082

Table 6.3: Simulation result of only grid

Month	**Energy Purchased (kWh)**	**Energy Sold (kWh)**	**Net Energy Purchased (kWh)**	**Peak Load (kW)**	**Energy Charge (kr)**	**Demand charge (kr)**
January	2,829	0	2,829	11	473.90	0
February	2,203	0	2,203	11	368.94	0
March	2,417	0	2,417	8	404.76	0
April	1,989	0	1,989	8	333.11	0
May	1,756	0	1,756	8	294.15	0
June	1,696	0	1,696	8	284.09	0
July	1,407	0	1,407	4	235.69	0
August	2,394	0	2,394	8	400.99	0
September	784	0	784	8	131.36	0
October	1,306	0	1,306	8	218.72	0
November	1,426	0	1,426	8	238.84	0
December	1,876	0	1,876	8	314.26	0
Annual	22,083	0	22,083	11	3,698.82	0

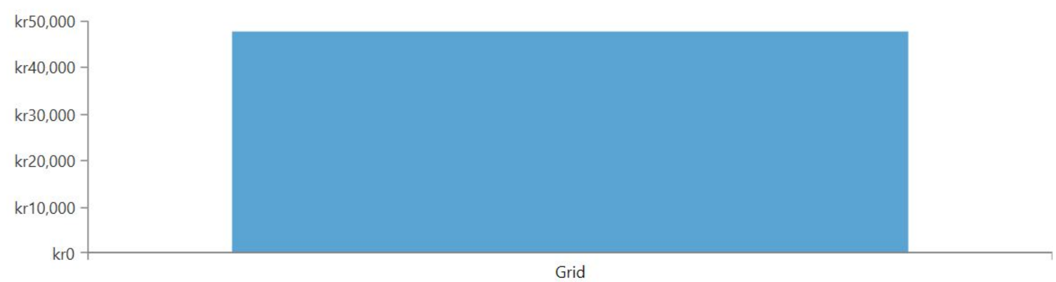


Figure 6.2: Cost summary of the grid

6.1.2 Grid-connected PV system with storage battery

As in figure 6.1, the grid-connected PV system with storage is the most optimal system for the household; the total NPC and COE are kr 160,712.90 and kr 0.5047. Figure **??** presents the cost summary of the PV grid-connected with the battery storage system, and the x-axis is the component of the system, and the y-axis is the cost in Norwegian krone.

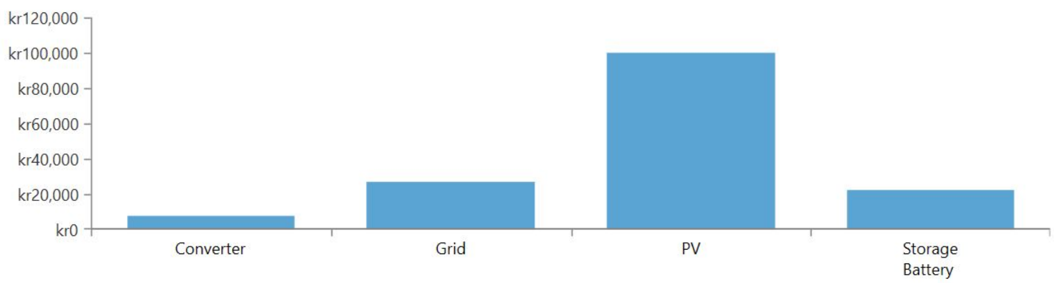


Figure 6.3: Simulation result of net present cost of the system

Table 6.4 presents The simulation result of the PV grid-connected with a storage battery. Grid sales present the total amount of electricity sold to the grid. Surplus energy generated from the PV can be sold back to the grid to reduce electricity bills and generate income. the result obtained show that the highest grid sales with an average amount of 2550 kWh/yr, respectively. Actually, this result can be explained by the fact that the highest PV electricity generation achieves the highest energy sold to the grid. Regarding reliability performance, the annual unmet load is used to measure the system's reliability in load supply. The result shows that the system is reliable with zero unmet loads.

Table 6.4: Simulation result PV grid-connected with battery storage

Month	**Enery Purchased (kWh)**	**Energy Sold (kWh)**	**Net Energy Purchased (kWh)**	**Peak Load (kW)**	**Energy Charge (kr)**	**Demand Charge (kr)**
January	2,515	34	2,481	11	415.58	0
February	1,752	74	1,679	9	281.17	0
March	1,758	114	1,644	8	275.34	0
April	1,329	207	1,122	8	187.89	0
May	1,314	388	925	8	155.01	0
June	1,077	337	740	8	123.99	0
July	898	425	473	4	79.24	0
August	1,680	167	1,513	8	253.45	0
September	574	442	132	7	22.07	0
October	1,008	206	801	6	134.20	0
November	1,259	91	1,168	8	195.56	0
December	1,723	63	1,660	8	277.97	0
Annual	**16,887**	**2,550**	**14,337**	**11**	**2,401.46**	**0**

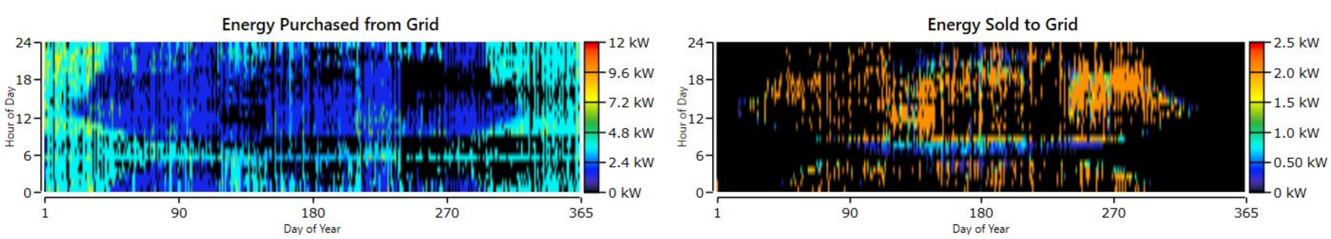


Figure 6.4: Energy purchase from the grid, and energy sales to the grid

The monthly average electricity production from PV is around 45.3% (13,480.0 kWh/yr), while the remaining amount of power required was purchased from the grid as presented in figure 6.5.

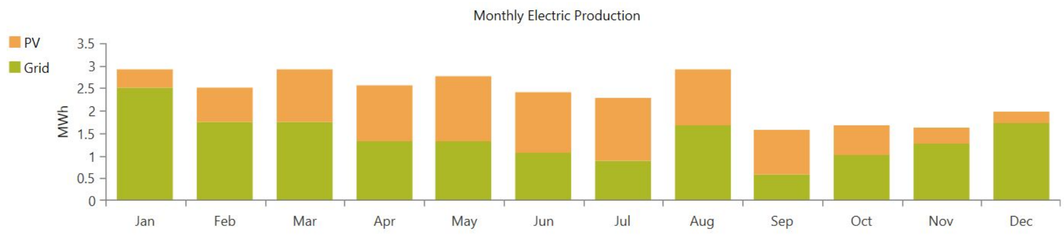


Figure 6.5: Monthly electrical production of grid-connected PV system

The output power generated by the PV system is only during the sunshine period. The data map of one year of time series in the figure 6.6 allows us to see the daily and seasonal patterns more clearly. The approximate peak sunshine during the day is between 10:00 am to 14:00 pm.

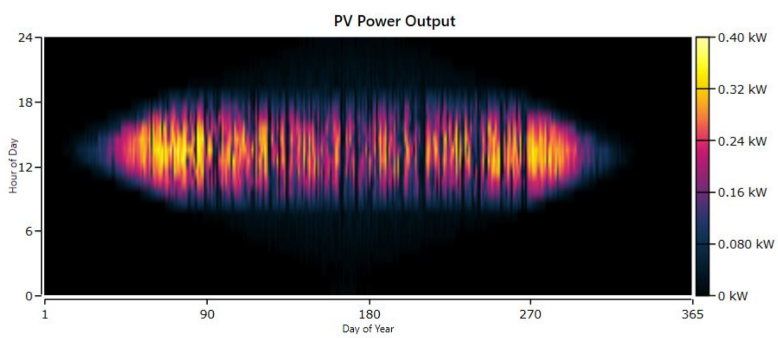


Figure 6.6: PV power output throughout the year and daytime

Battery throughput is defined as the total amount of energy that cycles through the storage bank in one year. Figure 6.7 shows the battery's input and output energy. Also, battery throughput gives an idea of a battery's operational lifetime, and there is an inverse relationship between the annual battery throughput and battery lifetime. The result indicates that the annual system throughput is 3,120 kWh/yr, meaning that the battery has an expected lifetime of 8.47 years. Based on the results, the system requires at least three times battery replacement during the project's lifetime. One of the important parameters for the battery is the autonomy hours. The number of hours a battery bank can supply the load demand without recharging during the main failure. It is found that the system yield battery autonomy of 6.88 h. The variation of the battery's SoC throughout the year is presented in figure

6.8. Usually, the utility may impose certain limits on the purchase of electricity from the grid due to some grid constraints.

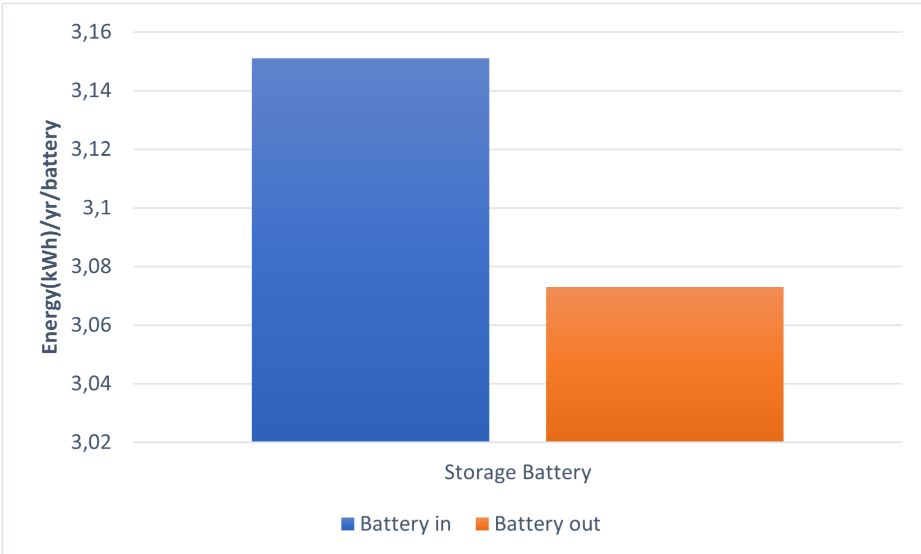


Figure 6.7: Input/output energy of the batteries

Figure 6.8: Battery's SoC variation throughout the year

The converter is an essential component in the system configuration. It is used as an inverter to convert the PV and battery power from DC to AC. It also works as a rectifier by converting the AC power of a grid to DC power to charge the batteries. The maximum inverter output of this system is equal to 1.77 kW. Figure 6.9 shows the inverter output, which the x-axis shows the day of the year and the y-axis shows the hour of the day, and the colors describe the inverter output power in kW.

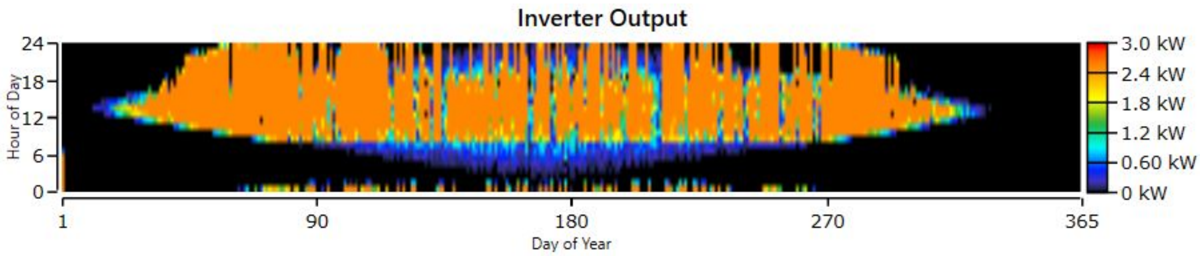


Figure 6.9: Hourly inverter output

The result indicates the system has zero rectifier output due to the grid prevented from charging the batteries in terms of the rectifier. Therefore, no AC to DC conversion can take place. The hourly rectifier output power of the system for the first year is presented in figure 6.10.

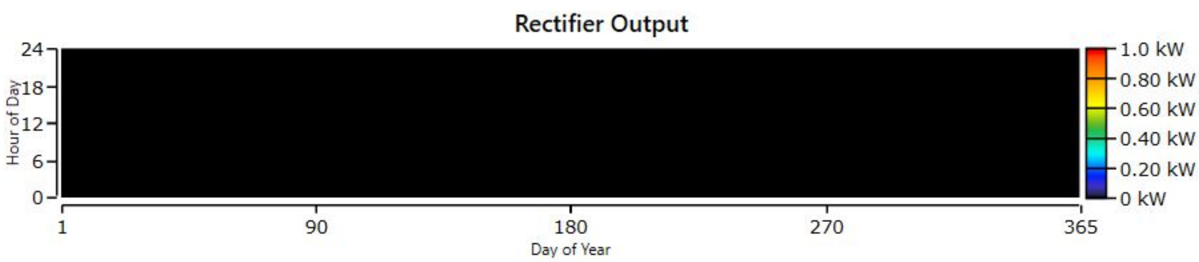


Figure 6.10: Hourly rectifier output

Electricity generated from the burning of fossil fuels burning releases different pollutants such as CO_2, NO_x, and SO_s. These pollutants have adverse effects on human health and can cause serious environmental damage. Emissions can be significantly reduced by connecting the grid with renewable energy sources. The case study has low CO_2 emission, estimated at 9873 kg/yr. The case study has low emission since the grid cannot charge the batteries; therefore, a lower grid purchase is achieved, leading to reduced fuel consumption and, hence, lower emission.

6.2 Economic analysis of the system

Figure 6.11 shows the summary cost for the case study. The following points outline details of capital, O&M, replacement, and salvage cost. The total replacement cost of the case study is kr3494.24. By the end of the lifetime, The salvage cost resulted from the remaining life of the PV, batteries, and converter.

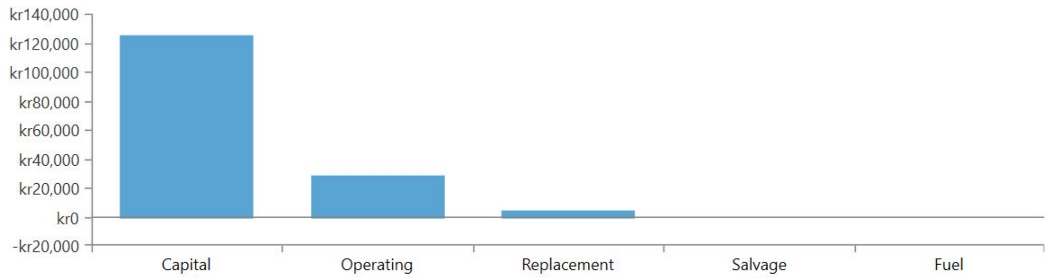


Figure 6.11: The cost summary of the case study

Figure 6.12 presents the PV output, the grid sales, batteries SoC, ambient temperature, and global solar in winter days (4st-10st of February). Furthermore, figure 6.13 shows the PV output, the grid sales, batteries SoC, ambient temperature, and global solar in the summer days (1st-7st). The lowest temperature during the year in February with an average between (-5 C° to 1 C°) with lowest energy sales, in the table 6.4 can see that the lowest energy sold to the grid in the month(November-February) due to low PV power output. On the other hand, during the summer, the PV power output is high due to high temperature, with the highest energy sold to the grid; the reason is high PV energy production and high temperature.

Electricity purchases and grid sales from and to the grid each month are essential. The power-shading of the component, along with the ambient temperature and load profile for one year, are shown in 6.14. It is evident that during the summer season, the ambient temperature and load demand are the highest. The system shows the highest grid purchases, while excess electricity can be sold to the grid. Figure 6.15 shows grid purchase and sales. For the winter(December-February) season, purchasing electricity from the grid was reduced due to reduced load demand from decreasing ambient temperature compared to the summer season (June-August). From figure 6.16 shows that the grid sales are high due to high temperatures in the summertime. The grid sales are highest during the summertime, and grid purchase highest during the wintertime, as we can see in figure 6.15 and figure 6.16.

Figure 6.12: PV output, grid sales, Soc, Ambient temperature and global solar in winter

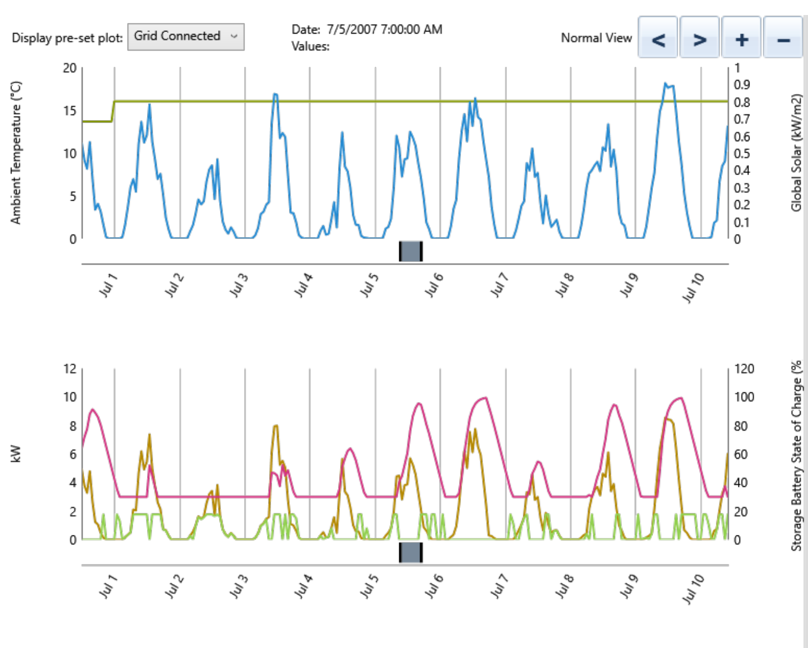


Figure 6.13: PV output, grid sales, Soc, Ambient temperature and global solar in summer

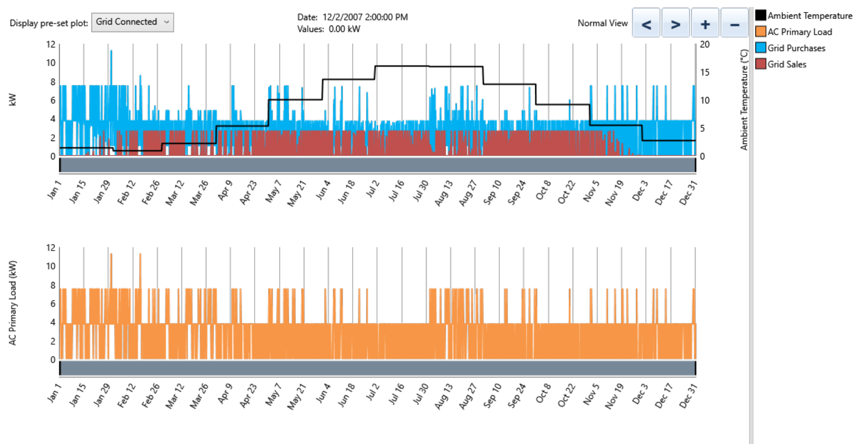


Figure 6.14: Monthly grid purchases and sales with load demand and ambient temperature

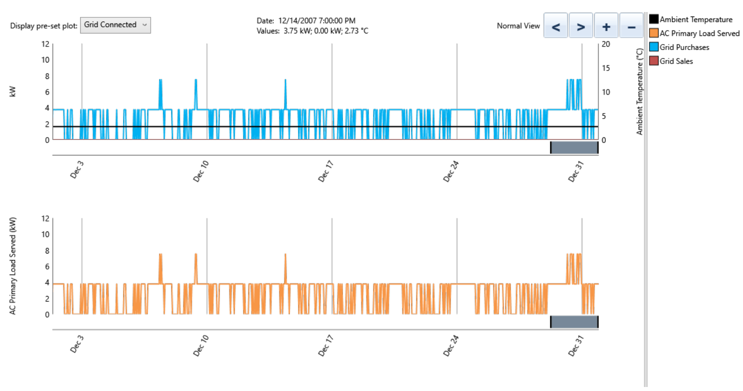


Figure 6.15: grid purchase and sales with load demand and ambient temperature (December-February)

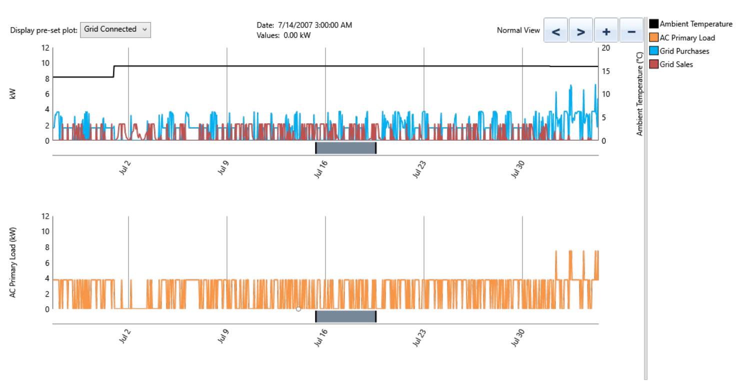


Figure 6.16: grid purchase and sales with load demand and ambient temperature (June-August)

From the grid sales curve shown in Figure 6.14, nearly no electricity was sold from the system between November to approximately March. However, there was power output in the period. This resulted in a reduced need for purchasing electricity from the grid, in a period where the grid power price was at its peak. A high load demand dampened this effect in the same period. The power output exceeded the load demand in start-March and continued to the end of October. Because of the constant sell-back rate, the income per kWh was not dependent on the time of day or year.

As described in reference [31] the domestic load may increase each year. The distribution network may need its capacity, and hence, there is a chance that the yearly grid purchase limit may also increase. Due to the enhancement of grid capacity, found that there are chances that utility may impose new electrical energy tariffs and as used in reference [31] typical Tou as shows in appendix C figure C.1. Can conclude that with 10% load growth per year as shown in appendix C figure C.2 the battery energy throughput has increased. PV contribution to the load also has been increased.

As described in reference [31], a typical day performance of BIPV system with storage battery as shown in figure 6.17. Energy contributions from the grid, PV contribution to load and grid, and battery energy throughput have been explained and provide how the contribution from the different sources will be. As presented in figure **??** the total demand of the household is met through the purchase from the grid **A** and through self-consumption. self-consumption as well, comprises of direct self-consumption from BIPV system **D** and indirect self-consumption from the BIPV energy storage **E**. For efficient and optimal utilization of the BIPV system, it is essential to optimize the self-consumption and then sell the excess electricity to the grid since the selling price of electricity is lower than the purchase price.

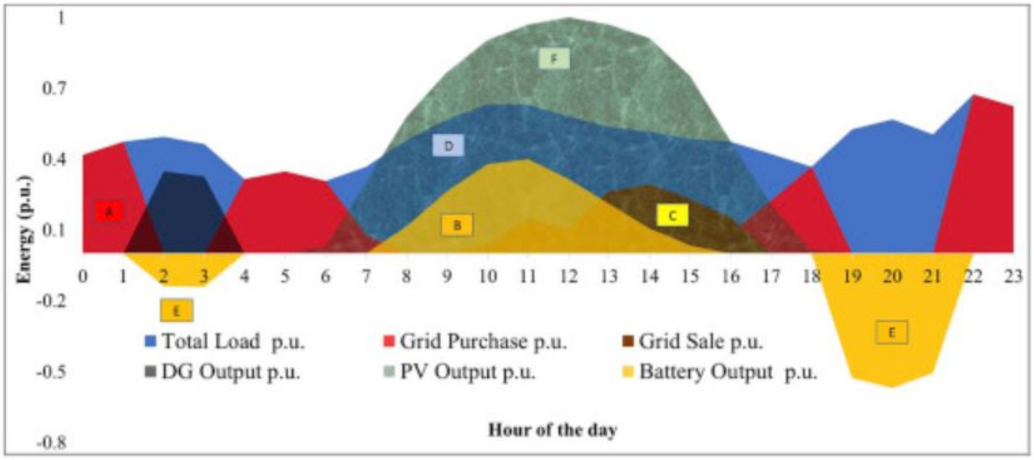


Figure 6.17: Energy production and consumption of typical day of the Southern Norway house [31]

The economic assessment is also needed to understand the energy contributions from the BIPV system with and without storage battery using certain assumptions. In [31] assumed that the BIPV system without energy storage had been already installed and their associated capital/installation costs are included in the mortgage of the building and not considered while computing the energy economic performance. The Time-of-Use tariff has been used in [31]. Through economic evaluation, it has been observed that the net present value of the BIPV system, based on mentioned economic assumptions, is higher without battery energy storage. It may be due to effective battery energy throughput consideration with the market energy price as has also been described in reference [31].

6.3 Summary and discussion of simulation result

Table 6.5 show the yearly electricity production and consumption which is are 38,117 kWh/yr and 24,632 kWh/yr.Table **??** presents the simulation result of the battery storage system, which can see 94,8 kWh/yr energy lost due to battery loss and battery storage depletion, and losses will be very high.

Table 6.5: Yearly production and consumption of the case study

Production	**kWh/yr**	**%**	**Consumption**	**kWh/yr**	**%**
PV	11,230	39.9	AC Primary Load	22,082	89.6
Grid Purchases	16,887	60.1	Grid Sales	2,550	10.4
Total	28,117	100	Total	24,632	100

Table 6.6: Summary of battery storage result

Quantity	**Value**	**Unit**	**Quantity**	**Value**	**Unit**
Autonomy	6.88	hr	Average Energy Cost	0	kr/kWh
Storage Wear Cost	0.0768	kr/kWh	Energy In	3,151	kWh/yr
Nominal Capacity	24.8	kWh	Energy Out	3,073	kWh/yr
Usable Nominal Capacity	17.3	kWh	Storage Depletion	17.3	kWh/yr
Lifetime Throughput	26,436	kWh	Losses	94.8	kWh/yr
Expected Life	8.47	yr	Annual Throughput	3,120	kWh/yr

The total amount of yearly emission of the system is lower than the grid-only system, as we can see in the table 6.7. The reason is grid-connected PVB system is more reliable and environmentally friendly.

Table 6.7: Emission simulation result of only-grid and grid-connected PVB system

Grid-only		**Grid-connected PVB system**	
Carbon Dioxide	13,956 [kg/yr]	Carbon Dioxide	10,672 [kg/yr]
Sulfur Dioxide	60.5 kg/yr]	Sulfur Dioxide	46.3 [kg/yr]
Nitrogen Oxides	29.6 [kg/yr]	Nitrogen Oxides	22.6 [kg/yr]

As we can see in table 4.16 the energy charge of the Grid-only less that the grid-connected PVB system

Table 6.8: Energy charge og grid-only and grid-connected PVB system

Grid-only	**Value**	**Grid-connected PVB system**	**Value**
Energy charge (kr)	3,698.82	Energy charge (kr)	2,401.46

I have sent e-mails to companies that work in solar energy, such as Fjordkraf and OTOVO, whether it is profitable to have an integrated solar cell in the houses. The answer was that it is beneficial to have an integrated solar cell. Most customers were satisfied with the solar production for domestic use. It is more profitable when they get support from ENOVA or others.

7 Conclusion

This thesis object has investigated the selected location (Grimstad, southern Norway) if local power production from grid-connected solar PV with storage battery could be economically feasible compared to today's solution with grid only. The proposed PV system with storage battery has been outlined and improved utilizing HOMER software; NPC and LCOE position all the enhancement and all other financial outputs are ascertained and finding the best cost of the system.

The simulation results show that the grid-only was the system configuration with the lowest Levelized cost of energy, which indicates that a customer who only cares about monetary costs should not invest in the local power generation, as provided in this simulation result. The LCOE of the grid-connected PV system with the storage battery and without are 0.505 kr/kWh and 0.460 kr/kWh showing that the difference in the cost is tiny.

The system using battery storage technology might not be profitable by itself, when necessitating a larger size of battery than would otherwise have been chosen, but in some circumstances, the further ancillary services enabled by a more powerful battery could make this more profitable, and site selected should be considering the building aggregated load profile, solar irradiation profile and optimum system design. The cost analysis results revealed that the optimization solution used 10 kW PV arrays and 24.8 kWh battery capacity and 10 kW converter and the power from the grid with an NPC kr 160,712.85.

7.1 Further work

For the further work, is the renewable energy resources include some uncertainty, for more accurate calculation, measured data and different software can be used to compare the result.

References

[1] *Energy consumption in households - SSB*. https://www.ssb.no/en/energi-og-industri/statistikker/husenergi/hvert-3-aar/2014-07-14. (Accessed on 05/26/2021).

[2] *Solar resource maps and GIS data for 200+ countries | Solargis*. https://solargis.com/maps-and-gis-data/download/norway. (Accessed on 05/26/2021).

[3] Amirnaser Yazdani and Prajna Paramita Dash. "A control methodology and characterization of dynamics for a photovoltaic (PV) system interfaced with a distribution network". In: *IEEE Transactions on Power Delivery* 24.3 (2009), pp. 1538–1551.

[4] *Solar panel types | Mono, Poly and thin film PV modules | Solar2Power*. https://solar2power.pt/solar-panel-types-mono-poly-and-thin-film-pv-modules/. (Accessed on 05/01/2021).

[5] Yinghao Chu and Peter Meisen. "Review and comparison of different solar energy technologies". In: *Global Energy Network Institute (GENI), San Diego, CA* (2011).

[6] Frank Vignola, Fotis Mavromatakis, and Jim Krumsick. "Performance of PV inverters". In: *Proc. of the 37th ASES Annual Conference, San Diego, CA*. 2008.

[7] Emmanuel Kymakis, Sofoklis Kalykakis, and Thales M Papazoglou. "Performance analysis of a grid connected photovoltaic park on the island of Crete". In: *Energy Conversion and Management* 50.3 (2009), pp. 433–438.

[8] Bill Marion et al. "Performance parameters for grid-connected PV systems". In: *Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, 2005.* IEEE. 2005, pp. 1601–1606.

[9] Konrad Mertens. *Photovoltaics: fundamentals, technology, and practice*. John Wiley & Sons, 2018.

[10] *How HOMER Calculates Clearness Index*. https://www.homerenergy.com/products/pro/docs/latest/how_homer_calculates_clearness_index.html. (Accessed on 05/27/2021).

[11] MHM Sidek et al. "GPS based portable dual-axis solar tracking system using astronomical equation". In: *2014 IEEE International Conference on Power and Energy (PECon)*. IEEE. 2014, pp. 245–249.

[12] Muhammad Iqbal. *An introduction to solar radiation*. Elsevier, 2012.

[13] Anitha S Subburaj, Bejoy N Pushpakaran, and Stephen B Bayne. "Overview of grid connected renewable energy based battery projects in USA". In: *Renewable and Sustainable Energy Reviews* 45 (2015), pp. 219–234.

[14] TY Chian et al. "A Review on Recent Progress of Batteries for Electric Vehicles". In: *International Journal of Applied Engineering Research* 14.24 (2019), pp. 4441–4461.

[15] *Li-Ion Scientists Earn Nobel for Powering the Future | EE Times*. `https://www.eetimes.com/li-ion-scientists-earn-nobel-for-powering-the-future/`. (Accessed on 05/02/2021).

[16] *• Norway: electricity production by source 2019 | Statista*. `https://www.statista.com/statistics/1025497/distribution-of-electricity-production-in-norway-by-source/`. (Accessed on 03/10/2021).

[17] Norges Vassdrags. "og energidirektorat (NVE): atlas. nve. no www. multiconsult. no Tegningsnr. Oppdragsnr". In: *Kontrollert Dato Målestokk Rev* 1 (2018), p. 1500.

[18] *HOMER - Hybrid Renewable and Distributed Generation System Design Software*. `https://www.homerenergy.com/`. (Accessed on 05/28/2021).

[19] Samir Kouro et al. "Grid-connected photovoltaic systems: An overview of recent research and emerging PV converter technology". In: *IEEE Industrial Electronics Magazine* 9.1 (2015), pp. 47–61.

[20] *How HOMER Calculates the PV Cell Temperature*. `https://www.homerenergy.com/products/pro/docs/latest/how_homer_calculates_the_pv_cell_temperature.html`. (Accessed on 05/16/2021).

[21] Mohanlal Kolhe, Sunita Kolhe, and JC Joshi. "Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India". In: *Energy economics* 24.2 (2002), pp. 155–165.

[22] Arman Ali, Nian Liu, and Li He. "Multi-party energy management and economics of integrated energy microgrid with PV/T and combined heat and power system". In: *IET Renewable Power Generation* 13.3 (2019), pp. 451–461.

[23] Arvind Sharma et al. "Performance assessment of institutional photovoltaic based energy system for operating as a micro-grid". In: *Sustainable Energy Technologies and Assessments* 37 (2020), p. 100563.

[24] *https://www.globalelectricity.org/unlocking-beneficial-electrification/?gclid=CjwKCAjwkN6EBhBNEi* https://www.globalelectricity.org/unlocking-beneficial-electrification/?gclid=CjwKCAjwkN6EBhBNEiwADVfya2RNcWGEnHTFrYgryJAfCjsz8y6c7wKM8cH7fGEwE3gUtL4WwpP_VRoCl24QAvD_BwE. (Accessed on 05/10/2021).

[25] A Cherif, M Jraidi, and A Dhouib. "A battery ageing model used in stand alone PV systems". In: *Journal of Power sources* 112.1 (2002), pp. 49–53.

[26] Mark Hankins. *Stand-alone solar electric systems: the earthscan expert handbook for planning, design and installation*. Earthscan, 2010.

[27] *AC Waveform and AC Circuit Theory of Sinusoids*. https://www.electronics-tutorials.ws/accircuits/ac-waveform.html. (Accessed on 05/28/2021).

[28] *Historical Market Data | Nord Pool*. https://www.nordpoolgroup.com/historical-market-data/. (Accessed on 04/23/2021).

[29] *Operating Cost*. https://www.homerenergy.com/products/pro/docs/3.14/operating_cost.html. (Accessed on 05/08/2021).

[30] Arvind Sharma. "Techno-Economic Performance Evaluation of Photovoltaic based Micro-Grid with Energy Management Strategies". In: (2021).

[31] Pooja Sharma, Mohan Kolhe, and Arvind Sharma. "Economic performance assessment of building integrated photovoltaic system with battery energy storage under grid constraints". In: *Renewable Energy* 145 (2020), pp. 1901–1909.

[32] *Electricity prices - SSB*. https://www.ssb.no/en/energi-og-industri/statistikker/elkraftpris/kvartal/2016-05-31. (Accessed on 05/26/2021).

Appendices

A Appendix

Design in HOMER software

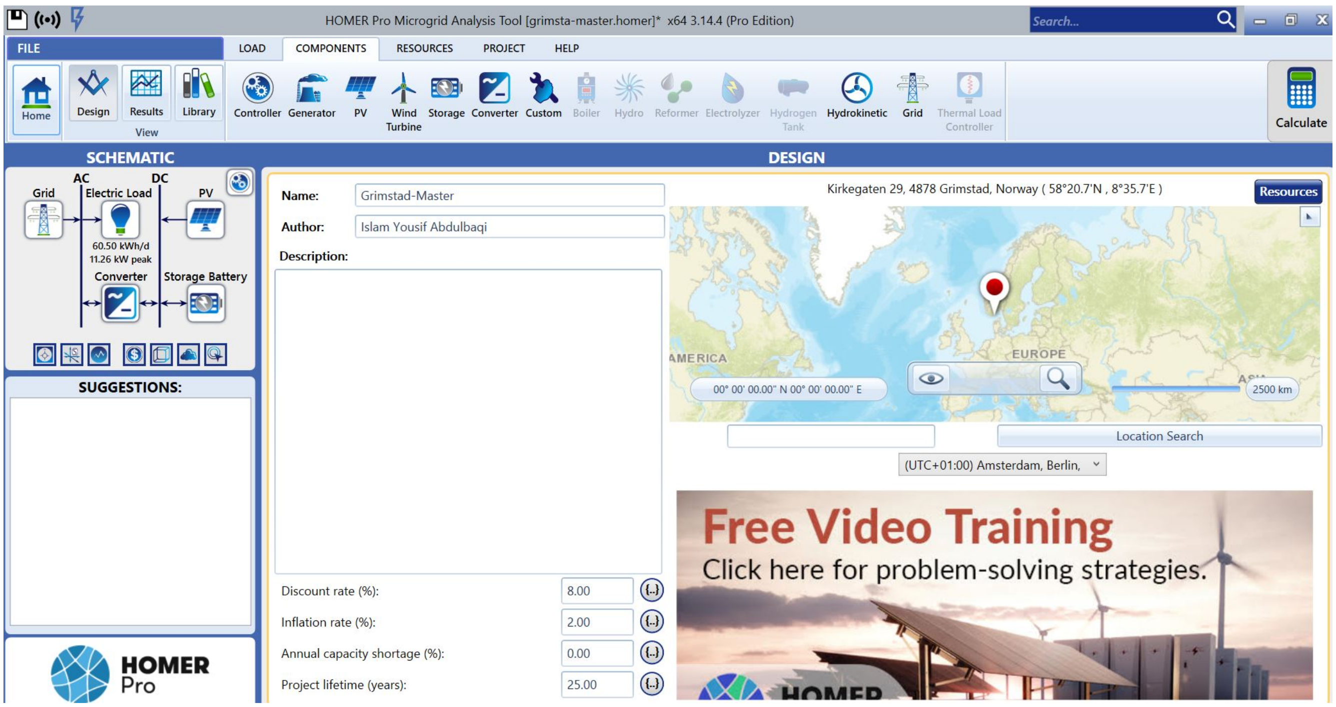


Figure A.1: Design in HOMER

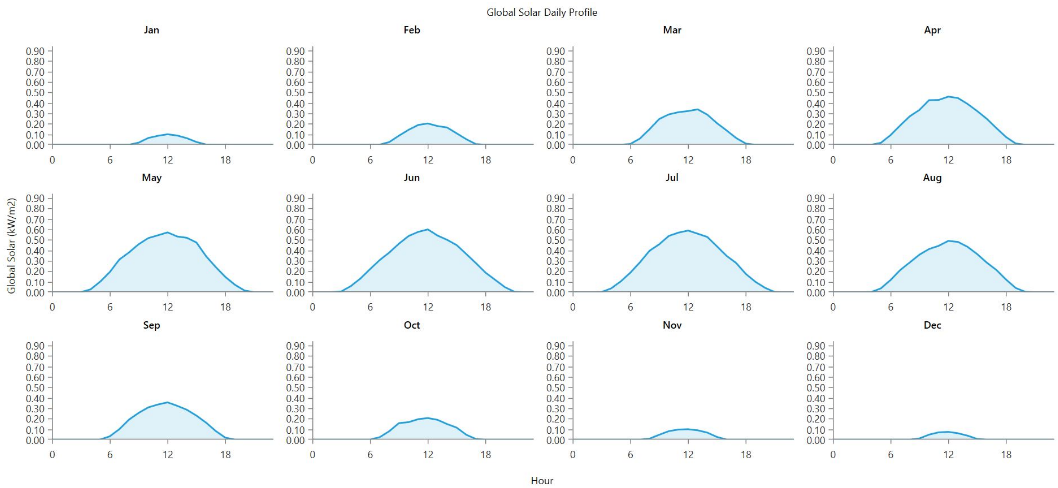


Figure A.2: Global solar daily profile

B Appendix

The cost of PV panels

To find out the cost of solar PV panels for homes, can describe that in five steps:

1. Knowing the average monthly household consumption of electricity.
2. Knowing the average daily household consumption of electricity.
3. Knowing the number of panels needed for the installation of the system.
4. Knowing the surface area required to install the system.
5. Find out the average cost of the system.

Knowing the average monthly household consumption of electricity

Table B.1 shows the monthly electricity consumption for a household.

Table B.1: The monthly electricity consumption

Month	Consumption kWh
January	2860.05
February	2532.3
Mars	2461.9
April	1582,82
May	1597.66
June	827.53
July	700.30
August	794.03
September	1128.82
October	1935.68
November	2441.5
December	2911.37
Annual	21773.98
Average	1814.50

Can also know this through the electricity bill where there is how much electricity the house consumed per kW. Instead of calculating the rate, can take or consider the maximum monthly consumption, which is often the enormous bill during the past 12 months. the following equation can be used to calculated the average monthly household consumption of electricity:

$$The\,average\,monthly\,kWh = \frac{kWh\,per\,month}{12} \tag{B.1}$$

This thesis uses measured data for a whole year provided by NVE (Norwegian Water Resources and Energy Directorate).

The average monthly household consumption of electricity for the case study is **1814.50 kWh**.

Knowing the average daily household consumption of electricity

The average monthly household consumption of electricity is **1814.50 kWh**, then the average daily consumption of electricity will be followed according to the following equation:

$$The\, average\, daily\, consumption\, of\, electricity = \frac{The\, average\, monthly\, consumption\, of\, electricity}{30} \tag{B.2}$$

Using equation B.2 to find out the average daily consumption of electricity.

The average daily consumption of electricity is **60,50 kWh**.

Knowing the number of panels needed for the system

The average daily consumption of electricity is **60.50 kWh**. We know that the sun is not shining throughout the day, but rather for 4-7 hours, depending on geographical locations. The average sunshine sun in Grimstad is 6 hours.

To find the generate PV capacity, we divide the average daily consumption by 6 hours.

$\frac{60.50kWh}{6} = 10kW$

The generated PV capacity is **10kW**.

Consequently, we need a number of solar panels with capacity of 330 W to generate 10 kW per hour or 60.5 kwh per day.

$$Number\, of\, panels = \frac{10kW}{330W} = \frac{10000W}{330W} = 30 solarpanels. \tag{B.3}$$

The system needs 30 solar panels to generate 10kw per hour.

Knowing the surface area required to install the system.

From the previous step we knew the number of panels required, and it was 30 panels, sin since we know the size of each panels from data-sheet. The dimension of solar panel is 1960 mm x 992 mm = 1.96 m x 0.992 = 1.94 m^2.

$$The\, area\, of\, all\, panels = The\, area\, of\, a\, single\, panel\, x\, The\, number\, of\, panels \tag{B.4}$$

By Using equation B.4 we get that:

The area of all panel = 1.94 m^2 x 30 = 58.2 m^2

Thus, the required area will not be more than 58.2 m^2.

Taking into account the absence of shades in this space, and there should be an appropriate distance between the panels and walls or fences for the installation work or dismantling with ease. In some countries, this distance is equal to 1.8 x the height of the wall.

Find out the average cos of PV solar cost

The PV solar cost depends mainly on the daily consumption of electricity by the house and the number of solar energy hours. The cost ranges from \$ 1000 to \$1500 or a little more per kW. In this thesis, the average daily consumption of electricity is 60.5 kWh, and the number of hours of sunshine is 6 hours, so the power generated is 10 kW per hour. That means the total cost ranges between 10kW $\cdot$ (\$ 1000 to \$1500) = \$10000 to \$15000. The cost in the Norwegian krone will be Kr.100000 to Kr.150000.

C Appendix

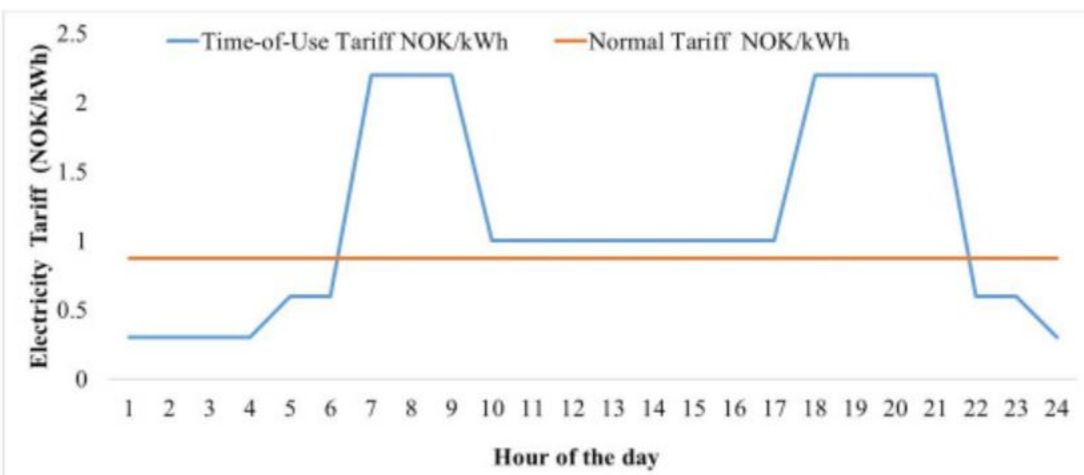


Figure C.1: ToU tariff and normal tariff of a typical day

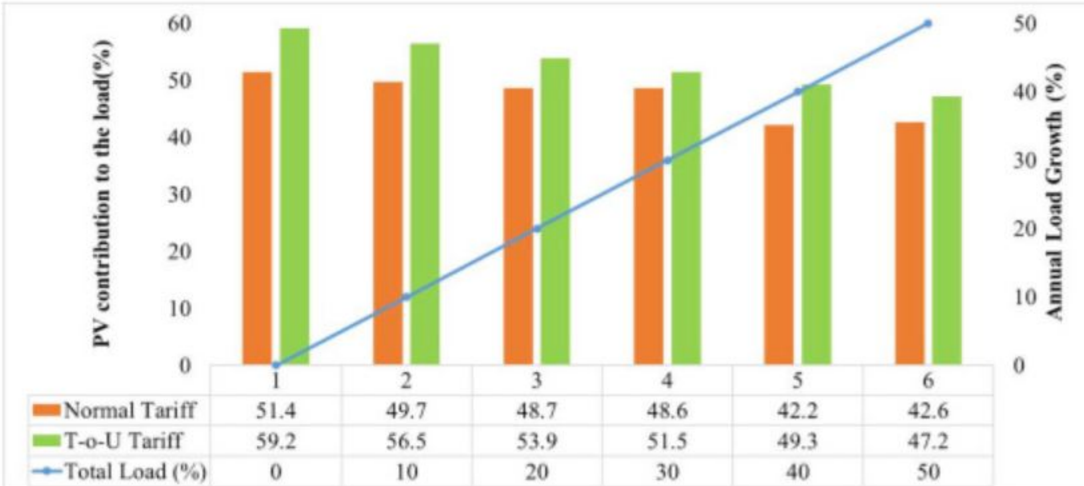
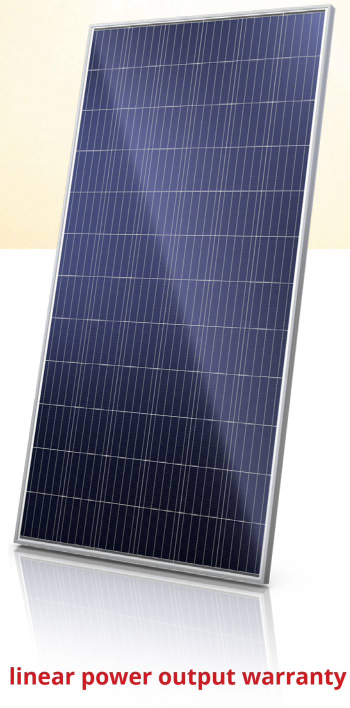


Figure C.2: PV contribution to the load with ToU and normal tariff and with annual load growth [32] [31]

D Appendix

NEW

CanadianSolar



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CS6U-315 | 320| 325| 330P

Canadian Solar's modules use the latest innovative cell technology, increasing module power output and system reliability, ensured by 15 years of experience in module manufacturing, well-engineered module design, stringent BOM quality testing, an automated manufacturing process and 100% EL testing.

25 years linear power output warranty

10 years product warranty on materials and workmanship

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- Excellent module efficiency of up to 16.97 %
- Cell efficiency of up to 18.8 %
- Outstanding low irradiance performance: 96.0 %
- No. 1 PTC — High PTC rating of up to 91.55 %
- IP67 — IP67 junction box for long-term weather endurance
- Heavy snow load up to 5400 Pa, wind load up to 2400 Pa

MANAGEMENT SYSTEM CERTIFICATES*

ISO 9001:2008 / Quality management system
ISO 14001:2004 / Standards for environmental management system
OHSAS 18001:2007 / International standards for occupational health & safety

PRODUCT CERTIFICATES*

IEC 61215 / IEC 61730: VDE / CE / CQC / MCS
UL 1703 / IEC 61215 performance: CEC listed (US)
UL 1703: CSA / IEC 61701 ED2: VDE / IEC 62716: VDE / Take-e-way
UNI 9177 Reaction to Fire: Class 1

* As there are different certification requirements in different markets, please contact your local Canadian Solar sales representative for the specific certificates applicable to the products in the region in which the products are to be used.

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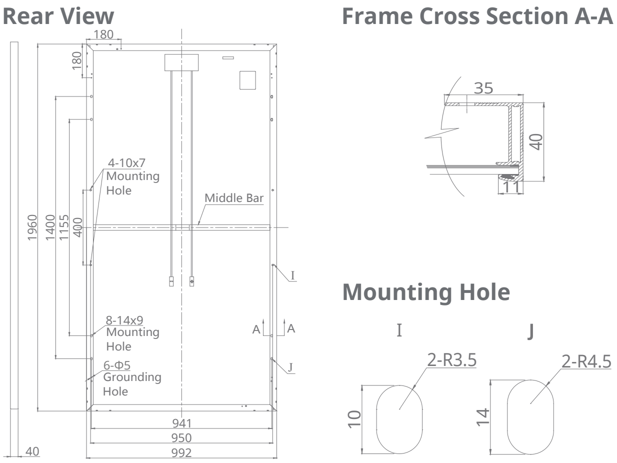
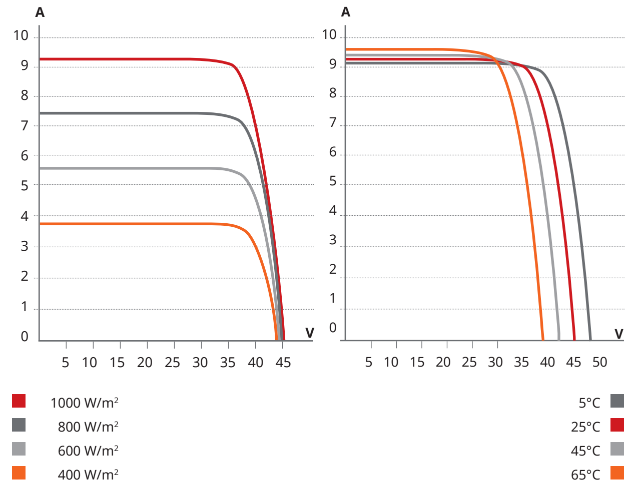
ENGINEERING DRAWING (mm)



CS6U-320P / I-V CURVES



ELECTRICAL DATA / STC*

CS6U	315P	320P	325P	330P
Nominal Max. Power (Pmax)	315 W	320 W	325 W	330 W
Opt. Operating Voltage (Vmp)	36.6 V	36.8 V	37.0 V	37.2 V
Opt. Operating Current (Imp)	8.61 A	8.69 A	8.78A	8.88 A
Open Circuit Voltage (Voc)	45.1 V	45.3 V	45.5 V	45.6 V
Short Circuit Current (Isc)	9.18 A	9.26 A	9.34 A	9.45 A
Module Efficiency	16.20%	16.46%	16.72%	16.97%
Operating Temperature	-40°C ~ +85°C			
Max. System Voltage	1000 V (IEC) or 1000 V (UL)			
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)			
Max. Series Fuse Rating	15 A			
Application Classification	Class A			
Power Tolerance	0 ~ + 5 W			

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

MECHANICAL DATA

Specification	Data
Cell Type	Poly-crystalline, 6 inch
Cell Arrangement	72 (6×12)
Dimensions	1960×992×40 mm (77.2×39.1×1.57 in)
Weight	22.4 kg (49.4 lbs)
Front Cover	3.2 mm tempered glass
Frame Material	Anodized aluminium alloy
J-Box	IP67, 3 diodes
Cable	4 mm² (IEC) or 4 mm² & 12 AWG 1000V (UL), 1160 mm (45.7 in)
Connector	T4 (IEC/UL)
Per Pallet	26 pieces, 635kg (1400lbs)
Per container (40' HQ)	624 pieces

ELECTRICAL DATA / NOCT*

CS6U	315P	320P	325P	330P
Nominal Max. Power (Pmax)	228 W	232 W	236 W	239 W
Opt. Operating Voltage (Vmp)	33.4 V	33.6 V	33.7 V	33.9 V
Opt. Operating Current (Imp)	6.84 A	6.91 A	6.98 A	7.05 A
Open Circuit Voltage (Voc)	41.5 V	41.6 V	41.8 V	41.9 V
Short Circuit Current (Isc)	7.44 A	7.50 A	7.57 A	7.66 A

* Under Nominal Operating Cell Temperature (NOCT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.41 % / °C
Temperature Coefficient (Voc)	-0.31 % / °C
Temperature Coefficient (Isc)	0.053 % / °C
Nominal Operating Cell Temperature	45±2 °C

PERFORMANCE AT LOW IRRADIANCE

Outstanding performance at low irradiance, average relative efficiency of 96.0 % from an irradiance of 1000 W/m² to 200 W/m² (AM 1.5, 25°C).

The specification and key features described in this datasheet may deviate slightly and are not guaranteed. Due to on-going innovation, research and product enhancement, Canadian Solar Inc. reserves the right to make any adjustment to the information described herein at any time without notice. Please always obtain the most recent version of the datasheet which shall be duly incorporated into the binding contract made by the parties governing all transactions related to the purchase and sale of the products described herein.

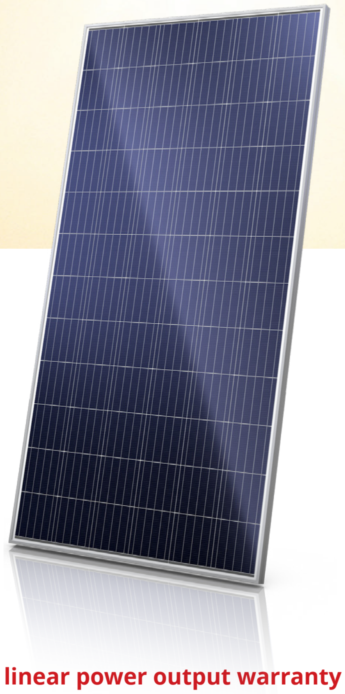
Caution: For professional use only. The installation and handling of PV modules requires professional skills and should only be performed by qualified professionals. Please read the safety and installation instructions before using the modules.

PARTNER SECTION

E Appendix

NEW

CanadianSolar



MAXPOWER
CS6U-315 | 320| 325| 330P

Canadian Solar's modules use the latest innovative cell technology, increasing module power output and system reliability, ensured by 15 years of experience in module manufacturing, well-engineered module design, stringent BOM quality testing, an automated manufacturing process and 100% EL testing.

25 years linear power output warranty

10 years product warranty on materials and workmanship

KEY FEATURES

- Excellent module efficiency of up to 16.97 %
- Cell efficiency of up to 18.8 %
- Outstanding low irradiance performance: 96.0%
- No. 1 PTC — High PTC rating of up to 91.55 %
- IP67 — IP67 junction box for long-term weather endurance
- Heavy snow load up to 5400 Pa, wind load up to 2400 Pa

MANAGEMENT SYSTEM CERTIFICATES*

ISO 9001:2008 / Quality management system
ISO 14001:2004 / Standards for environmental management system
OHSAS 18001:2007 / International standards for occupational health & safety

PRODUCT CERTIFICATES*

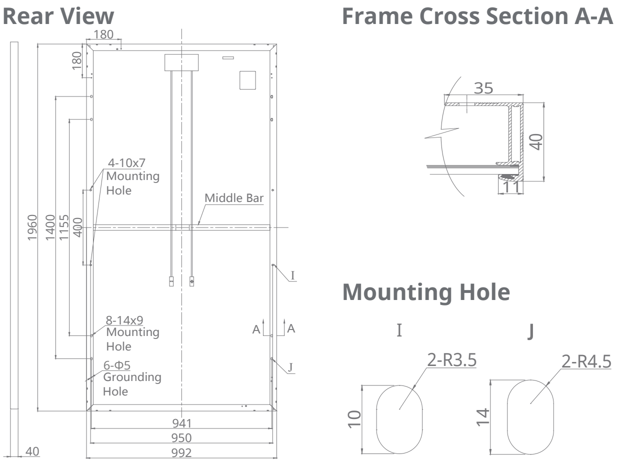
IEC 61215 / IEC 61730: VDE / CE / CQC / MCS
UL 1703 / IEC 61215 performance: CEC listed (US)
UL 1703: CSA / IEC 61701 ED2: VDE / IEC 62716: VDE / Take-e-way
UNI 9177 Reaction to Fire: Class 1

* As there are different certification requirements in different markets, please contact your local Canadian Solar sales representative for the specific certificates applicable to the products in the region in which the products are to be used.

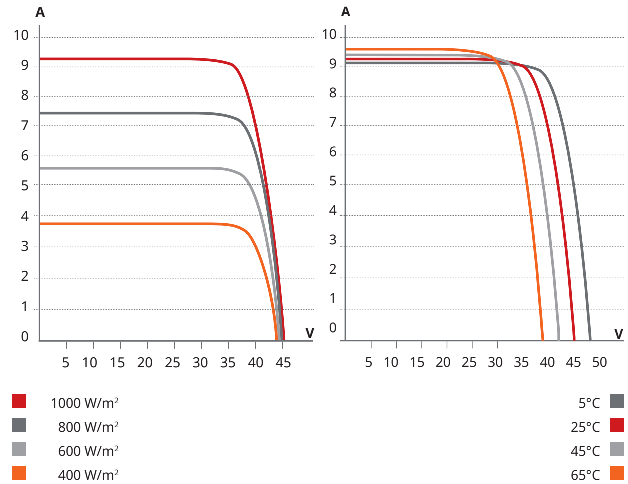
CANADIAN SOLAR INC. is committed to providing high quality solar products, solar system solutions and services to customers around the world. As a leading PV project developer and manufacturer of solar modules with over 15 GW deployed around the world since 2001, Canadian Solar Inc. (NASDAQ: CSIQ) is one of the most bankable solar companies worldwide.

CANADIAN SOLAR INC.
2430 Camino Ramon, Suite 240 San Ramon, CA, USA 94583-4385 | www.canadiansolar.com/na | sales.us@canadiansolar.com

ENGINEERING DRAWING (mm)



CS6U-320P / I-V CURVES



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PARTNER SECTION

F Appendix

X1-HYBRID HV/ X3-HYBRID HV

The World's Leading Hybrid Inverter Just Got Better

More than just an inverter, the innovative X-Hybrid is an intelligent energy management system that stores surplus energy in batteries for later use.

The X-Hybrid works by storing surplus energy in batteries for later use, making it possible to utilize solar power time-independently by storing unused capacity. It converts and directs solar power to where it is needed, when it is needed. X-Hybrid is also supplied with a built-in EPS, allowing the end-user to user their stored energy in the event of a power outage.

X-HYBRID GEN 3

X-HYBRID THREE PHASE

Get in touch now:

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DE: +49 7231 4180999
UK: +44 2476 586998
Email: info@solaxpower.com

	X-HYBRID GEN 3 (SINGLE PHASE)				X-HYBRID THREE PHASE (THREE PHASE)			
	X1-HYBRID-3.0T	X1-HYBRID-3.7T	X1-HYBRID-4.6T	X1-HYBRID-5.0T	X3-Hybrid-5.0T	X3-Hybrid-6.0T	X3-Hybrid-8.0T	X3-Hybrid-10.0T
INPUT (DC)								
Max.recommended DC power [w]	4000	5000	6000	6000	6000	8000	10000	13000
Max.DC voltage [V]	600	600	600	600	1000	1000	1000	1000
Norminal DC operating voltage [V]	360	360	360	360	720	720	720	720
Max.input current [A]	10/10	10/10	10/10	10/10	11/11	11/11	11/11	20/11
Max. short circuit current [A]	14/14	14/14	14/14	14/14	14/14	14/14	14/14	23/14
MPPT voltage range [V]	125-550	125-550	125-550	125-550	230-800	280-800	370-800	330-800
No. of MPP trackers	2	2	2	2	2	2	2	2
Strings per MPP tracker	1	1	1	1	1	1	1	2/1
OUTPUT AC								
Norminal AC power [VA]	3000	3680	4600	4999	5000	6000	8000	10000
Max. AC power [VA]	3000	3680	4600	4999	5000	6000	8000	10000
Rated grid voltage(AC voltage range) [V]	230(180 to 270)	230(180 to 270)	230(180 to 270)	230(180 to 270)	400(360 to 440)	400(360 to 440)	400(360 to 440)	400(360 to 440)
Rated grid frequency [Hz]	50/60	50/60	50/60	50/60	50/60	50/60	50/60	50/60
Norminal AC current [A]	13	16	20	21.7	7.6	9	12.2	15
Max. AC current [A]	14.4	16	21	21.7	8.5	10	13.5	16
Displacement power factor	0.8 leading ... 0.8 lagging				0.8 leading ... 0.8 lagging			
Total harmonic distortion(THD, rated power) [%]	<2				<2			
Parallel operation	Yes				Yes			
Load control	Yes (optional)				Yes (optional)			
OUTPUT DC (BATTERY)								
Battery voltage range [V]	90-400				200-500			
Recommended battery voltage [V]	300				200	240	320	400
Max.charging/discharging power [W]	6000				5000	6000	8000	10000
Max.charging/discharging current [A]	20				25			
Communication interfaces	CAN/RS485				CAN/RS485			
Reverse connect protection	Yes				No			
EPS OUTPUT (WITH BATTERY)								
EPS rated power [VA]	4000	4000	5000	5000	5000	6000	8000	10000
EPS rated voltage [V], Frequency [Hz]	230, 50/60	230, 50/60	230, 50/60	230, 50/60	400/230, 50/60	400/230, 50/60	400/230, 50/60	400/230, 50/60
EPS rated current [A]	17.4	17.4	21.7	21.7	7.6	9	12.2	15
EPS peak power[W];Duration [s]	10000,10	10000,10	10000,10	10000,10	10000,60	12000,60	16000,60	16000,60
Switch time [s]	<0.5				<0.5			
Total harmonic distortion(THD, linear load) [%]	<2				<2			
Parallel operation	Yes				Yes			
EFFICIENCY								
MPPT efficiency [%]	99.90	99.90	99.90	99.90	99.90	99.90	99.90	99.90
Euro efficiency [%]	97.00	97.00	97.00	97.00	97.00	97.00	97.00	97.00
Max. efficiency [%]	97.80	97.80	97.80	97.80	97.60	97.60	97.60	97.60
Battery charge/discharge efficiency [%]	98.50	98.50	98.50	98.50	96.00	96.00	96.00	96.00
POWER CONSUMPTION								
Internal consumption(night) [W]	<7				<7			
Idle mode	YES				YES			
STANDARD								
Safety	IEC62109-1-2 / IEC62040				IEC62109-1-2 / IEC62040/ AS3100			
EMC	EN61000-6-1/EN61000-6-2/EN61000-6-3				EN61000-6-1/EN61000-6-2/EN61000-6-3			
Certification	VDE0126-1-1 A1:2012/VDE-AR-N4105/G83/G59/AS4777/EN50438/CEI0-21/VDE2510				VDE0126-1-1 A1:2012/VDE-AR-N4105/G59-3/AS4777/EN50438/CEI 0-21/IEC62040/IEC62619/ISO13849-2/SN29500/IEC615086			
ENVIRONMENTAL PARAMETERS								
Protection class	IP65				Ip65			
Operating temperature range [°C]	-20 to+60 (derating at+45)				-25 to+60 (derating at+45)			
Altitude [m]	<2000				<2000			
Storage temperature [°C]	-20 to+60				-20 to+60			
Noise emission (typical) [dB]	<30				<30			
Over voltage category	III (electric supply side), II (PV side)				III (electric supply side), II (PV side)			
DIMENSIONS AND WEIGHT								
Dimensions (WxHxD) [mm]	460*477*181.5				650*453*222.5			
Weight [kg]	26.9				40			
Cooling concept	Natural				Natural			
Topology	Transformerless				Transformerless			
Communication	Ethernet, Meter, WIFI (optional), RF(optional), DRM, USB, ISO alarm, Parallel operation				Ethernet, Meter, WIFI (optional), RF(optional), DRM, USB, ISO alarm, Parallel operation			
LCD display	Backlight 20*4 character				Backlight 20*4 character			
Standard warranty [years]	5-10 (Dependent On Territory)				5-10			