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Economic feasibility analysis of microgrids in Norway

An application of Homer Pro

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Preface

During my summer internship in 2017 at the Electrical Engineering Section in COWI Norway Ltd in Oslo, I developed my interest in smart energy systems. Birgitte Fuglum, Head of the Electrical Engineering Section, wondered if I was interested in a master's thesis in the microgrid topic and she proposed Bjørnar Skaar Johansen as supervisor. Me and Bjørnar discussed that an investigation of the economic feasibility of microgrids in Norway would be of special interest for COWI, as stakeholders are usually most interested in the economic benefits of investments. The employees often lack the time to do comprehensive analyses and COWI wish that this thesis will provide some key insights in the topic of microgrid feasibility in Norway as microgrids have become an increasingly popular topic.

For the last five years I have been a student at the Norwegian University of Life Sciences (NMBU) in Ås, where I have acquired a wide range of knowledge, in physics, mathematics, statistics and programming. This thesis marks the end of my time as a student, which I truly have enjoyed because I have always been able to choose the specialisation courses that were in my fields of interest. I am therefore pleased with my master's thesis topic, as I got to use my multidisciplinary skills to solve the problems involved in the thesis.

There are many people who I think deserve special thanks regarding this thesis. I feel privileged since I have had the opportunity of having three supervisors. Thanks to Sonja Berlijn, Bjørnar Johansen and Jonas Nøland for supervising me throughout the semester. A special thanks to my fiancé Karoline who have supported me during the time of writing this thesis and my entire student life. I wish to thank my parents and grandmother for always being there for me and supporting me. Last but not least, thanks to my lovely dog Wilma who got me out in fresh air during the most intense writing sessions of this thesis.

Thanks to all my fellow students and lecturers at Ås who have contributed to a great time for me here at NMBU.

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Sammendrag

For å undersøke lønnsomheten til microgrids i Norge, ble fire forskjellige systemkonfigurasjoner modellert og simulert i programvaren kalt HOMER Pro. Det modellerte systemet er et verksted på Ryen i Oslo, hvor vedlikehold på t-bane tog blir gjennomført. Det er godt egnet å bruke solcellepaneler kombinert med energilagring i batteri, da taket på to bygninger på Ryen er egnet for montering av solcellepaneler. Bygningene på Ryen bruker mye energi til oppvarming, ved hjelp av en elektrisk kjele på 2 MW. Dermed er det gode muligheter til å senke energi- og strømforbruket ved å bruke fornybare ressurser.

Modellene laget i HOMER Pro og deres inputvariabler presenteres på en måte slik at andre kan lage de samme modellene og gjøre simuleringene for å få de samme resultatene. Fire forskjellige modeller ble opprettet og simulert; en basismodell som simulerer konfigurasjonen på Ryen i dag, en modell bestående av solceller, en modell bestående av batterilagrinssystemer for å redusere effektforbruket og en mikrogridmodell med både solceller og batterilagrinssystemer. Det er også utført en følsomhetsanalyse, da enkelte variabler har en viss grad av usikkerhet.

Den økonomiske egnetheten for hvert system ble bestemt ved å sammenligne nåverdien, også kalt livssykluskostnad, for hvert system mot nåverdien til basekonfigurasjonen. Simuleringsresultatene viste at basekonfigurasjonen hadde en nåverdi på 172 millioner kr. Solcellemodellen, modellen med batterilagring for effektutjevning og mikrogridmodellen fikk en nåverdi på henholdsvis 184, 178 og 190 millioner kr. Dette resulterte i en nåverdidifferanse for hvert system på henholdsvis -12, -6.0 og -18 millioner kr for solcelleanlegget, batterilagringssystemet og mikrogridkonfigurasjonen. Dermed er de tre simulerte systemkonfigurasjonene ikke økonomisk egnet på Ryen ifølge simuleringene, da alle tre ga en negativ nåverdidifferanse, dvs. en høyere nåverdi.

Følsomhetsanalysen viste at investeringskostnadene til solcelle- og batterilagringssystemene hadde en liten effekt på total nåverdi. Dette kan tyde på at investeringskostnadene for solceller er høye sammenlignet med lave energikostnader om sommeren, når solcelleanleggene produserer mest energi. Det ble observert at det ikke var økonomisk hensiktsmessig for batterilagringssystemet å lagre overskudsenergi produsert av solcellesystemene, fordi den høye erstatningskostnaden og kort levetid for batteriene bidro til en høy batterislitasjekostnad ved utladning. Ifølge resultatene fra simuleringene er en mikrogridskonfigurasjon bestående av solceller og batterilagring kanskje ikke økonomisk hensiktsmessig i Norge, med mindre kostnadene for energi (spesielt om sommeren) eller effekttariffen skulle øke, og/eller investeringskostnaden for batteriet og solcellepanelene skulle synke.

Abstract

To investigate the profitability of microgrids in Norway, four different system configurations was modelled and simulated in the software called Homer Pro. The modelled case is a workshop at Ryen in Oslo, where maintenance on underground trains are being performed. It was suitable to use solar photovoltaics (PVs) paired with battery energy storage systems (BESSs), as the rooftop of two buildings at Ryen are suitable for installing solar PVs. The buildings at Ryen use a lot of energy for heating purposes, using an electrical boiler rated to 2 MW. Thus, there is great possibilities of lowering the energy and power consumption costs using renewable resources.

The models created in Homer Pro and their input variables are presented in a way so others can create the same models and do the simulations to get the same results. A total of four different models was created and simulated; a base model to simulate the configuration at Ryen today, a model consisting of solar PVs, a model consisting of BESSs for peak shaving and a microgrid model with both solar PVs and BESSs. There is also performed a sensitivity analysis, as some model input variables have some degree of uncertainty.

The level of economic feasibility of each system was determined by comparing the net present cost (NPC) (also called life cycle cost) of each system to the NPC of the base system. The simulation results showed that the base configuration got an NPC of 172 million kr. The solar PV, peak shaving and microgrid model got an NPC of 184, 178 and 190 million kr, respectively. This resulted in a present worth of each system of -12, -6.0 and -18 million kr for the solar PV systems, BESS unit and microgrid configuration, respectively. Thus, the three simulated system configurations were not economically feasible at Ryen according to the simulation results, considering all three provided a negative present worth, i.e. a higher NPC.

The sensitivity analysis showed that the investment cost of the solar PV systems and BESS had a small effect on the total NPC. This may indicate that the investment cost of solar PVs is too high, compared to the low cost of energy in the summer, when the solar PV systems produce most energy. It was observed that it was not economically feasible for the BESS to store surplus energy produced by the solar PV systems, because the high replacement cost and short life time of the batteries contributed to a high battery wear cost when discharging. A microgrid configuration consisting of solar PVs and battery energy storage might not be feasible in Norway, based on the simulation results, unless the cost of energy (especially during summer) or demand charge were to increase, and/or the investment cost of battery and solar PV technology were to decrease.

Contents

1. Introduction

The world's solar photovoltaic (PV) capacity grew by 50 % in 2016 (International Energy Agency 2017). Solar PV additions rose faster than any other fuel, even surpassing the increase in net coal capacity. The growth in the solar PV and other renewable markets accounted for close to two-thirds the world's net power capacity increase in 2016. The increase in renewable power penetration is driven by cost reductions, political support and a common desire to reduce greenhouse gas emissions and meet the rising energy demand. Thus, 2016 resulted in an extraordinary year for the propagation of renewable energy in the world. This has led to more distributed generation (DG) methods which supply renewable power especially to low and medium voltage grids, i.e. the distribution grid. However, the natural intermittency of renewable resources cause instabilities in the power grid and it is a challenge to balance the power production and demand (Kuang, Li, and Wu 2011). Today's distribution grids are designed for power flowing in only one direction - from the producer to the consumer. This cause problems when the DGs in distribution grids deliver power from the consumers to the main grid.

It is not only the ways of generating power that have changed, but the general load characteristics in the distribution grid have changed as well. Transport stands for roughly a third of the greenhouse gas emissions in Norway (Skotland, Eggum, and Spilde 2016). As a result, policy measures have led to an increased penetration of electric cars in Norway the last couple of years and may continue to increase. Skotland, Eggum, and Spilde (2016) predict that it might be 1.5 million electric cars on Norwegian roads by 2030. They also explain how charging electric cars can overload distribution transformers in some areas. Energy storage units like batteries can be used as buffers to mitigate the overload in the distribution grid caused by charging electric cars. The DG units, energy storage units and controllable loads constitutes the term "distributed energy resources" (DERs), which needs to be integrated in the existing power grid in a convenient way. A much-researched method is the electric system configuration called microgrid, which will be reviewed in this thesis.

A microgrid is a small-scale electricity system that interconnect DERs like renewable resources and energy storage technologies. Microgrid systems can be considered as a single entity from the power grids perspective. One of the characteristics of microgrids is using locally produced power which grants the possibility to take advantage of the dissipated heat from production methods and reduce the need for transporting power, thus lowering transmission losses. By using energy storage and controllable production methods in addition to renewable resources, users will experience 20-25 % better power reliability, power quality and lower electricity costs in the distribution grid because the power production using renewable resources is better matched the power consumption (Basak et al. 2012). The first microgrid trials date back to the 1980s. However, because of a series of challenges, it is just recently that microgrids have started a commercial growth. The most common challenges are found in the categories; technical, regulatory, financial and stakeholder (Soshinskaya et al. 2014). If these mentioned barriers were to be broken, microgrids might evolve and become the building blocks that constitutes the smart grid of tomorrow (Shahidehpour et al. 2017).

This thesis is written in collaboration with COWI Norway Ltd. COWI is an international consulting business, with its head office in Lyngby, Denmark and more than 1100 employees in Norway. As microgrids have recently started a commercial growth, COWI is interested to find out if microgrid configurations are economically feasible in Norway and if configurations like these can be of interest to their customers. It is also desirable that the thesis explains how microgrid systems can be analysed from an engineer's perspective. The simulation program called HOMER Pro is chosen to function as the tool to conduct techno-economic analyses of different configurations. To put the topic of this thesis in context with work done by others, a literature review of previous work within the topic of economic feasibility analysis of microgrids and renewable power production and storage technologies will be given in the next chapter.

2. Literature review

This chapter will present previous work done by others in the area of economic feasibility analysis of microgrids and renewable hybrid energy systems. The results and conclusion of the work will be presented, and later compared to the results given in this thesis.

Last year at the Norwegian University of Life Sciences, Bøe (2017) used solar irradiation and wind speed data measured in Ås to conduct analyses using HOMER Pro to compare energy costs of different scenarios of hybrid energy systems. The goal was to examine the cost of energy of different grid connected system configurations, using solar PVs and a wind turbine to supply an average detached household with power. Bøe (2017) considered two different scenarios. One where he assumed a grid sell back rate of 1 kr/kWh and another where he assumed a grid sell back rate equal to the elspot values for every hour in a year. Simulation of the configurations in HOMER Pro showed that using neither solar PVs or a wind turbine (i.e. grid-connected only) was the optimal configuration with an average cost of energy throughout the lifetime of the system equal to 0.77 kr/kWh. Using 1 kWp (kilowatt peak) installed solar PV capacity and 5 kWp installed wind turbine capacity, the simulated average cost of energy was 1.85 kr/kWh for both scenarios. Because of the high cost of energy for all configurations, Bøe (2017) concluded that wind resources in Ås was not sufficient to make the simulated systems economically feasible. When he simulated a grid connected solar PV system of 1 kWp installed capacity, a cost of energy equal to 0.82 kr/kWh was achieved for both mentioned scenarios. Thus, grid sell back rate did not matter much when small amounts of surplus energy was produced.

Sarker (2016) preformed an economic feasibility analysis of a standalone house using HOMER Pro to investigate the economic viability of different remote microgrid configurations. He used average consumption data for residential houses and measured data for renewable resources like wind and solar irradiation in Grimstad, Norway. Numerous different configurations were analysed. The system with the lowest cost of energy was a system using a 2.5 kW generator fuelled by natural gas, 1 kW wind turbine and a battery with a capacity of 2.16 kWh. The average cost of energy throughout the lifetime of the system was 2.45 kr/kWh. Another configuration using only renewable resources achieved a cost of energy of 2.50 kr/kWh. The system consisted of 1 kW of installed solar PV capacity, 1 kW wind turbine, 2 kW generator fuelled with wood gas and the same battery with a capacity of 2.16 kWh. Sarker (2016) discovered a total of eight feasible system configurations, where three different configurations consisted only of power production methods using renewable resources.

Berner (2013) found the cost of energy provided by solar PV systems to be about 1.4 kr/kWh for solar PV systems in the 1000 kWp range of installed capacity in the Oslo area. The cost of energy was calculated to about 2.3 kr/kWh for solar PV systems with smaller capacities of 7 kWp.

There is a lot of previous work in other countries where HOMER Pro has been used for microgrid modelling, especially in the field of remote microgrids. These simulations show that the price of energy is relatively high compared to the cost of energy of a grid connected system in the same country. For example, Kolhe, Ranaweera, and Gunawardana (2013) use HOMER Pro to find an optimal remote microgrid solution with a cost of energy equal 2.93 kr/kWh in Sri Lanka. Sen and Bhattacharyya (2014) simulated a remote microgrid in India and found an optimal system configuration resulting in a cost of energy equal 3.42 kr/kWh. Hafez and Bhattacharya (2012) used HOMER Pro to simulate four different grid-connected microgrid cases. The case that provided the lowest cost of energy (0.58 kr/kWh) was a grid connected microgrid system consisting of hydro power as the only energy production method.

3. Problem description

The main contribution of this thesis is to the area of investigation of feasibility and economic benefits of microgrids and renewable production and storage technologies within the industry sector in Norway. A demonstration of an approach to model microgrid systems and conduct economic feasibility analyses in the software called HOMER Pro will be given as well. The goal is to model and simulate microgrid configurations and renewable production and storage technologies to find the most profitable composition of renewable power production and storage technologies for the given case. It will be attempted to generalise the simulation results to predict the feasibility of microgrid configurations in Norway in general. The procedure used to create the model and simulations will be presented in a way that give the readers an understanding of how microgrid configurations can be modelled and analysed, and how to replicate the results given by the simulations.

Previous work regarding economic studies of renewable production methods and energy storage technologies is presented in Chapter 2. Bøe (2017) used HOMER Pro to find the economic benefits of distributed generation. Sarker (2016) did an economic analysis of a remote microgrid using HOMER Pro. Berner (2013) did an economic feasibility analysis of solar PV systems in Norway using the software tool PVsyst. There have been several contributions to the area of techno-economic analysis of microgrids in other countries. However, there might be no work that contribute like the work in this thesis, as the modelled case is a grid connected industry system with different load characteristics than smaller loads in the private sector and opportunities for renewable power generation using solar PV systems with high capacity. At least not any work that is published to the knowledge of the author.

Even if microgrids might become the building blocks of the next generation power grid (Shahidehpour et al. 2017), there is still some barriers that need to be broken before microgrids can become more widespread. One of the most important barrier to overcome is the financial barrier, considering most stakeholders are concerned with the economic benefits of investments and there is some confusion about whether microgrid configurations and renewable production and storage technologies are profitable in Norway. This is the reason why the contribution of this thesis will be important for the penetration of renewable power generation using solar PV and storage systems, and the development of microgrid systems in Norway and other countries as well.

4. The HOMER Pro software

HOMER (Hybrid Optimisation of Multiple Energy Resources) Energy LLC was founded in 2009 by Dr. Peter Lilienthal (HOMER Energy LLC 2018). The company's goal was to commercialise the HOMER Pro (hereby called HOMER for the rest of the thesis) software that Dr. Lilienthal had originally developed during his 17 year-long career at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). Today, HOMER Energy continue the development of HOMER, which have been changed a lot since the initial product were launched in 2009. The company also provide consulting services and software training. HOMER has been downloaded by more than 150 000 people since its release.

The HOMER software is a tool for modelling most hybrid energy system configurations, including microgrids. It is used solely for the economic feasibility analyses and do not provide any documentation for the system, calculate fault currents etc. like some other programs. It is intended as a tool for finding the energy production and energy storage capacities that provide the lowest net present cost (NPC) for the system for its entire lifespan. The software simulates the system model designed by the user over the given lifespan of the system. The user can choose to provide the necessary data, like meteorological or energy consumption data, or let HOMER use its built-in meteorological data or different synthetic loads. Before the simulation of the given model, the user can choose to use the built-in search space or the HOMER Optimiser. To use the search space, different capacities for the distributed energy resources (DERs) that is interesting for the user must be entered. The optimiser finds the optimal solution by iterating through the different possible compositions of capacities of the different DERs. HOMER classify the optimal solution as the system that provide the lowest NPC during its lifespan. It is possible to do sensitivity analyses in HOMER as well. It can be investigated using economic variables like discount rate, or demand rate. More detailed information regarding the models simulated using HOMER is provided in Chapter 9.

HOMER was chosen as the software for modelling because it is user-friendly and easy to learn, considering the author have never used software like HOMER before. The graphical interface makes it easy to create models and simulate them. HOMER have access to meteorological data like temperature and solar irradiation, which makes data gathering easier when simulating systems with production methods like solar PVs. Although HOMER is intended as an easy-to-learn simulation program, it is possible to do comprehensive sensitivity analyses and simulate complex systems. This is exactly the tool needed to investigate the problem described in Chapter 3.

5. Microgrids

This chapter review the challenges connected to power quality and how microgrids configurations can improve the power quality in distribution grids with distributed generation (DG) units and energy storage systems (ESS).

The first section provides a very brief explanation of power quality to give the reader some idea what the term means, considering it is a fundamental concept when discussing the microgrid advantages in the second section of this chapter and the discussion in Chapter 12. The second section provide a clear definition of the microgrid configuration and its benefits. Finally, some microgrid cases with their barriers and success factors will be briefly reviewed.

5.1 Voltage and frequency stability

Renewable DG units provide energy production where it is geographically needed and at the same time lowering the carbon footprint. However, renewable DG units like solar PV systems and wind turbines provide intermittent and varying power production. As a result, the power quality of the distribution grids gets harder to maintain, because it is harder to match the power production and load. The term power quality can be considered as the ability of power systems to maintain the nominal voltage and frequency.

In Fig. 5.1, the main power grid is considered as an infinite bus, because of its many generators providing an approximately constant voltage. The load in the distribution grid is usually lower in the summer relative to the winter. Thus, a grid connected solar PV system inject power in the system when the voltage is relative high compared to winter, resulting in an even higher voltage, as can be seen as the red-dashed line in Fig 5.1. Assuming small phase shift across a distribution line, the voltage V_s at the sending end can be expressed as

$$V_s = V_r + \frac{RP + XQ}{V_r} \tag{5.1}$$

where V_r is the voltage on the receiving end, R is the resistance of the line, X is the impedance of the line, P is the transferred active power and Q is the transferred reactive power. The full derivation of Equation 5.1 is performed by Saadat 1999 on page 83-86. The voltage drop across the distribution line can be found by using Equation 5.1, by

$$\Delta V = V_s - V_r = \frac{1}{V_r}(RP + XQ) \tag{5.2}$$

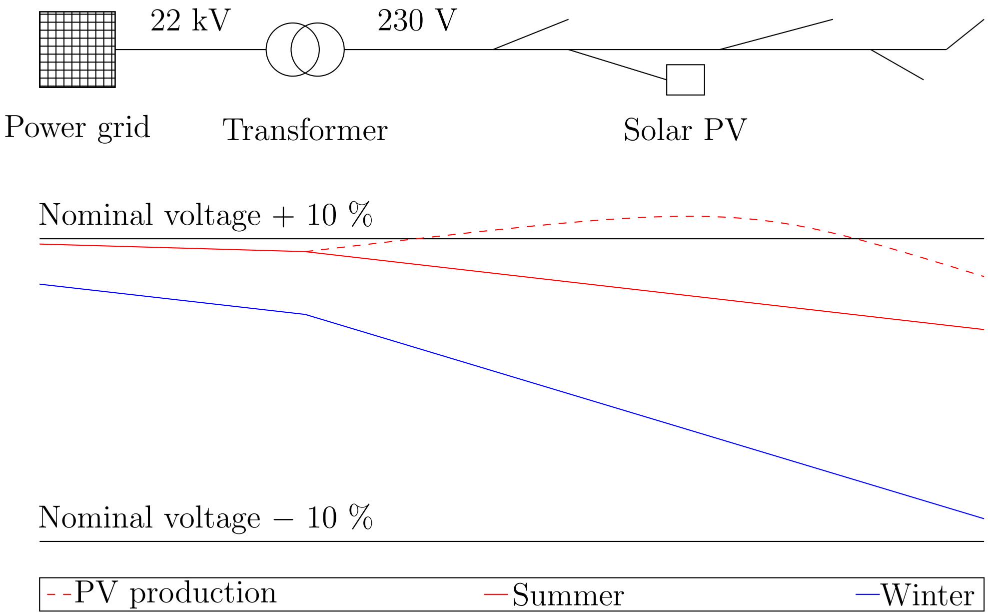

Figure 5.1: Schematic diagram of a distribution network and varying voltage. The branches symbolise residents or neighbourhoods. An increase in power consumption is expected in the cold winter in Norway. Thus, the voltage drop throughout the distribution grid is higher relative to summer. Adding a solar PV system result in more injected power in the system when it often not needed. This result in higher voltage at the power injected node - resulting in higher voltages.

Fig. 5.2 shows the different X/R-ratios for a typical distribution grid. As the resistance R is much greater than the impedance X in a typical distribution grid, the XQ-term in Equation 5.2 can be neglected, thus

$$\Delta V = \frac{RP}{V_r} \tag{5.3}$$

This is why injection of active power from the solar PV system in Fig. 5.1 result in an increase in voltage, and some electric car chargers that use a lot of power leads to a voltage drop. It can also be observed from Fig. 5.2 that regulating voltage in higher voltage grids is most efficient when using reactive power (according to Equation 5.2).

Frequency deviation of power systems are proportional to the mismatch between the generated active power and the active power consumption (Von Meier 2006). This is analogue to a combustion engine in a car. If the car goes uphill, more power is needed to maintain the car's speed. If the engines power is not adequate, the car will slow down. If the car goes downhill - the car will go faster, assuming the throttle is constant. The same happens in the power grid. If a load suddenly drops out, the power generation is higher than the total load and the frequency will increase. If a load suddenly gets turned on, the power production will be less than the total load and the frequency will decrease. It takes time for the system to react to this change (i.e. regulators). Thus, the frequency will deviate from the nominal frequency value during this time. The rotating mass of generators help mitigate

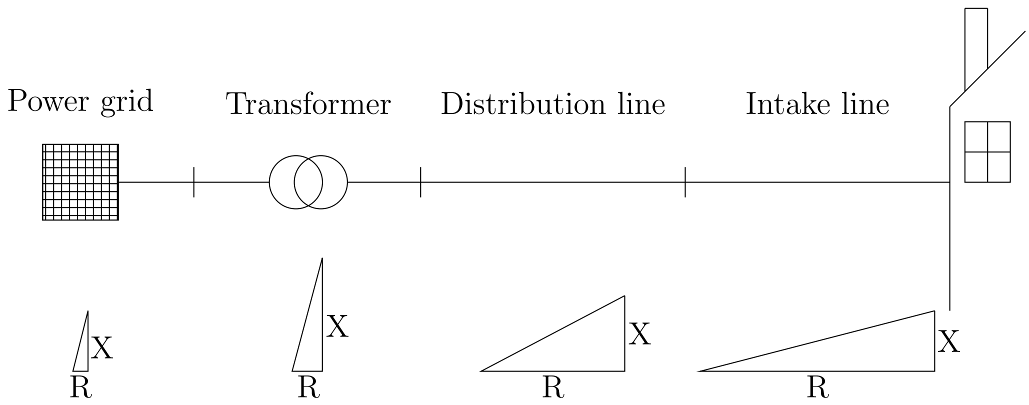

Figure 5.2: Schematic diagram of the resistance and impedance ratio of a typical distribution grid. Diagram is inspired by Hanssen and Visnes (2016).

sudden changes in frequency. As solar PVs do not have any rotating mass and wind turbines rotate to slow to contribute with much rotating mass, modern power electronics combined with ESSs can inject power in the grid to emulate rotating mass. Frequency deviation is a global phenomenon, which means that the entire grid will have the same same frequency. Voltage deviation, on the other hand, is a local phenomenon, as it happens between specific nodes in the grid.

5.2 Microgrid definition and advantages

There is no clear microgrid definition. Different organisations have different opinions about what defines microgrid systems. The International Council on Large Electric Systems (CIGRÉ), provides the following definition of microgrids:

> Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded. (Marnay et al. 2015)

The United States Department of Energy (US DoE) provide a slightly different microgrid definition:

> A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. (Ton and Smith 2012)

The US DoE's microgrid definition states that a grid-tied system is supposed to connect and disconnect from the main power grid to enter grid-connected and island-mode to be classified as a microgrid. If this is not possible, the system is not a microgrid and rather defined as an active distribution system, where the distributed energy resources (DERs) are coordinated through a distributed energy resource management system (DERMS). According to CIGRÉs definition, microgrids do not necessarily need to be able to switch between island and grid-connected mode. However, there is a mutual understanding that microgrids should have this feature as the system is more robust to faults (Soshinskaya et al. 2014). One of the greatest technical barrier to overcome is precisely disconnecting and especially re-synchronising the microgrid to the main grid. Very few microgrids can achieve this and may need better voltage and frequency controls to avoid large mismatches between power production and load.

The size of microgrids vary (Soshinskaya et al. 2014). The microgrid definition does state that microgrids are defined by their functionality - not their size. However, the microgrid design and size vary and it is usually considered as a subsystem of a medium or low voltage grid, or a isolated microgrid if permanently islanded - in the case of remote or rural microgrid. The size of a microgrid is defined by the installed capacity of its contained DERs, determined by the peak power required by the loads.

A varying set of components are needed for a microgrid to function properly (Soshinskaya et al. 2014). The main components are DG units, distributed energy storage (DS) and/or active loads. A physical network to interconnect the DERs consisting of wires and protective relays is needed as well. At the core of the microgrid is the microgrid controller, which is a advanced control and demand response technology. The microgrid controller operate and control the energy distribution and provides detailed information about the flow of energy and usage. The components are intended to complement each other to meet the demand of loads. Different power production methods combined with DS are needed, as renewable resources have intermittent and varying intensity.

The microgrid advantages are many. First, it integrates DGs closer to the load. This result in less transmission losses and an opportunity to collect waste heat from power production methods, like combined heat and power (CHP). Microgrids also increase the utilisation of DERs as energy storage units are usually present for the microgrid to enter island mode operation. This also enables microgrids to regulate its power export, which allows it to select how much power that will be injected at its point of interconnection to the main grid. As explained in the previous section, this allows the microgrid to help control the voltage and frequency in the main grid, as well as the microgrid itself. Thus, microgrids can contribute to the power quality in the main power grid in a positive way. This demonstrates the main reason why microgrids is well suited for integrating DERs in the main power grid - it turns the disadvantage of DERs into an advantage. Features and advantages are given by Joos et al. (2017) and Soshinskaya et al. (2014), and summarised in Table 5.1.

5.3 Microgrid cases

Most microgrids up to today are demonstration projects (Soshinskaya et al. 2014). However, some microgrids have crossed over from the experimental to commercial phases. A microgrid in Norway, at Utsira island, have provided power to residents since 2004. The microgrid at Utsira use wind turbines and fuel cells that is used

Table 5.1: Microgrid features and their corresponding advantages.

Feature	Advantage
Integrate DERs close to loads	Less transmission losses
Island-mode	Better power reliability and security
Voltage and frequency control services for the main grid	Enhances grid stability
Integrates renewable DERs	Lowering the carbon footprint and consumers use less energy from the main grid - saving energy costs
Control DERs in a coordinated way	Reduce power variations in the distribution grid
Plug and play configurations	Enhances existing distribution systems with better reliability and system operating efficiency
Enables market participation of DERs	Enable consumers to sell energy at better rates
Advanced controls	Matching power quality with load requirements
Efficient use of local energy resources	Better energy security and resiliency of the distribution grid
User self control	Empowers customers and end users

for electrolysis of water to create hydrogen that is stored and used in combustion engines to produce power when needed. Samsø Island in Denmark have a total DG capacity of more than 11 MW, using wind and solar resources.

There are several other microgrid cases all over the world, but reported challenges are linked to the implementation and operation of them (Soshinskaya et al. 2014). At Utsira, it was assumed that wind utilisation would be about 75 %. However, it was found that only 20 % was utilised. Thus, more efficient electrolysers are needed for systems using hydrogen as energy carriers. Utsira island experienced financial issues as well, regarding the fuel cell cost, which turned out to be too high for the 215 kW installed DG units. In the planning of the microgrid at Samsø island, it was experienced trust and self-interest issues. Several meetings were conducted with the local residents to get them on board with the new microgrid system. For example, a local resident proposed to build a nuclear plant instead of a microgrid with DG units, so he could provide with the concrete, as he was the owner of the local concrete factory. Although there are some barriers to overcome, some of the pilot projects have had some success factors. Samsø island is successful at creating a robust market model, selling power to the main grid in Denmark.

6. Energy production and storage

This chapter will provide relevant theory for solar PV systems and electrochemical batteries, which is used in the simulated models in this thesis. A brief general review of the technology will be given before an explanation of how the technologies are modelled in HOMER.

6.1 Photovoltaic cells

Solar photovoltaic (PV) systems are the most expanded energy production technology in recent years, as solar energy is one of the most abundant renewable energy resources (International Energy Agency 2017). Solar PV systems consist of one or more solar panels. The panel, also called module consist of several solar cells, either connected in series, parallel or a combination of both, where the last configuration is most common (Smets et al. 2016). The core principle of a working solar cell is based on the photovoltaic effect. The photovoltaic effect occurs when electromagnetic radiation generates a potential difference at the junction between two different materials. Most solar cell production today use silicon, which is cut into wafers from blocks. The wafers are doped with other materials to create a junction, as shown in Fig. 6.1. The most common doping materials in silicon are phosphorous to create the n-type region and boron to create the p-type region. Phosphorous is in group five in the periodic table. Thus, an excess electron will coexist when a phosphorous atom is bound to a silicon atom, which is in group four. Boron is in group three, which result in absence of an electron when a boron atom is bound to a silicon atom. This is more commonly called a "hole". A diffusion current of electrons and holes takes place when the two materials are close together, as the holes and electrons will diffuse to areas of lower concentration. A depleted region around the pn-junction is created because of this effect. The charge around the junction results in a formation of an internal electric field. The diffusion current cease when the force on the charge carriers from the concentration gradient is compensated by the force on the charge carriers from the electrical field.

When a photon with energy greater than the doped silicon semiconductor energy band gap get absorbed, an electron-hole pair gets created (Smets et al. 2016). Assuming this takes place in the n-type region, the minority carrier is the hole and the majority carrier is the electron. The hole will then make it across the junction and become a majority carrier. As the electron are now without a hole partner, it can be passed through an external circuit where it can do work, as seen in Fig 6.1.

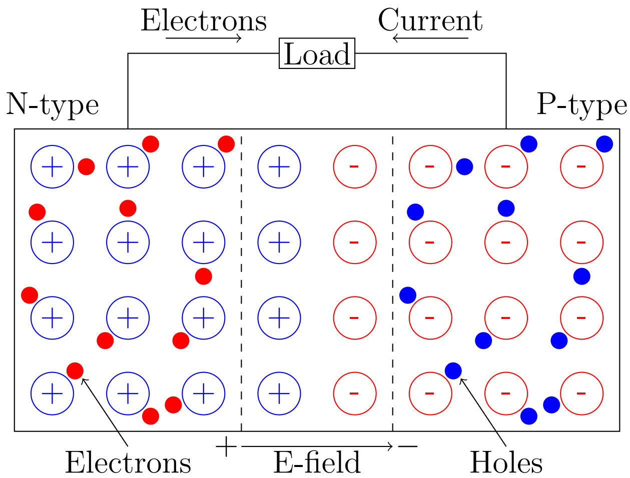

Figure 6.1: Schematic diagram of a silicon wafer (semiconductor). Doping the wafer can be considered as a n-type and p-type semiconductor that are brought together and forms a junction. A solar cell is in short a silicon wafer treated to not reflect light and installed with busbars (fingers) and a back contact to collect charge carriers at the surface.

It then enters the p-type region, annihilates with its hole partner and the circuit is completed. This is the fundamental idea of how a solar cell work. It may happen that the electron-hole pair annihilates before they are separated by the electrical field. This is called recombination and decreases the efficiency of the solar cell.

The short-circuit current and the open-circuit voltage are the maximum current and voltage, respectively from a solar cell (Smets et al. 2016). However, no power is produced at these two points. Thus, when solar cells are installed in solar modules that form a solar PV system, one or more maximum power point trackers (MPPTs) are installed to ensure that the modules deliver the maximum power by regulating the generated voltage and current. Solar modules are assumed to be installed with MPPTs to always deliver the maximum power relative to the irradiation in HOMER (HOMER Energy LLC 2017). Thus, the power production of a PV array in HOMER is calculated as

$$P_{PV} = Y_{PV} f_{PV} \frac{\bar{G}_T}{\bar{G}_{T,STC}} [1 + \alpha_P (T_c - T_{c,STC})] \tag{6.1}$$

where Y_{PV} is the rated capacity of the PV array (power output under standard test conditions (STC)), f_{PV} is the PV derating factor, $\bar{G}_T$ is the solar radiation incident on the PV array in the current time step, $\bar{G}_{T,STC}$ is the incident radiation at STC (1 $^{\mathrm{kW}}/_{\mathrm{m}^2}$), α_P is the PV modules temperature coefficient, T_c is the PV cell temperature in the current time step and $T_{c,STC}$ is the PV cell temperature under STC (25 °C). HOMER considers temperature losses, which is significant when the cell temperature is high, because this result in a smaller energy band gap in the silicon wafer and every excited charge carrier will have less energy (Smets et al. 2016). Elevated temperatures also affect the resistance of the conducting materials like busbars and wiring which result in more heat losses in the system. The derating factor f_{PV} account for factors like soiling, ageing, shading and wiring losses. HOMER use a rather complex equation for calculating the PV cell temperature T_c and will not be given in this thesis. However, the formula is presented in the HOMER Pro manual (HOMER Energy LLC 2017).

6.2 Electrochemical batteries

The use of electrochemical batteries has increased dramatically the last couple of years (Naceur and Gagné 2016). Thus, great decrease in cost have been observed as well, which have made batteries economically feasible in many configurations. It is the Lithium-ion battery cell that is the most used in modern technology, like electric cars, cellphones and battery energy storage systems (BESS). This is because of the high energy density per volume and mass. BESS units are a very suitable technology for microgrid systems. A stand-alone BESS unit is able to delay peak load, which is convenient when the load characteristic has a peak power demand that lasts for short periods of time and the demand charge is high in the geographical area. BESSs can in some cases be deployed to delay investments in the grid where the load exceeds the grids capacity in short periods of time throughout the year. BESSs is also efficient at maintaining the power quality. As explained in Chapter 5, it is possible (and usual) to control the power quality by injecting reactive and active power in the grid depending on the R/x-ratio. This makes BESSs viable for maintaining the power quality as they usually are able to change the power factor when discharging using modern power electronics. BESS units are often used in combination with solar PVs and wind power systems to help mitigate the intermittent power production. As microgrid configurations are intended to integrate DERs like solar PVs and wind turbines into the grid in a convenient way, microgrid configurations usually have some kind of energy storage technology to be able to function as a microgrid according to the definitions presented in Chapter 5.

There is numerous battery models available in HOMER. Some advanced models require the Advanced Storage Module, while other models do not. The advanced models take into account temperature dependent battery capacities and degradation rate, variable depth of discharge for increased battery life and better user control, as users can add their own batteries. The user can set how HOMER control the energy storage units by choosing the appropriate control scheme in the microgrid controller settings. The models in this thesis use the cycle charging dispatch strategy, where the power generation units work at full output power to serve the load and energy storage if the power generation exceeds the loads. This matter most when using controllable generator units like diesel generators. HOMER decides whether to discharge battery based on the cost of discharging the battery (HOMER Energy LLC 2017), which is given as

$$C_{batt,discharge} = C_{batt,energy} + C_{batt,wear} \tag{6.2}$$

where $C_{batt,energy}$ is the storage energy cost in time step n and $C_{batt,energy}$ is the average cost of energy that the system has incurred to deliberately charging the battery up to the current time step. At any time step, the cost of energy stored in the battery bank is calculated as

$$C_{batt,energy} = \frac{\sum_{i=1}^{n-1} C_{cc,i}}{\sum_{i=1}^{n-1} E_{cc,i}} \tag{6.3}$$

where $C_{cc,i}$ is the cost of cycle charging the storage in time step i and $E_{cc,i}$ is the amount of energy that went into the storage bank in time step i. The storage energy cost is the average cost of energy that the system has stored in the storage up until time step n. If a generator did not work to specifically charge the storage bank, the cost of energy $C_{cc,i}$ is set to zero. This would be the case if the energy $E_{cc,i}$ was generated by a solar PV system. However, for example for peak shaving purposes, where the storage bank is charged with energy bought from the grid, the cost of energy $C_{cc,i}$ is not set to zero. The battery wear cost $C_{batt,wear}$ is calculated in HOMER as

$$C_{batt,wear} = \frac{C_{batt,repl}}{Q_{lifetime}\sqrt{n_{rt}}} \tag{6.4}$$

where $C_{batt,repl}$ is the replacement cost of the battery, $Q_{lifetime}$ is the lifetime throughput of the battery and n_{rt} is the round trip efficiency of the battery. If the cost of discharging the battery (or any energy storage modelled in HOMER) is lower than alternative power generation methods, HOMER will discharge the battery. For example, HOMER will not charge the battery with energy generated by a solar PV system if the solar PV generated power is less than the load demand. This is how HOMER operate and control a BESS using the cycle charging dispatch strategy.

There are two independent factors that may limit the battery lifetime in HOMER (HOMER Energy LLC 2017). It is the lifetime throughput of the battery and the battery float life. Both the battery throughput and battery float life are set by the user as a battery model parameter. The user can choose whether to have HOMER limit the battery lifetime by either time, throughput or both. The battery lifetime R_{batt} is calculated in HOMER as

$$R_{batt} = \begin{cases} \frac{N_{batt}\ Q_{lifetime}}{Q_{thrp}} & \text{if limited by throughput} \\ R_{batt,f} & \text{if limited by time} \\ \mathrm{MIN}(\frac{N_{batt}\ Q_{lifetime}}{Q_{thrp}}, R_{batt,f}) & \text{if limited by throughput and time} \end{cases} \tag{6.5}$$

where N_{batt} is the number of batteries in the storage bank, $Q_{lifetime}$ is the lifetime throughput of a single battery (set by the user), Q_{thrp} is the annual battery throughput and $R_{batt,f}$ is the storage float life (set by the user).

7. Economics

This chapter presents key economic terms that are used to determine the most economic feasible system configurations. The economic terms are presented in a general way before the procedure of how HOMER calculates them is reviewed.

The chapter starts with reviewing the grid tariffs and possible investment subsidies available in Norway. Then, inflation and discount rate, which is input variables in HOMER are explained. Finally, the two economic terms called levelized cost of energy and net present cost used for evaluating the economic feasibility of the systems are presented.

7.1 Grid tariffs

An electric power consumer in Norway must pay for two different products. One is the fee the consumer pays to the local distribution system operator (DSO) for the transportation of power, called transmission fee. The other is for the cost of energy, paid to the power supplier. The DSO operates and maintains the distribution system that is in their geographical area. The DSOs have monopoly in their area. Thus, the DSOs in Norway are regulated by The Norwegian Water Resources and Energy Directorate (NVE). It is NVE that manage the maximum and minimum limit of how much the DSOs may demand in transmission fee from each customer. If the DSO demanded too much, or too little for a year, it will be considered in the transmission fee the year after. The transmission fee consists of several components. A component related to energy consumption, another to power consumption (i.e. demand rate) and a fixed fee for being connected to the distribution network. Another fee is the electricity certificates subsidy. Electricity certificates is an aid scheme which makes it more profitable for stakeholders to invest in renewable energy. The electricity certificates are financed by the customers, as the power supplier adds the electricity certificate cost to the energy cost. The electricity certificate scheme is managed by NVE. Norway and Sweden have the same electricity certificate market.

A prosumer is a consumer who produce surplus energy in periods of time. The sell back rate for prosumers in Norway are equal the elspot price. The elspot price is regulated by Nord Pool Spot, the leading power market in Europe. Nord Pool provides day-ahead market and intraday market. The day-ahead market consists of trading of electric energy, which is delivered the next day. The intraday market opens three hours after the day-ahead market closes and consist of a continuous trading where stakeholders may correct possible unbalances. Stakeholders may trade between elspot areas, if there is transmission capacity. There is also a new power supplier called Otovo in Norway. This power supplier provides installation of solar PV systems and guarantee that Otovo will buy the surplus energy for one Norwegian krone per kilowatt hour, which is significantly higher than the elspot price (Otovo Ltd. 2018). However, this is most relevant for smaller private prosumers, as Otovo provide prosumers with the high sell back rate up to 5000 kWh each year.

7.2 Investment subsidies

Enova SOE manage investment subsidies for private energy consumers and individual businesses to help them invest in new and climate friendly technologies. Enova is owned by the Norwegian Ministry of Petroleum and Energy. The level of investment subsidies varies with the size of the system and its purpose (Enova SOE 2018). However, Enova intends to contribute with subsidies, so the stakeholders may take a positive investment decision. Businesses might get subsidies for measures that reduce the consumption of either electric power, energy, increased efficiency for the existing system or conversion of existing power generation to renewable power. It is possible to get financial support for initiatives that leads to reduced greenhouse gas emissions. The project or system must reduce the energy consumption by 100 000 $^{\mathrm{kWh}}/_{\mathrm{year}}$ or convert the same amount of energy to energy from renewable resources. It is also possible to get financial support if the project is able to reduce the greenhouse gas emissions by 30 tons of CO^2-equivalents each year.

7.3 Inflation rate

Inflation is a rate of a persistent increase in the general level of cost of goods and services over a period. Inflation describes the decrease in purchasing power relative to the same month the previous year and reflect the annual change in general price level for a given class of goods or services. As an example, if a bottle of soda cost 20 kr at the time of writing (March 2018), it will cost 20.4 kr in March next year with an inflation rate of two percent.

7.4 Discount rate

To consider the fact that that future cash flows are worth less than present cash flows, the discount rate must be considered. The discount rate describes the burden stakeholders take when investing money in a project. In HOMER, a discount factor is used when calculating the present value of future cash flows (HOMER Energy LLC 2017). The discount factor f_d is given as

$$f_d = \frac{1}{(1+i)^N} \tag{7.1}$$

where i is the real discount rate and N is the number of years. The annual real discount rate i (also called the interest rate) is calculated in HOMER as

$$i = \frac{i' - f}{1 + f} \tag{7.2}$$

where i' is the the nominal discount rate and f is the expected inflation rate. The nominal discount rate is the rate at which a stakeholder could borrow money.

7.5 Net present cost

The total net present cost (NPC), i.e. life cycle cost (LCC), of a system is the present value of all the expenses for the system, generated over its lifetime. HOMER calculates the NPC by discounting the cash flows for every year in the systems lifetime using the discount factor in Equation 7.1 and summing the discounted cash flows (HOMER Energy LLC 2017). The cash flow for a system or component consist of the investment cost at year zero, replacement cost, salvage cost, operation and maintenance cost, fuel cost etc. The discount factor is used to account for the fact that future cash flows are worth less than present cash flows, hence the name net present cost. The NPC of a component ($C_{NPC,co}$) in a system is presented by Bøhren and Gjærum (2009) and given as

$$C_{NPC,co} = \sum_{t=0}^{T} \frac{X_t}{(1+r)^t} \tag{7.3}$$

where t is the year number, T is the lifetime of the project, r is the annual discount rate and X_t is the cash flow in year t. The NPC for the system is simply the sum of the NPC of all the components. Thus, the NPC for a system can be expressed as

$$C_{NPC,sys} = \sum_{co=1}^{n} C_{NPC,co} \tag{7.4}$$

where co is the component number and n is the number of components.

7.6 Levelized cost of energy

The levelized cost of energy (LCOE) can be considered as the average price of energy a system will provide during its lifetime, usually given in cost per kWh. The LCOE is given by Lambert, Gilman, and Lilienthal (2006) and calculated as follows in HOMER:

$$LCOE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{7.5}$$

where $C_{ann,tot}$ is the total annualised cost, E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively, that the system serves per year, and $E_{grid,sales}$ is the amount of energy sold to the grid per year. The total annualised cost is given as

$$C_{ann,tot} = C_{NPC,sys} CRF(i, R_{proj}) \tag{7.6}$$

where i is the annual discount rate, R_{proj} is the project lifetime and the function $CRF(i, R_{proj})$ is the capital recovery factor given as

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{7.7}$$

where N is the number of years.

8. Simulated case: Ryen workshop

The case that were simulated in this thesis is the Ryen workshop in Oslo, Norway. The workshop was chosen as the case for this thesis because it was a project in COWI during the writing of the thesis, which gave the opportunity to use the easy-to-access load data from Kinect (2018). The project was about reviewing different methods for saving energy at the workshop. The workshop also has an installed electrical system of a scale that can represent a typical COWI customer. This is important when the simulation results are to be generalised for other institutions in Norway as well, which is part of the scope of this thesis, described in Chapter 3. The workshop is owned by Sporveien Ltd, one of the largest suppliers of public transport in Norway. Ryen workshop is Sporveien's main workshop for subway trains. The six buildings at Ryen consist of an office, a building containing the switchgear for rails and another for the rectifier, guardhouse, workshop and tramshed. The buildings constitute a total area of 31 102 m^2. An overhead picture from Google (2018) are presented in Fig. 8.1, where all the buildings are shown. The workshop is responsible for maintenance of subway trains. This includes washing, cleaning and upgrades. The workshop operates around the clock and use warm water for heating the buildings, washing and cleaning the subway trains and sanitary purposes. The warm water is delivered to all the buildings from a central heating system in the workshop itself. It is installed an electric high voltage (11 kV) boiler as well as two oil boilers. However, the two oil boilers have not been used the last couple of years. The electric boiler has a capacity of 2 MW.

Figure 8.1: Overview of the buildings at Ryen (Google 2018).

The workshop at Ryen use most energy for heating. The electric boiler generates the majority of heat needed in buildings and there is installed a rail heater to prevent rail freezing during winter. Some energy is used for powering the subway trains to get them in and out of the tramshed and the workshop. The remaining energy consumption at Ryen workshop is used for lightning, compressed air and other smaller appliances. It is four different distribution boards that distributes power to the four different utilities, each with an installed energy measurement meter. The four meters are summarised in Table 8.1, with each meter's measured data for 2014 to 2017. The data are downloaded from the Kinect (2018) website.

Table 8.1: Energy meters at Ryen, with the utilities and measured energy consumption for the last four years (Kinect 2018).

		Energy consumption GWh			
Meter	Interconnected utilities	2014	2015	2016	2017
Electric boiler	Electric boiler and controls	3.33	2.99	3.65	4.04
Main switchboard	Lights, compressed air, etc.	3.47	3.58	3.35	3.36
Rectifier	Power for subway trains	2.15	3.58	3.23	2.54
Switchgear	Switchgear and rail heating	1.72	2.19	3.84	3.90
Total		10.7	12.3	14.1	13.8

The measured energy consumption data presented in Table 8.1 are presented graphically in Fig. 8.2. As the workshop building is poorly insulated, the electric boiler consumes much of the total energy each year.

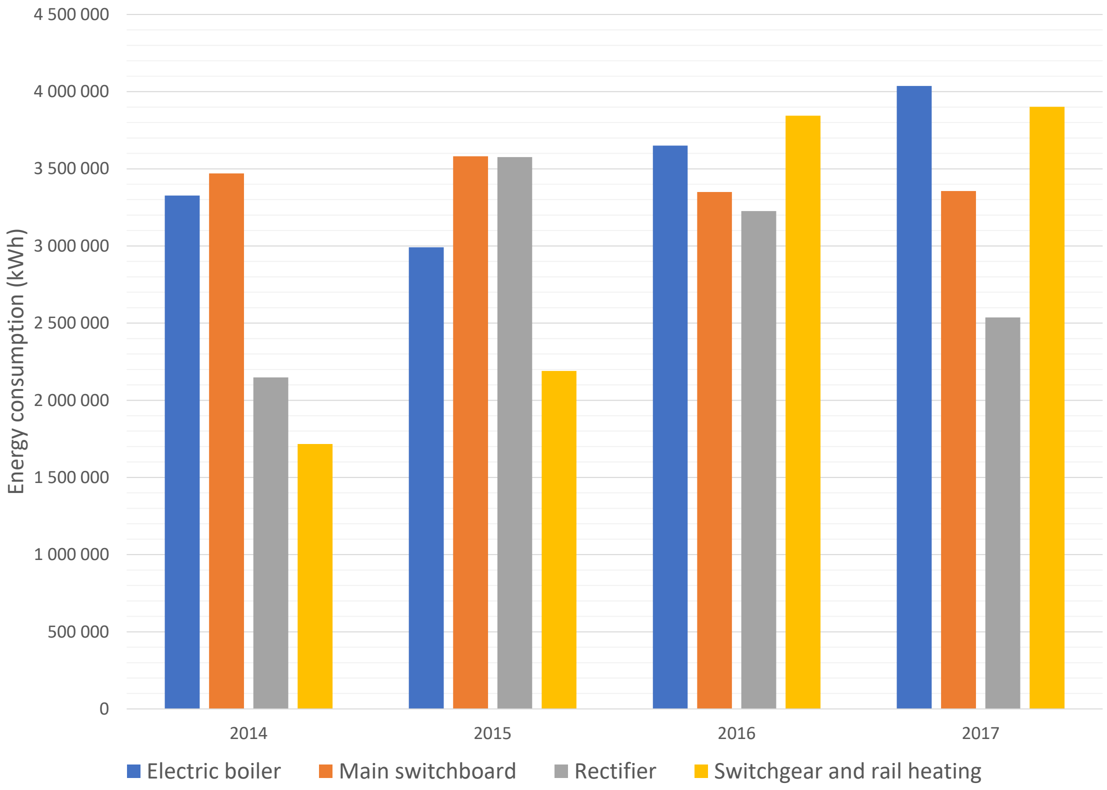

Figure 8.2: The energy consumption at Ryen workshop the last four years. Data from Table 8.1.

9. Method

This chapter explains the procedure of how HOMER was used as a simulation tool for four different system configurations for the described case. The input variables and design for each configuration are explained so thoroughly that others can also complete the simulations in HOMER.

The first section explains how the input data and variables for the model are obtained. This consist of load data, grid tariffs and economic variables that constitutes the foundation of the model and will not change in the different microgrid configurations. The different system configuration models created in HOMER are presented in the following order: First the base model, the model with solar PV systems, the model with battery energy storage system (BESS) for peak shaving purposes and finally the microgrid configuration with both solar PV systems and BESS.

9.1 Data preparation

The load data from Ryen workshop that was used are presented in Fig. 9.1. The load data used in HOMER are of hourly resolution. The load data are the average hourly load values for the last four years. The data are averaged to get the best estimated load data for the model. The data was downloaded from Kinect (2018).

The energy prices for Ryen workshop are presented in Fig 9.2. The elspot price data is downloaded from Nord Pool (2018) and have an hourly resolution. The hourly values are averaged for the last four years, just like the load data. The total cost of energy includes grid tariff, elspot price, demand rate and other taxes. However, the data have a monthly resolution, which means the total cost per kWh is the average cost of energy each month. The total cost of energy each month is the average of the cost of the last two years, because it was no data available at Kinect (2018) further back in time. The average monthly energy price was used in the model because Kinect (2018) did not offer data concerning energy cost with higher resolution.

The demand rates used in the model are presented in Table 9.1[1]. The demand rates are provided by the local distribution system operator (DSO), which is Hafs-

[1] The total cost per kWh in Fig. 9.2 got the demand rates included, so including these in the model as well causes the values to be counted twice. However, the demand rates are needed in the model, so HOMER can take into account that power have a cost just like the energy. More on this in the discussion.

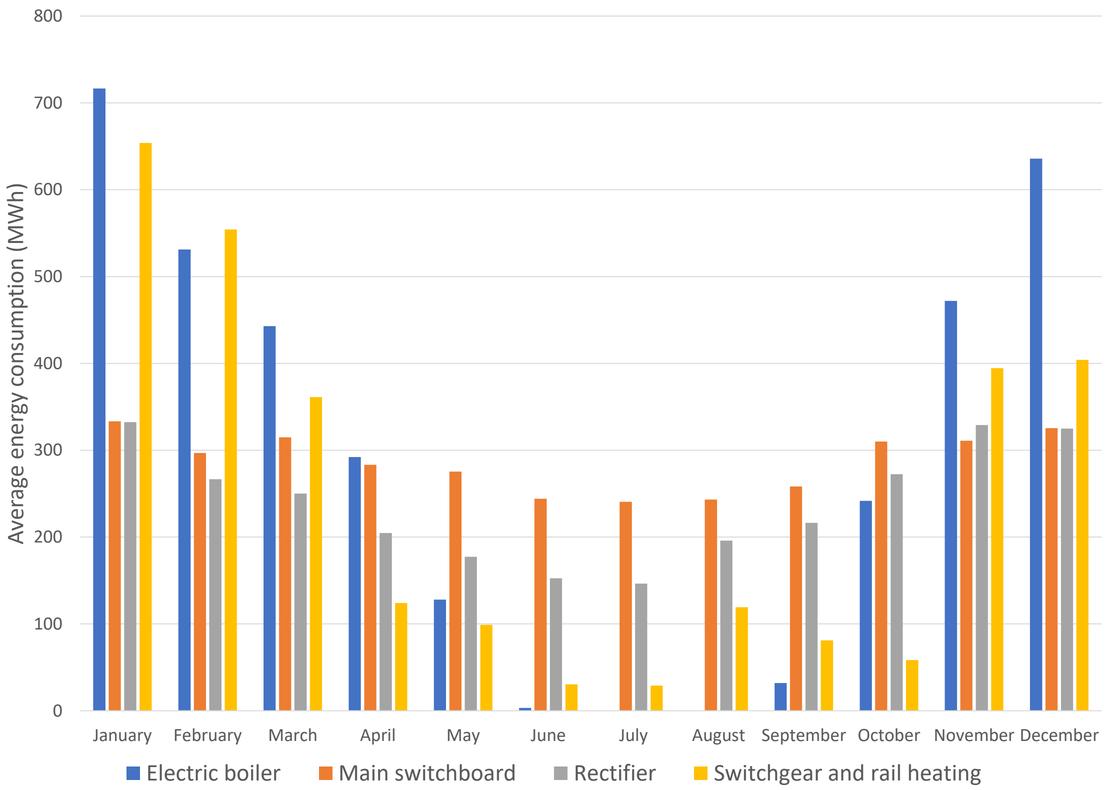

Figure 9.1: The average energy consumption at Ryen workshop the last four years, 2014 to 2017 (Kinect 2018). The average yearly consumption was calculated to 12.7 GWh.

lund in this case. The demand rates are taken from Hafslund Nett (2018) and only the low voltage rates are used in the model. The fixed fee for being connected to the main grid is not taken into account in the model. The fixed fees are of 340 kr/month for low voltage systems and 900 kr/month for high voltage systems, like the electric boiler (Hafslund Nett 2018).

The models created in HOMER require the economic variables reviewed in Chapter 7. This includes the expected inflation rate and nominal discount rate. The expected inflation rate was retrieved using statistics from Norway's central bank by taking the average of inflation rates dating back to January 2006, up to the February 2018 (Norges Bank 2018). The inflation rate was estimated to 2.1 %. As the discount rate are connected to investment risk and opportunity costs, it is not possible to find discount rates statistics as with inflation rates. Instead, it is set to a relative risk-free value of 5 %.

As the various variables are chosen with some degree of uncertainty, sensitivity analysis of the variables is conducted. An expected inflation rate interval from 1.3 % to 2.9 % was chosen based on the uncertainty in the inflation rate statistics. The discount rate varies with respect to what kind of project or investment the future cash flows are connected to. Thus, a interval of 2.5 % to 7.5 % was chosen. Table 9.2 provide a summary of the different input variables and data for the various model configurations.

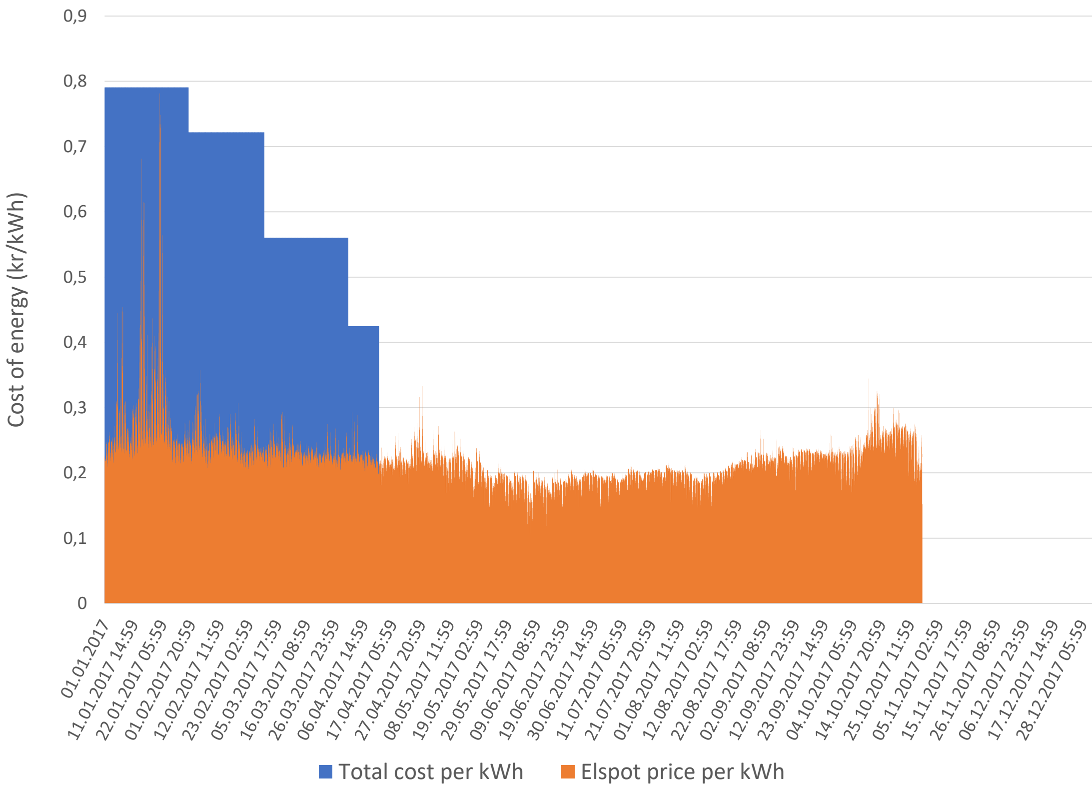

Figure 9.2: Average elspot price and average total energy cost. The elspot price is the average price the last four years (2014-2017) and downloaded from Nord Pool (2018). The total energy price is the average monthly total energy price for the last two years (2016-2017) and downloaded from Kinect (2018).

Table 9.1: Demand rates from the local DSO, Hafslund (Hafslund Nett 2018). The low voltage rates are used in the models.

	Demand rates $^{kr}/_{kW \cdot month}$	
Month	Low voltage	High voltage
January	150	122
February	150	122
March	77	50
April	19	14
May	19	14
June	19	14
July	19	14
August	19	14
September	19	14
October	19	14
November	77	50
December	150	122

Table 9.2: Overview of the input data and variables in the different model configurations in HOMER.

Variable	Lower	Expected	Upper
Expected inflation rate	1.3 %	2.1 %	2.9 %
Nominal discount rate	2.5 %	5.0 %	7.5 %
Data	Source		
Elspot rates	Average elspot prices from Nordpool		
Energy cost	Measured at Ryen workshop		
Demand rates	Given by the local DSO		
Load data	Measured at Ryen workshop		

9.2 Base model

A base model using today's configuration at Ryen workshop were simulated to compare the simulation results to the current state. The schematic diagram of the system is shown in Fig. 9.3. The models parameters are the same as in the previous section.

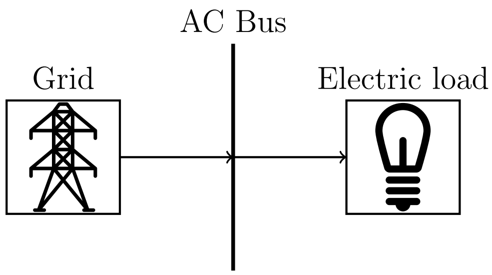

Figure 9.3: Schematic diagram of the base model created in HOMER. The model describes today's condition at Ryen workshop. The load is the sum of the average measured energy (2014-2017) for the four energy meters at Ryen.

9.3 Model with solar PV

As explained in Chapter 5, a microgrid have to be self-sufficient with power for periods in time to enter island mode. With no energy storage or controllable DGs, this is not possible in most cases. However, it is interesting to add only a solar PV system, as many do this and sell surplus energy to the grid. The investment cost of the solar PV system was taken from COWI's experience with designing solar PV system of similar size, which was 1700 $^{kr}/_{m^2}$ to 2000 $^{kr}/_{m^2}$. The investment cost is the total price for the system, including the solar modules, wiring, installation and converter costs. The expected investment cost of solar PVs was chosen to be equal 1850 $^{kr}/_{m^2}$, with lower and upper sensitivity investment cost of 1700 $^{kr}/_{m^2}$ and 2000 $^{kr}/_{m^2}$, respectively. The yearly operation and maintenance cost was set equal to 5 % of the investment cost (Berner 2013). The investment cost is applicable for standard mono crystalline solar modules with a capacity of approximately 270 watt peak (Wp) and an efficiency of about 15 %.

The solar PV system is modelled in HOMER as a generic flat panel using the technical data of the REC 270TP. The converter is modelled as a large, free converter, since the cost of the converter is already included in the price of the solar PV modules. The converter's efficiency is 95 % for both input and output. The converter's capacity is 100 % relative to the solar PV capacity. The solar PV investment cost is given in cost per installed capacity in HOMER. Thus, the solar PV investment cost was calculated to 10853 ± 880 kr/kWp installed capacity when assuming solar PV modules rated to 270 Wp and efficiency of 16.4 %. The operation and maintenance cost was calculated to 217 ± 18 kr/kWp per year. A schematic diagram of the system modelled in HOMER is given in Fig. 9.4.

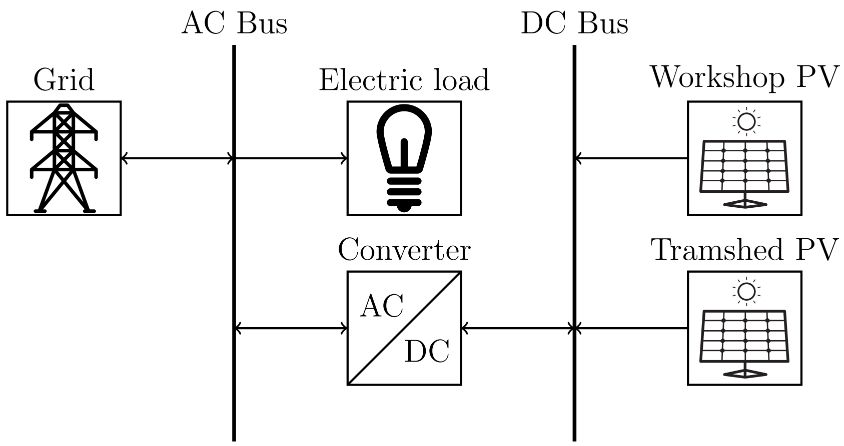

Figure 9.4: Schematic diagram of the model in HOMER with solar PV. As the system can not be self sustained with power, it is not a microgrid per se, but an active distribution system.

The power production of solar PV systems is proportional with the solar irradiation when modelled in HOMER, as stated in Equation 6.1. However, it exists some effects that lower the solar PV's power production (Berner 2013). An effect is ohmic losses in wires, cells and busbars which result in heat loss. There is also some degree of mismatch in generation at maximum power point (MPP) because solar PV modules have a slightly different generated current. The maximum generated current in a string of modules that are connected in series cannot exceed the current generated by the solar PV module that generate the lowest current at MPP. Solar PV systems experience some derating due ageing, and losses because of soiling and snow. These effects are accounted for in the derating factor in the model. The ambient temperature influences the solar PV modules efficiency as well. Thus, meteorological data is needed in the model. The data are taken from the HOMER built in data for the Ryen workshop's location. The data consist of average monthly values over the 22-year period from July 1983 to June 2005. The temperature and solar irradiation data are obtained by National Aeronautics and Space Administration (NASA) Surface meteorology and Solar Energy.

The workshop building has the most suitable rooftop for installation of solar PV panels because of its south facing sawtooth-shape. The incline angle varies from 23 degrees to 30 degrees. However, the optimal angle for a solar PV system without tracking is about 46 degrees (PVGIS 2018). The average incline angle is calculated to 27 degrees for the workshop roof. The total area of the roof is calculated to approximately 6500 m^2. As the solar PV modules are not able to fill the whole area, it is estimated that the roof has room for a total of 2556 solar PV modules. This constitutes a total installed power capacity of 690 kWp. The rooftop of the Tramshed have an area of 10570 m^2. However, the roof is flat, so the solar PV modules will be installed in horizontal position. It is assumed an effective area utilisation of 50 %, as it is needed some space between solar modules and walkways for rescue personnel in case of fire. The Tramshed's rooftop is estimated to be capable to have a maximum of 860 kWp of solar PV capacity. The standard ground reflectance in HOMER of 20 % is used for the solar PV system at the workshop, considering its incline angle. However, the ground reflectance for the solar PV system at the Tramshed is set to zero because of its horizontal inclination. The derating factor is set lower to account for a longer snow cover. The input values for the solar PV systems in the HOMER model are given in Table 9.3.

Table 9.3: Summary of the input variables for the solar PV systems in the model.

Variable	Lower	Expected	Upper
Investment cost	9973 kr/kWp	10853 kr/kWp	11733 kr/kWp
O&M costs	199 kr/kWp	217 kr/kWp	235 kr/kWp
Constants	**Tramshed**		**Workshop**
Solar PV module		REC 270TP	
Nominal power		270 W	
Efficiency at STC		16.4 %	
Temperature effects on power		-0.36 %/°C	
Nominal operating cell temperature		44.6 °C	
Converter efficiency		95 %	
Economic lifetime		25 years	
Derating factor	85 %		90 %
Solar module inclination	0 degrees		27 degrees
Ground reflectance	0 %		20 %
Total PV capacity	860 kW		690 kW

9.4 Peak shaving model

The peak shaving model was used to investigate the economic feasibility of an energy storage system (ESS) used to lower the peak load at Ryen. The schematic diagram of the system is presented in Fig. 9.5. The electrical load and converter is unchanged from the solar PV system model. However, an ESS consisting of numerous batteries are added for peak shaving purposes. Constraints to the peak demand the grid is able to deliver each month is added as well. The goal were to lower the peak demand to reduce the demand costs presented in Table 9.1.

The energy storage unit model is based on a lithium-ion battery ESS (BESS)

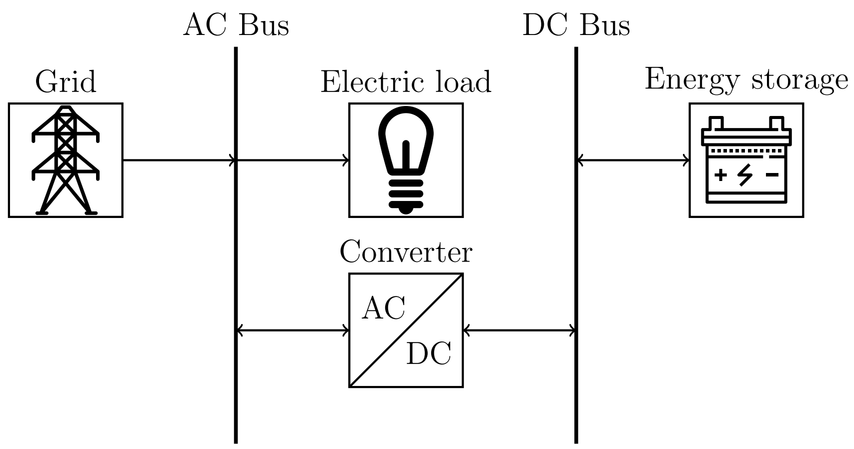

Figure 9.5: Schematic diagram of the peak shaving model.

from ABB. It is a container solution with 10 parallel strings of 14 batteries, i.e. a total of 140 batteries. It is a "plug and play" solution where the converters, control systems and installation are included in the price. Thus, the same large, free converter do not need to be changed in the model. The investment cost of the system is 5.2 million kr. The batteries themselves are produced by LG Chem and modelled in HOMER as the LG Chem RESU, with a nominal capacity of 6.4 kWh. The lithium-ion battery technology will experience great cost reductions according to Naceur and Gagné (2016). Thus, it is assumed a replacement cost of 3 million kr for the BESS, as it is the batteries that will need replacement after a 10-year period, and not the whole system. The battery parameters that constitutes the BESS are presented in Table 9.4.

9.5 Microgrid model with battery storage

Integrating both the BESS and solar PV system constitutes a microgrid configuration, as the system is able to be self-sufficient with energy in periods of time. The purpose of the BESS is to overall reduce the peak power consumed from the grid and the purpose of the solar PV system is to reduce the energy consumed from the grid. The BESS can also help mitigate the intermittent power output from the solar PV system to reduce, or even deny any energy sale to the grid. This is convenient as the sell back rate is lower than the price of energy.

The system components are the same as the previous sections in this chapter. The microgrid schematic is presented in Fig. 9.6. Note that even if the BESS sets up a DC Bus voltage of 715 V, it does not influence the MPP voltage, set by the solar PV system. The battery voltage given in HOMER is mainly a tool to help with keeping track of how many batteries that are in each string.

Table 9.4: Summary of the input variables in the BESS model in HOMER.

Variable	Lower	Expected	Upper
Investment cost	5.0 M kr	5.2 M kr	5.4 M kr
Replacement cost	1.0 M kr	3.0 M kr	5.0 M kr
Battery constants	**Value**		
Nominal Voltage	51.1 V		
Nominal Capacity	6.44 kWh / 126 Ah		
Round-trip efficiency	95 %		
Maximum charge current	42 A		
Maximum discharge current	42 A		
Throughput	34 770 kWh / about 5000 cycles		
Economic lifetime	10 years (or more)		
Minimum state of charge	10 %		
BESS constants	**Value**		
Nominal capacity	901 kWh		
Usable nominal capacity	811 kWh		
Peak charge/discharge power	300 kW		
Number of batteries	140		
String size	14		
Strings in parallel	10		
DC Bus voltage	715 V		

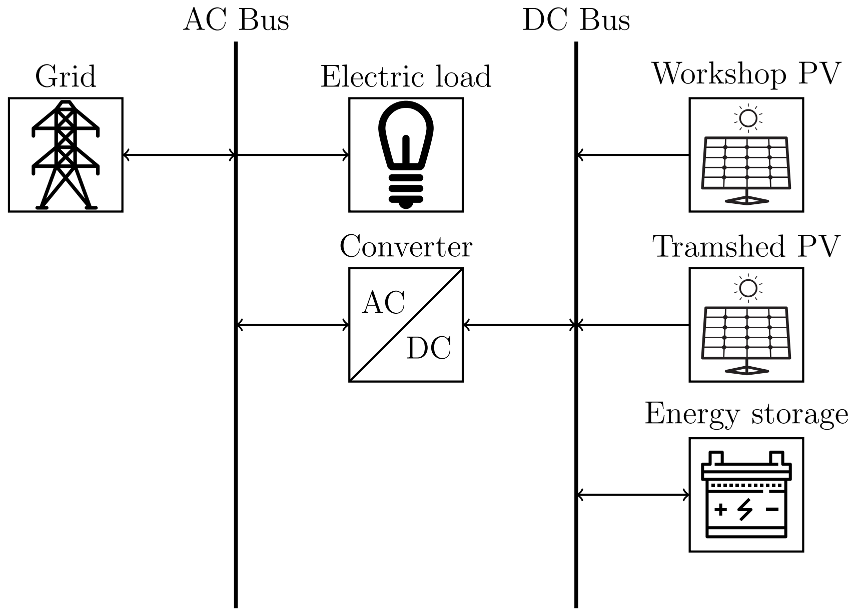

Figure 9.6: Schematic diagram of the microgrid model with solar PVs and BESS.

10. Results

This chapter present the results from the simulations of the system configurations presented in the previous chapter. The system configurations will be compared and the results not available in the system simulation reports created in HOMER will be presented. The system simulation reports for the base, solar PV, peak shaving and microgrid configuration are presented in Appendix A, B, C and D, respectively. The analysis and evaluation of the results are given in the next chapter.

The simulation results are presented in the same order as the system configurations in the previous chapter; base, solar PV, peak shaving and then the microgrid configuration. The results from the sensitivity analysis are presented after the simulation results of the system configurations. It will be referenced to figures and tables in the system simulation reports to keep the results orderly.

10.1 Simulation results

The simulation of the base model gave a LCOE of 0.762 kr/kWh. The NPC was estimated to 172 million kr and the operating cost was estimated to 9.62 million kr. The operating cost in this case consist only of the cost of energy consumed from the grid. Note that simulation results mentioned in this thesis is with the expected values for variables, like nominal discount rate and expected inflation rate, unless the variables have other specified values according to the sensitivity analysis. The results from the base model simulation conducted in HOMER are presented in Table 10.1, with the different combinations of expected inflation rate and nominal discount rate, yielding the minimum, expected and maximum NPC.

Table 10.1: Simulated system cost for the base case.

Variables	Minimum NPC	Expected NPC	Maximum NPC
Nominal discount rate %	7.50	5.00	2.5
Expected inflation rate %	1.30	2.10	2.90
LCOE kr/kWh	0.762	0.762	0.762
Operating cost kr/year	9.69 M	9.69 M	9.69 M
NPC kr	122 M	172 M	255 M

Installing a maximum solar PV capacity of 860 kWp and 690 kWp on the Tramshed's and Workshop's roof, respectively, gave a NPC of 184 million kr according to the simulation. Compared to the base model, the solar PV system gave a present worth of −11.9 million kr. The present worth is the difference in NPC between the base model and, in this case, the solar PV model. This means that the solar PV system generated a total cost of 11.9 million kr more than the base configuration. The simulation results presented in Table 10.2 are an excerpt of the different simulated solar PV capacities. It can be seen that all the configurations provide a higher NPC and LCOE compared to the base configuration.

It can be seen in Appendix A and B that the base configuration consumed 12.7 GWh, and the solar PV configuration consumed 11.3 GWh from the grid, respectively. This result is consistent with the reduced operation and maintenance cost for the solar PV configurations presented in Table 10.2, compared to the base case. Ryen would consume about 1.4 GWh less from the grid with the solar PV system of maximum capacity. This would result in about 0.6 million kr less energy costs each year at Ryen.

Table 10.2: Different solar PV capacities and costs arranged after low to high NPC. The different solar PV capacities are an excerpt of the search space used in HOMER.

Workshop PV capacity kWp	Tramshed PV capacity kWp	Investment kr	LCOE kr/kWh	NPC kr	Operating cost kr/year
100	0	1.09 M	0.765	172 M	9.66 M
690	0	7.49 M	0.781	176 M	9.50 M
500	200	7.60 M	0.783	176 M	9.53 M
0	600	6.51 M	0.785	177 M	9.61 M
690	600	14.0 M	0.802	181 M	9.43 M
690	860	16.8 M	0.810	184 M	9.41 M

It can be seen in Table 10.2 that solar PV systems at the Workshop's roof provide a lower NPC per kWp, compared to solar PV systems at the Tramshed's roof. For example, an installed solar PV system with capacity of 600 kWp at the Tramshed's roof provided a higher NPC than an installed solar PV system at the Workshop's roof and Tramshed's roof with capacity of 500 kWp and 200 kWp, respectively. The solar PV system of 690 kWp produced more energy annually, compared to the 860 kWp solar PV system at the Tramshed's roof according to the solar PV configuration system report in Appendix B, although the Tramshed roof's solar PV system had a greater capacity.

The goal with peak shaving using a standalone battery was to lower the demand costs. The simulation results are presented in Table 10.3. Using one BESS unit resulted in a 148 thousand kr decrease in demand cost. Adding another BESS unit had less effect on demand charge and a third BESS unit or more had no significant effect compared to two BESS units. Thus, the results from three or more BESS are not presented. The simulation results show that peak shaving with both one and two BESS units provided a greater LCOE and NPC than the base case.

The monthly simulated demand charge for Ryen for no BESS unit, one BESS unit and two BESS units are presented in Fig 10.1. It can be seen that peak shaving had significant effect on demand charge where the demand charge is high, i.e. winter. One BESS unit was able to lower the monthly demand charge by an average of

Table 10.3: Results from the peak shaving model simulation with one and two BESS units.

No. of BESS units	Demand cost decrease kr/year	Investment kr	LCOE kr/kWh	NPC kr	Operating cost kr/year
1	147551	5.2 M	0.788	178 M	9.72 M
2	181761	10.4 M	0.823	185 M	9.75 M

11 %, while two BESS units was able to lower the monthly demand charge by an average of 16 %. Two BESS units preformed about 5.5 % better than one BESS unit on average. The BESS units were most effective at peak shaving in the mid-year. Where one BESS unit was able to lower the peak power consumption relative to the grid by 20 % in August, and two BESS units was able to lower the peak power consumption by 22 % in July. However, this did not constitute a significant effect on the decrease in total demand cost as the demand charge was equal 19 kr/kW · month in the summer (see Table 9.1). Two BESS units had the best effect relative to one BESS unit in December. The monthly peak demand can be found in Appendix C.

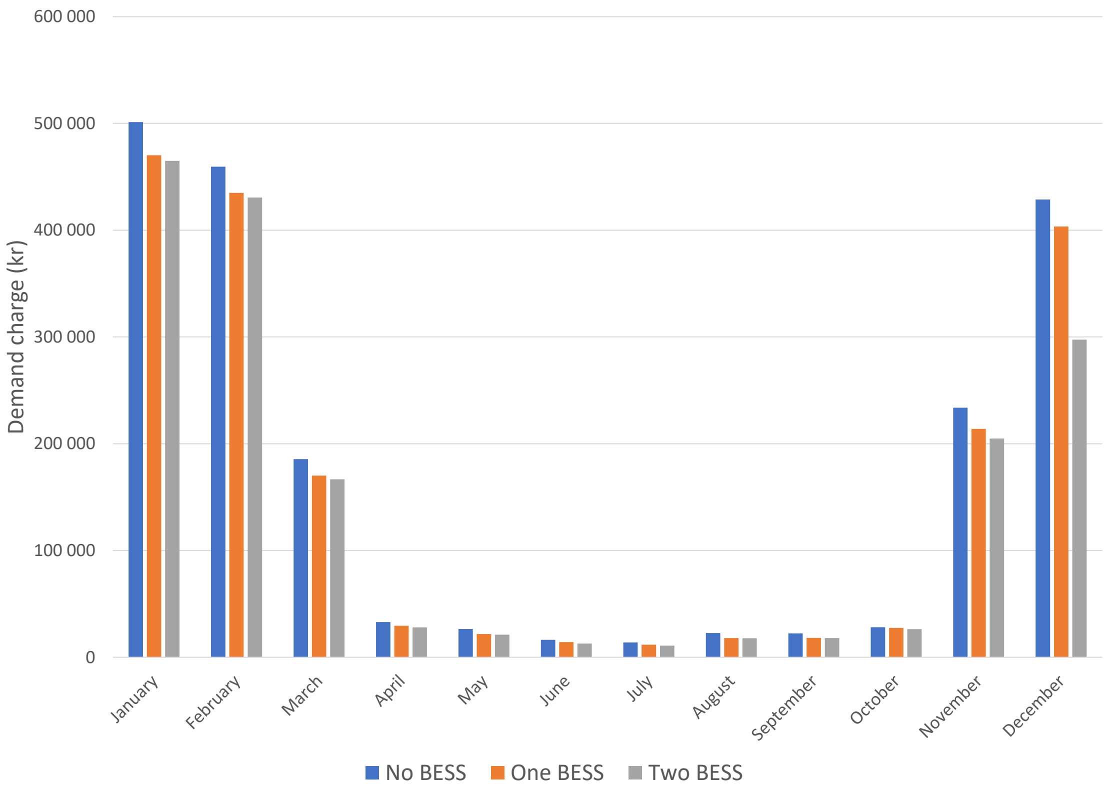

Figure 10.1: The effect of BESSs on demand charge when peak shaving.

The NPC for the microgrid configuration with one and two BESS units was simulated to 190 million kr and 191 million kr, respectively. This means that the microgrid configuration with one BESS gave a present worth of −18 million kr and the microgrid configuration of two BESSs gave a present worth of −19 million kr. With solar PV systems combined with one BESS unit in a microgrid configuration, the average peak demand was reduced to 3100 kW (35 kW less compared to the peak shaving model with one BESS). However, the total demand cost was about 100 thousand kr over the peak shaving model. Two BESSs reduced the average peak demand another 50 kW, namely 3050 kW. This system gave the lowest total demand cost of 1.79 million kr, 13 thousand kr lower than the peak shaving model with two BESSs. It can be seen in the HOMER system simulation report in Appendix D that the BESS units was not able to store any surplus energy from the solar PV systems. More on this in the next chapter.

The annual cash flow for all the simulated system configurations are presented in Fig. 10.2. It can be seen that the system configuration with only solar PVs, and the system configuration with one BESS unit for peak shaving provided a lower annual operation and maintenance cost than the base case. However, the two systems combined in a microgrid configuration provided a higher operation and maintenance cost except for the first five years of the system lifetime.

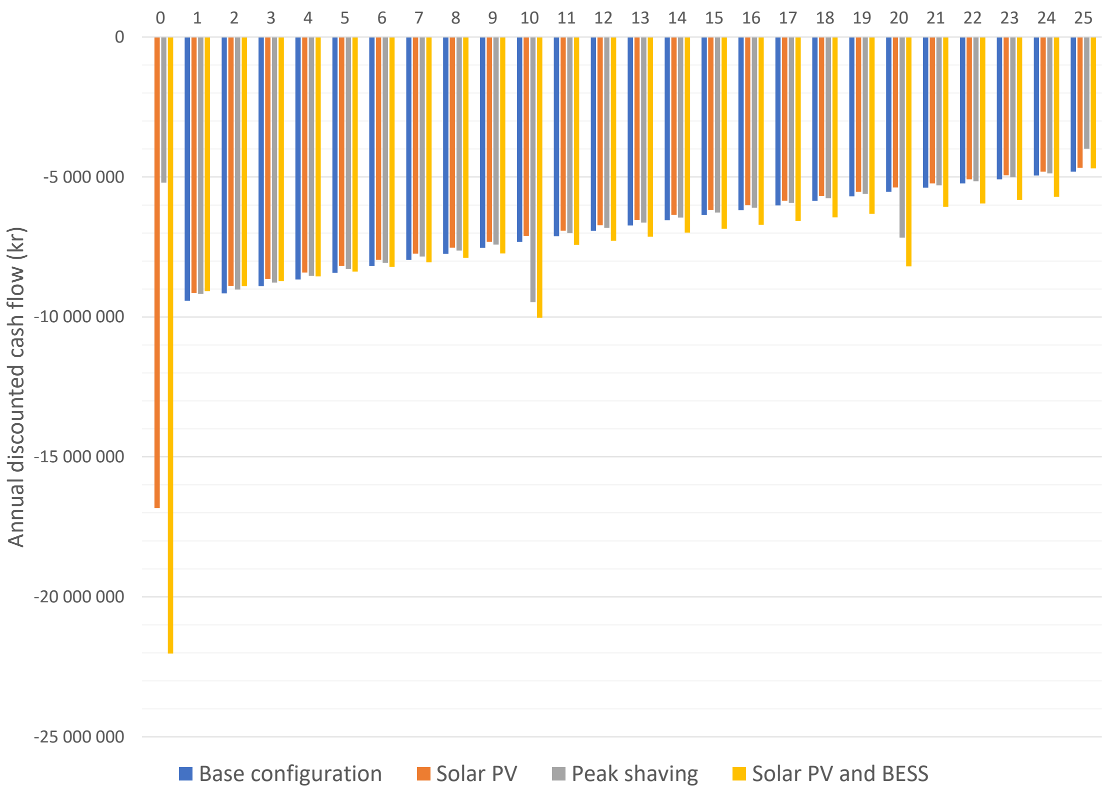

Figure 10.2: Discounted annual cash flows for the four simulated system configurations. The BESS unit have a replacement cost every 10th year.

In Table 10.4 are the key results for evaluating each system configuration presented. It can be seen that the system that provided the lowest NPC and LCOE was the base configuration, i.e the configuration of today at Ryen. Second came the configuration with one BESS unit for peak shaving with a present worth of −6 million kr. The solar PV system with maximum solar PV capacity came third with a present worth of −12 million kr. Finally, the microgrid configuration with one BESS and maximum solar PV capacity gave a present worth of −18 million kr.

Table 10.4: Simulated system cost for the different system configurations. Simulations with solar PV systems and/or BESS have maximum solar PV capacity and one BESS unit installed.

Model configuration	Investment kr	LCOE kr/kWh	NPC kr	Operating cost kr/year
Base	-	0.762	172 M	9.69 M
Solar PV	16.8 M	0.810	184 M	9.41 M
Peak shaving	5.2 M	0.788	178 M	9.72 M
Solar PV and storage	22.0 M	0.836	190 M	9.45 M

10.2 Sensitivity analysis

As there is some degree of uncertainty associated with the model input variables, a sensitivity analysis was conducted. The effect of investment cost on the total NPC for the three system configurations is presented in Table 10.5. The base configuration model is not included, as there was no investment costs for the system.

Table 10.5: Result of how investment cost affects the total NPC of the three system configurations. The NPC for the peak shaving model is for one BESS and the NPC for the microgrid configuration is for maximum solar PV capacity and and one BESS.

Variables	Min NPC	Expected NPC	Max NPC
Solar PV investment cost kr/kWp	9973	10853	11733
BESS investment cost kr/BESS	5.0 M	5.2 M	5.4 M
BESS replacement cost kr/BESS	1.0 M	3.0 M	5.0 M
NPC solar PV only kr	182 M	184 M	185 M
NPC peak shaving kr	176 M	178 M	179 M
NPC microgrid kr	187 M	190 M	192 M

Fig. 10.3 presents how all the sensitivity variables affect the total NPC of the microgrid configuration system. Note that the operation and maintenance cost sensitivity analysis for the solar PV systems are not conducted due extreme simulation time. This made no impact on the results, as the maintenance cost for solar PV systems are very low. It can be seen that the nominal discount rate and expected inflation rate have the greatest effect on the total NPC for the system. The investment and replacement cost had lesser effects, consistent with the results presented in Table 10.5.

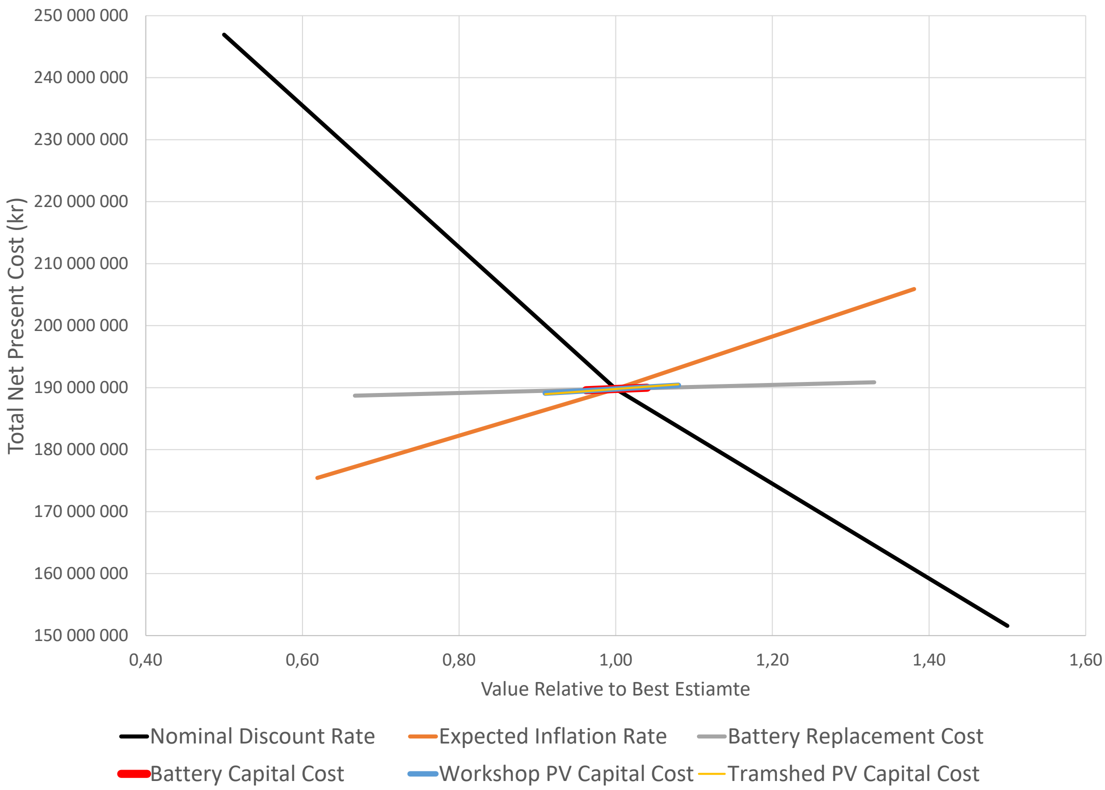

Figure 10.3: Plot of how sensitivity variables affect the total NPC for the microgrid configuration with maximum solar PV capacity and one BESS.

11. Evaluation of results

The results presented in the previous chapter will be analysed and evaluated in this chapter. The different simulated system configurations will be compared to the base case to investigate their economic feasibility at Ryen. The systems will be evaluated, and the meaning of the results will be explained. It will also be analysed why the results became as they did.

The chapter is mostly structured as the two previous chapters, starting the evaluation of the results from the simulation of the solar PV configuration, the peak shaving configuration and then the microgrid configuration. Finally, the effect of the sensitivity variables on the total system NPC is evaluated.

The NPC of the different solar PV system capacities presented in Table 10.2 are all greater than the NPC of the base model. Both the LCOE and NPC increase with increasing solar PV capacity. Thus, the solar PV system configurations are not profitable relative to the base configuration. It can be seen in Fig. 10.2 that the solar PV have a lower negative cash flow each year, relative to the base case. This might mean that the system configuration with solar PV systems do consume less energy from the grid, hence saving energy costs, but it is not enough to justify the solar PV investment cost. However, the investment cost do not affect the NPC that much according to Fig 10.3. This might mean that solar PV systems is not that feasible in Norway, at least not at Ryen with very low energy cost, which is about 0.3 kr/kWh in the summer. Thus, there is a mismatch in time between when the solar PV systems generate the most power in the summer, and when the load is high during winter. This can be seen in the figure at the last page of the system simulation report in Appendix D. About 83 MWh was sold during summer because of the low load at Ryen according to the system report in Appendix B. This is not optimal, considering the low sell back rate. However, with the sell back rate being just 0.1 kr below the price of energy during summer, this did not contribute to a higher NPC. For example, combinations of solar PV capacities that were not great enough to sell surplus power to the grid, did not provide a positive present worth compared to the base configuration.

It can be seen in Appendix A that the base system configuration generated an annual demand cost of 1.98 M kr. Thus, it was convenient to see if a battery system would be able postpone some of the peak load to reduce the demand cost. One BESS unit was able to reduce the demand cost by 148 thousand kr, as can be seen in Table 10.3. However, the system simulation results show that one BESS gave a present worth of −5.8 million kr and two BESSs gave a present worth of −14 million kr, relative to the base model. This means that the stakeholder would lose 5.8 or 14 million kr by investing in one or two BESS units, respectively, for peak shaving at Ryen. Adding more than one BESS for peak shaving purposes would only increase the NPC, as lowering the peak demand further would require a lot more energy per unit of power, as the demand last for longer periods in time.

Combining the solar PV systems with the BESS in a microgrid configuration resulted in a NPC of 190 million kr. This resulted in a net present worth of −18 million kr, relative to the base case. This means that a microgrid configuration with a solar PV system and BESS would not be economically feasible at Ryen. This was expected, considering the fact that the simulation of the BESS and solar PV system alone gave a higher NPC than the base case, i.e. a negative present worth relative to the base case. The two non-profitable systems configurations would not be profitable if integrated in the same system, unless the BESS could store the surplus energy generated by the solar PV system to avoid selling energy at the low sell back rate. However, this was not possible, as it was sold 82 MWh to the grid according to the microgrid system report in Appendix D. This can be explained by how HOMER choose to operate the BESS. The lifetime of the BESS unit is limited by both time and throughput, which means that charging and discharging the batteries will add a wear cost as explained in Chapter 6. In this case, the wear cost of the batteries was too high. Thus, as the HOMER software always aims to minimise the system cost, it was more profitable to sell the surplus energy, despite the low sell back rate. The lifetime throughput was adjusted up to investigate how storing the surplus energy from the solar PV systems would affect the total NPC of the system. It did not reduce the NPC by an significant amount. This is because the low cost of energy in the summer at Ryen, as explained earlier in this chapter.

The results presented in Table 10.1 show that the expected inflation rate and nominal discount rate have significant effect on the NPC, considering that the NPC range from 122 million kr to 255 million kr. The same can be observed from Fig. 10.3 as well. It is the highest nominal discount rate and the lowest expected discount rate that constitutes the lowest NPC. This is because the annual cash flows presented in Fig. 10.2 get discounted in a larger degree, according to Equation 7.3 and 7.4. The low expected inflation rate makes future cash flow worth less as the future purchasing power increase less rapidly. As the cash flows in the base model only consist of expenditures, the NPC decrease with a low expected inflation rate and a high nominal discount rate and increase with a high expected inflation rate and low nominal discount rate.

Based on the results, it would seem that especially the energy storage technology was not feasible at Ryen because of the BESS wear cost was too great for the BESS to store surplus power generated by the solar PV systems. This was a surprising result, considering mitigating the intermittent solar PV power production is the main reason for having any kind of energy storage system in a microgrid configuration. The Lithium-ion battery technology must improve, the cost must decrease, or a combination of both for the BESS to be viable in this case. The same can be said about the solar PV technology. However, as the investment cost of the different energy production and storage technologies did not have that much effect on the NPC of the different system configurations, it would seem that the technology is not that suitable in Norway. This is because of the low price of energy and demand charge, in addition to low load during summer when the solar PV systems produce the maximum power.

12. Discussion

The uncertainty in model variables and the simulation results will be discussed in this chapter. The simulation results will be compared to previous work done by others, which is presented in Chapter 2. It will also be attempted to generalise the simulation results of the simulation case for Norway in general.

This chapter is divided in three pars. First, the different assumptions and uncertainty is addressed. Then the results will be discussed and compared to previous research. Finally, a brief discussion of other benefits than profitability of the renewable technology systems addressed in this thesis will be given, and how these technologies may become more viable in the future.

12.1 Assumptions and uncertainties

Hafslund also take a fixed fee for being connected to the main grid each month, in addition to the demand rates and cost of energy. The fixed fee is not taken into account in the model because it would be the same for all the simulated systems and not contribute to a difference between models. As the fixed fee of 340 kr to 900 kr per month, plus 1592 kr per year, is small relative to the cost of energy and demand rate of about 8 and 2 million kr per year, respectively, the absence of the fixed fee in the model should not make a significant effect on the simulation results.

The demand rate at Ryen workshop has two different rates, as there is a high voltage system (electric boiler) and a low voltage system. However, in HOMER it is only possible to add the demand rates to the grid, not the load. The low voltage demand rates were used because the majority of power is used by low voltage loads. Considering the electric boiler makes a big contribution to the overall power consumption, the demand rates could have been weighted according to the proportion of total power consumption measured by the four power meters. However, this was not done because the same demand rates are used for the different models.

The total energy cost data was of monthly resolution, and not of hourly resolution like the load and elspot price data. Thus, it was not possible to account for price variations during the day, nor month. This made it impossible to simulate grid arbitrage, where cheaper energy could be stored and sold or used later in the day when the energy could be more expensive. As mentioned in Chapter 9, the total energy cost have the demand rates included. This means that the demand rates are accounted into the energy consumption and not the power consumption like they should. This is the reason why the demand rates are added in HOMER as well, so the control strategies of the battery energy storage (BESS) can account for the demand rates. This was mandatory for peak shaving.

The nominal discount rate was set to a risk-free value of 5.0 %. The value was taken from Berner (2013) and Sarker (2016), which also was similar of value that Bøe (2017) used. As the discount rate often is compared to the interest rate because the alternative to an investment is storing the money in the bank, the lower sensitivity nominal discount rate was set to 2.5 %, which was equal to the interest rate given by the Norwegian central bank at the time of writing (March 2018). As this was a 2.5 % difference from the expected discount rate, it was appropriate to study an upper sensitivity discount rate of 7.5 %.

The investment cost of solar PVs is given as a total cost, which includes cost connected to installation, converters, wiring, etc. This can make the model less accurate, because the lifetime of today's converters is often assumed to be around 15 years, and not 25 years like the solar PV modules themselves. However, some converter suppliers can provide an extended warranty up to 25 years, where the supplier is responsible for the extended warranty and must provide routine inspection and maintenance (Berner 2013). This is not common in Norway, as most suppliers do not have a developed network of service professionals. It is a challenge to provide an investment cost for converters when the solar PV system design is not set. The system could be designed to use for example one single central inverter, or several micro converters. As this thesis do not address in-depth system design, it was more convenient to have a solar PV investment cost that included all components. It is also important to state that converters usually have the same lifetime as the solar PV modules (Berner 2013). Berner (2013) estimated the investment cost for solar PV systems to 18 000 kr/kWp in 2013. It has been observed a great drop in costs for solar PVs since then (International Energy Agency 2017). Thus, the estimated investment cost for solar PVs of 10 853 kr/kWp used in this thesis is consistent according to the cost reductions the last five years.

The BESS from ABB was chosen because COWI had received an offer for this particular BESS before for another project. This made the investment cost more accurate than other energy storage systems available in Norway. However, information about replacement, and operation and maintenance cost were uncertain, hence the greater range in sensitivity variables for the replacement cost compared to investment cost. The replacement cost of the batteries was set a little lower than the investment cost, as it was the batteries which had the lowest expected lifetime of 10 years. It has also been observed a price drop in Lithium-ion batteries the last couple of years which may continue (Naceur and Gagné 2016). Thus, it was assumed a lower replacement cost, relative to the investment cost. The operation and maintenance cost were set to zero, as batteries often are assumed to be maintenance free during their lifetime. This is not necessary true. For example, ABB advice to have an available spare battery for the BESS, which may indicate that some battery cells can have shorter lifetime than expected. There may also be maintenance cost connected to system control and required software updates.

It was not possible to add sensitivity variables for the cost of energy and sell back rate (elspot price) in HOMER. Thus, it was not possible to take the rising cost of energy into account. However, the price of energy may not increase that much the next years. Bøhnsdalen et al. (2016) predict a 30% increase in cost of energy towards 2030.

The Tramshed and Workshop building at Ryen might need to be reinforced before solar PV systems can be installed. However, it is assumed that the solar PV systems can be installed on the Tramshed's and Workshop's roof as they are today. Thus, only the investment costs of the solar PV systems are accounted for when investing in the systems. It would be appropriate to insulate especially the workshop building better, as a lot of heat escapes the building. However, this is not investigated in this thesis.

12.2 Generalisation of results and comparison to previous work

The results presented by Bøe (2017) showed that a solar PV system was not economic feasible, even when the simulated case used a much smaller solar PV system compared to the solar PV systems in this thesis. Bøe (2017) concluded that a solar PV system was not economic feasible, as the solar resources was to scarce in Norway. The results also showed that the solar PV capital cost affected the NPC and LCOE in a small degree. Sarker (2016), Kolhe, Ranaweera, and Gunawardana (2013), Sen and Bhattacharyya (2014) and Hafez and Bhattacharya (2012) used HOMER to simulate a remote microgrid, which is not directly comparable with the one in this thesis, as it is grid connected. However, the results show that the simulated cases got a much higher LCOE than a grid connected system.

Results from the other work presented in Chapter 2, and mentioned above corresponds to the findings in this thesis. Solar PV systems are not well suited in Norway because the maximum production takes place in the summer, when the price of energy and load is low. Thus, the stakeholder saves little per kWh in the summer when the solar PV system's power production is at maximum. This means that the solar PV investment cost do not greatly affect the NPC of the whole system and the cost of solar PV systems must be much lower to be profitable in Norway, as solar resources throughout the year is low. For example, reducing the investment cost of the solar PV systems in the solar PV model to only 4000 kr/kWh (about 60 % less than expected), gave a present worth of 1 million kr relative to the base model and a payback time of the system equal 15 years. Solar PV systems would become much more viable in Norway if the price of energy during summer became much higher relative to the solar PV investment cost. This is the same result that was found by Bøe (2017).

According to the simulation results of the microgrid configuration, the Lithium-ion electrochemical battery technology is not mature enough for system configurations in Norway where the energy throughput is high. This is another effect of the low cost of energy and demand charge during summer when the solar PV systems generate the most power. The system wear cost of the battery was too high to save the energy for later. I.e. the wear cost of discharging the battery was higher than the low cost of energy in the summer, relative to the cost of energy during winter. This is the result of a high replacement cost, which leads to a high battery wear cost. However, the simulations done in this thesis have only been done with one type of BESS unit, so there might be other BESSs that are more suitable for the simulated case. The BESS used in the simulations did best for peak shaving purposes, compared to mitigating the intermittent solar PV power output. This can be explained by the high battery wear cost, but also the relative low amount of annual sold energy to the grid with the solar PV systems with the biggest capacity. Considering that the solar PV system produced about 1.5 GWh and sold only 83 MWh annually. The BESS did not provide a positive present worth, but it did lower the total demand charge by a significant amount. For example, peak shaving with one BESS would result in a present worth of 1 million kr if the demand charge were to increase three times as much compared to today when keeping the investment and replacement cost constant or reducing the investment and replacement cost by 75 % when keeping the demand charge constant.

12.3 Feasibility of the system configurations

The system configurations could be suitable in cases where the main goal of the system is something else than being being profitable, like lowering the carbon footprint or providing better power quality. The main purpose of renewable energy technology is producing clean power, which lower the carbon footprint. This is the reason why there is investment subsidies given by Enova in Norway, so stakeholders may invest in renewable energy without having to invest in a non-profitable system. This is usually the case in Norway, as renewable technology like solar PVs and energy storage is not suitable in Norway with relative low cost of energy compared to other countries.

Especially BESSs may be feasible in areas where there are power quality issues in the power grid. As explained in Chapter 6, BESS choose the power factor to contribute to power quality efficiently, either stand-alone or in a microgrid configuration. This means that a microgrid could help to contribute with better power quality at its point of interconnection to the grid. It will be interesting to see in the future if local distribution system operators (DSOs) would give investment subsidies to systems that contribute to better power quality in areas where the power quality is shifting.

Even if a solar PV system was not profitable in this particular case at Ryen, solar PV systems can be more suitable in other cases in Norway, or in the future when the technology is improved (better efficiency) or lower investment cost. Solar PV systems could also become more profitable in Norway if the price of energy (especially in the summer) were to increase. As both the price of energy will increase (Bøhnsdalen et al. 2016), and solar PV cost will decrease (International Energy Agency 2017), solar PV systems may have a have a brighter future in Norway. The same goes for the Lithium-ion battery technology (Naceur and Gagné 2016).

13. Conclusion and future work

The scope of this thesis was to investigate if microgrid configurations consisting of solar PVs and energy storage capabilities is economically feasible in Norway. Three system configurations in addition to the base configuration was simulated in the HOMER Pro software; two solar PV systems, battery energy storage system (BESS) for peak shaving purposes and a microgrid configuration consisting of solar PVs and BESSs. The simulated case was a workshop for underground trains at Ryen in Oslo, owned by Sporveien.

One of the greatest challenges was finding relevant research done by others to compare results. There might not be any published work that investigate the economic feasibility of renewable energy production technologies and microgrid configurations like this thesis. At least not to the knowledge of the author. This thesis separate itself from previous work done by others by analysing the feasibility of the simulated systems in the industry sector in Norway, while the work presented in the literature review in Chapter 2 is with focus on the private sector, the research is conducted in other countries or the analysed cases are rural systems where the cost of energy is usually higher compared to a grid connected system. Some of the research is outdated because of great price reductions for the energy production and storage technologies the last couple of years.

13.1 Conclusion

Simulation of the base model gave a net present cost (NPC) of 172 million kr and a levelized cost of energy (LCOE) of 0.762 kr/kWh. The base system had an operation and maintenance cost of 9.69 million kr, which is the cost of energy that the buildings at Ryen consumed annually. The solar PV systems was able to reduce the operation and maintenance cost to 9.41 million kr. The solar PV system simulation resulted in an NPC of 184 million kr and a LCOE of 0.810 kr/kWh. The stand-alone BESS was able to reduce the annual demand charge by about 148 thousand kr. The simulation of the system gave an NPC of 178 million kr and a LCOE of 0.788 kr/kWh. The simulation of the microgrid configuration consisting of solar PVs and a BESS unit gave a LCOE of 0.836 kr/kWh and an NPC of 190 million kr.

By comparing the three system configurations to the base configuration, it can be seen that

- The solar PV system provided a present worth of -12 million kr.

- The BESS for peak shaving provided a present worth of −6.0 million kr.
- The microgrid configuration provided a present worth of −18 million kr.

This mean that none of the simulated system configurations was economically feasible at Ryen, as they provided a negative present worth. An investment in the simulated solar PV system, the BESS unit for peak shaving or the microgrid configuration would result in an economically loss of 12, 6, or 18 million kr, respectively.

The sensitivity analysis show that the expected inflation rate and nominal discount rate had the greatest effect on the NPC, but did not make any of the three systems economically feasible compared to the base configuration. The investment and replacement cost of the solar PV systems and BESS had very little effect on the NPC. This indicates that the solar PV system and BESS did not contribute to lower energy costs, or demand costs, relative to the high investment cost of the systems. It may seem that the investment cost is too high for solar PV systems, relative to the low cost of energy in Norway during summer when solar PV systems produce most power. The Lithium-ion battery technology used in the BESS, might not be mature enough for a system with similar load characteristics as the buildings at Ryen. The investment cost was too high relative to the low demand charge for the BESS to be economically feasible. The BESS was not suitable for mitigating the intermittent power production of the solar PV systems in the microgrid configuration, as the battery wear cost of discharging was higher than the sell back rate during summer.

Solar PVs and energy storage systems may be feasible in Norway for other purposes than profit. For example, it is given investment subsidies to renewable energy projects that either lower the energy consumption, or carbon footprint by Enova in Norway. The investment subsidy is intended to lower the investment cost, so the system would not be an expense for the investor, i.e. a present worth of minimum zero.

13.2 Questions for future research

Even if a microgrid configuration consisting of solar PVs and BESSs might not be economically feasible in Norway, there may exist other microgrid configurations that are economically feasible. Naturally, there is an increased energy consumption in the winter. Thus, if a systems purpose is to utilise solar energy, it would be convenient to save the solar energy until winter to fully utilise it. This is possible by using solar collectors that convert the solar energy to heat, which can be stored in the ground and used when needed. Solar collectors have a very varied efficiency but have in general a much better efficiency than solar PVs (unless the ambient temperature is low), as it is easier to convert solar energy to heat, instead of electricity. However, storing energy in the ground may have a much lower efficiency than a battery. Unfortunately, it was not possible to model solar collectors in HOMER, but it would be interesting to investigate if a system consisting of solar collectors paired with thermal storage capabilities is more suitable in Norway, compared to solar PVs paired with battery storage.

The system configurations simulated in this thesis was not economically feasible. However, similar systems might be more suitable for other cases with different grid and load characteristics. BESSs may be economically feasible where more extreme demand peaks take place for short periods of time and solar PV systems might be suitable where the cost of energy is higher during summer. It is possible model many other power production and storage technologies relevant for microgrid configurations in addition to the ones used in this thesis, and it would be very interesting to implement the HOMER Pro software on other scenarios to investigate the economically feasibility of other systems.

It would also be interesting to investigate if there exist areas in the power grid in Norway where microgrid configurations or BESSs is a better alternative to invest in new, or several transmission lines. If the increase of the number of electric cars will continue, it might be suitable to install BESSs in rural areas in Norway at electric car charging stations to mitigate the varying demand of power in the distribution grid. Systems like these could be paired with solar PV systems to reduce the energy consumption as well.

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A. Base simulation report

System Simulation Report

www.homerenergy.com

File: base_model.homer

Author: Christian Olsen Rendall

Location: Vårveien 55, 1182 Oslo, Norway (59°53,6'N, 10°48,2'E)

Total Net Present Cost: kr 171 698 100,00

Levelized Cost of Energy (kr/kWh): kr 0,762

Notes: Base model and simulation of the configuration of today at Ryen Workshop. This work is for Christian Olsen Rendall's master's thesis 2018.

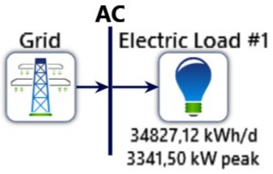
Sensitivity variable values for this simulation

Variable	Value	Unit
ExpectedInflationRate	2,10	%
NominalDiscountRate	5,00	%

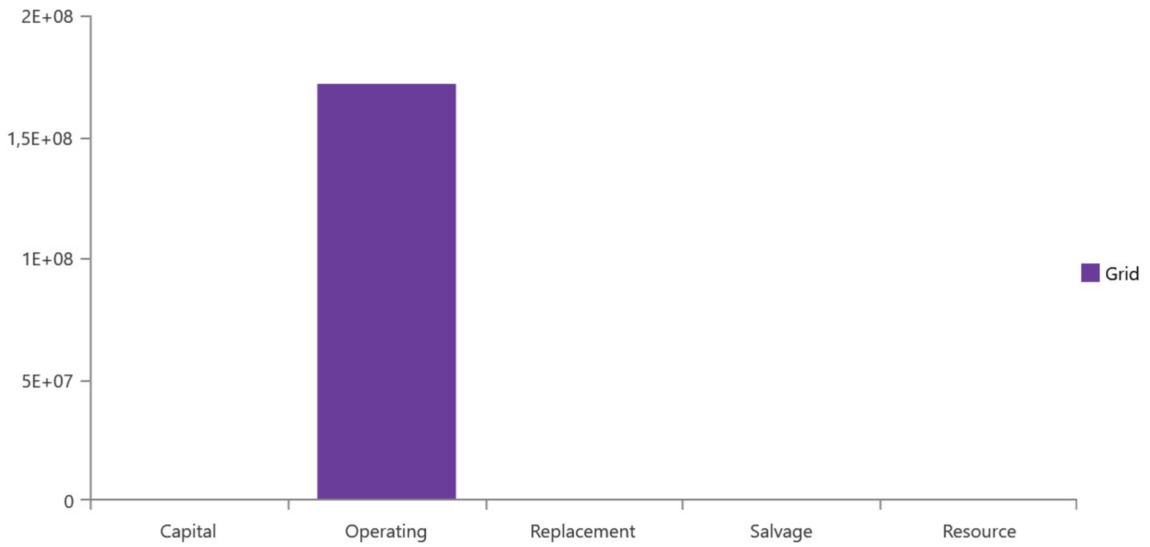
System Architecture

Component	Name	Size	Unit
Grid	Grid	999 999	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



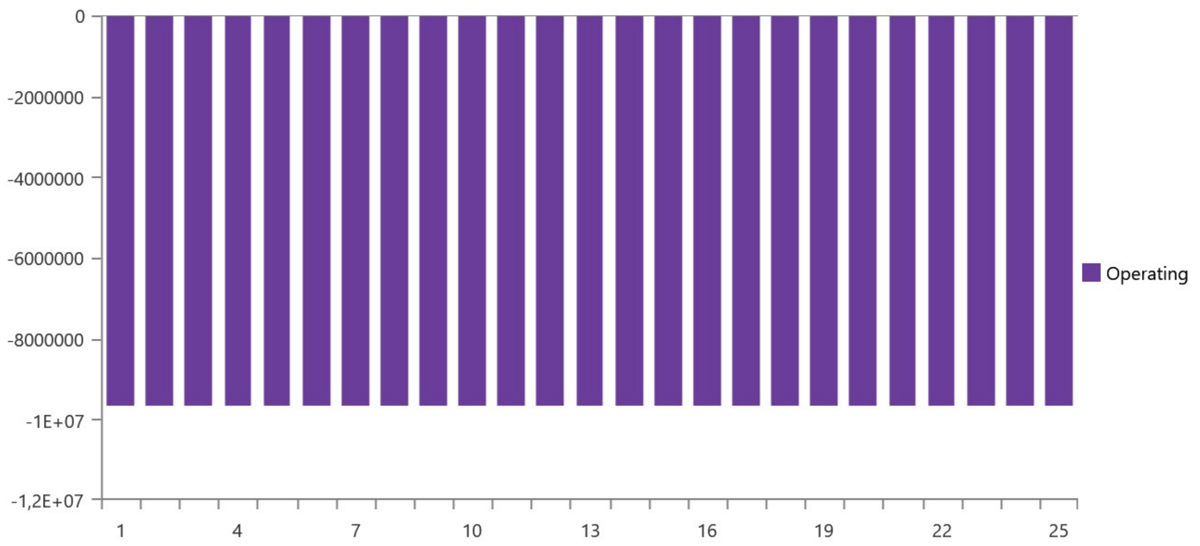
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	kr 0,00	kr 172M	kr 0,00	kr 0,00	kr 0,00	kr 172M
System	kr 0,00	kr 172M	kr 0,00	kr 0,00	kr 0,00	kr 172M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	kr 0,00	kr 9,69M	kr 0,00	kr 0,00	kr 0,00	kr 9,69M
System	kr 0,00	kr 9,69M	kr 0,00	kr 0,00	kr 0,00	kr 9,69M

Cash Flow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7
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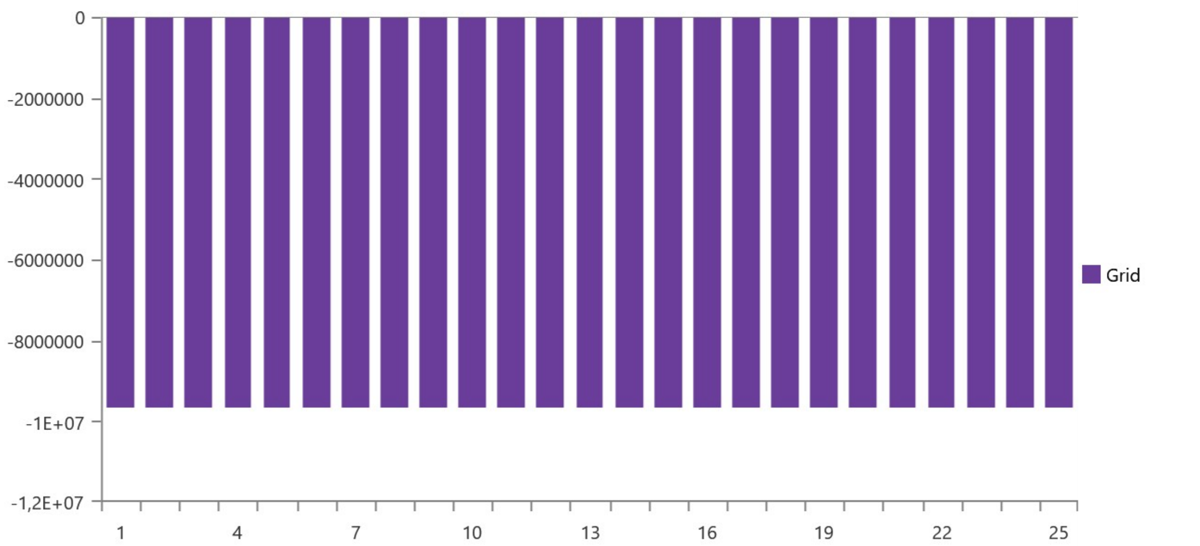
19
22
25
Operating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-6000000
-8000000
-1E+07
-1,2E+07
1
4
7
10
13
16
19
22
25
Grid

Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Grid Purchases	12 711 899	100
Total	12 711 899	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	12 711 899	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	12 711 899	100

Grid: Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	3 342	kr 0,00	kr 501 225
February	0	0	0	3 063	kr 0,00	kr 459 488
March	0	0	0	0	kr 0,00	kr 0,00
April	0	0	0	0	kr 0,00	kr 0,00
May	0	0	0	0	kr 0,00	kr 0,00
June	0	0	0	0	kr 0,00	kr 0,00
July	0	0	0	0	kr 0,00	kr 0,00
August	0	0	0	0	kr 0,00	kr 0,00
September	0	0	0	0	kr 0,00	kr 0,00
October	0	0	0	0	kr 0,00	kr 0,00
November	0	0	0	0	kr 0,00	kr 0,00
December	0	0	0	2 858	kr 0,00	kr 428 683
Annual	0	0	0	3 342	kr 0,00	kr 1,39M

Grid rate: Demand 2

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	kr 0,00	kr 0,00
February	0	0	0	0	kr 0,00	kr 0,00
March	0	0	0	2 410	kr 0,00	kr 185 589
April	0	0	0	0	kr 0,00	kr 0,00
May	0	0	0	0	kr 0,00	kr 0,00
June	0	0	0	0	kr 0,00	kr 0,00
July	0	0	0	0	kr 0,00	kr 0,00
August	0	0	0	0	kr 0,00	kr 0,00
September	0	0	0	0	kr 0,00	kr 0,00
October	0	0	0	0	kr 0,00	kr 0,00
November	0	0	0	3 035	kr 0,00	kr 233 714
December	0	0	0	0	kr 0,00	kr 0,00
Annual	0	0	0	3 035	kr 0,00	kr 419 304

Grid rate: Demand 3

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	kr 0,00	kr 0,00
February	0	0	0	0	kr 0,00	kr 0,00
March	0	0	0	0	kr 0,00	kr 0,00
April	0	0	0	1 737	kr 0,00	kr 32 998
May	0	0	0	1 398	kr 0,00	kr 26 553
June	0	0	0	860	kr 0,00	kr 16 340
July	0	0	0	720	kr 0,00	kr 13 685
August	0	0	0	1 195	kr 0,00	kr 22 700
September	0	0	0	1 180	kr 0,00	kr 22 415
October	0	0	0	2 008	kr 0,00	kr 38 157
November	0	0	0	0	kr 0,00	kr 0,00
December	0	0	0	0	kr 0,00	kr 0,00
Annual	0	0	0	2 008	kr 0,00	kr 172 848

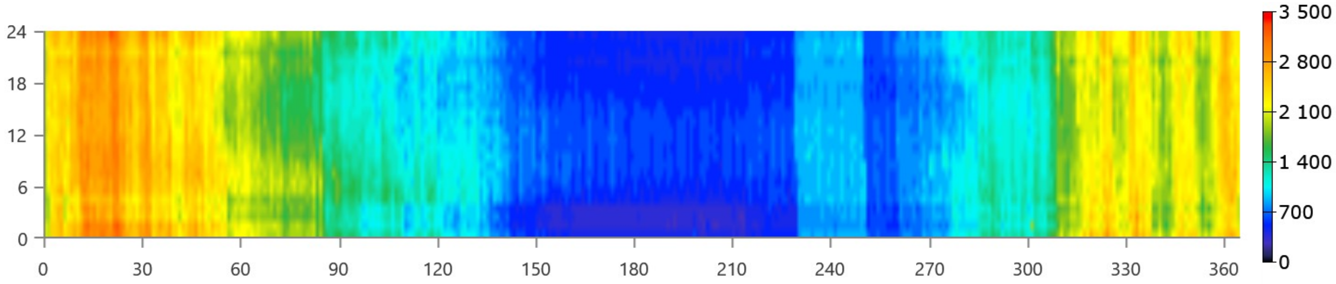
Grid rate: Rate 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2 036 127	0	2 036 127	0	kr 1,61M	kr 0,00
February	1 649 014	0	1 649 014	0	kr 1,19M	kr 0,00
March	1 370 575	0	1 370 575	0	kr 767 522	kr 0,00
April	903 897	0	903 897	0	kr 384 156	kr 0,00
May	679 018	0	679 018	0	kr 297 410	kr 0,00
June	430 321	0	430 321	0	kr 129 096	kr 0,00
July	415 918	0	415 918	0	kr 128 099	kr 0,00
August	558 741	0	558 741	0	kr 166 505	kr 0,00
September	587 694	0	587 694	0	kr 277 979	kr 0,00
October	882 984	0	882 984	0	kr 410 587	kr 0,00
November	1 507 578	0	1 507 578	0	kr 978 159	kr 0,00
December	1 690 032	0	1 690 032	0	kr 1,36M	kr 0,00
Annual	12 711 899	0	12 711 899	0	kr 7,70M	kr 0,00

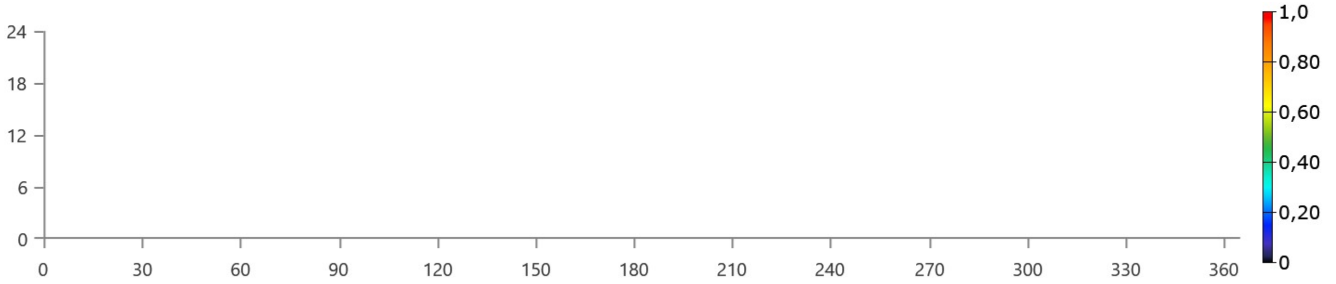
Grid rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2 036 127	0	2 036 127	3 342	kr 1,61M	kr 501 225
February	1 649 014	0	1 649 014	3 063	kr 1,19M	kr 459 488
March	1 370 575	0	1 370 575	2 410	kr 767 522	kr 185 589
April	903 897	0	903 897	1 737	kr 384 156	kr 32 998
May	679 018	0	679 018	1 398	kr 297 410	kr 26 553
June	430 321	0	430 321	860	kr 129 096	kr 16 340
July	415 918	0	415 918	720	kr 128 099	kr 13 685
August	558 741	0	558 741	1 195	kr 166 505	kr 22 700
September	587 694	0	587 694	1 180	kr 277 979	kr 22 415
October	882 984	0	882 984	2 008	kr 410 587	kr 38 157
November	1 507 578	0	1 507 578	3 035	kr 978 159	kr 233 714
December	1 690 032	0	1 690 032	2 858	kr 1,36M	kr 428 683
Annual	12 711 899	0	12 711 899	3 342	kr 7,70M	kr 1,98M

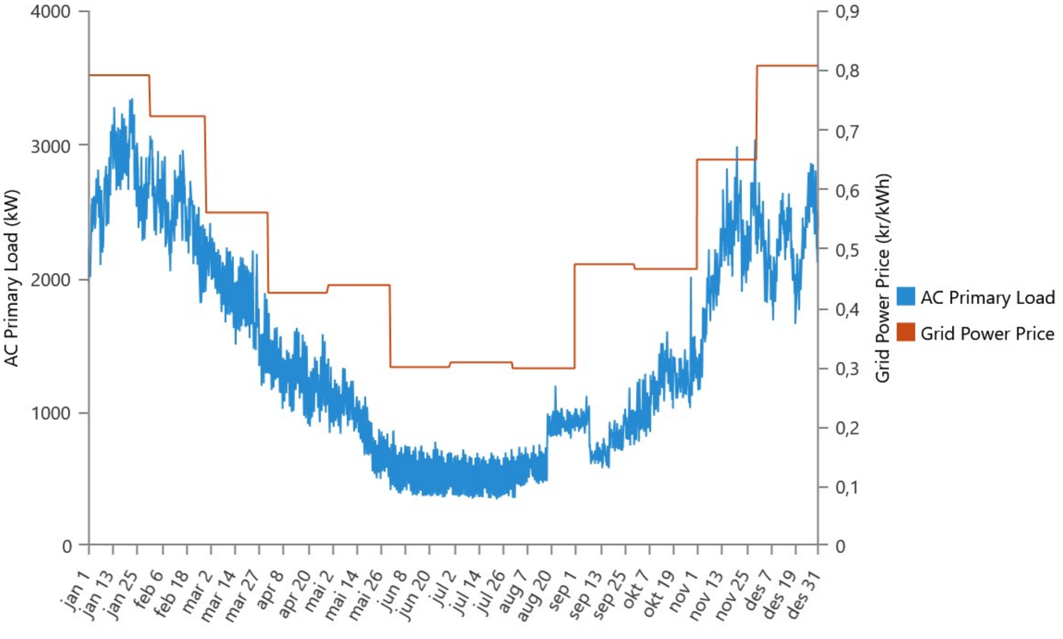
Energy Purchased From Grid (kW)



Energy Sold To Grid (kW)



Time series charts:



B. Solar PV simulation report

System Simulation Report

www.homerenergy.com

File: solarPV_model.homer

Author: Christian Olsen Rendall

Location: Vårveien 55, 1182 Oslo, Norway (59°53,6'N, 10°48,2'E)

Total Net Present Cost: kr 183 628 000,00

Levelized Cost of Energy (kr/kWh): kr 0,810

Notes: Model and simulation of Ryen workshop with solar PV systems. This work is for Christian Olsen Rendall's master's thesis 2018.

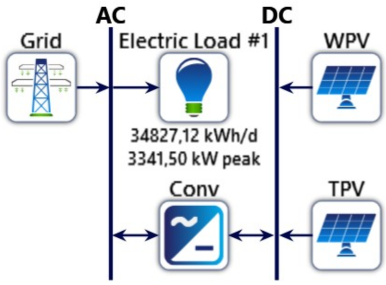
Sensitivity variable values for this simulation

Variable	Value	Unit
WPV Capital Cost Multiplier	1,00	*
WPV O&M Cost Multiplier	1,00	*
ExpectedInflationRate	2,10	%
NominalDiscountRate	5,00	%

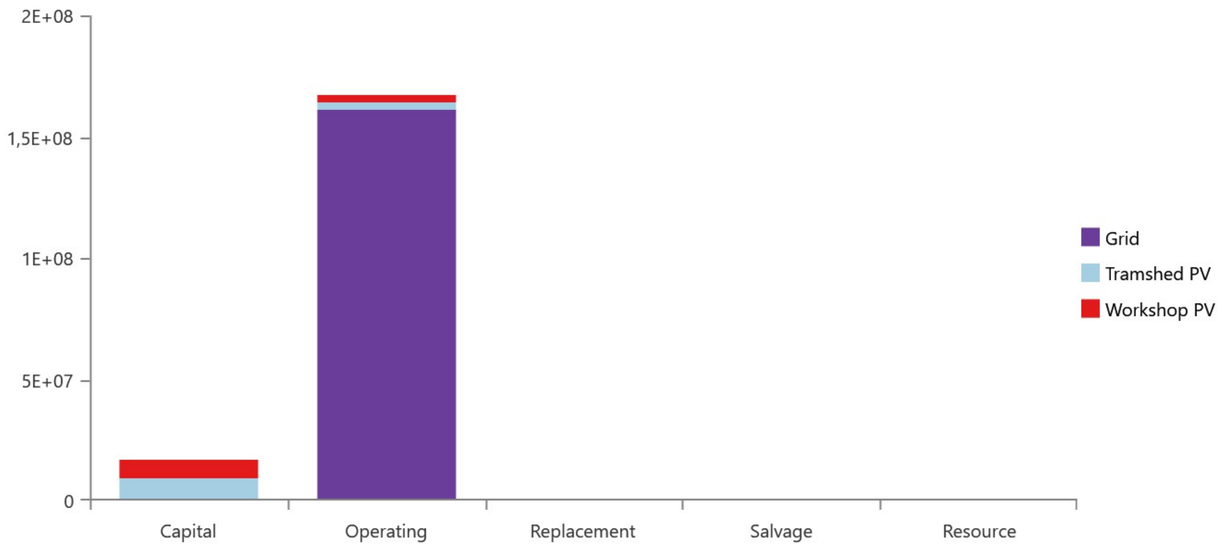
System Architecture

Component	Name	Size	Unit
PV #1	Workshop PV	690	kW
PV #2	Tramshed PV	860	kW
System converter	Generic large, free converter	999 999	kW
Grid	Grid	999 999	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



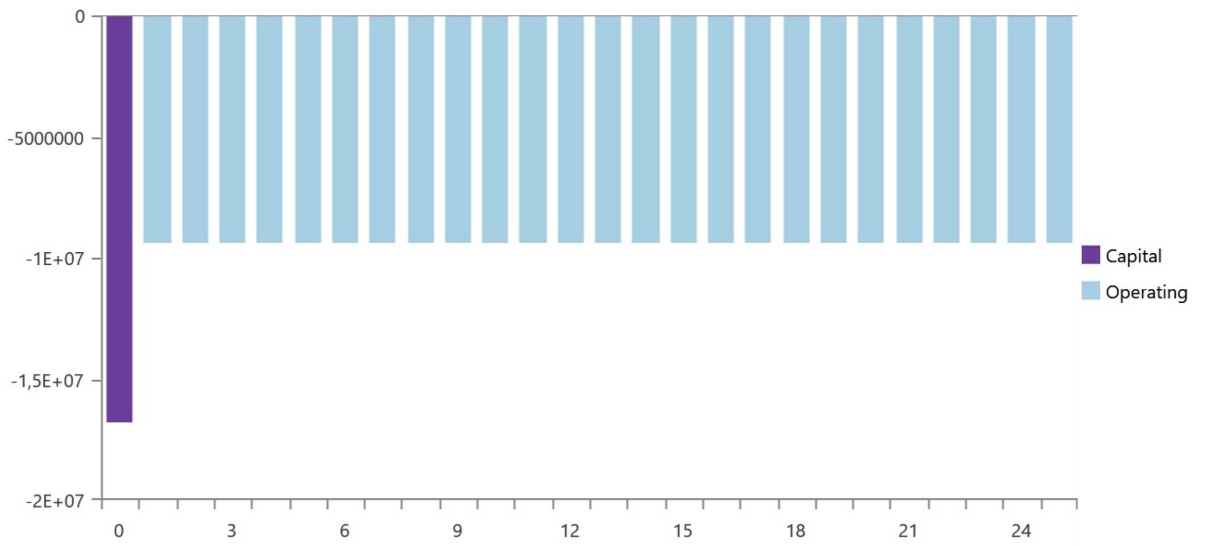
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	kr 0,00	kr 161M	kr 0,00	kr 0,00	kr 0,00	kr 161M
Tramshed PV	kr 9,33M	kr 3,31M	kr 0,00	kr 0,00	kr 0,00	kr 12,6M
Workshop PV	kr 7,49M	kr 2,65M	kr 0,00	kr 0,00	kr 0,00	kr 10,1M
System	kr 16,8M	kr 167M	kr 0,00	kr 0,00	kr 0,00	kr 184M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	kr 0,00	kr 9,07M	kr 0,00	kr 0,00	kr 0,00	kr 9,07M
Tramshed PV	kr 526 518	kr 186 620	kr 0,00	kr 0,00	kr 0,00	kr 713 138
Workshop PV	kr 422 439	kr 149 730	kr 0,00	kr 0,00	kr 0,00	kr 572 169
System	kr 948 956	kr 9,41M	kr 0,00	kr 0,00	kr 0,00	kr 10,4M

Cash Flow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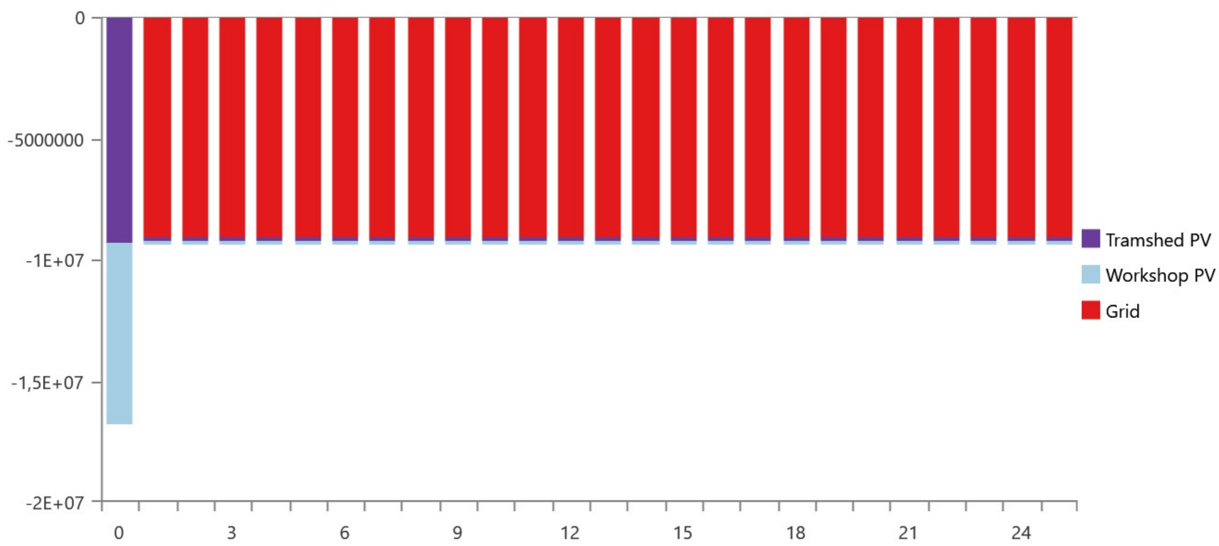
-2E+07
0
3
6
9
12
15
18
21
24
Capital
Operating


0
-5000000
-1E+07
-1,5E+07
-2E+07
0
3
6
9
12
15
18
21
24
Tramshed PV
Workshop PV
Grid

Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Workshop PV	782 289	6,08
Tramshed PV	745 375	5,79
Grid Purchases	11 343 493	88,1
Total	12 871 156	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	12 711 899	99,4
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	82 874	0,648
Total	12 794 773	100

PV: Workshop PV

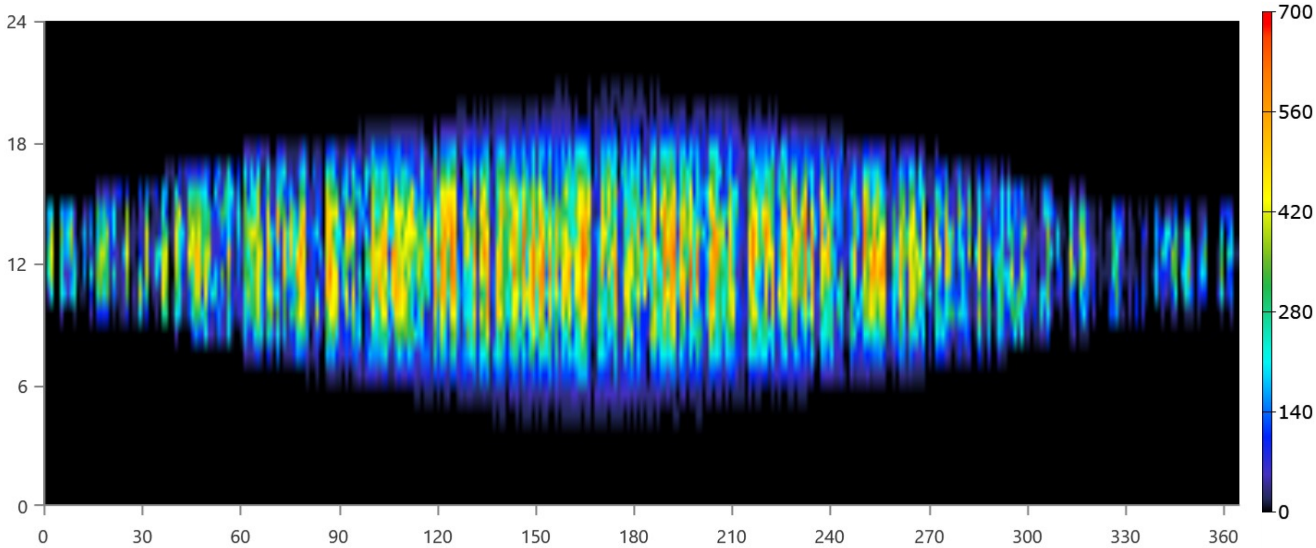
Workshop PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	667	kW
PV Penetration	6,15	%
Hours of Operation	4 391	hrs/yr
Levelized Cost	0,731	kr/kWh

Workshop PV Statistics

Quantity	Value	Units
Rated Capacity	690	kW
Mean Output	89,3	kW
Mean Output	2 143	kWh/d
Capacity Factor	12,9	%
Total Production	782 289	kWh/yr

Workshop PV Output (kW)



PV: Tramshed PV

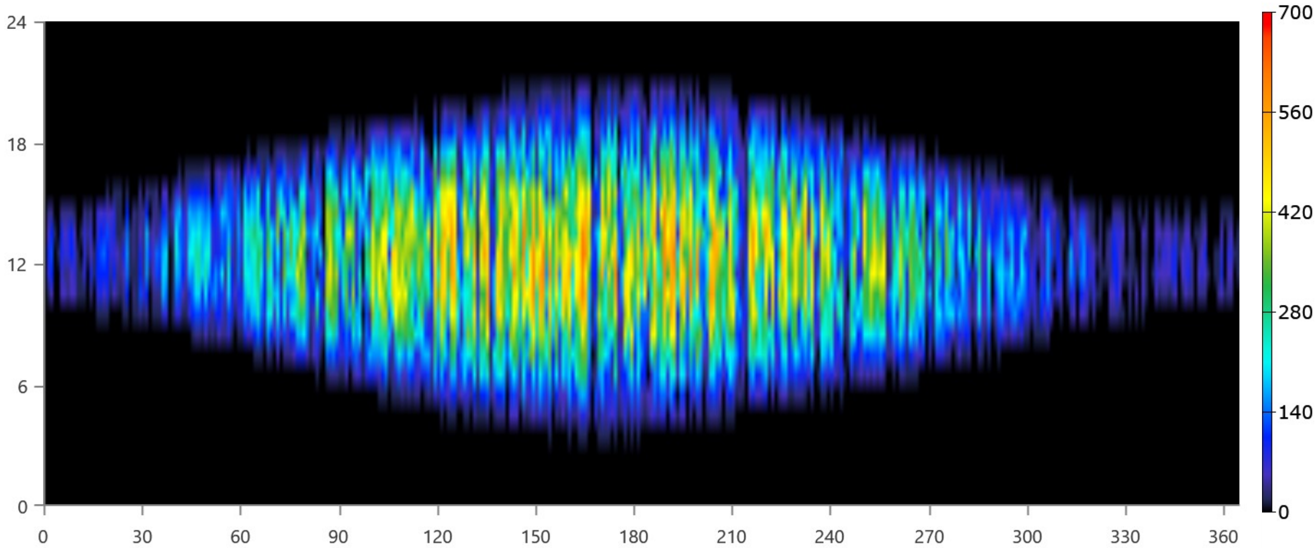
Tramshed PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	645	kW
PV Penetration	5,86	%
Hours of Operation	4 391	hrs/yr
Levelized Cost	0,957	kr/kWh

Tramshed PV Statistics

Quantity	Value	Units
Rated Capacity	860	kW
Mean Output	85,1	kW
Mean Output	2 042	kWh/d
Capacity Factor	9,89	%
Total Production	745 375	kWh/yr

Tramshed PV Output (kW)



Converter: Generic large, free converter

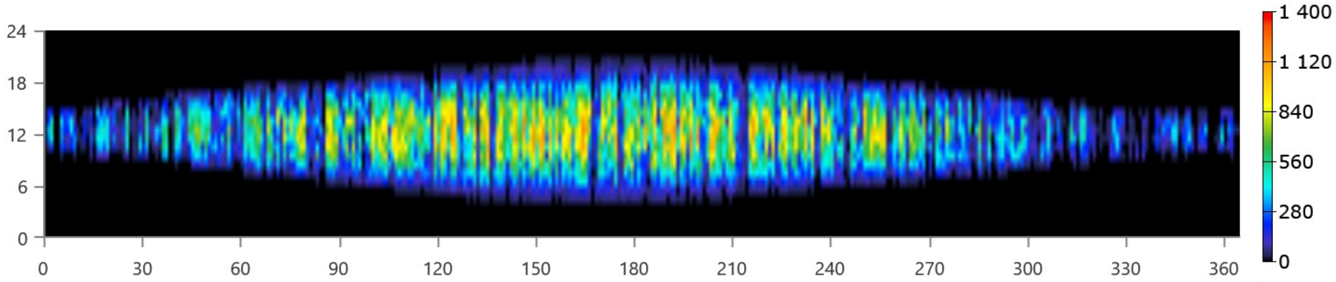
Generic large, free converter Electrical Summary

Quantity	Value	Units
Hours of Operation	4 391	hrs/yr
Energy Out	1 451 280	kWh/yr
Energy In	1 527 663	kWh/yr
Losses	76 383	kWh/yr

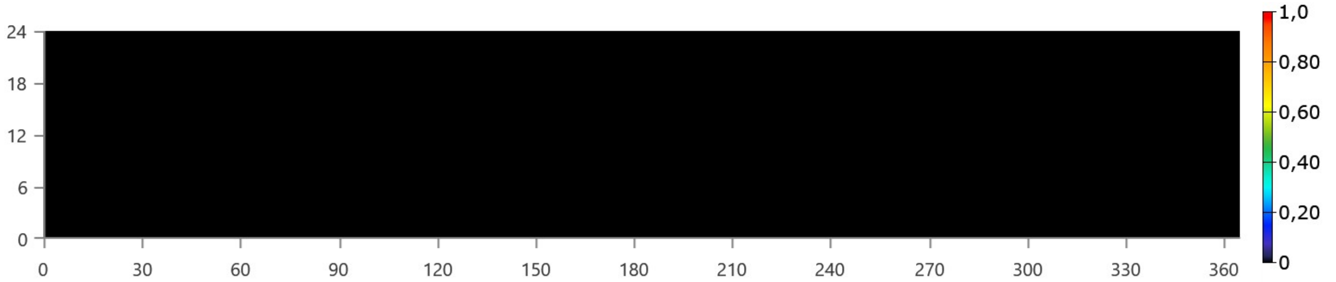
Generic large, free converter Statistics

Quantity	Value	Units
Capacity	999 999	kW
Mean Output	166	kW
Minimum Output	0	kW
Maximum Output	1 247	kW
Capacity Factor	0,0166	%

Generic large, free converter Inverter Output (kW)



Generic large, free converter Rectifier Output (kW)



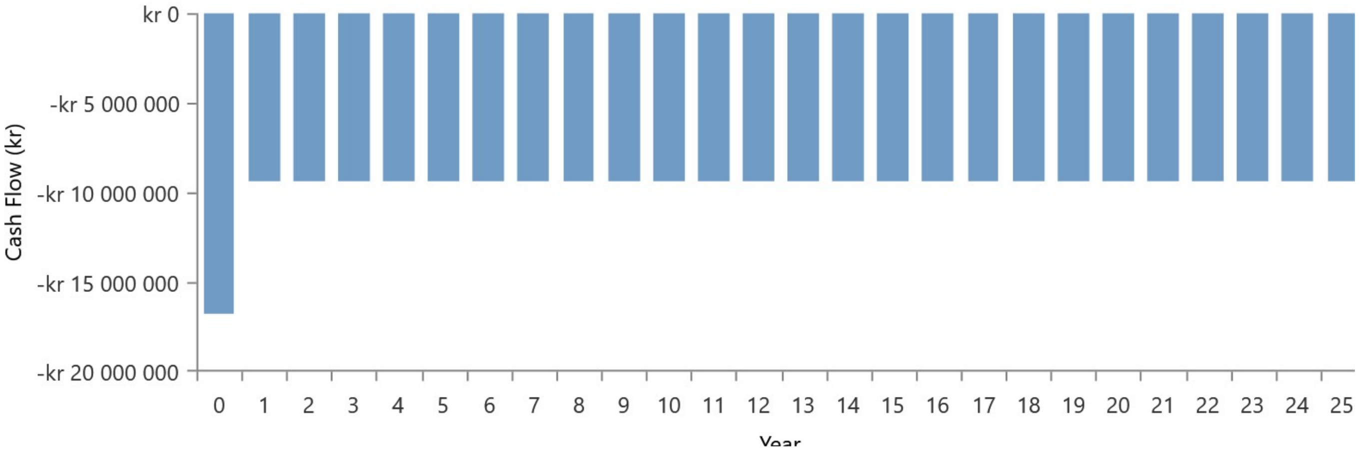
Compare Economics

Architecture									Cost	
					WPV (kW)	TPV (kW)	Grid (kW)	Conv (kW)	NPC (kr)	Initial capital (kr)
							999 999		kr 172M	kr 0,00
					690	860	999 999	999 999	kr 184M	kr 16,8M

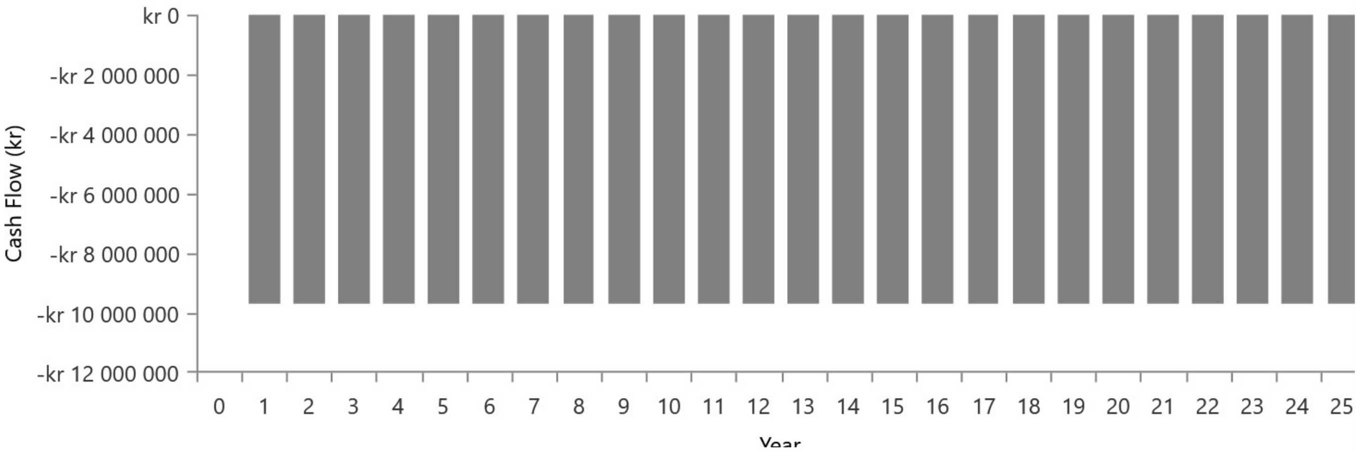
Base case is highlighted in green.

Metric	Value
Present worth (kr)	-kr 11 929 890
Annual worth (kr/yr)	-kr 672 978
Return on investment (%)	-2,4
Internal rate of return (%)	n/a
Simple payback (yr)	n/a
Discounted payback (yr)	n/a

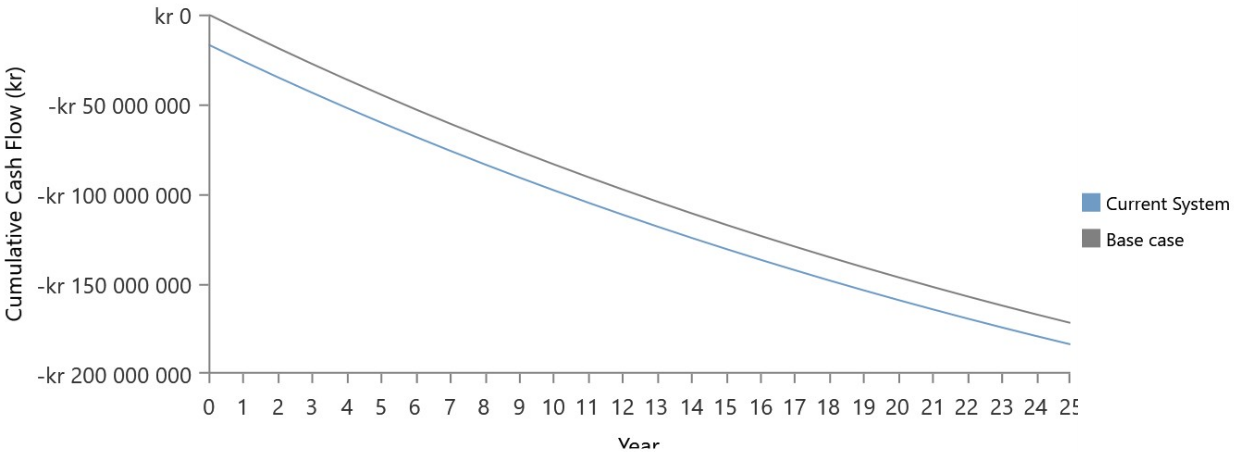
Current Annual Nominal Cash Flows



Base Case Annual Nominal Cash Flows



Cumulative Discounted Cash Flows



Grid: Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	3 342	kr 0,00	kr 501 225
February	0	0	0	3 063	kr 0,00	kr 459 488
March	0	0	0	0	kr 0,00	kr 0,00
April	0	0	0	0	kr 0,00	kr 0,00
May	0	0	0	0	kr 0,00	kr 0,00
June	0	0	0	0	kr 0,00	kr 0,00
July	0	0	0	0	kr 0,00	kr 0,00
August	0	0	0	0	kr 0,00	kr 0,00
September	0	0	0	0	kr 0,00	kr 0,00
October	0	0	0	0	kr 0,00	kr 0,00
November	0	0	0	0	kr 0,00	kr 0,00
December	0	0	0	2 858	kr 0,00	kr 428 683
Annual	0	0	0	3 342	kr 0,00	kr 1,39M

Grid rate: Demand 2

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	kr 0,00	kr 0,00
February	0	0	0	0	kr 0,00	kr 0,00
March	0	0	0	2 410	kr 0,00	kr 185 589
April	0	0	0	0	kr 0,00	kr 0,00
May	0	0	0	0	kr 0,00	kr 0,00
June	0	0	0	0	kr 0,00	kr 0,00
July	0	0	0	0	kr 0,00	kr 0,00
August	0	0	0	0	kr 0,00	kr 0,00
September	0	0	0	0	kr 0,00	kr 0,00
October	0	0	0	0	kr 0,00	kr 0,00
November	0	0	0	3 035	kr 0,00	kr 233 714
December	0	0	0	0	kr 0,00	kr 0,00
Annual	0	0	0	3 035	kr 0,00	kr 419 304

Grid rate: Demand 3

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	kr 0,00	kr 0,00
February	0	0	0	0	kr 0,00	kr 0,00
March	0	0	0	0	kr 0,00	kr 0,00
April	0	0	0	1 735	kr 0,00	kr 32 965
May	0	0	0	1 398	kr 0,00	kr 26 553
June	0	0	0	678	kr 0,00	kr 12 873
July	0	0	0	630	kr 0,00	kr 11 970
August	0	0	0	1 024	kr 0,00	kr 19 447
September	0	0	0	1 119	kr 0,00	kr 21 252
October	0	0	0	2 008	kr 0,00	kr 38 157
November	0	0	0	0	kr 0,00	kr 0,00
December	0	0	0	0	kr 0,00	kr 0,00
Annual	0	0	0	2 008	kr 0,00	kr 163 215

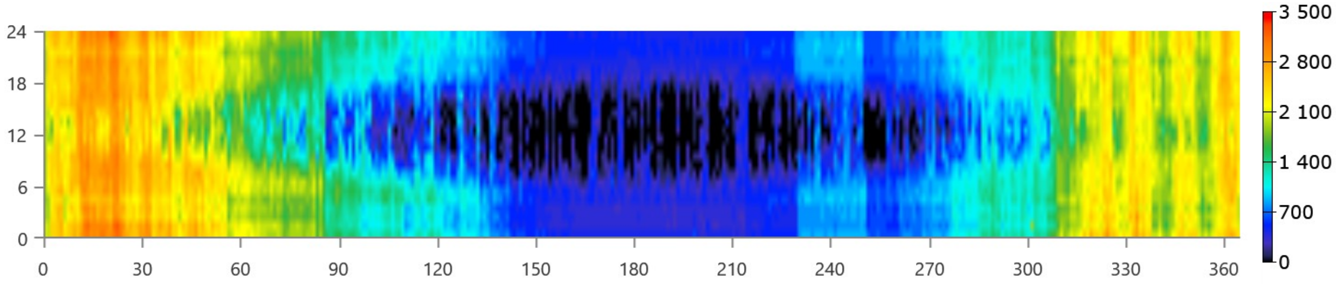
Grid rate: Rate 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2 004 913	0	2 004 913	0	kr 1,59M	kr 0,00
February	1 586 257	0	1 586 257	0	kr 1,15M	kr 0,00
March	1 250 307	0	1 250 307	0	kr 700 172	kr 0,00
April	743 109	0	743 109	0	kr 315 821	kr 0,00
May	465 880	7 951	457 929	0	kr 202 497	kr 0,00
June	240 957	24 864	216 093	0	kr 67 571	kr 0,00
July	229 486	33 908	195 578	0	kr 63 998	kr 0,00
August	392 226	11 309	380 917	0	kr 114 679	kr 0,00
September	466 513	4 842	461 671	0	kr 219 558	kr 0,00
October	814 189	0	814 189	0	kr 378 598	kr 0,00
November	1 479 306	0	1 479 306	0	kr 959 811	kr 0,00
December	1 670 350	0	1 670 350	0	kr 1,35M	kr 0,00
Annual	11 343 493	82 874	11 260 619	0	kr 7,10M	kr 0,00

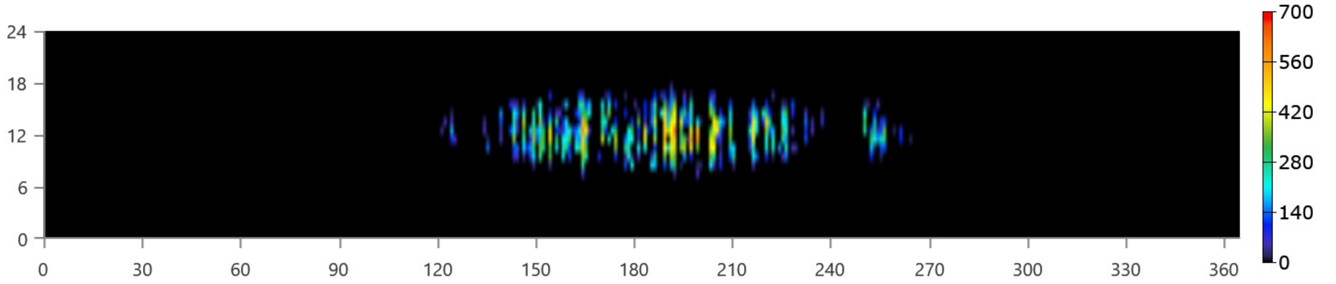
Grid rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2 004 913	0	2 004 913	3 342	kr 1,59M	kr 501 225
February	1 586 257	0	1 586 257	3 063	kr 1,15M	kr 459 488
March	1 250 307	0	1 250 307	2 410	kr 700 172	kr 185 589
April	743 109	0	743 109	1 735	kr 315 821	kr 32 965
May	465 880	7 951	457 929	1 398	kr 202 497	kr 26 553
June	240 957	24 864	216 093	678	kr 67 571	kr 12 873
July	229 486	33 908	195 578	630	kr 63 998	kr 11 970
August	392 226	11 309	380 917	1 024	kr 114 679	kr 19 447
September	466 513	4 842	461 671	1 119	kr 219 558	kr 21 252
October	814 189	0	814 189	2 008	kr 378 598	kr 38 157
November	1 479 306	0	1 479 306	3 035	kr 959 811	kr 233 714
December	1 670 350	0	1 670 350	2 858	kr 1,35M	kr 428 683
Annual	11 343 493	82 874	11 260 619	3 342	kr 7,10M	kr 1,97M

Energy Purchased From Grid (kW)



Energy Sold To Grid (kW)



C. Peak shaving simulation report

System Simulation Report

www.homerenergy.com

File: peakshaving_model_1.homer

Author: Christian Olsen Rendall

Location: Vårveien 55, 1182 Oslo, Norway (59°53,6'N, 10°48,2'E)

Total Net Present Cost: kr 177 552 100,00

Levelized Cost of Energy (kr/kWh): kr 0,788

Notes: Model and simulation of Ryen workshop with batteries for peak shaving. This work is for Christian Olsen Rendall's master's thesis 2018.

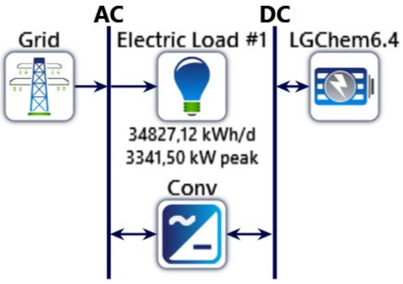
Sensitivity variable values for this simulation

Variable	Value	Unit
ExpectedInflationRate	2,10	%
NominalDiscountRate	5,00	%
LGChem6.4 Capital Cost Multiplier	1,00	*
LGChem6.4 Replacement Cost Multiplier	1,00	*

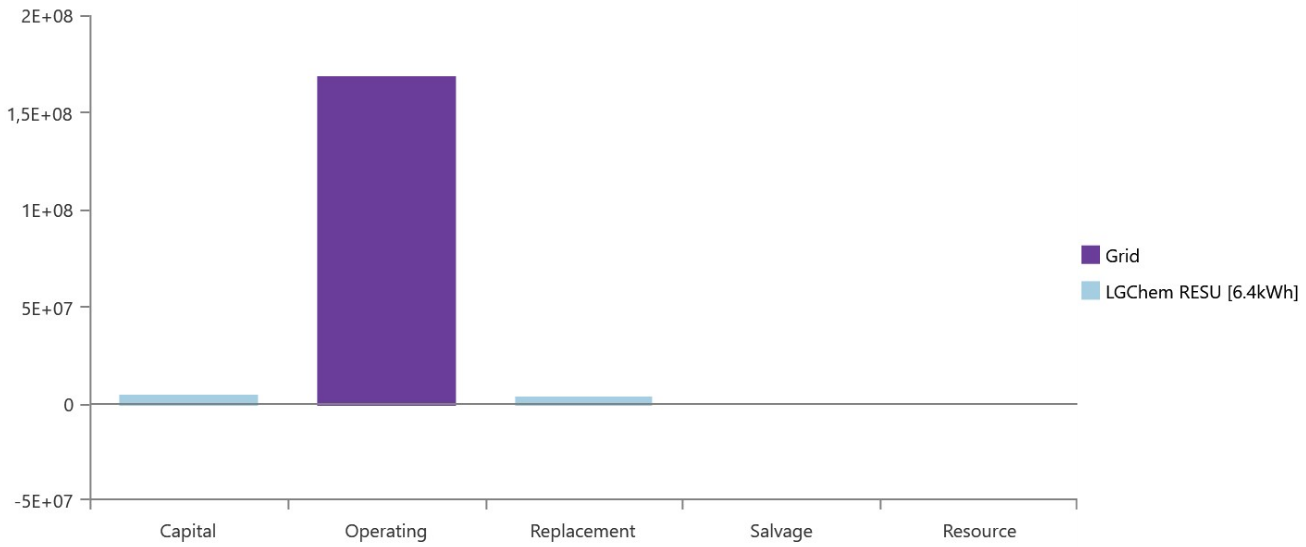
System Architecture

Component	Name	Size	Unit
Storage	LGChem RESU [6.4kWh]	10	strings
System converter	Generic large, free converter	999 999	kW
Grid	Grid (jan:3135,000000 feb:2900,000000 mar:2210,000000 apr:1550,000000 mai:1150,000000 jun:750,000000 jul:620,000000 aug:950,000000 sep:960,000000 okt:1450,000000 nov:2778,000000 des:2690,000000 kW)	0	
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



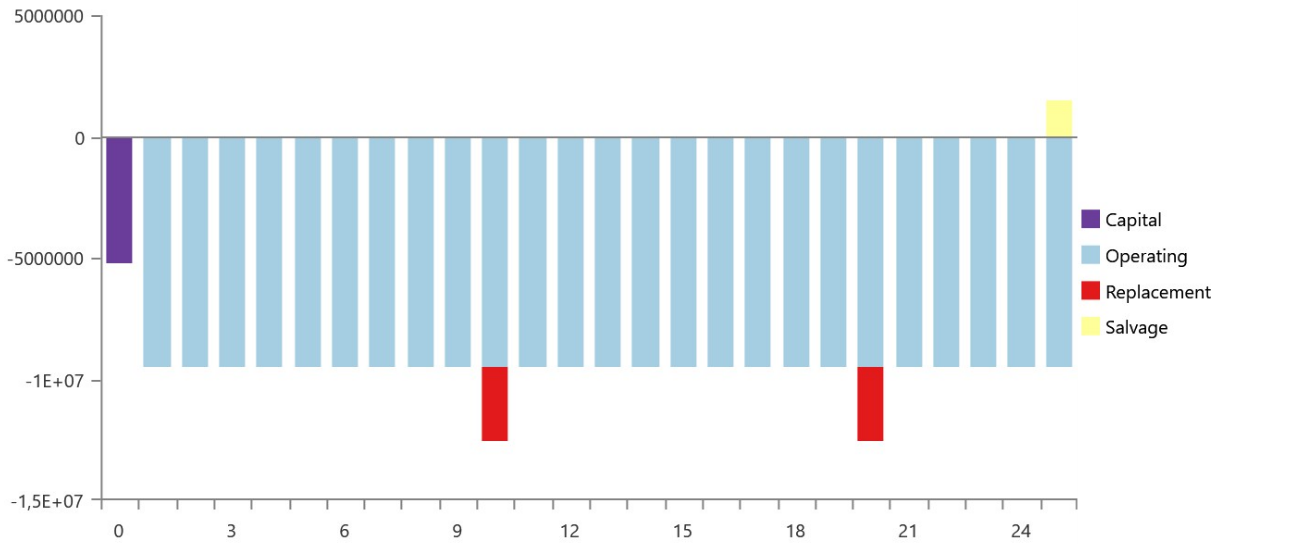
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	kr 0,00	kr 169M	kr 0,00	kr 0,00	kr 0,00	kr 169M
LGChem RESU [6.4kWh]	kr 5,20M	kr 0,00	kr 3,98M	-kr 744 736	kr 0,00	kr 8,44M
System	kr 5,20M	kr 169M	kr 3,98M	-kr 744 736	kr 0,00	kr 178M

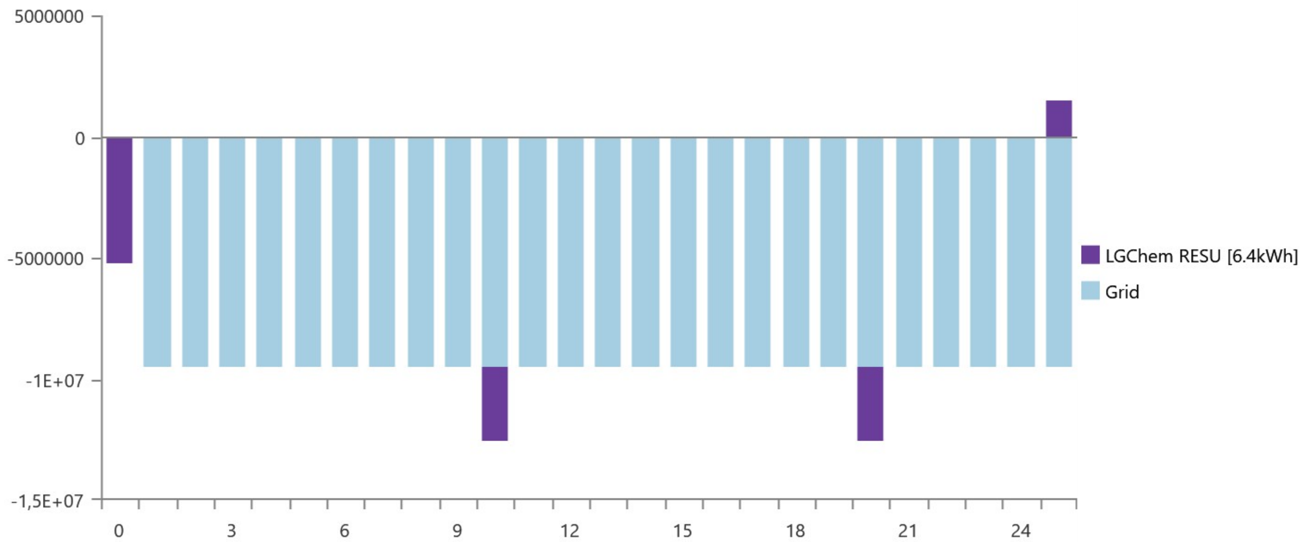
Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	kr 0,00	kr 9,54M	kr 0,00	kr 0,00	kr 0,00	kr 9,54M
LGChem RESU [6.4kWh]	kr 293 338	kr 0,00	kr 224 547	-kr 42 011	kr 0,00	kr 475 873
System	kr 293 338	kr 9,54M	kr 224 547	-kr 42 011	kr 0,00	kr 10,0M

Cash Flow



5000000
0
-5000000
-1E+07
-1,5E+07
0
3
6
9
12
15
18
21
24
Capital
Operating
Replacement
Salvage



5000000
0
-5000000
-1E+07
-1,5E+07
0
3
6
9
12
15
18
21
24
LGChem RESU [6.4kWh]
Grid

Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0	kWh/yr
Unmet Electric Load	551	kWh/yr
Capacity Shortage	12 691	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Grid Purchases	12 716 197	100
Total	12 716 197	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	12 711 347	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	12 711 347	100

Storage: LGChem RESU [6.4kWh]

LGChem RESU [6.4kWh] Properties

Quantity	Value	Units
Batteries	140	qty.
String Size	14,0	batteries
Strings in Parallel	10,0	strings
Bus Voltage	715	V

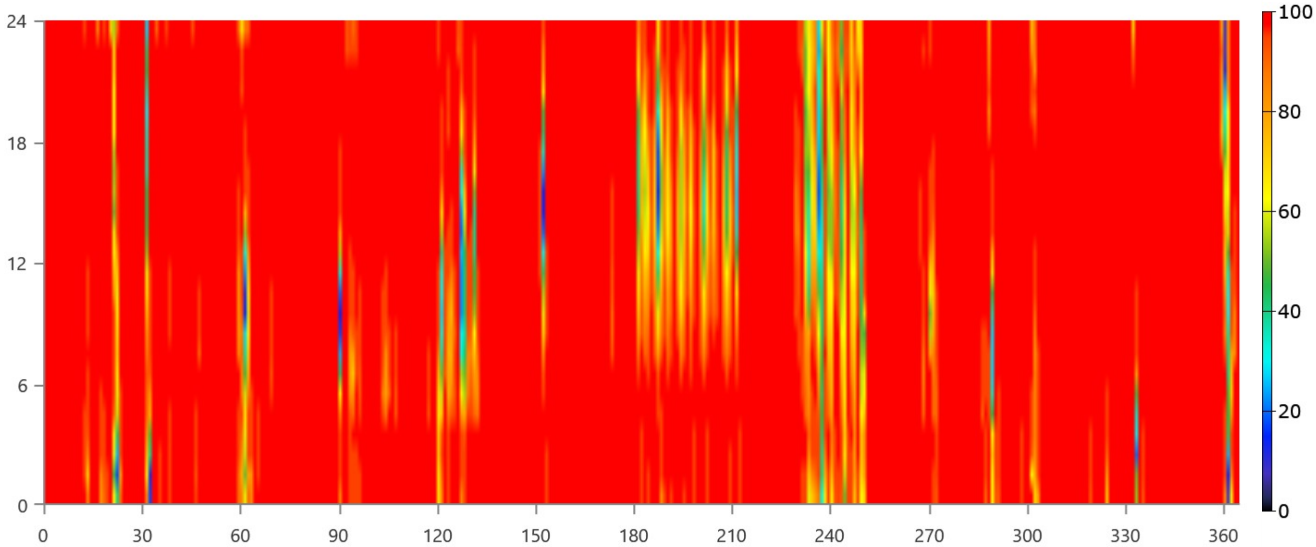
LGChem RESU [6.4kWh] Result Data

Quantity	Value	Units
Average Energy Cost	0,586	kr/kWh
Energy In	32 300	kWh/yr
Energy Out	30 685	kWh/yr
Storage Depletion	0	kWh/yr
Losses	1 615	kWh/yr
Annual Throughput	31 482	kWh/yr

LGChem RESU [6.4kWh] Statistics

Quantity	Value	Units
Autonomy	0,559	hr
Storage Wear Cost	0,632	kr/kWh
Nominal Capacity	901	kWh
Usable Nominal Capacity	811	kWh
Lifetime Throughput	314 820	kWh
Expected Life	10,0	yr

LGChem RESU [6.4kWh] State of Charge (%)



Converter: Generic large, free converter

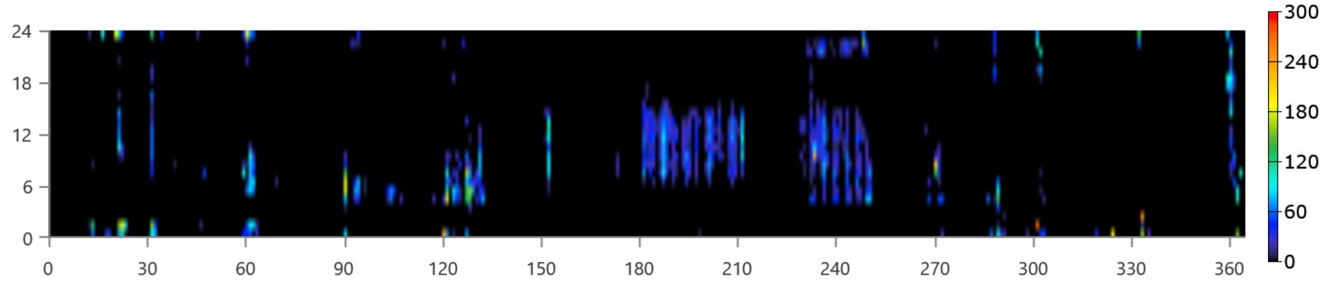
Generic large, free converter Electrical Summary

Quantity	Value	Units
Hours of Operation	693	hrs/yr
Energy Out	29 151	kWh/yr
Energy In	30 685	kWh/yr
Losses	1 534	kWh/yr

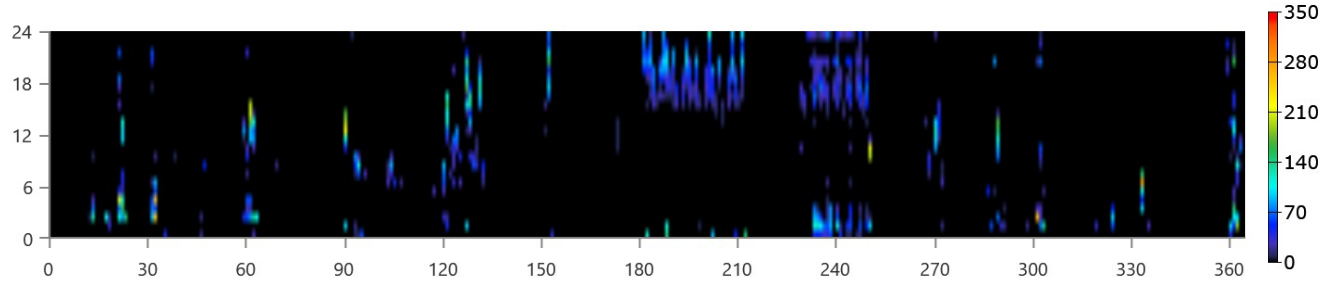
Generic large, free converter Statistics

Quantity	Value	Units
Capacity	999 999	kW
Mean Output	3,33	kW
Minimum Output	0	kW
Maximum Output	278	kW
Capacity Factor	0,000333	%

Generic large, free converter Inverter Output (kW)



Generic large, free converter Rectifier Output (kW)



Grid: Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	3 135	kr 0,00	kr 470 250
February	0	0	0	2 900	kr 0,00	kr 435 000
March	0	0	0	0	kr 0,00	kr 0,00
April	0	0	0	0	kr 0,00	kr 0,00
May	0	0	0	0	kr 0,00	kr 0,00
June	0	0	0	0	kr 0,00	kr 0,00
July	0	0	0	0	kr 0,00	kr 0,00
August	0	0	0	0	kr 0,00	kr 0,00
September	0	0	0	0	kr 0,00	kr 0,00
October	0	0	0	0	kr 0,00	kr 0,00
November	0	0	0	0	kr 0,00	kr 0,00
December	0	0	0	2 690	kr 0,00	kr 403 500
Annual	0	0	0	3 135	kr 0,00	kr 1,31M

Grid rate: Demand 2

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	kr 0,00	kr 0,00
February	0	0	0	0	kr 0,00	kr 0,00
March	0	0	0	2 210	kr 0,00	kr 170 170
April	0	0	0	0	kr 0,00	kr 0,00
May	0	0	0	0	kr 0,00	kr 0,00
June	0	0	0	0	kr 0,00	kr 0,00
July	0	0	0	0	kr 0,00	kr 0,00
August	0	0	0	0	kr 0,00	kr 0,00
September	0	0	0	0	kr 0,00	kr 0,00
October	0	0	0	0	kr 0,00	kr 0,00
November	0	0	0	2 778	kr 0,00	kr 213 906
December	0	0	0	0	kr 0,00	kr 0,00
Annual	0	0	0	2 778	kr 0,00	kr 384 076

Grid rate: Demand 3

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	kr 0,00	kr 0,00
February	0	0	0	0	kr 0,00	kr 0,00
March	0	0	0	0	kr 0,00	kr 0,00
April	0	0	0	1 550	kr 0,00	kr 29 450
May	0	0	0	1 150	kr 0,00	kr 21 850
June	0	0	0	750	kr 0,00	kr 14 250
July	0	0	0	620	kr 0,00	kr 11 780
August	0	0	0	950	kr 0,00	kr 18 050
September	0	0	0	960	kr 0,00	kr 18 240
October	0	0	0	1 450	kr 0,00	kr 27 550
November	0	0	0	0	kr 0,00	kr 0,00
December	0	0	0	0	kr 0,00	kr 0,00
Annual	0	0	0	1 550	kr 0,00	kr 141 170

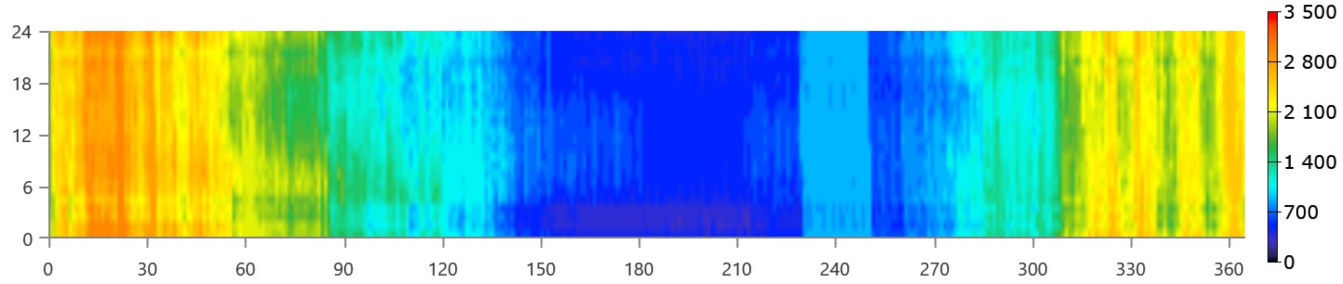
Grid rate: Rate 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2 036 449	0	2 036 449	0	kr 1,61M	kr 0,00
February	1 649 222	0	1 649 222	0	kr 1,19M	kr 0,00
March	1 370 896	0	1 370 896	0	kr 767 702	kr 0,00
April	904 162	0	904 162	0	kr 384 269	kr 0,00
May	679 609	0	679 609	0	kr 297 669	kr 0,00
June	430 452	0	430 452	0	kr 129 136	kr 0,00
July	416 899	0	416 899	0	kr 128 401	kr 0,00
August	559 451	0	559 451	0	kr 166 717	kr 0,00
September	588 269	0	588 269	0	kr 278 251	kr 0,00
October	883 000	0	883 000	0	kr 410 595	kr 0,00
November	1 507 729	0	1 507 729	0	kr 978 257	kr 0,00
December	1 690 058	0	1 690 058	0	kr 1,36M	kr 0,00
Annual	12 716 197	0	12 716 197	0	kr 7,71M	kr 0,00

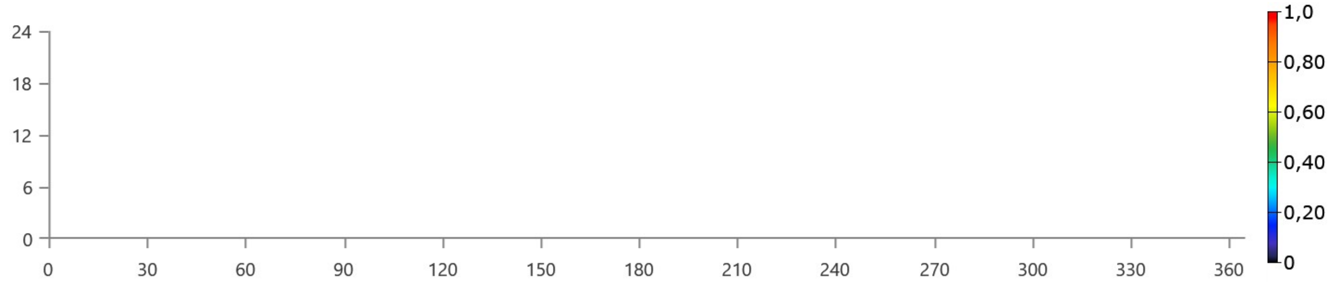
Grid rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2 036 449	0	2 036 449	3 135	kr 1,61M	kr 470 250
February	1 649 222	0	1 649 222	2 900	kr 1,19M	kr 435 000
March	1 370 896	0	1 370 896	2 210	kr 767 702	kr 170 170
April	904 162	0	904 162	1 550	kr 384 269	kr 29 450
May	679 609	0	679 609	1 150	kr 297 669	kr 21 850
June	430 452	0	430 452	750	kr 129 136	kr 14 250
July	416 899	0	416 899	620	kr 128 401	kr 11 780
August	559 451	0	559 451	950	kr 166 717	kr 18 050
September	588 269	0	588 269	960	kr 278 251	kr 18 240
October	883 000	0	883 000	1 450	kr 410 595	kr 27 550
November	1 507 729	0	1 507 729	2 778	kr 978 257	kr 213 906
December	1 690 058	0	1 690 058	2 690	kr 1,36M	kr 403 500
Annual	12 716 197	0	12 716 197	3 135	kr 7,71M	kr 1,83M

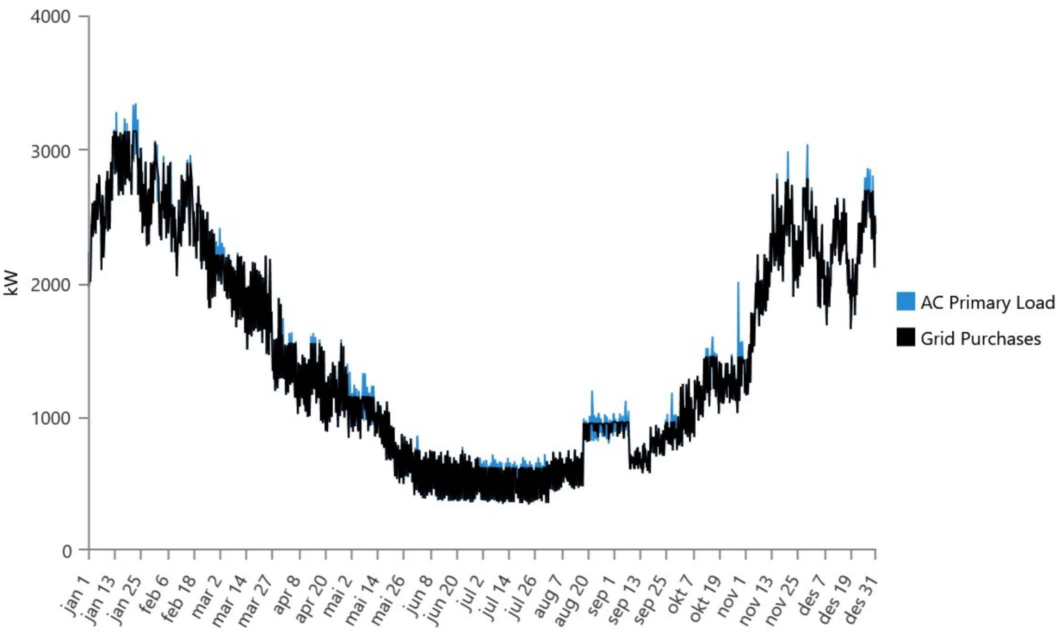
Energy Purchased From Grid (kW)

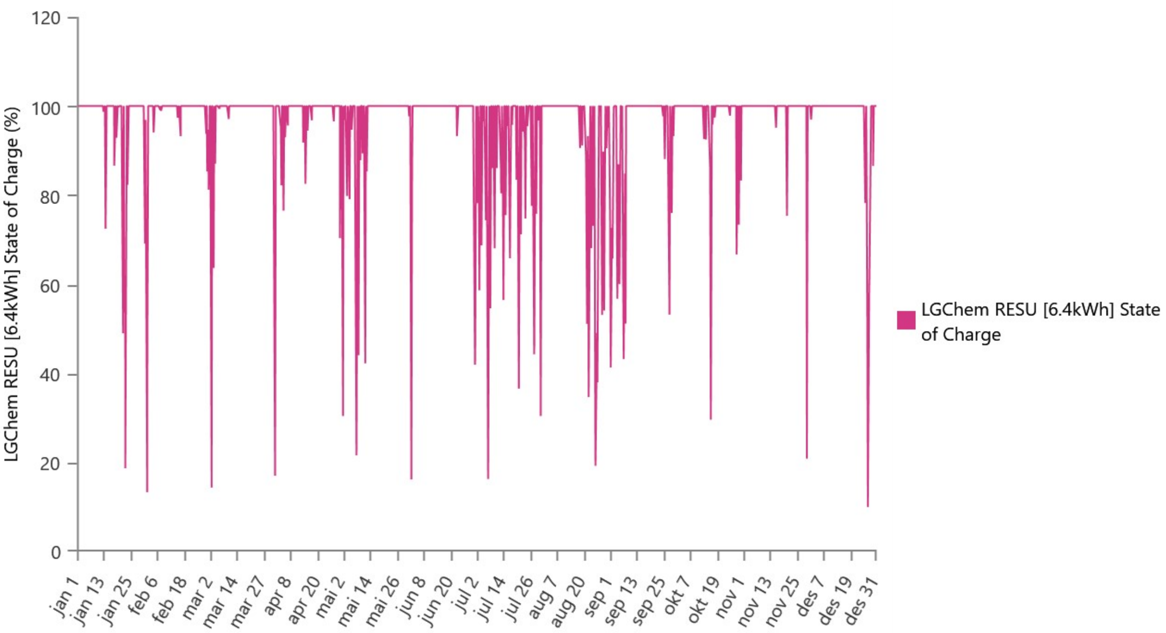


Energy Sold To Grid (kW)



Time series charts:





D. Microgrid simulation report

System Simulation Report

www.homerenergy.com

File: solarPVand1BESSmax_model.homer

Author: Christian Olsen Rendall

Location: Vårveien 55, 1182 Oslo, Norway (59°53,6'N, 10°48,2'E)

Total Net Present Cost: kr 189 785 700,00

Levelized Cost of Energy (kr/kWh): kr 0,837

Notes: Model and simulation of Ryen workshop with solar PV systems and a BESS unit. This work is for Christian Olsen Rendall's master's thesis 2018.

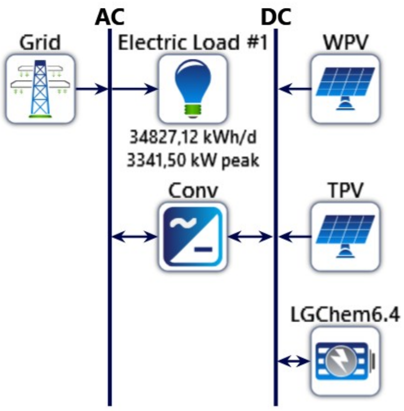
Sensitivity variable values for this simulation

Variable	Value	Unit
WPV Capital Cost Multiplier	1,00	*
TPV Capital Cost Multiplier	1,00	*
ExpectedInflationRate	2,10	%
NominalDiscountRate	5,00	%
LGChem6.4 Capital Cost Multiplier	1,00	*
LGChem6.4 Replacement Cost Multiplier	1,00	*

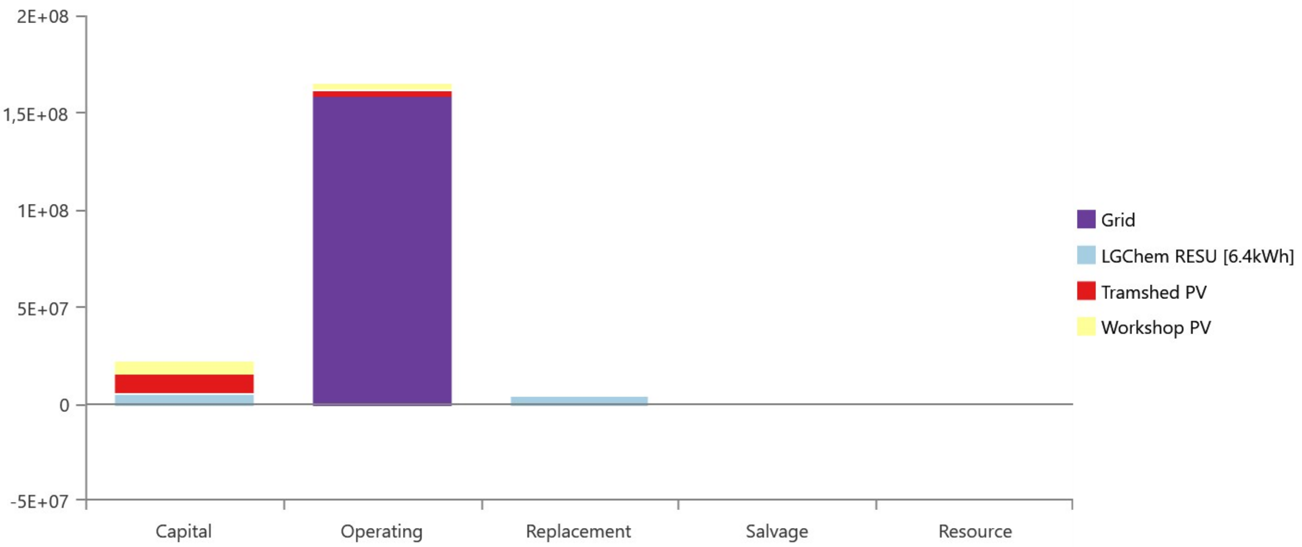
System Architecture

Component	Name	Size	Unit
PV #1	Workshop PV	690	kW
PV #2	Tramshed PV	860	kW
Storage	LGChem RESU [6.4kWh]	10	strings
System converter	Generic large, free converter	999 999	kW
Grid	Grid (jan:3100,000000 feb:3720,000000 mar:2190,000000 apr:1510,000000 mai:1090,000000 jun:530,000000 jul:450,000000 aug:890,000000 sep:950,000000 okt:1450,000000 nov:2765,000000 des:2700,000000 kW)	0	
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



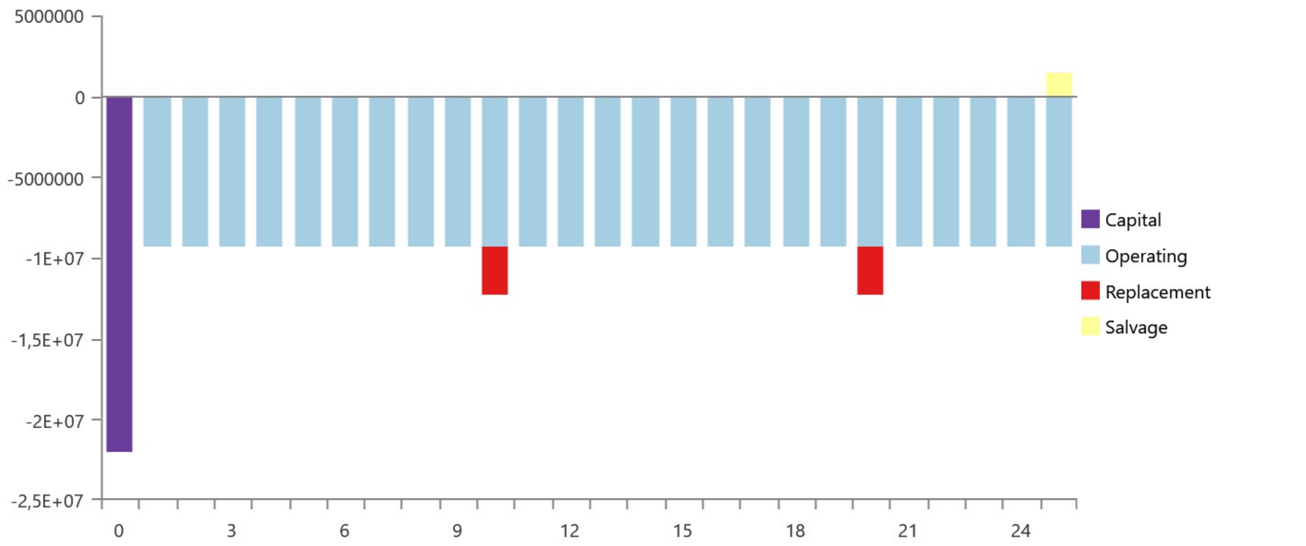
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	kr 0,00	kr 159M	kr 0,00	kr 0,00	kr 0,00	kr 159M
LGChem RESU [6.4kWh]	kr 5,20M	kr 0,00	kr 3,98M	-kr 744 736	kr 0,00	kr 8,44M
Tramshed PV	kr 9,33M	kr 3,31M	kr 0,00	kr 0,00	kr 0,00	kr 12,6M
Workshop PV	kr 7,49M	kr 2,65M	kr 0,00	kr 0,00	kr 0,00	kr 10,1M
System	kr 22,0M	kr 165M	kr 3,98M	-kr 744 736	kr 0,00	kr 190M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	kr 0,00	kr 8,94M	kr 0,00	kr 0,00	kr 0,00	kr 8,94M
LGChem RESU [6.4kWh]	kr 293 338	kr 0,00	kr 224 547	-kr 42 011	kr 0,00	kr 475 873
Tramshed PV	kr 526 518	kr 186 620	kr 0,00	kr 0,00	kr 0,00	kr 713 138
Workshop PV	kr 422 439	kr 149 730	kr 0,00	kr 0,00	kr 0,00	kr 572 169
System	kr 1,24M	kr 9,28M	kr 224 547	-kr 42 011	kr 0,00	kr 10,7M

Cash Flow



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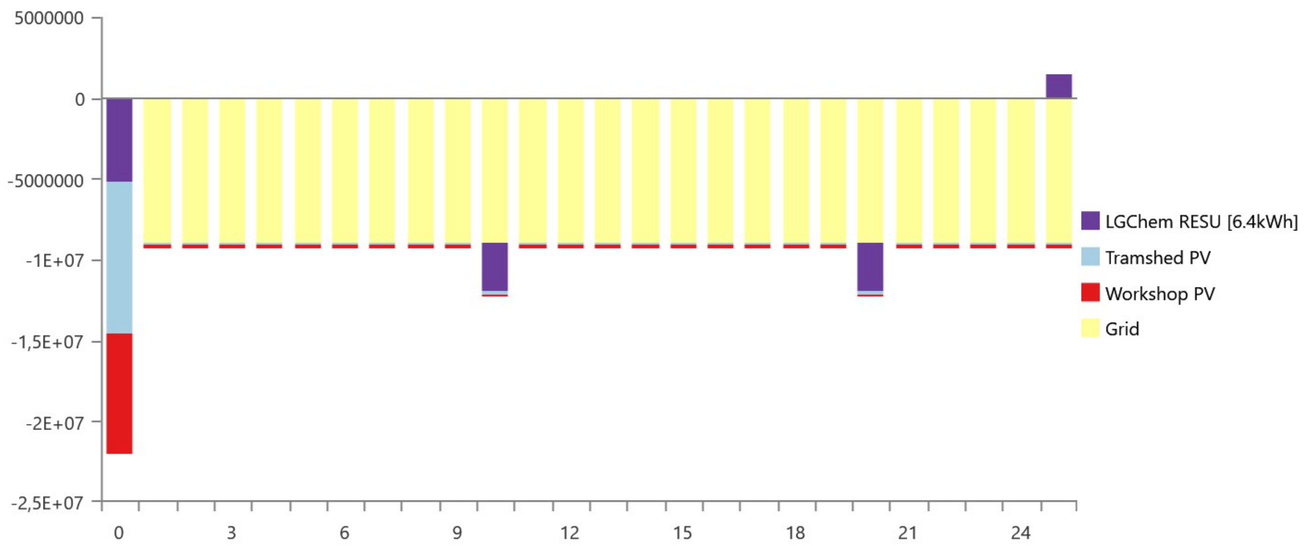
-5000000
-1E+07
-1,5E+07
-2E+07
-2,5E+07
0
3
6
9
12
15
18
21
24
Capital
Operating
Replacement
Salvage



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12
15
18
21
24
LGChem RESU [6.4kWh]
Tramshed PV
Workshop PV
Grid

Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0	kWh/yr
Unmet Electric Load	309	kWh/yr
Capacity Shortage	12 705	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Workshop PV	782 289	6,08
Tramshed PV	745 375	5,79
Grid Purchases	11 347 033	88,1
Total	12 874 696	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	12 711 589	99,4
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	82 261	0,643
Total	12 793 850	100

PV: Workshop PV

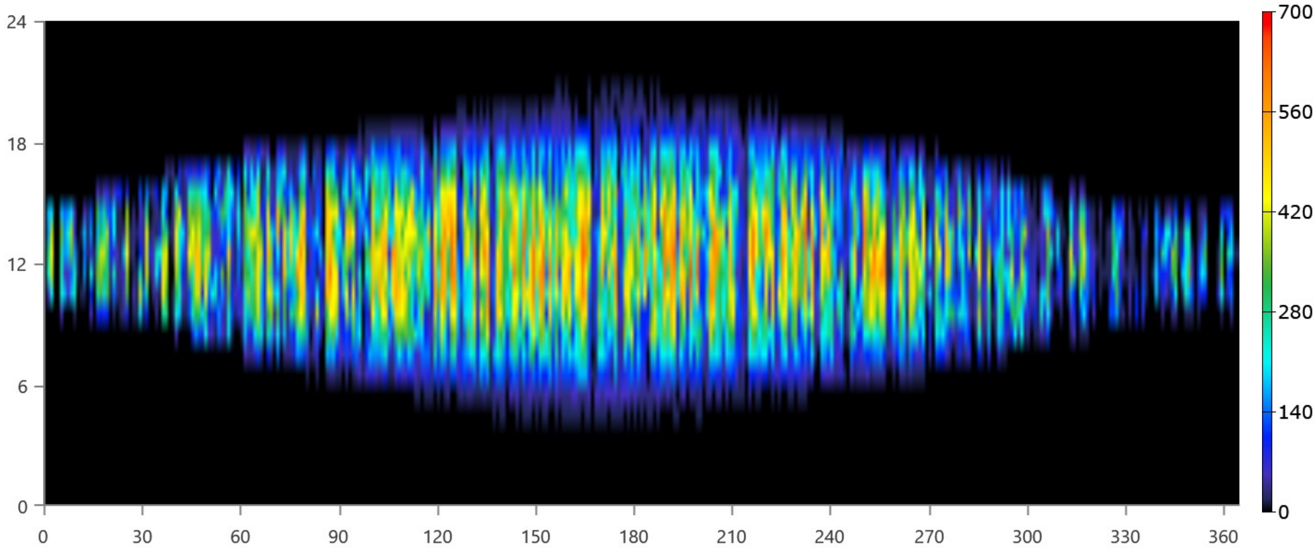
Workshop PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	667	kW
PV Penetration	6,15	%
Hours of Operation	4 391	hrs/yr
Levelized Cost	0,731	kr/kWh

Workshop PV Statistics

Quantity	Value	Units
Rated Capacity	690	kW
Mean Output	89,3	kW
Mean Output	2 143	kWh/d
Capacity Factor	12,9	%
Total Production	782 289	kWh/yr

Workshop PV Output (kW)



PV: Tramshed PV

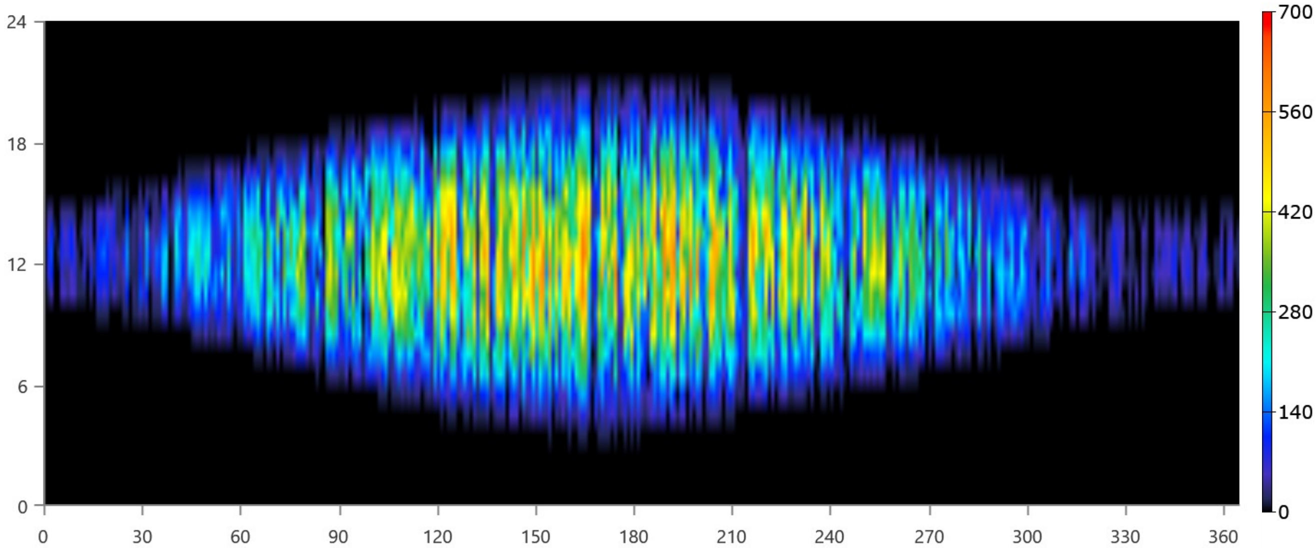
Tramshed PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	645	kW
PV Penetration	5,86	%
Hours of Operation	4 391	hrs/yr
Levelized Cost	0,957	kr/kWh

Tramshed PV Statistics

Quantity	Value	Units
Rated Capacity	860	kW
Mean Output	85,1	kW
Mean Output	2 042	kWh/d
Capacity Factor	9,89	%
Total Production	745 375	kWh/yr

Tramshed PV Output (kW)



Storage: LGChem RESU [6.4kWh]

LGChem RESU [6.4kWh] Properties

Quantity	Value	Units
Batteries	140	qty.
String Size	14,0	batteries
Strings in Parallel	10,0	strings
Bus Voltage	715	V

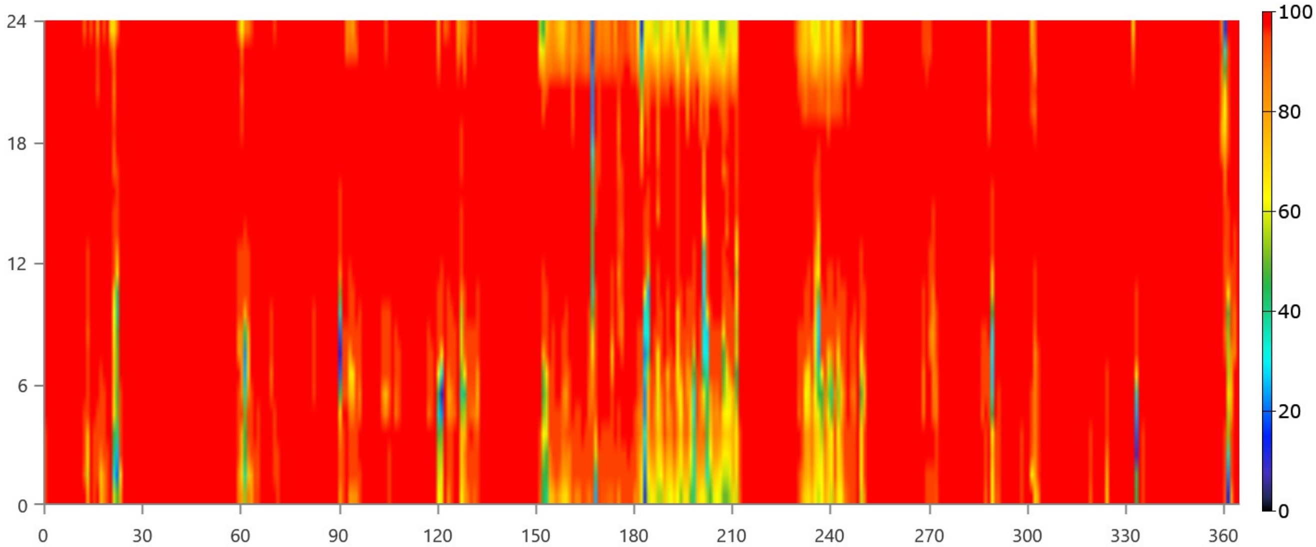
LGChem RESU [6.4kWh] Result Data

Quantity	Value	Units
Average Energy Cost	0,557	kr/kWh
Energy In	45 054	kWh/yr
Energy Out	42 538	kWh/yr
Storage Depletion	-270	kWh/yr
Losses	2 246	kWh/yr
Annual Throughput	43 643	kWh/yr

LGChem RESU [6.4kWh] Statistics

Quantity	Value	Units
Autonomy	0,559	hr
Storage Wear Cost	0,632	kr/kWh
Nominal Capacity	901	kWh
Usable Nominal Capacity	811	kWh
Lifetime Throughput	436 429	kWh
Expected Life	10,0	yr

LGChem RESU [6.4kWh] State of Charge (%)



Converter: Generic large, free converter

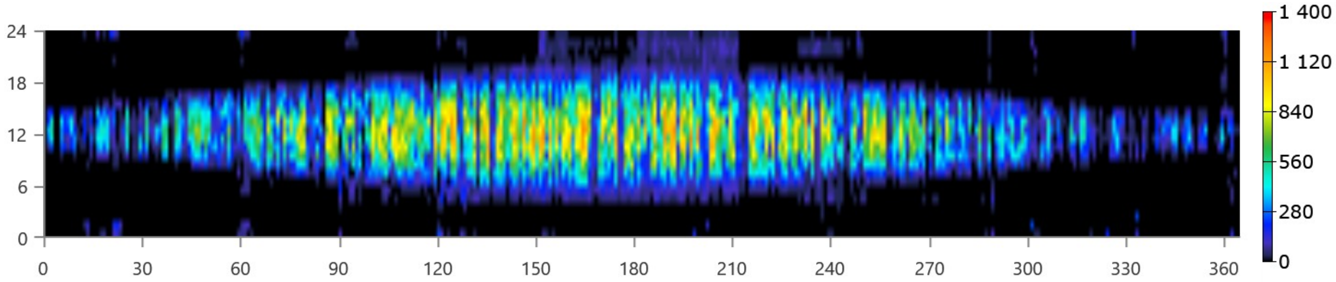
Generic large, free converter Electrical Summary

Quantity	Value	Units
Hours of Operation	4 854	hrs/yr
Energy Out	1 468 072	kWh/yr
Energy In	1 545 339	kWh/yr
Losses	77 267	kWh/yr

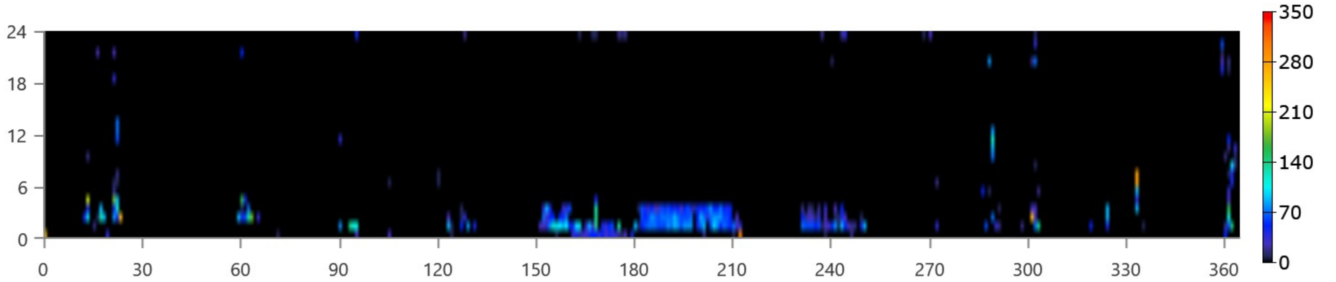
Generic large, free converter Statistics

Quantity	Value	Units
Capacity	999 999	kW
Mean Output	168	kW
Minimum Output	0	kW
Maximum Output	1 247	kW
Capacity Factor	0,0168	%

Generic large, free converter Inverter Output (kW)



Generic large, free converter Rectifier Output (kW)



Grid: Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	3 100	kr 0,00	kr 465 000
February	0	0	0	3 063	kr 0,00	kr 459 488
March	0	0	0	0	kr 0,00	kr 0,00
April	0	0	0	0	kr 0,00	kr 0,00
May	0	0	0	0	kr 0,00	kr 0,00
June	0	0	0	0	kr 0,00	kr 0,00
July	0	0	0	0	kr 0,00	kr 0,00
August	0	0	0	0	kr 0,00	kr 0,00
September	0	0	0	0	kr 0,00	kr 0,00
October	0	0	0	0	kr 0,00	kr 0,00
November	0	0	0	0	kr 0,00	kr 0,00
December	0	0	0	2 700	kr 0,00	kr 405 000
Annual	0	0	0	3 100	kr 0,00	kr 1,33M

Grid rate: Demand 2

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	kr 0,00	kr 0,00
February	0	0	0	0	kr 0,00	kr 0,00
March	0	0	0	2 190	kr 0,00	kr 168 630
April	0	0	0	0	kr 0,00	kr 0,00
May	0	0	0	0	kr 0,00	kr 0,00
June	0	0	0	0	kr 0,00	kr 0,00
July	0	0	0	0	kr 0,00	kr 0,00
August	0	0	0	0	kr 0,00	kr 0,00
September	0	0	0	0	kr 0,00	kr 0,00
October	0	0	0	0	kr 0,00	kr 0,00
November	0	0	0	2 765	kr 0,00	kr 212 905
December	0	0	0	0	kr 0,00	kr 0,00
Annual	0	0	0	2 765	kr 0,00	kr 381 535

Grid rate: Demand 3

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0	kr 0,00	kr 0,00
February	0	0	0	0	kr 0,00	kr 0,00
March	0	0	0	0	kr 0,00	kr 0,00
April	0	0	0	1 510	kr 0,00	kr 28 690
May	0	0	0	1 090	kr 0,00	kr 20 710
June	0	0	0	530	kr 0,00	kr 10 070
July	0	0	0	450	kr 0,00	kr 8 550
August	0	0	0	890	kr 0,00	kr 16 910
September	0	0	0	950	kr 0,00	kr 18 050
October	0	0	0	1 450	kr 0,00	kr 27 550
November	0	0	0	0	kr 0,00	kr 0,00
December	0	0	0	0	kr 0,00	kr 0,00
Annual	0	0	0	1 510	kr 0,00	kr 130 530

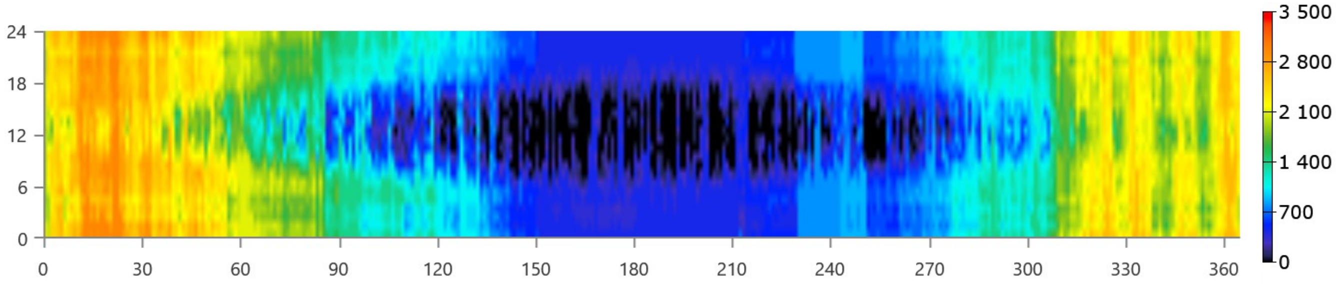
Grid rate: Rate 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2 005 558	0	2 005 558	0	kr 1,59M	kr 0,00
February	1 586 257	0	1 586 257	0	kr 1,15M	kr 0,00
March	1 250 517	0	1 250 517	0	kr 700 289	kr 0,00
April	743 305	0	743 305	0	kr 315 905	kr 0,00
May	466 070	7 951	458 119	0	kr 202 580	kr 0,00
June	241 570	24 864	216 706	0	kr 67 755	kr 0,00
July	229 901	33 294	196 606	0	kr 64 246	kr 0,00
August	392 673	11 309	381 363	0	kr 114 813	kr 0,00
September	466 975	4 842	462 133	0	kr 219 776	kr 0,00
October	814 167	0	814 167	0	kr 378 588	kr 0,00
November	1 479 475	0	1 479 475	0	kr 959 920	kr 0,00
December	1 670 566	0	1 670 566	0	kr 1,35M	kr 0,00
Annual	11 347 033	82 261	11 264 772	0	kr 7,10M	kr 0,00

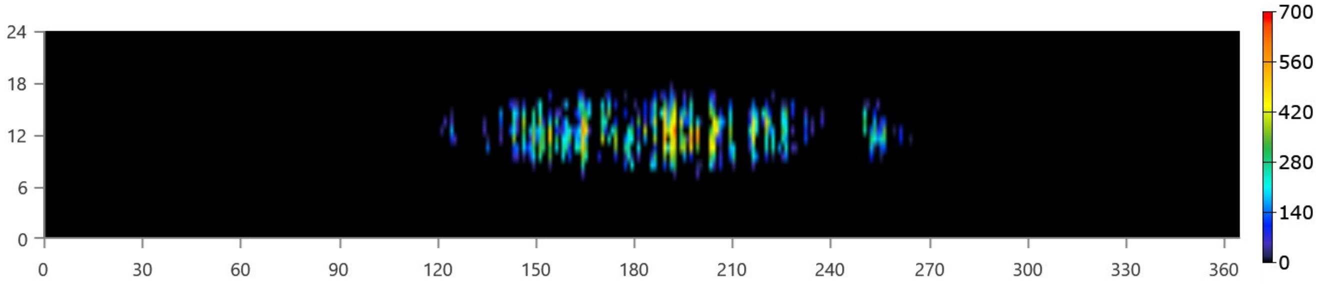
Grid rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2 005 558	0	2 005 558	3 100	kr 1,59M	kr 465 000
February	1 586 257	0	1 586 257	3 063	kr 1,15M	kr 459 488
March	1 250 517	0	1 250 517	2 190	kr 700 289	kr 168 630
April	743 305	0	743 305	1 510	kr 315 905	kr 28 690
May	466 070	7 951	458 119	1 090	kr 202 580	kr 20 710
June	241 570	24 864	216 706	530	kr 67 755	kr 10 070
July	229 901	33 294	196 606	450	kr 64 246	kr 8 550
August	392 673	11 309	381 363	890	kr 114 813	kr 16 910
September	466 975	4 842	462 133	950	kr 219 776	kr 18 050
October	814 167	0	814 167	1 450	kr 378 588	kr 27 550
November	1 479 475	0	1 479 475	2 765	kr 959 920	kr 212 905
December	1 670 566	0	1 670 566	2 700	kr 1,35M	kr 405 000
Annual	11 347 033	82 261	11 264 772	3 100	kr 7,10M	kr 1,84M

Energy Purchased From Grid (kW)



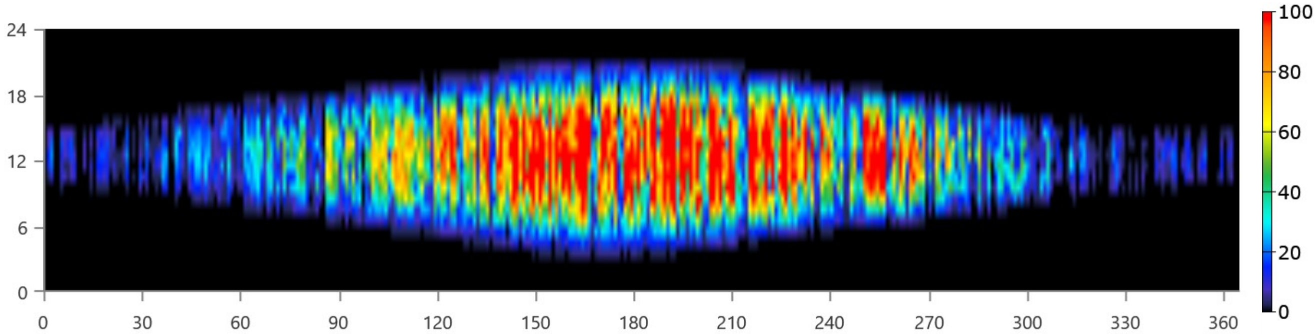
Energy Sold To Grid (kW)



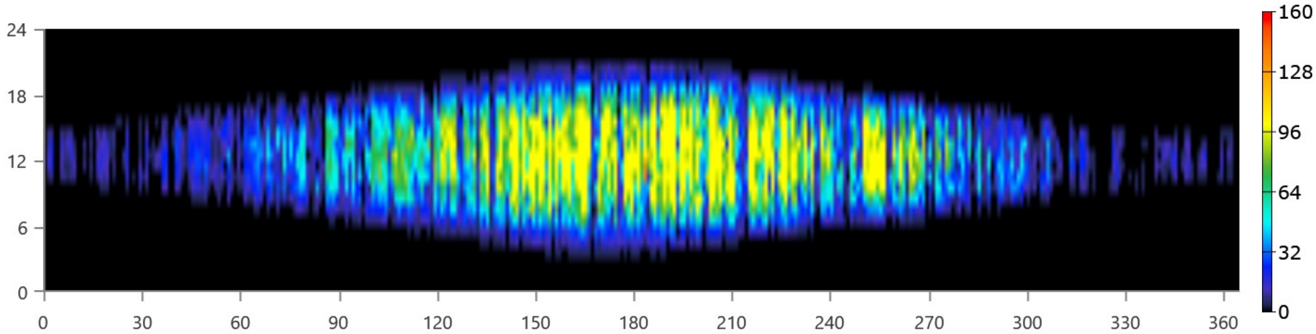
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	**Value**	**Unit**
Total renewable production divided by load	11,9	%
Total renewable production divided by generation	11,9	%
One minus total nonrenewable production divided by load	100	%
Peak values	**Value**	**Unit**
Renewable output divided by load (HOMER standard)	140	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

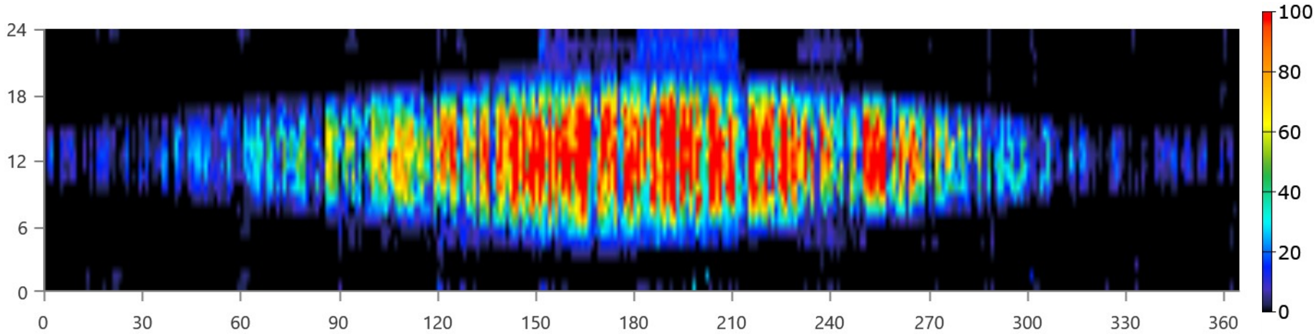
Instantaneous Renewable Output Percentage of Total Generation



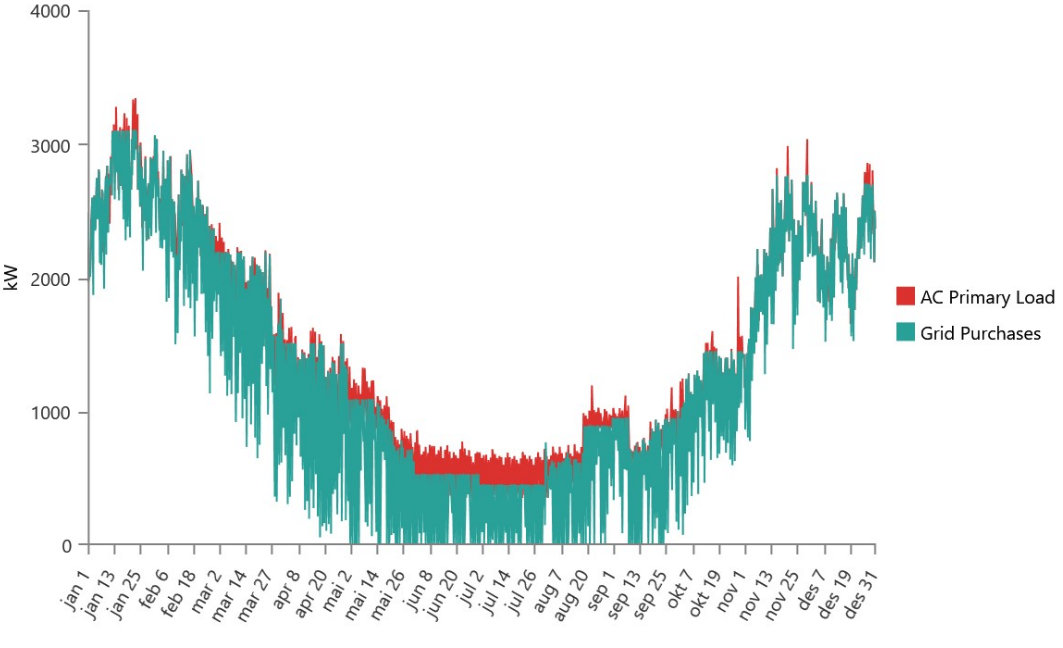
Instantaneous Renewable Output Percentage of Total Load

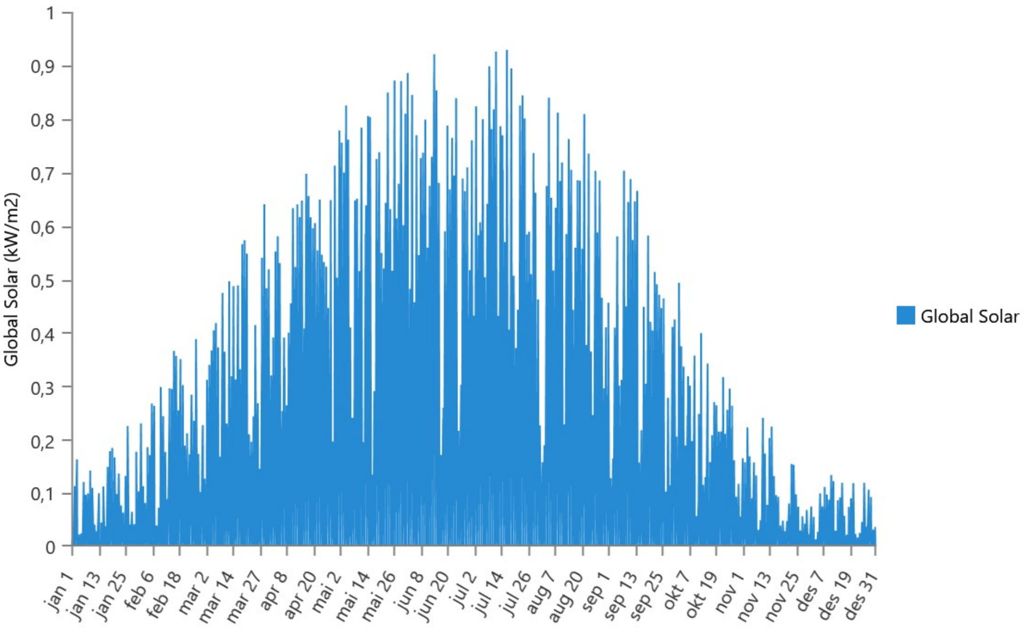


100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Time series charts:





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