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Solar energy production and storage in an apartment complex in Trondheim

A study of the interaction between in-house energy production and storage used for electric vehicle charging

Bachelor's thesis in Renewable Energy, Engineering
Supervisor: Steven Boles
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May 2022

Bachelor's thesis

NTNU
Norwegian University of Science and Technology
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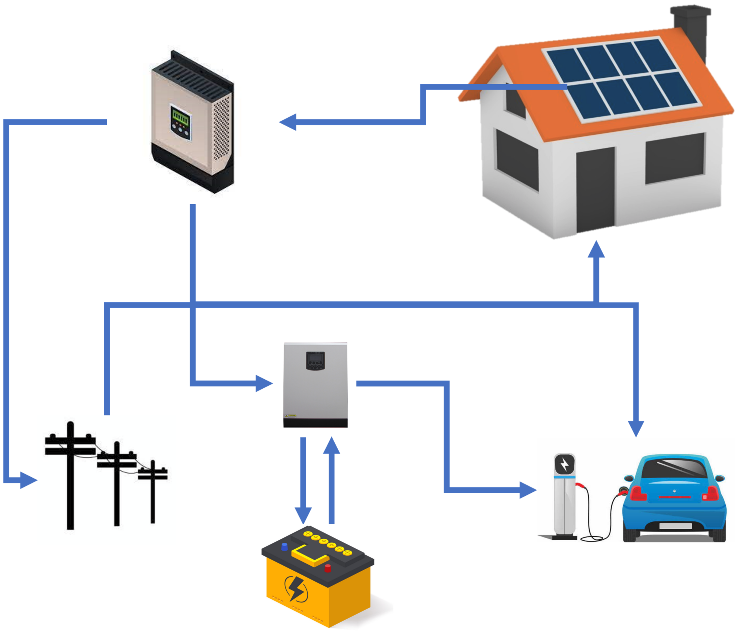

Figure composition by Kristoffer Liset

Norwegian University of Science and Technology

SOLAR TECHNOLOGIES SCANDINAVIA

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NTNU
Kunnskap for en bedre verden

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Bachelor thesis

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Preface

This bachelor thesis is the final project of the three-year program, *Bachelor in Engineering, Renewable energy* at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU). The purpose of this thesis is to utilize the knowledge that we have acquired during this program of study to identify, compile and solve a relevant task.

Society today demands new energy sources and solutions due to climate change and an increasing power requirement. This thesis shall explore the different opportunities of alternative power supply systems in a populated area. More specifically, the thesis will explore how a building's outside area can be used to produce the power that the building itself consumes, and how that energy can be stored in order to create a well-functioning overall system.

We would like to thank our supervisor, Professor Steven Boles at NTNU for frequent guidance and support while writing this thesis. We would also like to extend our gratitude to our external supervisor Trond Øines, Chief Commercial Officer and co-founder of Solar Technologies Scandinavia (STS), for continuous support, ideas and professional guidance regarding the task at hand.

We would also like to thank the people and organizations that have contributed with relevant data, information and advice for the thesis, which include Ane Tinmannsvik, project manager at Frost Eiendom AS, Nord Pool, Ohmia Charging and Trondheim city archives. We give them all our sincere gratitude for their help with data used in this thesis.

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Trondheim, 20. May 2022

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Sammendrag

For å holde global oppvarming i sjakk, må en energiomstilling til. Denne omstillingen er allerede i gang, og den innebærer mange typer tiltak, hvorav et av dem er elektrifisering. Dette skaper nye utfordringer i samfunnet, og stiller krav til nye typer infrastruktur. Slik infrastruktur inkluderer mange typer teknologier, som for eksempel energiproduksjon fra fotovoltaiske (FV) systemer, og energilagring i form av batterier. Disse teknologitypene er fokuset i denne oppgaven.

I denne oppgaven, vil ideen om et energiproduksjon og -lagringssystem i et leilighetsbygg i Ola Frosts veg 1 (OFV1) i Trondheim undersøkes. Videre vil det bli undersøkt hvordan et slikt tenkt system kan fungere, i tillegg til mulige konsekvenser av systemet.

Systemet i OFV1 vil bestå av to hoveddeler: et FV-system på byggets tak, og et batterisystem i det tilknyttede parkeringsanlegget. Batterisystemet vil lagre energien som produseres av FV-systemet, og bruke energien til å lade elektriske biler (elbiler). I tillegg har batterisystemet et tiltenkt formål om å kunne kutte effekttopper. To forskjellige FV-systemer blir undersøkt, et som er sørvendt (S) og et som er øst- og vestvendt (ØV). For batterisystemet analyseres to ulike scenarioer. Scenario 1 har 9 elbiler som må lades, hvilket er det samme som dagens situasjon, og Scenario 2 er et mulig framtidig scenario hvor antall elbiler i parkeringsanlegget er 90, som følge av at andelen elbiler forventes å fortsette å øke i de kommende årende.

Av de to FV-systemene, hadde ØV-systemet høyest energiproduksjon. Dette systemet hadde også flest FV-paneler. S-systemet hadde høyere energiproduksjon per kWp installert kapasitet. Resultatene viser at de to presterte relativt likt ellers. Økonomisk sett virker ØV-systemet til å være den beste investeringen i løpet av systemets antatte levetid.

De to scenarioene som blir analysert for batterisystemet benytter seg begge av litium-ion-batterier (LiBer). Begge batterisystemene blir designet i henhold til den tiltenkte bruken og den tilgjengelige energien fra FV-systemet. I Scenario 1 har batterisystemet en kapasitet på 100 kWh, og i Scenario 2 har batterisystemet en kapasitet på 150 kWh. Scenario 2 gir de største økonomiske fordelene når det gjelder elbil-lading. Batterisystemet i Scenario 2 analyseres videre med tanke på å kutte effekttopper. Batterisystemet ser ut til å kunne minke effekttoppene som kan komme som følge av 90 elbiler.

Etter å ha gjennomført analysen, ser OFV1 ut til å være et mindre optimalt valg for et FV-system, gitt de forutsetningene som er satt for analysen. De simulerte batterisystemene anses også som en svak investering. Likevel er håpet at denne analysen kan gi perspektiv og mulig inspirasjon for et potensielt reelt tilfelle.

Abstract

In the effort to keep global warming at bay, an energy transition needs to happen. This has already begun, and involves many different types of measures, one of them being electrification. This creates new challenges for society, and requires new types of infrastructure. This infrastructure includes many types of technology, such as energy production from photovoltaic (PV) systems, and energy storage in the form of batteries. These types of technologies are the focus of this thesis.

In this thesis, the concept of an in-house energy production and storage system in an apartment complex in Ola Frosts veg 1 (OFV1) in Trondheim is explored. Further, how the system might function is addressed, as well as the consequences the system might bring.

The system in OFV1 consists of two main parts: a PV system on the building's roof, and a battery system in the associated parking garage. The battery system stores the produced energy from the PV system and uses the energy to charge electric vehicles (EVs), with power peak shaving as part of the intention. Two different PV systems are looked into, one that is South-oriented (S) and one that is East- and West-oriented (EW). For the battery system, two possible scenarios are considered. Scenario 1 has 9 EVs that need charging, which is the same number of EVs as the current situation, and Scenario 2 is considered a possible future scenario where the number of EVs is 90, as the percentage of EVs is expected to keep increasing in the years to come.

Out of the two PV systems, the EW system has the highest energy production. This system also has the highest number of PV panels. The S system has a higher energy production per kWp of installed capacity. As far as the results show, the systems have a pretty similar performance otherwise. Financially, the EW system appears to be the best investment over the system's estimated lifetime.

The two scenarios considered for the battery system both use Lithium-ion batteries (LiBs). The battery systems are both designed with their intended use in mind, as well as the available energy from the PV system. The battery systems of Scenario 1 and Scenario 2 are 100 kWh and 150 kWh respectively. For the purpose of EV charging, Scenario 2 gives the largest financial benefits. In regards to power peak shaving, the battery system designed in Scenario 2 is further analyzed. The battery system appears to have good potential to contribute to lowering the power peaks that 90 EVs could cause.

After conducting the analysis, OFV1 is regarded as a sub-optimal choice for a PV system within the boundaries that were included in this analysis. The simulated battery systems are also considered to be an investment with weaknesses. The hopes are still that this analysis can bring some perspective and perhaps inspiration for a potential real case system.

Contents

List of Symbols

Symbol	**Unit**	**Description**
I	A	Current
P	W	Electric Power
U	V	Voltage
Q	$\frac{kWh}{area}$	Insolation on a surface area
η	-	Efficiency

List of Terms and Abbreviations

Term/Abbreviation	**Description**
AC	Alternating current
AM	Air Mass
DC	Direct current
DH	District heating
DoD	Depth of Discharge
EU	European Union
EU ETS	EU Emissions Trading System
EV	Electric vehicle
EW	East- and west-oriented
IEA	International Energy Agency
IT	Insulated Terra network
kWp	Kilowatt-peak. The power delivered from a solar energy system at STC
LCOE	Levelized cost of electricity
MPP	Maximum power point
MPPT	Maximum power point tracker
OFV1	Ola Frosts veg 1
PV	Photovoltaic
S	South oriented
SoC	State of Charge
SoH	State of Health
Specific energy	Energy per unit of mass/volume
Specific power	Power per unit of mass/volume
STC	Standard test conditions. 1000 W/m^2, 25°C and AM = 1,5
TN	Terra Neutral network
UN	United Nations
VAT	Value added tax

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1 Introduction and background

In order to keep global climate change to a minimum, an energy transition needs to happen. As much as 31 % of the world's greenhouse gas emissions originate in electricity and heat, and 72 % of the world's emissions come from all energy production combined [7], so making a transition in this industry will be crucial to reach The United Nations' (UN) objective to keep global warming below 1,5°C.

This thesis shall explore how a building's outside area can be used to produce the power that the building itself consumes. This will be done by utilizing the sun as an energy source and analyse how to use the generated solar energy from a PV system. The thesis will further consider a battery system to make use of the generated solar energy in a convenient way. Additionally, the thesis will look into how the battery system can provide parked electric vehicles (EVs) with in-house electricity and in this way making the system less dependent on a grid-connected power supply system.

1.1 Climate objectives

With climate change and the environment high on their priority lists, authorities on different levels all over the world have made vows that aim to promote and encourage environmentally friendly actions. These plans of action include measures on different scales; some are local environmental initiatives, most countries have climate action plans of some kind, and there are international climate action plans, set by international organizations such as the UN.

International objectives

The most well-known climate objectives are the UN's goals for sustainable development. These goals are made for the nations of the world to have a shared plan to build a sustainable future for the planet and the people on it. The sustainable development goals can be seen in Figure 1.1. There are 17 sustainable development goals, and each goal has several sub-goals.

As can be seen in Figure 1.1, goal number 7 is "Affordable and clean energy". Goal number 11 is "Sustainable cities and communities", and number 13 is "Climate action". Out of the 17 goals, these 3 are considered the most relevant for this thesis, as the focus is renewable energy in an urban area. A lot of the focus within these 3 goals is on renewable energy, and to replace the fuel of processes that run on fossil fuels with clean energy sources.

The Paris Agreement was ratified in 2015, and is an important international agreement on the subject of climate change. The agreement sets goals for the countries who have signed the agreement. The Paris Agreement has recently been followed by the Glasgow Climate Pact, finalized in November 2021. This most recent agreement stated that the world must recognize that climate change is an emergency and accelerate action. The suggested actions include

Figure 1.1: The UN's sustainable development goals. [8]

reducing the use of fossil fuels, by phasing out “inefficient” fossil fuel subsidies, and phasing down coal power, as well as following through on promises made to finance various climate change-related efforts in developing countries [9].

National objectives

Norway has set goals for the country's climate change impact. The overriding objective is to reduce Norway's emissions of greenhouse gases with 50 to 55 % by 2030, compared to emission levels in 1990. Norway's climate change agreement with the European Union (EU) also means that Norway has a commitment to collaborate with the EU to reach this goal [10].

Among the national goals for lowering emissions is electrifying the transport sector. In this sector, Norway has come way further than many other countries, and no country has as many electric cars per capita than Norway. This is further elaborated on in chapter 1.4.

Other measures include regulatory solutions such as the out-phasing of oil-fired residential heating, and general fees and taxes on emissions. In addition to this, there are agreements between cities and the national government that state that growth in transportation should be done by use of public transportation, walking or by bicycle. There are also several national programs that support and give grants to zero- and low emission projects, such as Enova, Klimasats, Norges Forskningsråd and Innovasjon Norge [10].

Local objectives

The municipality of Trondheim has set goals for climate action on the local level. The goal is for Trondheim to be a leading municipality in developing solid solutions for the climate and the environment. The goal is to reduce greenhouse gas emissions with 80 % by 2030, compared to numbers from 2009 [11]. This is an ambitious goal, and according to Trondheim municipality, some important measures to reach this goal are [11]:

- Increased electrification of the car population
- Zero emission transportation of goods
- Replacing travel by car with other ways of traveling
- Zero emission construction plans
- Carbon capture and storage from the local incineration plant

1.2 The solar power market

Solar power is a renewable energy source that can technically be implemented almost anywhere, and system sizes can range from large scale power plants to small scale systems on buildings. The flexibility of the technology makes it relatively conflict free, and it can be a useful supplement to Norway's power supply, which today consists mainly of hydropower.

On an international level, solar power has had an enormous increase over the past years. In 2010, total solar power energy production in the world was 32,2 TWh, and in 2020 it was 821 TWh. Solar power is the second fastest growing renewable energy source in the world, second only after wind power. In 2020, solar power accounted for 3,1 % of global electricity production. Solar PV is also becoming the lowest-cost option for electricity production in the world. The International Energy Agency (IEA) has set a Net Zero Scenario, where the goal is that the world's solar energy production reaches 6970 TWh in 2030, although this would require a greater level of policy ambitions than what has been seen so far. [12]

The price of solar power has decreased dramatically the last decade, as shown in Figure 1.2. This figure shows the levelized cost of electricity (LCOE), which is defined as the price at which the generated electricity should be sold at for the system to break even at the end of it's lifetime. This trend is caused by lower production costs for a PV panel as well as the PV panels having a higher efficiency and therefore need fewer panels to produce the same amount of energy. This trend of more efficient PV systems and cheaper solar energy is assumed to continue, but at a slower rate than the last decade [13]. A lot of solar energy projects are now profitable without being subsidized. This can help push the cost further down, and make solar energy an even more attractive choice [12].

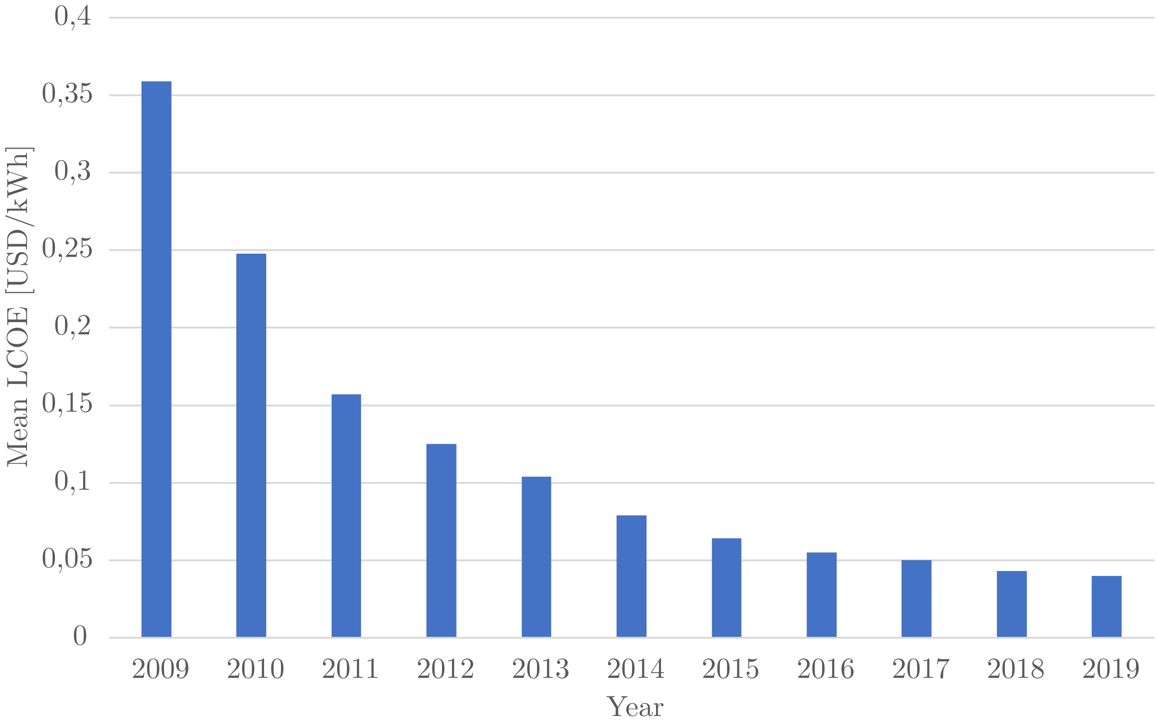

Figure 1.2: LCOE evolution for PV systems. Data from Lazard [14].

1.2.1 Solar power in Norway

Although Norway is located far north, up to a latitude of 71°, the conditions are still suitable for PV installations in many parts of the country. Being further away from the equator is generally equivalent to lower irradiation. For PV systems however, other factors like surrounding temperature and reflection from snow influence their performance in a beneficial way. Different ways to customize PV systems to fit the conditions they operate in, such as adjusting angles and orientation, can also drastically improve their production.

Solar power is still a small source of energy in Norway, but it is growing rapidly. In 2021, the installed solar power capacity in Norway increased by 30 %, which brought the capacity up to 186,5 MW [15]. This equals an energy production of approximately 150-160 GWh per year, which is a rather small fraction of the country's total energy consumption of about 123-130 TWh/yr in the past few years [16].

Analyzes from NVE show that the solar power industry will grow considerably in the years to come, so much that the production may be 5-10 TWh per year within the next couple of decades [15]. Higher power rates are named as a reason for a large interest in residential PV systems, as well as Enova increasing their subsidies as of February 2022 [15]. Trondheim county currently has an installed capacity of 16,9 MWp [17].

Solar facilities in Norway can be divided into installations connected to the power grid and free-standing facilities, which traditionally in Norway have been mostly facilities connected to a cottage. Today, almost 90 % of the solar power production in Norway is connected to the power grid. This is also the type of facilities that is increasing the fastest [17].

An average solar power system on a roof in Norway generates between 650-1000 kWh per kWp in a year. If one considered a single family home, the average energy consumption would be around 20 000 kWh/yr. A PV system consisting of twenty solar panels would then be able to cover about 25 % of the residence's power consumption [17].

1.3 The electrification of society

Society is largely dependent on electricity as an energy source, and a lot of systems would collapse without the supply of electrical power. The dependency on electrical power is constantly growing, as more and more processes are being electrified continually. An example of this is the electrification of vehicles of various kinds, most commonly cars.

In Norway, business sectors can be divided into two categories: those who fall under the EU Emissions Trading System (EU ETS), and those who do not. The business sectors that fall under the EU ETS are sectors like the petroleum industry, steel production, refining aluminum production, mineral production, transport by airplanes, and so on. Sectors that do not fall under the EU ETS are transportation by roads and sea, households, service industries, agriculture, buildings, and so on [18].

Out of the industries that do not fall under the EU ETS, the transportation sector is the sector that is responsible for the largest greenhouse gas emissions. This includes transportation by sea, roads, railroads and off-road transportation on land. Emission data from 2018 shows that 25,7 million tons of CO_2-equivalents came from the transportation sector. The largest contributor to this was fossil fuels used for transportation on roads, with a total of 9,1 million tons. This was followed by transportation at sea, with emissions of 3,2 million tons CO_2-equivalents. Based on this, electrification of the transportation sector is an important measure to reach the national goals of reducing greenhouse gas emissions. Increased electrification of the transportation sector is estimated to contribute a national increase in energy use of 5,2 TWh/year by 2030 [18].

The business sectors that *do* fall under the EU ETS will also be subject to electrification. The existing plans to electrify the petroleum industry will lead to an estimated increase in energy consumption of 3 TWh in 2030 [18]. If more oil fields than estimated are electrified, this amount can quickly increase. Land-based industrial processes will also be electrified. Data from NVE suggests that land-based industry can lead to 10 TWh/year increase in energy consumption in 2030 [18].

As Norway's energy consumption increases, the electrical power grid needs to keep up. This is made more complicated as the power demand increases. The maximum power use for Norway as a whole increased with as much as 33 % from 1990 to 2016 [19]. The energy use for Norway also shows a slightly increasing trend, as shown in Figure 1.3. These trends are expected to continue, and Energi Norge estimates that Norway's total energy use may increase by 18 TWh by 2030. By 2040, the energy consumption may increase with as much as 30 TWh [20]. The past few years, Norway's power consumption has been approximately 125-130 TWh. This means that an increased consumption of up to 30 TWh is a significant difference in transported energy on the power grid. Different sources give different estimates on the increase in energy consumption, but there seems to be a consensus that the consumption will increase.

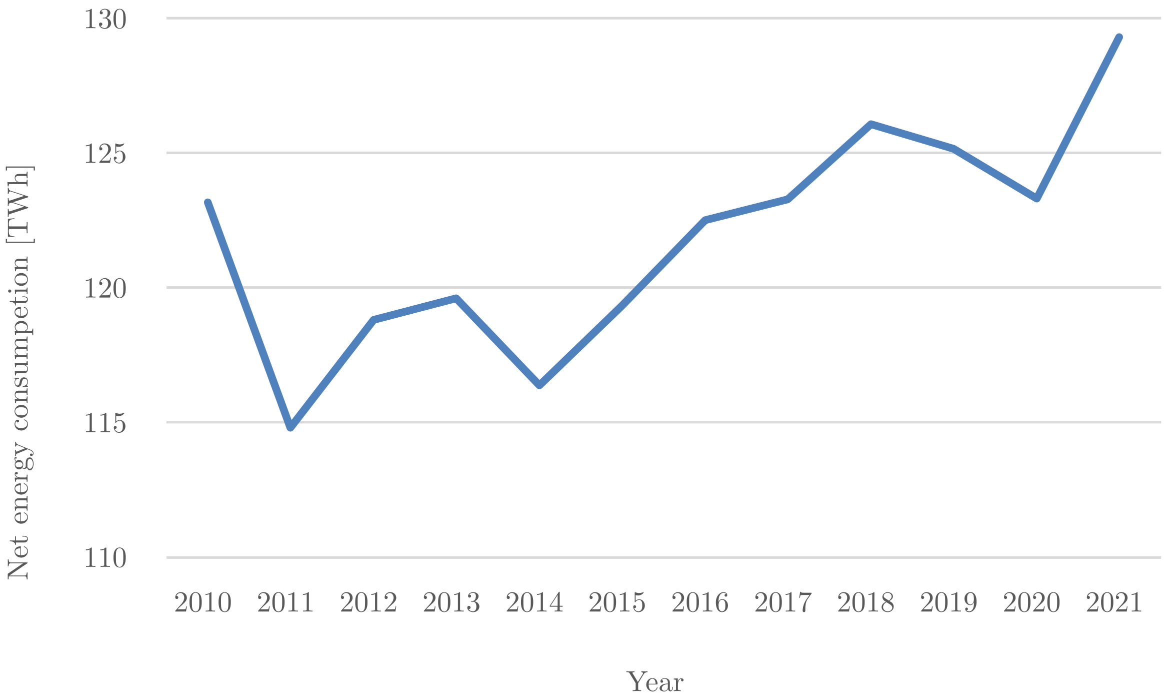

Figure 1.3: Total net use of electrical energy in Norway in the years 2010-2021. Data from Statistics Norway [16].

Some of the biggest contributors to a future increase in power and energy demand in Norway are the electrification of transportation and industrial processes. This especially includes electricity going from the mainland to the offshore petroleum industry, as well as an increase in power intensive industrial processes. Data centers are also expected to increase in size and numbers, and these have a high electricity demand. [21]

The expected increase in energy consumption will also partly come from household consumption, and will go towards charging cars. In addition, household consumers may install private PV systems, and in turn produce their own electricity, in some cases more than they consume themselves. This can further complicate the issues that the power grid experiences, especially the local power distribution grid. This is especially true if the power consumption increases. [21]

An increase in PV electricity production and wind energy production is a challenge for both local and regional power distribution grids, because they are unpredictable power sources. The increased consumption in the industrial sector and petroleum sector mostly pose an issue for the regional distribution grids. [21]

To the power grid, the power demand is the biggest factor to consider for dimensioning. Grid components that often and over longer periods of time have to operate close to their capacity limits may get a shorter life or lower capacity limits. The modern changes that come from a changed consumption pattern are expected to lead to peaks in the power demand, which may cause issues if the power grid is not dimensioned for these peaks. In a modern consumption pattern, the power consumption peaks are expected to be bigger than previously. The peaks are expected to happen at different times and have a different duration than what has previously been normal. [21]

1.3.1 Consequences

The modern consumption patterns for electrical power can have different effects on the power grid. This chapter will mention in short what challenges can arise from an increase in electrification.

Electrification can lead to an increase in power peaks, which occur when a lot of electrical power is consumed at the same time. In Norway, the increasing amount of electric vehicles (EVs) is seen as an important contribution to such an increase. What time people charge their EVs is highly dependant on their habits; plugging in the EV charger when arriving home from work every day, for example. If a majority of EV users charge their cars in the same time period, this will lead to a significant peak in power usage. This effect is so significant that a report from DNV-GL and Pöyry from 2019 shows that switching from charging EVs every afternoon to charging them at night can save society as much as 11 billion NOK as a result of saved power grid investments [22].

Other causes for power peaks can be electrical ferries, buses, transportation of goods, etc. Ferries may cause larger local power peaks when they charge, which happens periodically throughout the day. This issue has the potential to be solved by having batteries on the ferry docks. Buses and other types of transportation are expected to have a slightly more evenly distributed consumption. The increase in electricity consumption in the industrial sector and the petroleum sector are expected to be even more uniformly distributed throughout the day. [21]

An increase in energy consumption and power consumption can make the voltage in the power grid vary. This can in turn cause the voltage supply to not be within the quality norm's limit of a 10 % variation from the nominal voltage. Low voltage can cause electrical appliances to malfunction, and higher voltage can lead to the destruction of electrical appliances. [21, 23]

Power grids have several components that function as safety measures or protection measures. An example of this is safety fuses of different kinds. The safety measures are in place to protect the other grid components from unintended incidents, such as lightning strikes. The safety measures that are currently in place in the power grid are not designed for a change in power consumption that may come from electrification. This can lead to two different scenarios. The first scenario is that the safety measures do not work when they are supposed to, which can lead to damage to the power grid and other facilities, as well as personal injuries. The other scenario is that the safety measures *do* work when they are *not* supposed to, which can lead to unnecessary power outages and overload on other parts of the grid, which in turn can lead to system damage. [21]

The short circuit performance is a measurement of how robust a power grid is. To determine the short circuit performance, one must analyze how much the grid voltage is affected by energy consumption and production. If the voltage is affected to a large degree, this means that the short circuit performance is low. Low short circuit performance leads to difficulties with regulating the grid voltage, which in turn worsens variations in the grid voltage and harmonic distortions. Energy consumption and production which runs through a converter leads to a lower short circuit performance. An example of such energy production is production from PV systems. [21, 23]

As society becomes even more reliant on electrical power, power outages get more severe consequences. It is not possible to guarantee a power grid with zero outages, but the goal should be to have as close to zero outages as possible.

1.3.2 Possible strategies

To avoid issues with the power grid, there are a number of possible strategies that can be implemented. These can vary between being physical solutions, market strategic solutions or regulatory solutions. As stated in a report by DNV-GL for Energi Norge, [21], these options can include:

- Demands to implement industry standards for components used in the power grid. This can include standards for PV systems, chargers for EVs, buses, and so on.

- Digitalization: consumers or producers using smart control systems and communication technology, which will make the power system use more flexible. New and standardized digital solutions create data that gives valuable insight and makes information sharing easier.

- Using pricing to adjust the consumption by implementing network tariffs or market solutions. The customers' power requirement is the major determining factor for expenses in the power grid. The tariffs that the customers currently pay for using the power grid are dependant on the energy consumption instead of the power, but the power sector has discussed power based tariffs for a long time. This way the network tariff that the customer has to pay would more accurately reflect the expenses that this amounts to for the power grid provider. The decision to implement such a pricing solution has been made, and it was meant to take effect from 1. January 2022, but was postponed to 1. July 2022 [24]. As this solution will take effect in 2022, it will thereby have an impact on the future cost of electricity.

- Batteries can be used to primarily help improve stability and utilization of the power grid, as well as batteries that store energy for specific purposes, such as for EV charging. This is an alternative when the consumer's consumption is not sufficiently flexible. EVs are seen as a relevant source of flexibility in a long-term perspective through smart charging and possibly also discharging onto the power grid.
- Active system management in local power distribution grids: solutions that can optimize local power consumption and production to best utilize the existing grid capacity.
- Upgrading the power grid the "traditional way": this is seen as the easiest alternative in a technical sense, but it is also the most expensive one. Upgrading the capacity of a working power grid before its end of life is an expensive process. With enough time however, all existing power infrastructure needs to be replaced because of old age, and performing upgrades to the grid capacity at the same time can be done at a relatively low cost. Power grids have a long expected life however, so this would take many years.

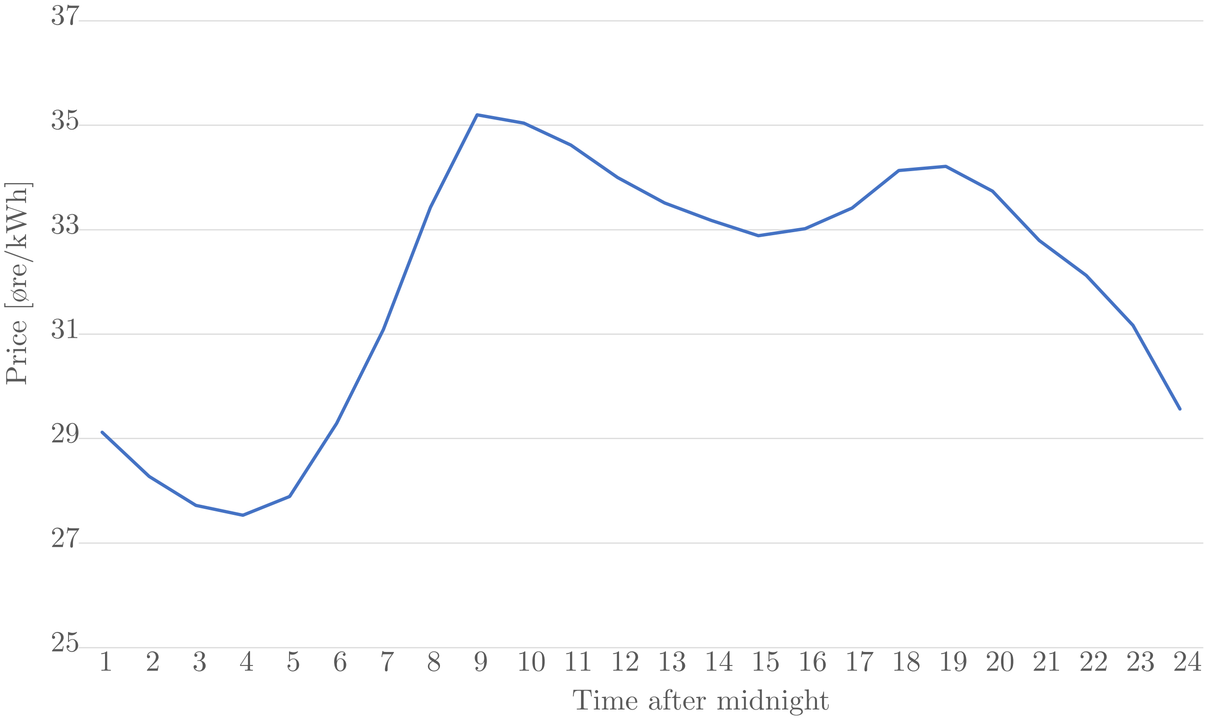

Figure 1.4: Average daily electricity price for the last five years in Trondheim. Data from Nordpool [25]

The electricity prices are determined by the Nordic power market, where a central element in the decision of the price is the supply and demand. The variations in the electricity price throughout a day are tied to the power demand. This is illustrated in Figure 1.4. The figure shows that the prices at nighttime are lower and that the daytime prices are higher. Other elements that have an impact on the electricity prices in Norway are the price of fossil fuels, price of carbon credits, available output capacity and the current situation for the Norwegian hydro power [26]. An analysis from NVE indicates that Norway can expect increased electricity prices in the future. This is mainly due to the increased capacity exchange between the Nordic region and Europe, and expected high CO_2 emission prices in the years ahead [27].

Most of the mentioned solutions to solve power grid issues cannot easily be implemented on a local level, or by individuals. Most of the suggested solutions have to be implemented on a regional or national level to have any significant effect. However, for some alternatives, individuals or small communities can affect the system with their actions, at least on a local level. EVs are examples of this.

1.4 Electric vehicles in Norway

EVs are popular in Norway, and no country in the world has more electric cars per capita. By the beginning of May 2021, the portion of electric cars among the total car population in Norway was 13%. In 2020, electric cars made up 53% of new car sales. [28]

Norway has set national goals regarding vehicles and their emissions. In the national transportation plan for 2018 to 2029, the Norwegian government established some target figures for vehicles. Among these targets is the following:

> “New passenger cars and light vans shall be zero-emission vehicles (including electric cars and hydrogen cars) within year 2025.” [28]

The market for electric cars in Norway has as mentioned increased over the past years. In 2018, the total amount of registered electric passenger cars was 194 900 cars. From then until the first quarter of 2022, the amount of registered electric passenger cars has increased to 480 226 cars[29]. There are several reasons for this increase of electric cars bought in Norway, but part of the reason could be the benefits established by the Norwegian government. These benefits include:

1. Relief from the vehicle excise duty and value added tax (VAT). This makes it economically favorable to buy an electric car versus another car ran on fossil fuel.

2. The electric cars gets a number of benefits in traffic, such as:

    - Free or reduced price at ferry
    - Access to use the public-transport lane

- Relief from road tolls on national highways
- Free parking

There are few other European countries that have a similar tax system to Norway, and by that they do not have the same opportunity to offer financial benefits when purchasing electric vehicles. [28]

1.5 Electric vehicles in Trondheim

To demonstrate the increase of electrical cars in the total car population in Norway, Figure 1.5 is a good illustration. This Figure shows the amount of vehicles of various fuels in Trondheim municipality. The data behind these columns show that the amount of electric vehicles in Trondheim has increased with 227 % over the past five years.

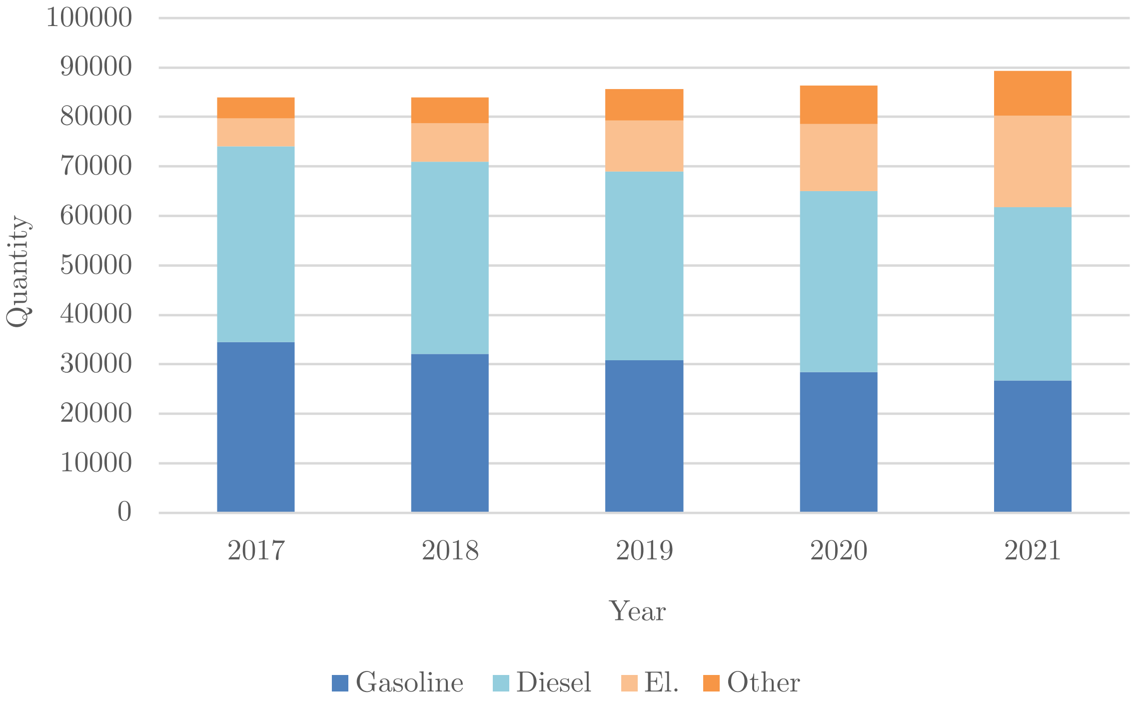

Figure 1.5: Number of vehicles of various fuel in Trondheim. Data from Statistics Norway [30].

It is reasonable to assume that the amount of electric cars in the total car population in Norway, and Trondheim, will increase. This is based on the increase of electric vehicles in the car population, and the dimension figures for vehicles set by the Norwegian government.

1.6 Benefits of batteries

Today, the power drain can be shifted with minutes or a few hours, with minimal impact on the consumer's comfort. This can have a major positive impact on the security of the supply, as it helps relieve the power grid in hours where there is a power peak. Consumer flexibility, also called "demand side response", means to shift the consumption to adapt to the capacity of the grid, by either decreasing or increasing the consumption in certain time periods. This way, loads that are already present in the system can be used more like conventional energy storage, but often at a fraction of the cost. Demand side response does require access to digital platforms and smart control systems however, which increases costs [31].

Energy that is stored behind the electricity meter can be used to reduce the consumption in peak load hours when the electricity rates are high, and can with that also reduce the electrical bill. If the consumer also has a power based tariff, like mentioned in chapter 1.3.2, energy storage can be used to reduce the maximum power consumption and thereby lower the electrical bill even further. This will be relevant for consumers in Norway in the near future as power based tariffs are implemented more and more. [31]

Charging an energy storage system when the electricity prices are low, and discharging it when electricity prices are high, will reduce the electricity bill. This is a form of arbitrage. The electricity prices often reflect the demand at a given time, and this type of arbitrage can contribute to smaller variations in the demand. Consumers with local energy production can also increase the amount of self-consumption by integrating an energy storage system, as well as engaging in arbitrage. This is well suited for the production profile for more unpredictable renewable energy sources such as solar energy. The solar energy production rarely follow consumption profiles exactly. An energy storage system can harmonize this by storing energy in times of production surplus, and supply energy in peak load hours. [31]

DNV-GL has done an evaluation of which battery technologies that are most suitable for delivering a given service, or which services the technology is well suited for. In this evaluation, DNV-GL concludes that for a battery technology for energy consumers, the LiBs are quite well suited. For energy consumers, or end users, an LiB can: reduce peak power, engage in arbitrage and lead to increased self-consumption. LiBs were rated as the most suitable battery technology for these services, and is also the most used technology for this purposes. This technology will be explained in further detail.

2 Theory

The theory section is the basis of knowledge that a thesis is based on. This chapter includes information about the sun and its radiation, semiconductors, photovoltaic (PV) systems, and the parts that need to be included in a PV system. Additionally, it contains information about batteries and energy from PV to grid.

2.1 Insolaton on earth

The sun is the star located in the center of the solar system. The earth and other planets orbit the sun. It emits sunlight and is the main source of energy to the surface of the earth [32]. The sun provides light, heat and other types of energy to earth. Energy comes from deep inside the sun's core and originates in nuclear fusion reactions. In such reactions, the nucleus is created by joining two atomic nuclei together. The way fusion releases energy is by converting nuclear matter into energy. [33]

Insolation is the amount of solar radiation that is received by the earth. The insolation can either reach the earth's surface, or be absorbed or reflected by the atmosphere. How directly the sunlight hits the surface at any given location and the provided energy from the sun to the earth, is dependent on both the inclination of its axis of rotation as well as its distance from the sun. This is also dependent on daily variation in cloudiness and seasonal variation [34]. The letter Q is usually used to describe insolation, and it describes the solar radiation incident on a horizontal surface per square meter integrated over a certain period of time. [35]

The position of the sun in the sky changes from hour to hour and day to day. As is well known, the sun's position is higher in the sky in the summer than in the winter. The motions of the sun and earth are systematic and predictable. The earth moves around the sun in an orbit that is elliptical in shape, and the time this orbit takes corresponds to a year in our calendar. Also, every 24 hours, the earth rotates around its axis. The earth is tilted at an angle of approximately 23,45 °to the plane of the elliptic, and the elliptic axis corresponds with the sun's equator and the earth's orbital plane. [32]

Every day, the sun moves in a motion of an arc across the sky, reaching the highest point at midday. The sunrise and sunset points move gradually northward along the horizon as the seasons change. As the seasons change from winter to summer, the days get longer as the sun rises earlier and sets later each day, and the sun's path moves higher in the sky. The insolation on the earth changes throughout the year. For the Northern Hemisphere, the day when the sun is at its northernmost position with respect to the earth is on June 21. This is the day when the daytime is at its maximum length, and it is called summer solstice. Similarly, six months later, on December 21 the sun is at it's southernmost position, and the daytime is at its minimal length. This is called winter solstice.

2.1.1 Solar angles

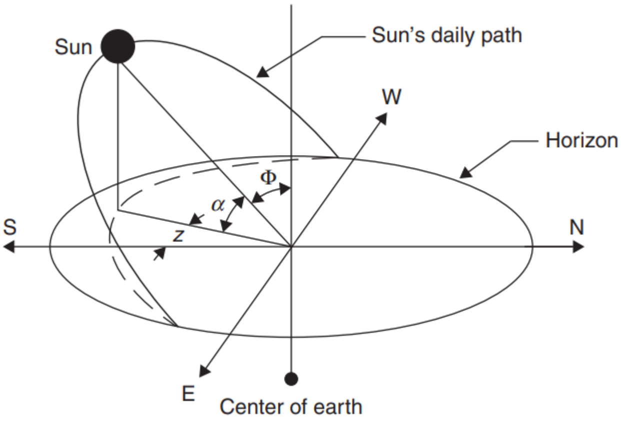

Figure 2.1: Solar angles [32]

The way the insolation hits the earth is defined in different angles. Some of these angles are shown in Figure 2.1 and described in Table 2.1.

Table 2.1: Solar angles [32].

Name	Symbol	Description
Solar altitude angle	α	The angle between the sun's rays and the horizontal plane
Zenith angle	Φ	The angle between the sun's rays and the vertical
Azimuth angle	z	The angle of the sun's rays measured in the horizontal plane from the true south for the Northern Hemisphere

For the azimuth angle, the true south means in which direction during the day the sun will be at its highest. The westward position is designed as positive for the azimuth angle. Other factors that make an impact on the insolation from the sun are the Latitude and Longitude as well as the day length. [32]

To maximize the power from the sun onto PV panels, the tilt angle is also a factor to consider. Tilt angle (β) is defined as the angle between the plane of the tilted surface and the horizontal plane. Figure 2.2 illustrates that tilting the PV panels towards the sun, will increase the beam absorption G_B to G_{Bt}. The maximum value of G_{Bt} is achieved when $\theta = 0$, so it follows that $G_{Bt} = G_{Bn}$, as shown in equation 2.1. A well known practice on tilting the PV modules is the latitude tilt. This is to tilt the module to an angle equal to the geographic latitude, as this will minimize the average incidence angle throughout the year. [32]

$$G_{Bt} = G_{Bn} \cdot cos(\theta) \tag{2.1}$$

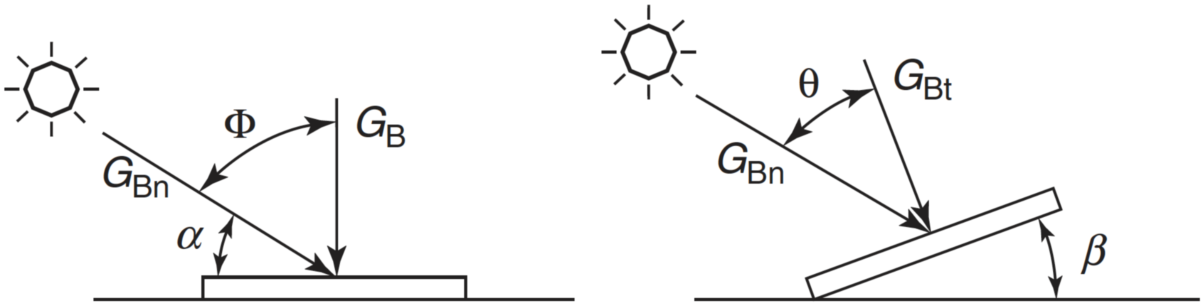

Figure 2.2: Illustration of how the tilt of a surface will effect the solar irradiance. [32]

2.2 Diffuse irradiation on PV systems

Within solar irradiance there are two components, direct and diffuse irradiance. The direct irradiance component is the solar radiation that comes directly from the sun to the point of observation. The direct irradiance is undisturbed, without scattering or absorption from the particles and molecules of the atmosphere. The radiation received at a point after it has been scattered by the molecules and particles is called the diffuse radiation. [36]

Besides considering the direct irradiance for calculations of PV systems, the diffuse radiation is also important to take into account. An inaccurately calculated diffuse irradiance can lead to over- or under-estimations of the annual energy yield of a PV system. According to Hofmann, [37], these estimations can lead to as much as 8 % of the annual energy yield of the system. Therefore, in 2017 a new model for estimating the diffuse fraction of solar irradiance for photovoltaic system simulations was presented. This model is named Hofmann and this model utilizes geographical information and time series of global irradiance in one-minute resolution as input. [37]

Kalogirou [32, p.95 Kalogirou 2014] explains that the insolation received by a surface on earth is the sum of diffuse and the normal component of beam radiation. Further, Kalogirou states that the solar energy at any point on earth depends on four variables:

1. The ozone layer thickness
2. The distance traveled through the atmosphere to reach that point
3. The amount of haze in the air (dust particles, water vapor, etc.)
4. The extent of cloudiness

The atmosphere surrounds the earth and contains gasses, suspended dust, liquid and solid particulate as well as clouds. The sun's radiation travels through the atmosphere and is depleted of energy in its passage. Reduction of radiation that will hit the ground happens with an increase in zenith angle, as this will increase the sun's irradiation distance travel through the atmosphere, as shown in Figure 2.3.

Air mass (AM) is a term that explains the distance of the sun's radiation's travel through the atmosphere, and it is related to the zenith angle Φ, without considering the earth's curvature. The equation for air mass is shown in equation 2.2, and this is illustrated in figure 2.3. [32]

$$AM = \frac{AB}{BC} = \frac{1}{cos\,\Phi} \tag{2.2}$$

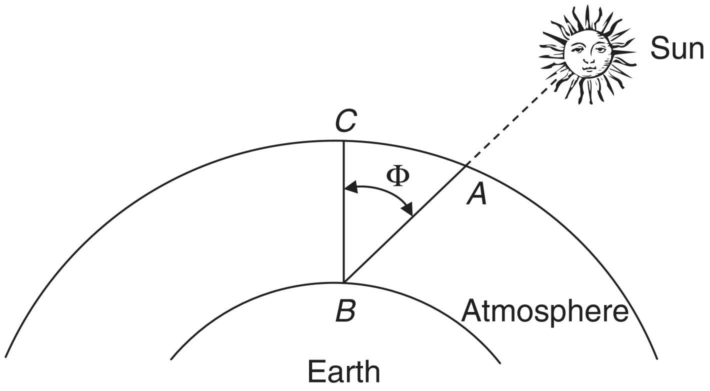

Figure 2.3: Air mass definition. [32]

2.3 Performance ratio

The performance ratio (PR) of a solar energy system is often used as a measure of quality factor for the system. The equation for the PR is given in 2.3, where the actual reading of the power plant output is the power produced by the system over one year per area. The calculated, nominal plant output is the annual incident solar irradiation at the generator surface per area, multiplied with the efficiency (*eta*) for the PV panel at Standard Test Conditions (STC) [38]. STC have a radiation of 1000 W/m^2, a temperature of 25 °C and an Air Mass (AM) of 1,5.

$$PR = \frac{Actual\,plant\,output\;[\frac{kWh}{area}]}{Calculated\,nominal\,plant\,output\;[\frac{kWh}{area}]} = \frac{Actual\,plant\,output\;[\frac{kWh}{area}]}{Q\;[\frac{kWh}{area}]\cdot\eta} \tag{2.3}$$

2.4 Semiconductors, mono- and polycrystalline silicon

PV systems are made from a semiconductive material, and this is necessary for the PV cells to be able to deliver electric energy. The chosen semiconductor material for PV panels is often silicone, which can come in a monocrystalline or a polycrystalline structure. This section will elaborate further on how these things make energy production from PV cells possible.

2.4.1 The structure of an atom

Atoms are made up of a nucleus, and electrons that orbit the nucleus. As atoms of different substances have different numbers of electrons, how many orbitals the substances have also differs. In atoms with multiple orbitals, the electrons closest to the nucleus have the largest amount of energy, while the electrons in the outermost orbital have the smallest amount. [32]

The electronic energy levels of individual atoms can change when the atoms are brought close together, and can form energy bands. The energy bands have different characteristics, where some bands can contain electrons and some do not. The highest normally filled energy band is the valence band, and these outermost electrons are the only ones that interact with other atoms. They can "jump" from their original orbital to an orbital in a neighboring atom when the atoms are brought close together. The valence band can contain electrons that possess a lot of energy, which can allow them to jump into a higher energy band, called the conduction band. They are then responsible for the conduction of electricity and heat. The energy difference in an electron in the inner orbitals of the conduction band, and in the valence band, is called the band gap. Atoms with no electrons in their conduction band, and a full valence band are called *insulators*, because the electrons in the valence band cannot carry any current. The valence electrons cannot accept energy, because they cannot access empty states in the conduction band. *Conductors* are atoms with an empty valence band, and with some electrons in the conduction band. Metals are examples of conductors. [32]

2.4.2 Semiconductors

A semiconductor is neither an insulator nor a conductor. Semiconductors have partly filled valence gaps and intermediate band gaps. In these materials, the band gap is smaller than 3 eV (electronvolts), and they have the same band structure as insulators, but with smaller band gaps. There are two different kinds of semiconductors, called intrinsic and extrinsic semiconductors. Intrinsic semiconductors are pure materials, and the valence electrons can easily be excited to the conduction band, where the electrons can move freely. Extrinsic semiconductors are doped with small amounts of impurities [32].

For current to flow in the right direction a semiconductor, a diode needs to be formed. This can be achieved by the formation of a junction between disparate materials, meaning a semiconductor doped with materials with different properties. Silicon, the most commonly used semiconductor, can be doped with for example boron to form a p-type (positive) material, and with phosphorous to form an n-type (negative) material. [39]

A p-type semiconductor is doped with a material that has fewer electrons in the valence band than the semiconductor itself. The p-type material has missing electrons in its structure, called electron holes, that create a positive charge. Holes are formed when the semiconductor is doped with elements from group 3 of the periodic table [32].

In an n-type semiconductor, the material that is used for doping has more electrons than the semiconductor itself. The material is electronically neutral, but has excess electrons that are able to move freely. An n-type semiconductor can be achieved by doping the semiconductor with substances from group 5 in the periodic table [32].

When a p-type material and an n-type material are combined, they form what is called a p-n junction. The p-type material then draws electrons from the n-type material, and the n-type materials draws holes from the p-type material. This happens because the particles are mobile, and diffuse through the composite material, and leaves the n-type material positively charged and the p-type material negatively charged. The positive charges by the junction on the n-type material make the movement of additional electrons from the p-type material easier, while the negative charges on the p-type material restrict the movement of electrons from the n-type material. Figure 2.4 illustrates what happens at a p-n junction.

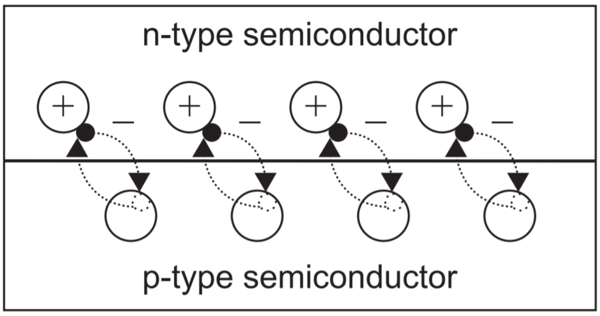

Figure 2.4: A visual presentation of a p-n junction. [32]

2.4.3 The photovoltaic effect

The photovoltaic effect was discovered by Becquerel in 1839, and is what makes electricity production from solar energy possible [32].

A photon is an elementary particle which all visible light and other forms of electromagnetic radiation is made up of. Although photons are not charge carriers, they are able to interact with electrons, as they do carry energy. This is the basis for the PV effect [40].

A photon can either be absorbed, reflected or transmitted when it hits a photovoltaic material. When a photon is absorbed by a valence electron, the energy of the electron increases with the corresponding energy of the photon. If the energy of the valence electron now is greater than the band gap between the valence band and the conductor band, the electron will jump to the conduction band. This makes the electron able to move freely, and can then be removed from the atom if an electric field is present, thus creating a current. [39]

2.4.4 Monocrystalline and polycrystalline silicon

There are many materials to choose from when making a PV panel. The most common material is crystalline silicon, which in turn can be divided into monocrystalline and polycrystalline silicon. Each of these have their advantages. Crystalline silicon is also the most suitable material for moderate climates, such as Norway. Based on silicon being the most commonly used material for PV modules, making up about 80 % of the PV market [32], this material will be elaborated on in this section.

Monocrystalline silicon has a continuous crystal lattice structure. It does not have grain boundaries, and has very few defects and impurities. The cells are made from thin wafers, that are produced by melting polycrystalline silicon and casting this into ingots. The ingots are in turn sliced very thin, to form wafers. The wafers are then assembled to form cells. The material's qualities makes its efficiency quite high, up to 15-20 %, and this is expected to increase [41]. PV modules made from monocrystalline silicon are the most expensive to purchase, due to the production process being fairly complicated. The process produces large amounts of silicon waste, and is energy-intensive, and this drives up the cost [41]. The costs have been reduced in recent years however, to a level where the prices are more competitive. The price of monocrystalline PV modules is still quite high however, which makes them best suited for installations with a need to maximize power output per unit of space [32].

Polycrystalline silicon cells are made from material that is constructed from a large amount of grains of monocrystalline material. The overall production process of the polycrystalline cells is simpler than the one for the monocrystalline cells, which makes the cost of the product lower. However, the material structure makes the cells have a slightly lower efficiency, at 13-16 %, which is also expected to increase [41]. Their relatively high efficiencies and moderate costs makes polycrystalline a widely used option for many kinds of applications.

Visually, there is also a difference between monocrystalline and polycrystalline cells. Monocrystalline cells have a more uniform color, and are usually the darkest. Polycrystalline cells can be somewhat lighter in color, and the color can vary, creating almost a pattern. These differences are shown in figure 2.5.

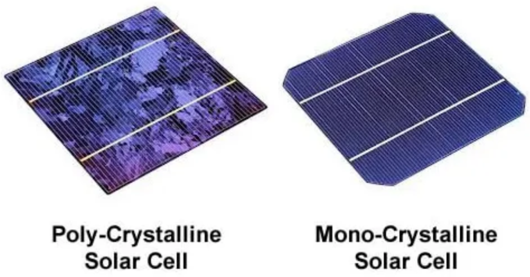

Figure 2.5: The visible difference between monocrystalline and polycrystalline cells in PV modules. [42]

2.4.5 Power from solar cells

A solar cell with no load connected will have a voltage of V_{OC} and a current, $I = 0$. If the cell is short-circuited, the current will be maximized, I_{SC}, and the voltage, $V = 0$. Between short-circuit and open-circuit we will have both voltage and current and therefore electric power, as long as the irradiance is adequate.

The I-V characteristics for a PV cell are shown in figure 2.6. When connecting the PV cell to a load, the resistance of the load will decide the point on the graph based on the size of the

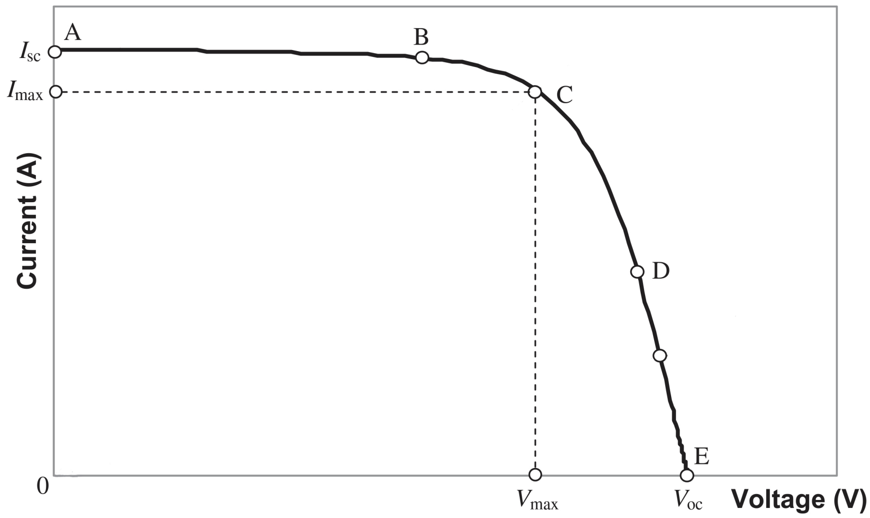

Figure 2.6: IV characteristics for a solar cell. [32]

resistance. The power from the PV cell can be calculated by the product of voltage and current as shown in equation 2.4, where P is the power measured in watt, U is the voltage, and I is the current in ampere. The I-V curve will change with change in irradiance and cell temperature as shown in figure 2.7. It is clear from this figure that a high irradiance and a low temperature will result in a high output power for a solar cell.

$$P = U \cdot I \tag{2.4}$$

One PV panel contains many PV cells connected in series. The I-V curve for a PV panel with PV cells connected in series with the same conditions for all cells, will have the same short-circuit current I_{SC}, but the open-circuit voltage V_{OC} will be added together for the whole panel. If the cells are connected in parallel, the open-circuit voltage V_{OC} will be identical for one cell and the short-circuit current I_{SC} will be added together from each cell.

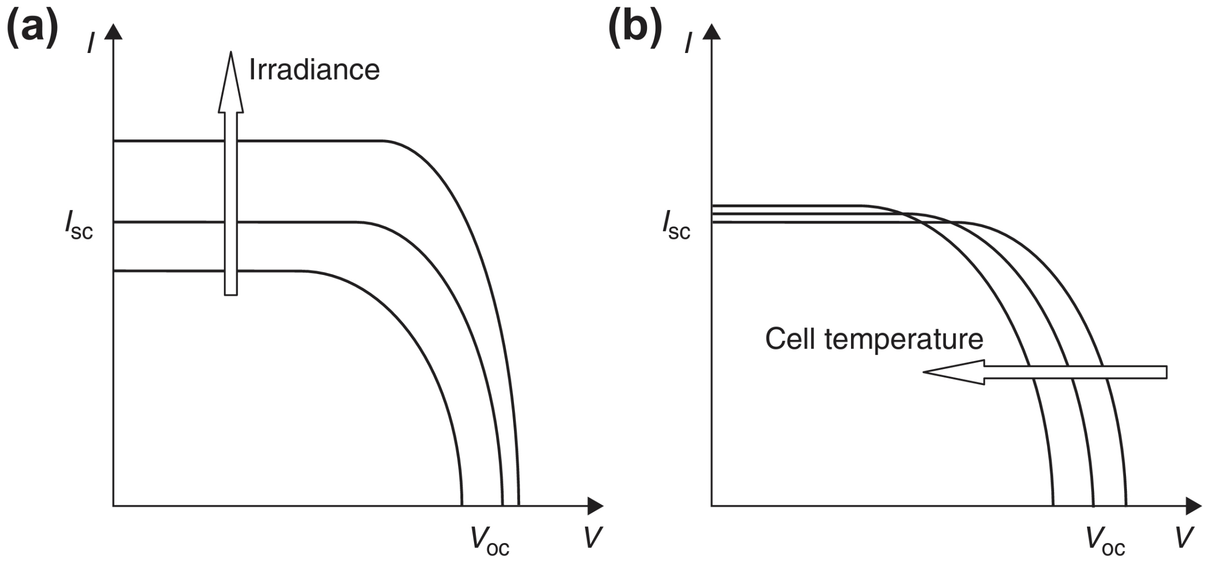

Figure 2.7: Influence of irradiance (a) and temperature (b) on IV characteristic for a solar cel. [32]

Figure 2.8 shows the power characteristics for a PV cell. In most cases, it is preferred to produce ash much power as possible, as this is the main reason for installing PV panels in the first place. The load resistance is therefore optimal where the the PV graph in figure 2.8 is at its maximum. This point corresponds to point C in figure 2.6 and is called the maximum power point. There are different types of technologies to locate this point and adjust the load to force the solar cell to produce its maximum and this is called a maximum power point tracker (MPPT).

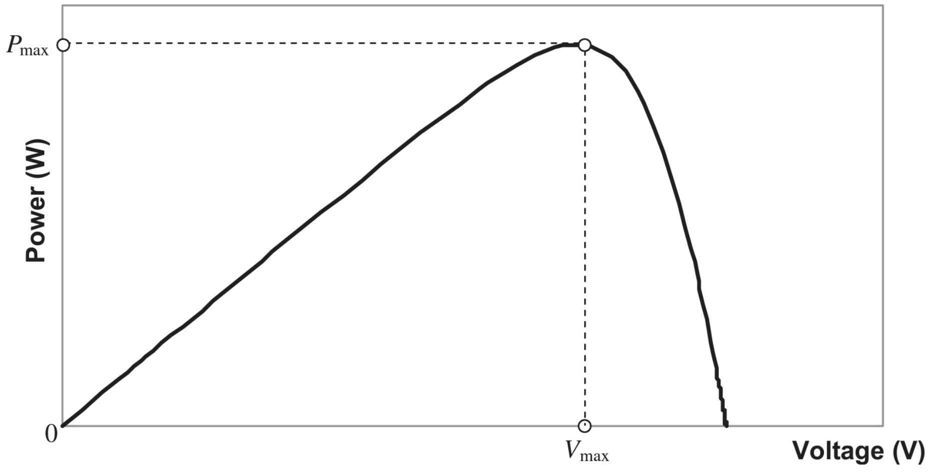

Figure 2.8: Power characteristics for a solar cell. [32]

2.5 Power from PV to grid

A PV panel produces direct current (DC) at a voltage around 12-40 V. Most distribution grids today use alternating current (AC). In the EU, TN (Terra Neutral) networks are the most common, which have a voltage of 400 V. The most common grid type in Norway is the IT

(Insulated Terra) network, which has a voltage of 230 V. Therefore, it is important to have an inverter that is designed for the network you will use. An inverter can invert a DC voltage to an AC voltage so that the power is ready to be utilized by the grid or other AC consumers. For PV systems, there are mainly three kinds of solutions that are commonly used: string inverters, micro inverters and power optimizers. [43, 44, 45]

2.5.1 String inverters

String inverters are used when one has multiple solar panels of the same size, angle, and with the same amount of sunlight hitting the panels. One string inverter has a capacity from a couple of hundred watts and up to hundreds of kilowatts. That means that one can connect several solar panels in series or parallel to a string inverter. Since the panels are connected in series or parallel, a string inverter will see all of the connected panels as one panel that has one IV curve. The MPPT in the inverter will locate the maximum power point for the whole system, but this will not make each of the panels produce their maximum, as each panel will have a different IV curve. If one of the cells is shaded or not able to produce current, this cell will act as a resistance and absorb some of the current the other cells generate. This will cause the shaded cell to heat up and can eventually damage the module. Stringinverters are therefor recommended for systems where the panels have as identical IV curves as possible. To prevent hot spots, bypass diodes are placed regularly in the PV network and are often also placed inside each panel to prevent hot spots, and optimize the energy production. [46, 47]

2.5.2 Micro inverters

Micro inverters work the same way as string inverters, but like the word implies, these are smaller inverters. One micro inverter is used for one panel and is installed right at the panel. So if one has a system with micro inverters, the system will need to have one micro inverter for each PV panel. This allows each panel to produce its maximum as each micro inverter has it own MPPT. The micro inverters then invert the DC to AC, and the power can be delivered straight to the grid. The total output power for the PV system will be the sum of the output for each solar panel. [48]

2.5.3 Power optimizer

A power optimizer is a DC to DC converter that converts one voltage into another voltage. The power optimizer also have a MPPT that make sure the panels the power optimizer is connected to is producing its maximum. One power optimizer can be connected to every panel, or to panels that is connected together. The system also has one DC to AC inverter similar to a string inverter. The DC voltage output from the power optimizer is converted so the voltage or current is identical to the other power optimizers' output. If the modules are connected in series, the power optimizer will output the same current, and if the modules are connected in parallel, the modules will have the same voltage. DC to DC converters are cheaper than a DC to AC inverter, and are therefore often preferable over micro inverters. [49]

2.5.4 Voltage quality

Inverters come in different sizes and with different connections. Some inverters are only connected to 1 phase, and this can contribute to throw off the balance between the phases. A solution to this is to have multiple inverters connected to different phases. Another solution that is preferred for bigger scaled PV plants is a 3 phase inverter which delivers power evenly between the phases. [50]

The inverter will output a voltage that varies with the output of the PV system. The output voltage from the inverter should be close to the grid voltage, if the power is being transported to the grid. As mentioned previously, the maximum and minimum allowed voltage in the grid is $\pm 10\% \cdot 230V$, which equals 207 V as a minimum and 253 V as a maximum voltage for IT grids. This is required for all the parts of the network. Buildings that are located far from the voltage source have a lower voltage because of a voltage drop that occurs during transportation over long distances. To deliver the required voltage to the buildings far away, the voltage in the buildings close to the voltage source must have a higher voltage. [50]

Figure 2.9 shows how the voltage develops as it experiences voltage drop. The red line illustrates a typical voltage during the summer. The voltage is usually higher in the summer, as the power consumption is lower, since the need of heat has decreased. The blue line indicates the winter with a lower voltage for the system.

Solar power systems will produce most of their energy during the summer, and therefore also contribute to raise of voltage in various places in the grid. As Figure 2.9 shows with the red dashed line, the voltage can at some point rise over the maximum value due to energy production. In most cases, the inverter will be triggered if the voltage is too high, and a safety fuse will stop the PV production. [50]

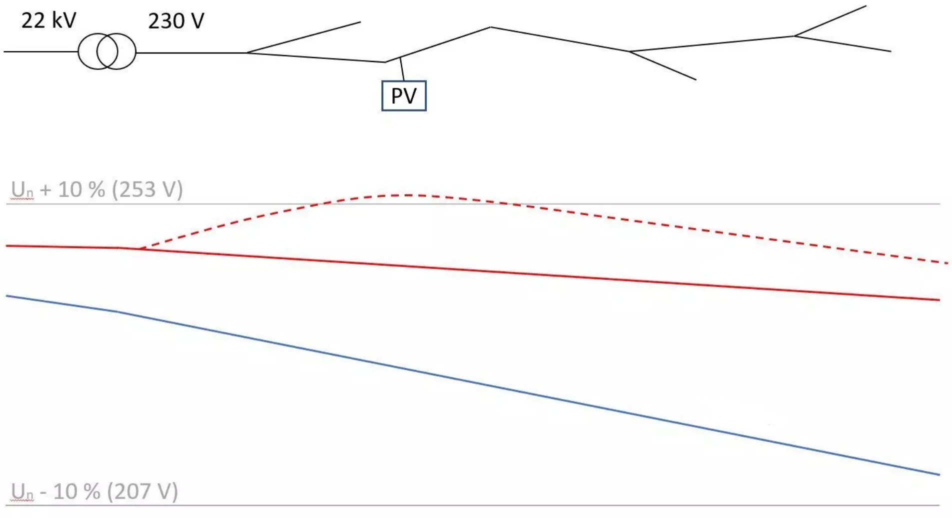

Figure 2.9: Voltage development in the grid. The blue line shows the voltage in the winter, and the red line in the summer. The dotted line is the voltage with an imaginary PV facility connected. [50]

2.6 Battery technologies

Batteries used for self-consumption in residential or small commercial buildings and for time-of-use management usually have installations sized between 2 kW and 200 kW. Generally, all types of batteries can be feasible for self-consumption and time-of-use management. [51]

Although all batteries are feasible for use, there are battery technologies that are more commonly used than others. Technologies like Li-ion Titanate (LTO) and Li-ion nickel manganese cobalt oxide (NCA) have not been used that much due to their higher cost [52]. Therefore, the most prominent battery technologies for households are lead-acid (LA) batteries, high temperature batteries (e.g. NaS or NaNiCl), flow batteries and Lithium-ion batteries (LiBs) [51]. These will be further elaborated on.

Compared to conventional batteries, flow batteries have some significant advantages. The batteries are safe, have a long life time and have the power and energy constrains separated. This enables an easy optimization of the configuration. However, these advantages are accompanied by high investment costs, more complex system requirements and related high maintenance costs. Flow batteries have been commercialised for home-storage systems, but they are considerably more expensive than for example LiBs. This makes flow batteries less attractive for smaller scale storage applications and are therefore unlikely to be used in residential applications in the near future. [51, 52]

For high temperature batteries, the most used technology is the NaS battery. This battery has advantages like high energy density, high cycle life, high efficiency and low maintenance. High temperature batteries operate at very high temperatures, which can be a safety issue. Other issues for safety can occur by the challenging chemical environment and formation of corrosion in insulators, or when the battery is in contact with air, an explosion can occur. Since the high temperature batteries need a constant power throughput to maintain the high temperature, they are not well suited for small applications such as self-consumption in households.[51, 52]

The oldest technology for batteries in households and commercial buildings is the LA battery technology. LA batteries are technically well suited, and have in many years been used in these applications. It is a mature and relatively cheap technology. For a LA battery, the most significant disadvantages is the the low cycle depth and fast battery degradation. [51, 52]

The most used battery technology nowadays is the LiB technology. In many markets, the LA battery technology has been rapidly replaced by LiBs due to their superior performance. LiBs have several relative advantages and among these are no gassing, higher lifetime, no maintenance, higher efficiencies and due to lifetime and efficiency, a lower total cost of ownership. Difference from a LA battery, the LiBs are easier to install. LA batteries require special skills at installation because they need to be filled with electrolyte. Also, LiBs can be installed hanging on a wall, which gives a better aesthetic impression for the consumer. [51]

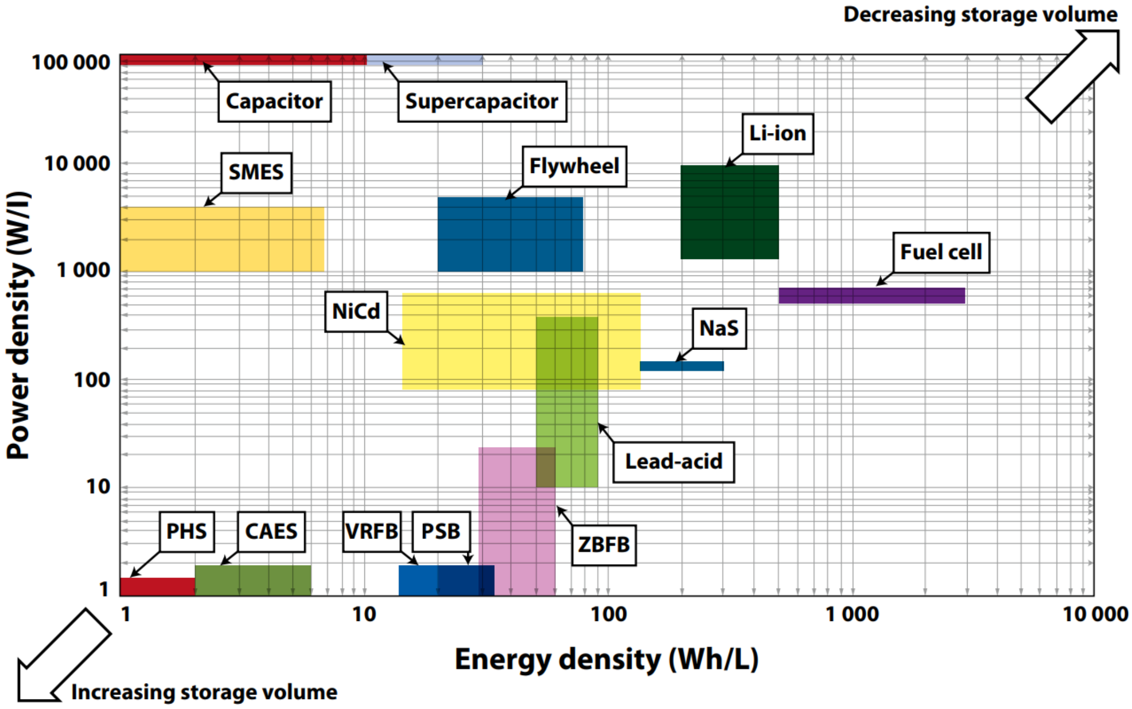

Figure 2.10: Ragone plot: comparing energy density and power density for selected energy storage technologies [51]

To illustrate the comparison of the different battery technologies, Figure 2.10 shows a Ragone plot. A Ragone plot compares various energy-storage devices by plotting the energy density versus the power density. In this case, the power density is volumetric, and specifies the ability an energy storage device has to take on or deliver power per liter. The energy density is the capacity an energy storage device has to store energy per liter. Normally, both the vertical and horizontal axes have a logarithmic scale, which makes for a convenient comparison of the performance of various battery technologies. [53]

The mentioned battery technologies that are the most prominent for households, are shown in Figure 2.10. The vanadium redox flow battery (VRFB) and the zinc-bromine flow battery (ZBFB) are two different types of flow batteries. The plot shows that the flow batteries have both lower energy density and power density than the other battery technologies. The power density ranges from 1-20 W/L and the energy density ranges from 15-60 Wh/L. For the LA battery, the power density ranges from 10-300 W/L, and the energy density from 50-90 Wh/L. For the high temperature batteries, which often are NaS batteries, the power density has a smaller range of about 13-16 W/L. The range is bigger for energy density, where it ranges from 105-120 Wh/L. The LiBs are clearly better among the four most prominent battery technologies for households. The power density for LiBs range from approximately 2000-10000 W/L and the energy density ranges from 200-500 Wh/L.

2.6.1 Lithium ion batteries

Chemical batteries can store energy and be used whenever needed. LiBs are a chemical type of battery and can be built with different materials and in different shapes. What all LiBs have in common is that lithium ions travel through the electrolyte. Electrons travels through a circuit as shown in Figure 2.11 and is what produces the current. [54]

An LiB can simplified be described with three parts as shown in Figure 2.11. The anode is termed negative during discharge. This is where the oxidation reaction happens during discharge and the reduction reaction happens during charging. The second part is the cathode, which is termed positive during discharge. This is where the reduction reaction happens during discharge and the oxidation reaction happens during charging. The last part is the electrolyte, which separates the anode and the cathode. The electrolyte transports the lithium-ions inside the cell and forces the electrons to traverse the external circuit and through the light bulb as shown in Figure 2.11. [55, 56]

If the light bulb was exchanged with a power supply, one would connect the positive pole to the cathode, and the negative pole to the anode in order to charge the battery. Since the electrons are negatively charged, they will be forced towards the now positive cathode and through the power supply. The lithium ion is now positively charged and will go through the electrolyte towards the negative anode. When the lithium ions and electrons are at the anode side, the battery is fully charged. When the light bulb or another load is placed over the battery, the process of discharging will automatically start again. [56]

2.6.2 Degradation

LiBs will start to experience some sort of degradation from the moment they are made. It is said that if the battery capacity is lower than 70-80 % of its original capacity, the battery is at

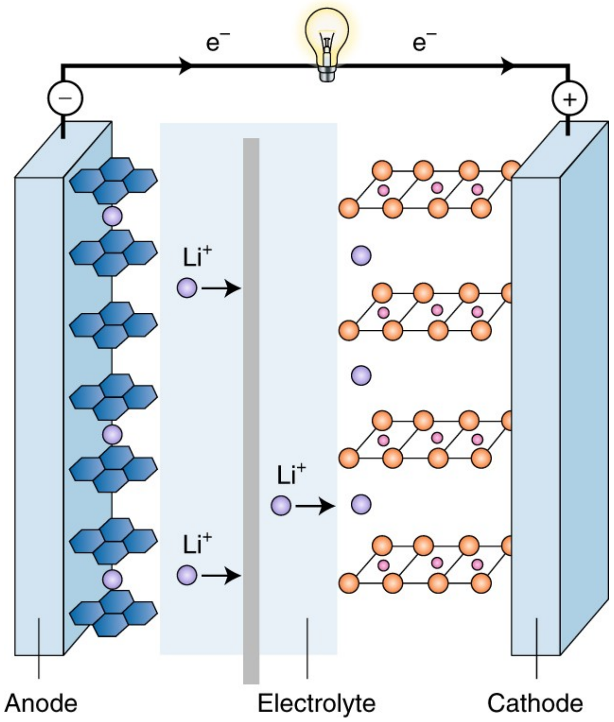

Figure 2.11: Simple model of a Lithium ion battery cell. [56]

its end of life. A battery capacity can be measured in State of Health (SoH) which indicates the current capacity of the battery compared to the capacity it had when it was new. The process of degradation is a complex thing, and some theory about what can causes degradation is presented below [57]:

Charge cycles

One charge cycle refers to one full drain of the battery from 100 % SoC to 0 % SoC. One cycle can also be to discharge the battery twice from 100 % SoC to 50% SoC. Both examples represent one full cycle.

The more cycles a battery goes through, the more it degrades. This is due to some loss of lithium-ions when they go through the electrolyte. The electrode can also contribute to degradation as a result of Lithium-ions moving in and out of the electrode during one cycle, which can cause structural disorder at the electrode and that can reduce the number of Li-ions that will go into the structure of the electrode, and therefore also reduce the SoH. [57]

The depth of the charging cycle will also effect the SoH of the LiB. Figure 2.12 shows an experiment done to show how different depth of cycles would effect the SoH with many cycles repeated. Worth mentioning is that one dynamic stress test (DST) cycle stands for one discharge and one charge for the given SoC interval. This is not the same as one full cycle. The yellow line's DST cycle is the same as 10 % of a full cycle, and there is therefore less energy in one DST cycle for the yellow line compared to the other lines. As seen in the figure, the black line experiences the biggest degradation. This is also the line with the largest DST cycle. [58]

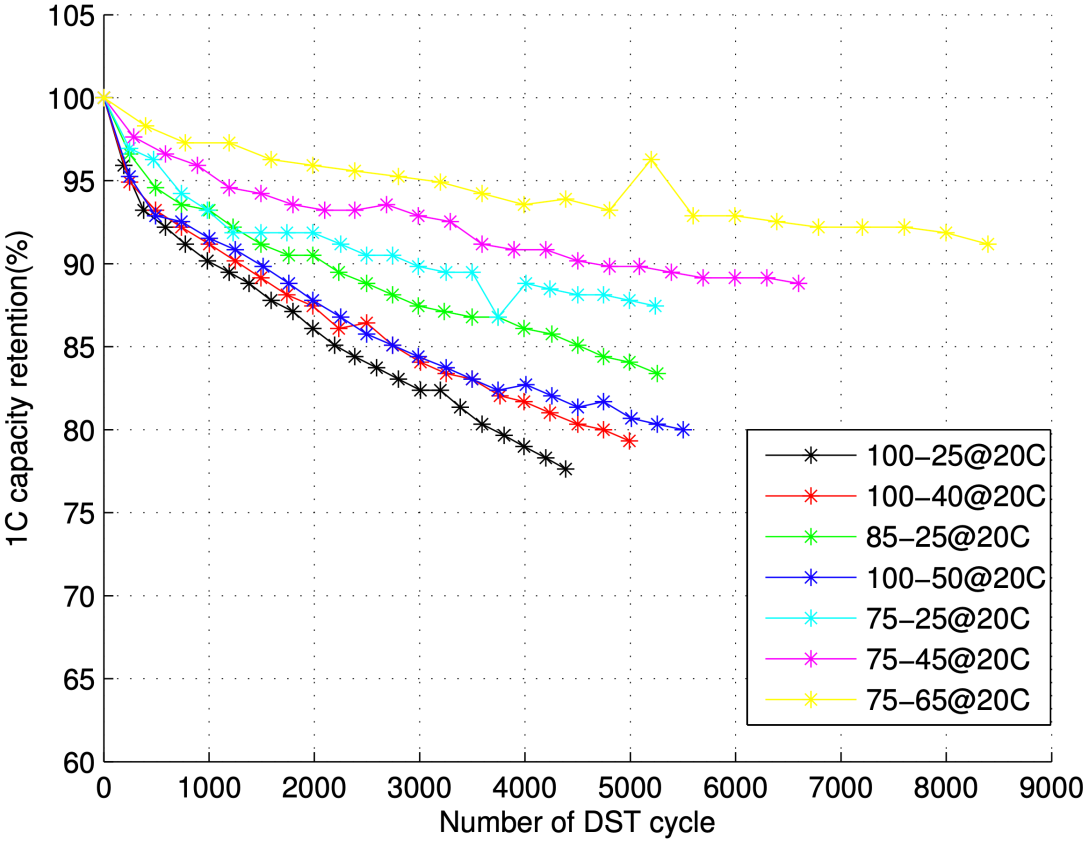

Figure 2.12: Degradation of LIB depending on how deep the cycle is. [58]

The blue line uses 50 % of the total capacity of the battery. From the test result shown in Figure 2.12, it will take around 3000 cycles before the SoH is 90 %, which equals $3000 DST\ cycles \cdot 0,5 full\ cycle/DST\ cycles = 1500 full\ cycles$. The black line uses 75 % of the total capacity for the battery, and it will take around 1000 cycles before the SoH is 90 %. This equals $1000 DST\ cycles \cdot 0,75 full\ cycle/DST\ cycles = 750 full\ cycles$. As shown, a lower DST would result in a longer battery life. [58]

Battery temperature

High temperatures will damage the battery and cause irreversible losses. This is among other due to damage on the electrolyte that breaks down at high temperatures and loses its capacity for lithium-ion shuttling. Other processes in the battery will also suffer with high temperatures, and contribute to the reduction of SoH. The faster the battery charges, the more heat will be generated due to losses, and this can lead to reduction of SoH. Therefore, a low charging rate can be preferred if a long lifetime is a priority. [57]

The lifetime of an LiB has become longer in recent years, and there is a lot of research going on to try to extend this in the future. [59]

2.6.3 Recycling of batteries

The battery industry has been growing exponentially the last twenty years, especially the industry for LiBs. The applications for LiBs have become even more diverse as the battery technology has evolved. Today, LiB use varies from electric/hybrid electric vehicles to consumer portable electronics. However, even with the rise of LiB development, the recycling industry is lagging [60]. Currently, all batteries are meant to be recycled in the public recycling scheme in Norway. This scheme involves that all battery distributors and recycling plants are obligated to accept battery waste, without charge [61]. As much as possible of the batteries' material is recycled. The battery recycling industry is constantly evolving due to the high increase in used LiBs, and several companies have began to do something about it.

Among these companies is the Finnish company "Fortum", which delivers end-of-life services for batteries. The recycling process combines mechanical processing and hydrometallurgical processing technologies to recycle. The mechanical processing enables the recovery of plastic, copper, aluminium and black mass, where the black mass is collected and taken for hydrometallurgical processing. The hydrometallurgical process involves a precipitation methodology that is chemical and allows scarce minerals to be recovered from the black mass. After that, it is delivered to battery manufacturers for reuse in the production of new batteries. [62]

3 Ola Frosts veg 1

The building chosen for this project is an apartment complex at Ola Frosts veg 1, 7031 Trondheim, from now on referred to as OFV1. The building was built in 2005, and is owned and rented out by Frost Eiendom. It contains 54 residential units across 4 storeys, which are either single bedroom apartments or studio apartments. Frost Eiendom estimates that the building has around 80 residents. Figure 3.1 shows an illustration of OFV1's facade. The building has a flat roof, which makes it suitable for a solar power system. [63]

Figure 3.1: OFV1's south-facing facade. [64]

3.1 General information

3.1.1 Heat supply

The heat supply in the building is district heating. The heat is first supplied by a heat pump that uses exhaust air from the building's ventilation system to heat up water, which is used to distribute the heat [63]. The remainder of the required heat comes from district heating. These two measures combined means that a smaller portion of the electricity consumption goes towards heating, something that is normally a large expense in an apartment building such as this one. [65]

3.1.2 Electricity consumption

The building's electricity consumption is recorded in a shared electricity meter. The consumption is then split among the apartments based on their size in square meters, meaning that what each apartment pays for their electricity each month is proportional with the size of the apartment [63]. This in turn means that each apartment's own electricity consumption affects their power bill to a rather small extent. The common electricity meter does not measure the import of external heating energy, but this data has been supplied separately.

3.1.3 Parking facilities

OFV1 has a shared parking garage with 3 other apartment complexes, all owned by Frost Eiendom. The parking garage has 94 parking spots, and all offer the possibility of using an EV charger. The EV chargers are owned by a company called Ohmia Charging, a charging distributor that rents out the chargers that are installed. The number of EVs that use the parking facilities is assumed to be 9 vehicles, and it can be assumed that the number of EVs will increase in the future [63]. There is also an outdoor parking space available, with a capacity for a higher number of vehicles than the indoor parking garage.

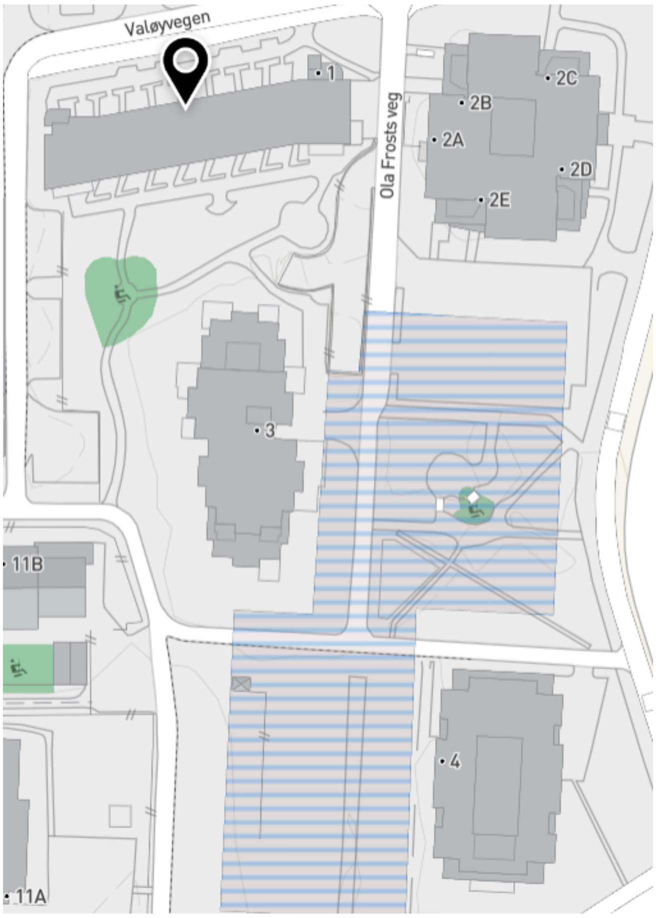

Figure 3.2: Ola Frosts veg 1-4. The shaded blue area is the parking facilities. [66]

3.1.4 Surrounding buildings

The apartment buildings that OFV1 shares a parking garage with are Ola Frosts veg (OFV) 2, 3 and 4. The buildings' position relative to each other can be seen in Figure 3.2. Like the map in the Figure shows, OFV1-3 are positioned relatively close to each other. This can involve shading on OFV1, as the buildings' heights are respectively [64]:

- OFV1: 11,4 m
- OFV2: 36,6 m
- OFV3: 41,0 m

The fact that the OFV1's neighboring buildings are much taller, means that they likely cast a shade on OFV1 during the day. When considering adding a PV system to a roof, one wants as little shade on the area as possible. The effects of shading are shown in the results in chapter 4.4.

3.2 Consumption data

Frost Eiendom has provided OFV1s energy consumption for 2021 in hourly resolution. This level of detail is useful, and gives a good foundation for energy analyses.

Since the common electricity meter does not measure the electricity used for heating, the electric power consumption data is based on other kinds of electricity use, like kitchen appliances and various activities. Figure 3.3 shows the monthly energy consumption, and it is worth noting that the electricity consumption has little variation throughout the year. The district heating, on the other hand, shows big variations over a year, due to outside temperatures. The total energy consumption in a year is 562,3 MWh for the whole building, including both electricity and district heating. This gives an average energy consumption of 10 413 kWh per apartment per year.

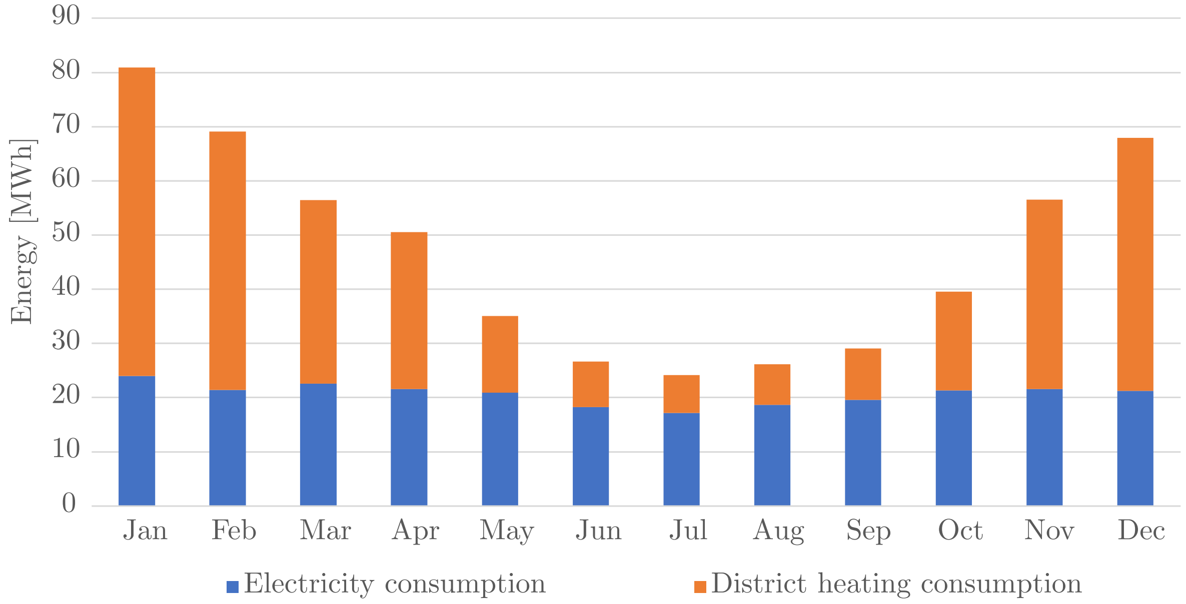

Figure 3.3: Energy consumption in OFV1, divided into electricity and district heating consumption. Data from Frost Eiendom [63].

When analyzing OFV1's power consumption, a useful aspect can be what parts of the consumption is adjustable, in the sense that it can either be decreased, redistributed in some form, or be scheduled to happen at a different time of day.

Since the building's heat consumption is mostly provided through district heating, adjusting the building's heating requirements will not do much for its electricity consumption. What can be adjusted is rather the consumption that is user controlled.

3.3 Sun exposure of OFV1

To be able to assess the conditions for a PV system in OFV1, the location's exposure to the sun is relevant to take into consideration. Figure 3.4 shows the sun's height angle and horizon angle for each month at OFV1's location. The sun's height affects the amount of radiation on the earth's surface. The sun's maximum average height at OFV1's location occurs in June and is just over 50°, which results in an air mass equal to 1,56, which can be calculated using equation 2.2. This makes June the time where the maximum radiation from the sun will hit the earth surface at OFV1's location. [67]

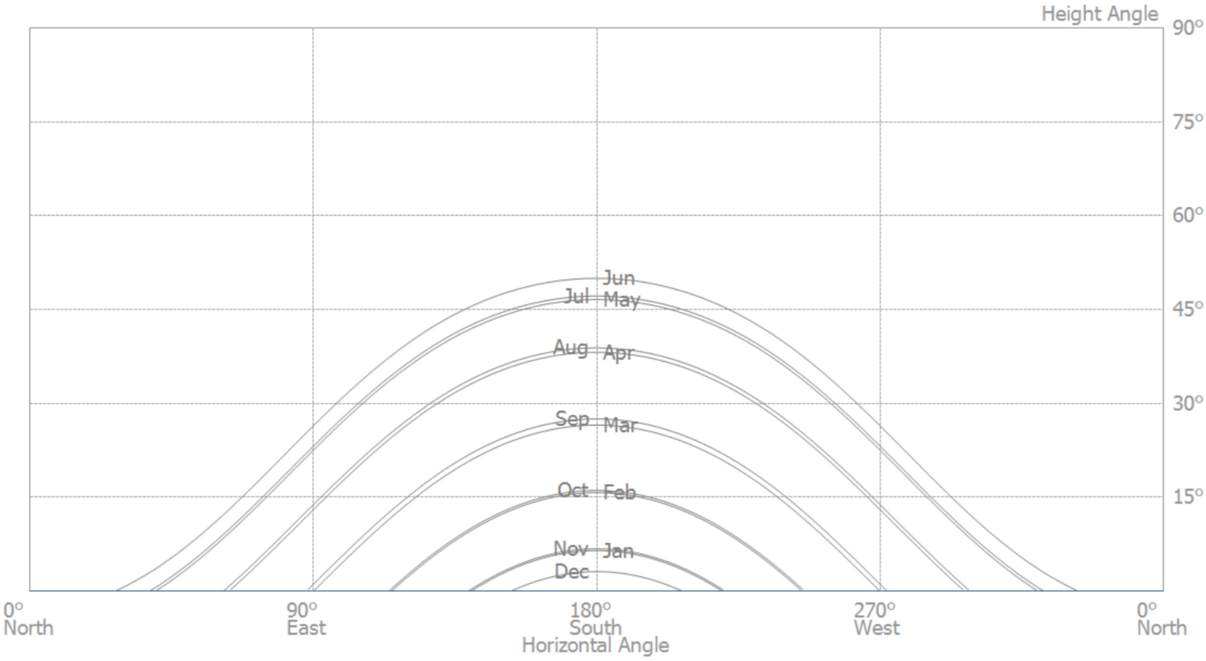

*Figure 3.4: Sun horizon line for Ola Frosts Veg 1. Image created in PV*SOL.*

4 Simulations of PV systems

This chapter will cover simulations of two different PV energy systems designed for OFV1. One will be facing south, while the other will be east- and west-oriented. The background for designing two different systems is that it is interesting to compare the two, and see which would be the most beneficial solution.

The chosen tool to perform these simulations was the software PV*SOL. PV*SOL is a simulation program that is used to plan and design PV systems. This software gives the opportunity to design customized solar energy systems, and allows for a multitude of factors to be taken into account. This includes sizing and orientation of the system, as well as the general climate and sun radiation on the system. Also, the energy consumption of a building and the usage time of electrical appliances can be uploaded and used in a simulation. [68]

The reason for using the PV*SOL software for this thesis, is that this is the software that STS, the external supervisor for this thesis, uses in their work. PV*SOL is the software used to process customer requests and design PV systems that STS supplies.

First, this chapter will give general information about how the software PV*SOL works, and how it is used. This is followed by descriptions of the PV systems that are designed, and then the following results of the simulations.

4.1 Designing in PV*SOL

When designing a PV system in PV*SOL, there are many tools that can be made use of. Using all of the tools available in PV*SOL would make for highly complicated simulations. Such simulations would also likely be inaccurate, as they would require large amounts of data that realistically is not possible to get without making significant assumptions. Based on this, the choice was made to make these simulations relatively simple. This way makes it possible to only use data that is credible and does not need to be estimated to a too large extent. This chapter will elaborate on the tools and functions that are relevant to the system simulation in OFV1.

The first step in designing a PV system in PV*SOL is to define the physical/geographical area that the system will potentially be located in. For an existing building, a way to do this is to make a three-dimensional (3D) module of the building and its surroundings. This is done in PV*SOL by locating the building on the program's map service, which can be done by inputting either an address or coordinates. It is then possible to select buildings from aerial photographs. The default map provider is Google Satellite, but there are other options for map services, such as Bing and some local map databases for selected areas outside of Norway.

Once the desired area is located, the building designated for a PV system can be sketched on the map. When this is done, the building's height is defined. These steps are also performed for the surrounding buildings, in order to know what kind of shading they will cause on a PV system. These steps can also be performed for objects on the building's roof that may cause shading.

The 3D design section is also where the actual system is designed. PV*SOL lets the user place panels in any way that is physically possible on the surface that is specified. Once the user has chosen what type of PV panel that will be used, PV*SOL has calculated the size of the roof/surface based on data from maps, and therefore knows how many panels are able to fit. Once the orientation and incline angle is input, the distance between the panels must be specified. A border around the edge of the area/roof can also be applied, where panels cannot be placed. This is in order to make sure that the panels do not go out to the very edge of a roof for example, as this would cause various practical issues in regards to service and management of the PV system. Once this is all taken into consideration, the designated area can be covered with PV panels. PV*SOL has a long list of available PV manufacturers to choose from, and what PV panel models they offer. Choice of PV panels can be done on the basis of desired wattage or other parameters that are considered deciding factors.

After the panels are placed, the associated components also need to be determined. This includes inverters, cables and any energy storage that may be relevant. PV*SOL gives a variety of options for choice of inverters from different manufactures. Worth mentioning is that PV*SOL only provides inverters for 400 V TN grid, as this is the most common grid type in Europe. Since OFV1 has a 230 V IT grid, the inverter in real life will be a different type, but the same suppliers usually have the same models that are compatible with 230 V IT grid and with the same specifications. Energy storage is mostly relevant for systems where the solar production is higher than the building's consumption during the day. The length and width of cables will cause a certain loss of energy due to resistance.

The general climate and solar radiation of the system is a factor to consider when simulating a PV system in PV*SOL. MeteoSyn is the supplied module for climate data in PV*SOL. Data in MeteoSyn is based on the software Meteonorm that calculates irradiation of locations all over the world. Meteonorm is developed by the Swiss climate and weather data experts, Meteotest [69]. The global climate database in Meteonorm provides thirty different weather parameters. The database consists of 8000 weather stations, five geostationary satellites and a globally calibrated aerosol climatology. Based on this information, Meteonorm generates accurate and representative years of weather simulations for most places on earth.

PV*SOL also gives the option to input the energy consumption that the PV system should supply energy to. The most reasonable way to do this is to input the energy consumption in an hourly resolution. More detailed consumption than this is hard to obtain, even though PV*SOL gives the option to upload data as detailed as a resolution of 1 minute. The energy consumption that is uploaded should take into consideration as much of the facility's consumption as possible.

PV*SOL compares the consumption that is input with the production from the simulated PV system. This shows to what extent the PV system can cover the facility's energy consumption. If the PV system at any time yields more than the facility consumes, this electricity is exported to the grid. If the opposite is the case, the facility needs to import electricity from the grid.

When simulating a PV system it is necessary to take into consideration the output losses due to soiling of the PV modules. Soiling can cause considerable losses at locations that are dusty, with low-rain, or where the PV modules are very flat-mounted. Losses due to soiling vary depending on the location of installation [69].

After the whole system is designed, PV*SOL offers a tool for financial analysis. This enables calculations of a project's profitability based on a variety of factors. These are factors such as the initial investment, rate of interest, project lifetime, income and expenditures.

4.2 Method for simulating in PV*SOL

The first step in simulating a PV system for OFV1 in PV*SOL was to construct a 3D model of the building, as well as its neighbors. This was done according to the description in chapter 4.1. Worth noting is that the roof of OFV1 has a total of 10 ventilation ducts that stick up from the roof, which makes the 3D model slightly more complex. The ventilation ducts were also a challenge when placing the PV panels, as they restricted the area that was available for use and also cause shading on parts of the roof. OFV1 has two tall neighbour buildings located at west and south, as explained it chapter 3. These buildings has a height of 36,6 and 41,0 meters and will cause partially shading on the roof of OFV1.

The climate data used for simulations in PV*SOL is obtained from the weather station located in Trondheim, Værnes, Norway. This station is located with the coordinates 63,47°in northern latitude and 10,93°longitude. This data is provided from Meteonorm. For the given time period the data is obtained from, the weather station state that the annual sum of global irradiation is 895 $\mathrm{kWh/m^2}$ and the annual average temperature was 6,2°C.

The used climate file model for diffuse irradiation in PV*SOL is the Hofmann module. The model for irradiation on the inclined plane is the Hay & Davies module, which both are default modules in PV*SOL.

The output losses due to soiling of the PV modules are important for the energy production from the PV modules. The soiling of the PV modules vary throughout the year. It can vary because of several things, for instance because of dust, like pollen at summer times, and especially in Norway, snow in the winter. For the simulation, the input is monthly losses due to soiling given in percentage for each month. The values for each month is based on STS' experience and knowledge [70]. The monthly values are listed in Table 4.1.

Table 4.1: Output losses due to soiling of the PV modules

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percentage [%]	65	45	2	2	2	2	2	2	2	2	35	55

Manufacturers try to minimize the losses in the different components of a PV network. Yet, there will always be a certain amount of losses when transferring electricity. For this system the total cable loss due to transfer of electricity from the PV cells to the grid is estimated to 0,75 %. This estimation is based on STS' experience with similar projects [70].

The design of the system itself was done by first determining what PV panel model should be used for the simulation. Secondly, the mounting of the PV panels had to be input. This included what angle the panels were mounted at, their orientation, as well as the distance between the modules. This distance was determined by the typical attachment system used for PV panels by STS, as this was their recommended mounting distance in around 90 % of the systems they installed. The mounting distance used was 28,6 cm. [70]

The energy consumption of OFV1 was included in the simulation. The consumption of both electricity and district heating were supplied by Frost Eiendom. The electricity consumption was measured data from a meter that covers all of OFV1. The district heating meter measures the energy consumption of both OFV1 and OFV2, which is the neighboring building. Frost Eiendom estimates that 30 % of the consumption belongs to OFV1, and this is what the simulation has been based on. The energy consumption was used to compare the system's expected energy production with the building's energy consumption, to see how much of the consumption the PV system could cover. The energy consumption had an hourly resolution, and was considerably lower in the summer months than in the winter.

Electricity prices in Trondheim for the economic simulation was provided by Nordpool [25]. Hourly rates from 2017-2021 were used to calculate the average price for one 24 hour cycle representing each month in the year. The price in the simulations include the given grid fees for OFV1 in 2022. All hourly energy prices are between 0,71 NOK/kWh and 0,93 NOK/kWh, since PV*SOL only provides 12 different prices for the from-grid tariff, the calculated values had to be rounded to the closest price step, with 12 steps between 0,71 NOK/kWh and 0,93 NOK/kWh. These values for the different hours is shown in Appendix *C*. These prices were used for the *import* of electricity from the grid. All prices in this calculation include VAT. The price for the export of the solar electricity is set to 0,316 NOK/kWh, as this is the average of the spot price in Trondheim over the last 5 years. The electricity prices are estimated with a 2 % annual inflation, which is what the Norwegian government is trying to accomplish [71].

Homeowners in Norway can receive a financial contribution from Enova if they implement a PV system, or other renewable or energy efficient technologies on their private house. Today, there is no such thing as financial contribution from the government for apartment complexes like OFV1, since this is under the category of commercial buildings. As a consequence of this, subsidies have not been included in the PV*SOL calculations. [72, 70]

Based on experience and competence at STS, the market price for south-oriented PV panels equals about 17 NOK/Wp and for east- and west-oriented PV panels 14 NOK/Wp The price is dependent of the total installed watt-peak in the PV system, as well as other factors such as price of mounting systems, etc. [70].

4.3 The simulated PV systems

This section covers the resulting systems that were designed in PV*SOL. This includes the type and number of the different components, as well as a few other design choices.

In these systems, some design choices were made based on STS' recommendations, as the company has many similar projects behind them as contractors. These choices include the type of PV panels used, their angle and mounting distance, as well as inverters.

The panels used in the simulations in PV*SOL were Jinko Solar Tiger Pro JKM395M-54HL4. This model has a monocrystalline Si structure, with a listed efficiency of 20,23 % and a 395 Watt peak in STC. The panels are listed with a 0,55 % annual degredation over 25 years [73]. The reason for this choice of panel is that Jinko Solar is a large, renowned and reliable solar panel manufacturer. This reassures that their business is dependable, and is likely to continue to be so. This is valuable for systems that are likely to have a lifespan of 25 years or more [70].

The system will preform better with power optimizers or micro inverters due to quite a bit of shading from the nearby buildings and the ventilation pipes on the roof. Power optimizers are preferred over micro inverters for larger systems and is therefore used for the following systems [70].

Two different systems were designed. One had south-oriented PV panels, and the other had east- and west-oriented PV panels. From here on, the PV systems will be referred to as the S system and the EW system. The following chapters will describe resulting design.

4.3.1 Option 1: South-oriented PV panels

The S PV system is described in Table 4.2.

For the S PV system, 127 panels can fit on the roof of OFV1, with an inclination angle of 40°. The system's azimuth angle will be set to follow the edge of the roof to maximize the amount of panels that can be mounted there. The roof is oriented 170°South, which makes the PV system actually face 10°eastwards from the geographical South. The choice of collector tilt angle of the PV modules depends on different factors. A tilt corresponding to OFV1's latitude would

Table 4.2: Components of the S PV system.

Object	
PV panel model	Jinko Solar Tiger Pro JKM395M-54HL4
PV panels	127 pcs
PV Generator surface	248,0 m^2
Inverter model	Solaredge SE50K
Power optimizers	71 pcs
Incline angle of panel	40°
Distance between panels	28,6 cm
Installed capacity	50,17 kWp

minimize the average incidence angle throughout the year. However, since it it preferable to place panels in rows, a latitude tilt would lead to shading of adjacent modules as well as an increase in wind load. When the sun is lower in the sky, the surrounding buildings and the ducts on the roof will cause shading. Therefore, a smaller inclination angle on the PV modules seems like a good solution in order to take more advantage of the summer months, when the solar flux is higher due to the low air mass when the sun is higher in the sky. A lower angle will also enable a shorter distance between the PV panels, as they will create less shade. The chosen collector tilt angle is therefore 40°, as this seems like an appropriate tilt for OFV1 [70].

For this system configuration, power optimizers were used. This system achieved an installed capacity of 50,17 kWp. The inverter chosen for this system was the three phase inverter called Solaredge SE50K. These inverters have a maximum power capacity of 50 kWp and a European weighted efficiency of 98,3 %. The sizing factor for the inverter is 100,3 %, and the inverter has a more than big enough capacity, as the panel is not likely to ever have maximum output from all of its panels at the same time [70]. The system has a power optimizer for every other panel and ten of the panels have their own power optimizer, which means that in total there are 71 power optimizers for the given S PV system.

*Figure 4.1: The south-oriented PV system as seen from above. Image created in PV*SOL.*

4.3.2 Option 2: East- and west-oriented PV panels

The EW PV system is described in Table 4.3.

Table 4.3: Components of the EW PV system.

Object	
PV panel model	Jinko Solar Tiger Pro JKM395M-54HL4
PV panels	172 pcs.
PV Generator surface	335,9 m^2
Inverter model	Solaredge SE25K
Power optimizers	86 pcs
Incline angle of panel	10°
Distance between panels	28,6 cm
Installed capacity	67,94 kWp

The EW PV system consists of 172 panels. This system configuration made it possible to fit more PV panels than for the S system. This is due to the positioning of the panels. The EW panels are placed in couples, where the panels are oriented in opposite directions with a 10°angle, as shown in Figure 4.2.

This system configuration gave an installed capacity of 67,94 kWp. The chosen inverter model was the three phase inverter called Solaredge SE25K, which is listed with a maximum capacity of 25 kW and has a European weighted efficiency of 98 %. The EW system has two identical inverters, one for the east-oriented panels, and one for the west-oriented panels. The reason for why this inverter model with a total capacity of 50 kWp can still be used, is also that the system is unlikely to ever have maximum output from all panels at the same time, especially since the panels are oriented in opposite directions. So it is reasonable to think that a sizing factor of 135,9 % is a well suited inverter size for the given system. There is one power optimizer installed for every other panel, which gives a total of 86 power optimizers. The panels that is placed next to each other and facing the same direction is connected to the same power optimizer.

*Figure 4.2: The EW PV system as seen from above. Image created in PV*SOL.*

4.4 Results from PV system simulations

This chapter will cover the outcome of the simulations done in PV*SOL for both of the two simulated systems. The results show how much energy the systems could be able to produce in a year, as well as how much of this energy can be utilized by the building itself. These results are shown in detail in Appendix *D*. In addition to this, the financial aspects are taken into account, and the cash balances of the systems will be addressed. The results regarding the cash balances of the systems are shown in detail in Appendix *F*

The production results are given on a monthly basis. Without more detailed data, the level of details in the calculations and results is limited. For most calculations, a sum or an average value is used.

4.4.1 Option 1: South-oriented PV panels

The results from the S PV system are displayed in Table 4.4. The results are also shown graphically in Figures 4.3, 4.4 and 4.5.

Table 4.4: Results from the south-oriented system simulated for one year.

Total electricity production from PV	38,51 MWh
Total energy consumption (electricity and DH)	562,26 MWh
Total electricity from PV exported to grid	0,051 MWh
Percent of energy consumption covered by PV production	6,84 %
Percent of energy imported from electricity grid/DH supply	93,15 %
Percent of produced PV energy used by building's consumption	99,87 %
Percent of produced PV energy exported to electricity grid	0,13 %
Performance ratio	69,7%
Energy production per unit installed capacity	767,6 kWh/kWp
Yield reduction due to shading	22,8 %/yr
First year of net positive cash balance	None
Cash balance at end of life (year 30)	-3908 NOK

The total annual energy production of the S PV system is 38,51 MWh, as Table 4.4 shows. This is a rather small amount compared to the annual energy consumption of OFV1, which is a total of 562,26 MWh, including both electricity and district heating. This makes the amount of the total consumption that is covered by PV production 6,84 %.

The month with the largest coverage from PV production is July, when 26,2 % of the energy consumption could be covered by energy from the PV system. This can be seen in Figure 4.3.

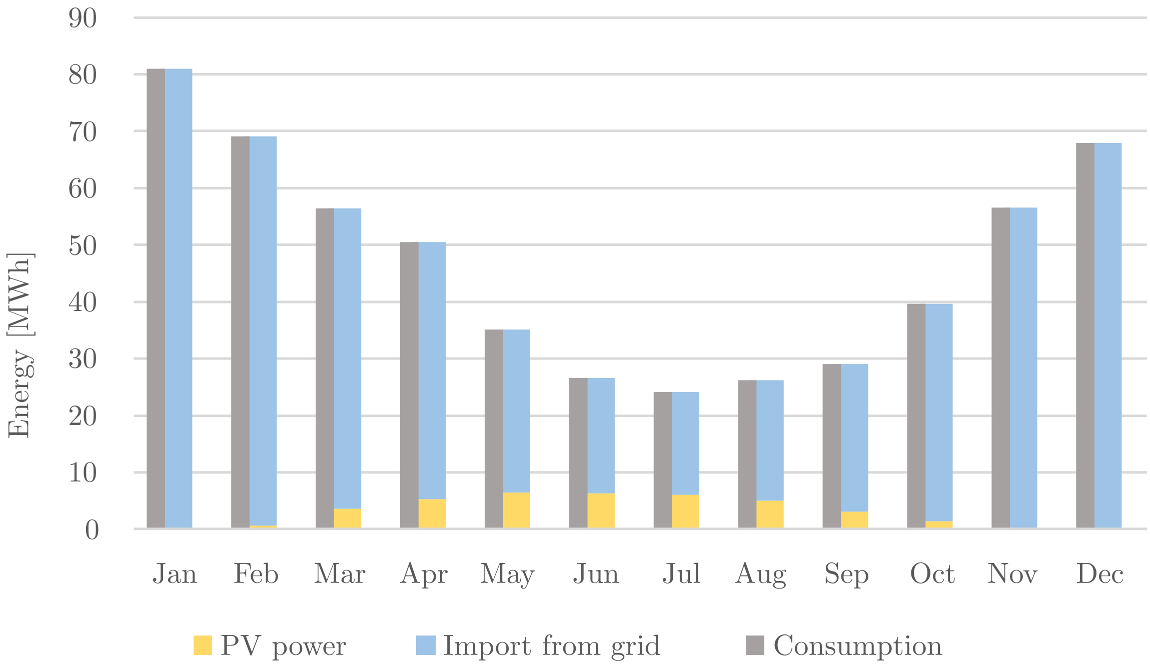

*Figure 4.3: PV production of the south-oriented system. Data from PV*SOL.*

The S PV system only had one month with any export of electricity to the power grid, which can be seen from the small blue bar in Figure 4.4. This occurred during the month of May, which is also the month with the largest PV production, producing 6,56 MWh total. The month with the lowest PV production is December, with a production of 0,0063 MWh.

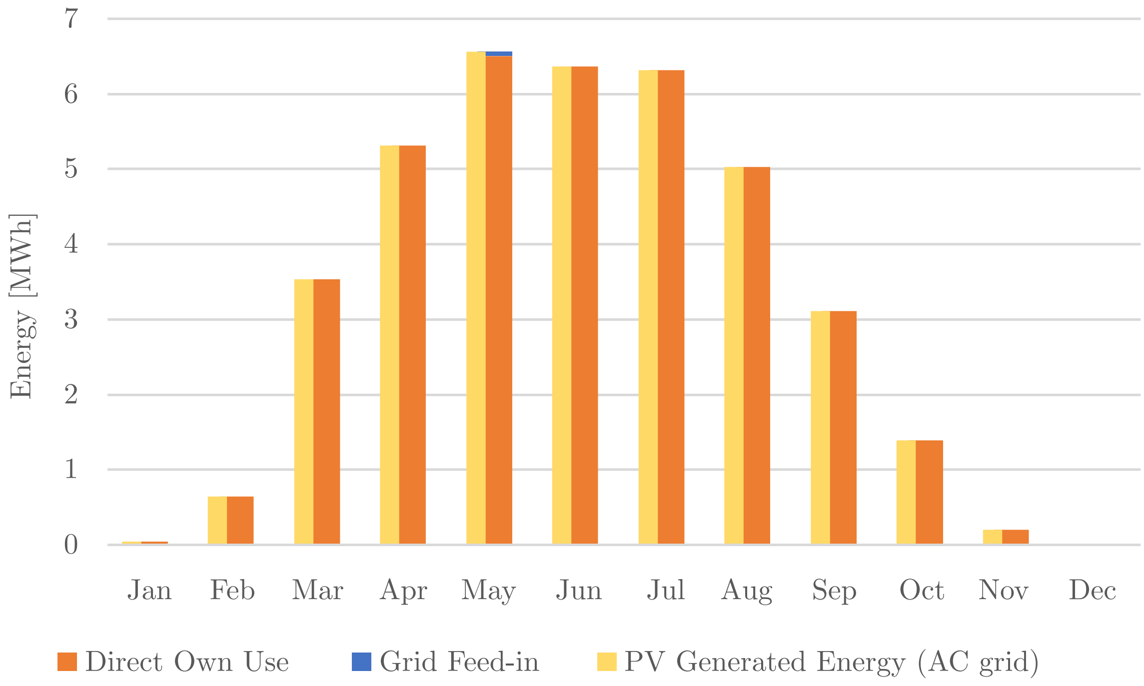

*Figure 4.4: Utilization of the energy production from the south-oriented system. Data from PV*SOL.*

The system has a production of 767,6 kWh per kWp. This is somewhat on the lower end of what is normal for PV systems in Norway, compared to the range of 650-1000 kWh per kWp as stated in chapter 1.2.1.

The losses due to shading are 22,8 % per year. Some losses from shading were expected, but the amount of loss was not estimated beforehand.

Worth noting is that in Figure 4.3, the production from the PV system is almost inversely proportional to the energy consumption of the building. This is also true for the EW system, as shown in Figure 4.6.

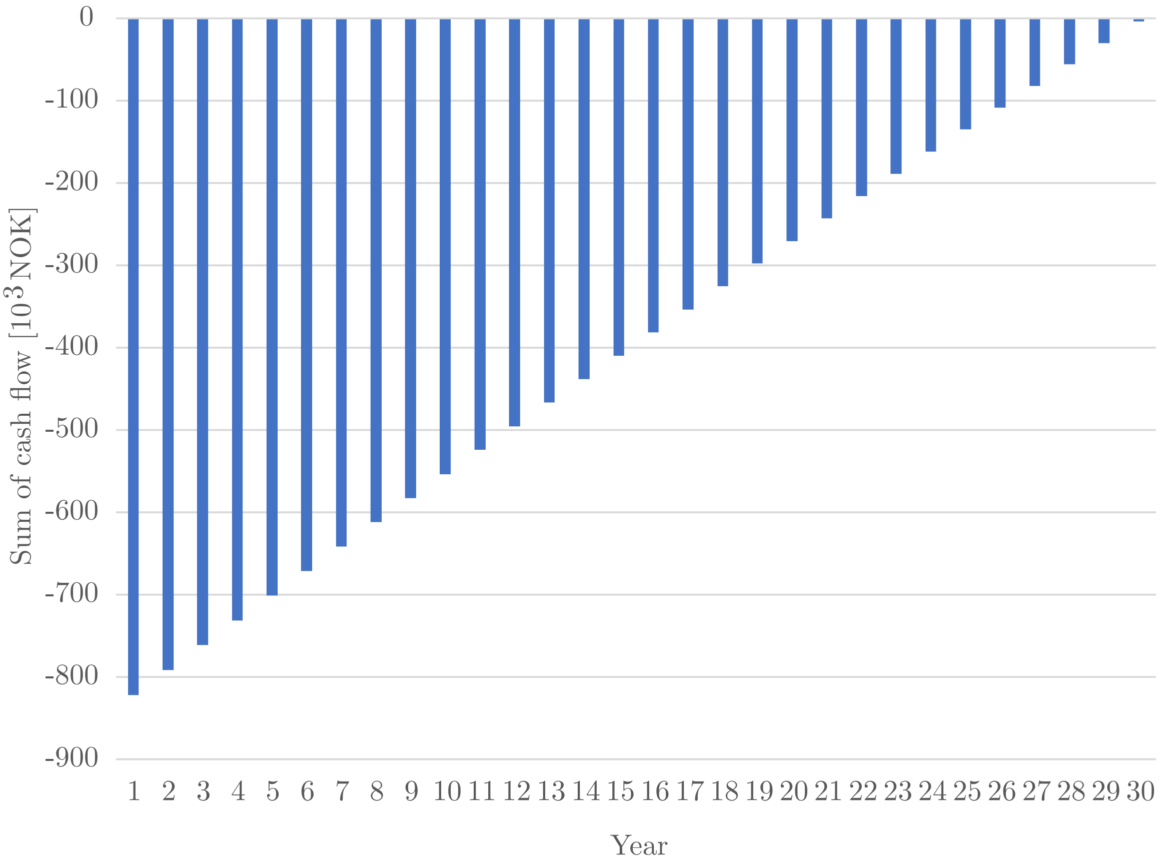

*Figure 4.5: Cash balance of south-oriented system, in thousand NOK. Data from PV*SOL.*

Figure 4.5 shows the accrued cash balance over the first 30 years for the S PV system. The price of the S PV system was calculated from 17 NOK per Wp installed. With a total of 50,17 kWp installed, the investment cost of the system would be approximately 850 000 NOK in year 0. The costs of the system do not break even during the system's estimated lifetime, and the balance at the estimated end of life is -3908 NOK.

4.4.2 Option 2: East- and west-oriented PV panels

The results from the south-oriented PV system are displayed in Table 4.5. The results are also shown graphically in Figures 4.6, 4.7 and 4.8.

Table 4.5: Results from the EW system.

Total electricity production from PV	45,01 MWh
Total energy consumption (electricity and DH)	562,26 MWh
Total electricity from PV exported to grid	0,610 MWh
Percent of energy consumption covered by PV production	8,00 %
Percent of energy imported from electricity grid/DH supply	92,11 %
Percent of produced PV energy used by building's consumption	98,65 %
Percent of produced PV energy exported to electricity grid	1,35 %
Performance ratio	76,6%
Energy production per unit installed capacity	662,5 kWh/kWp
Yield reduction due to shading	17,5 %/yr
First year of net positive cash balance	Year 29
Cash balance at end of life (year 30)	38 960 NOK

The total production of the system over the course of a year is 45,01 MWh. This is more than the 38,51 MWh that the S system could produce. The reason for the EW-system's production being higher is likely due to the higher number of PV panels. As stated in section 4.3.1, the required placement of the south-oriented panels restricted the number of PV panels that the area could fit. The increased production of the EW system could also be related to the insolation, and that this system had a more beneficial positioning in regards to the sun's exposure. The energy consumption is the same for both system simulations, but with an increase in energy production, the share of energy that is covered by the PV energy production is 8,00 %.

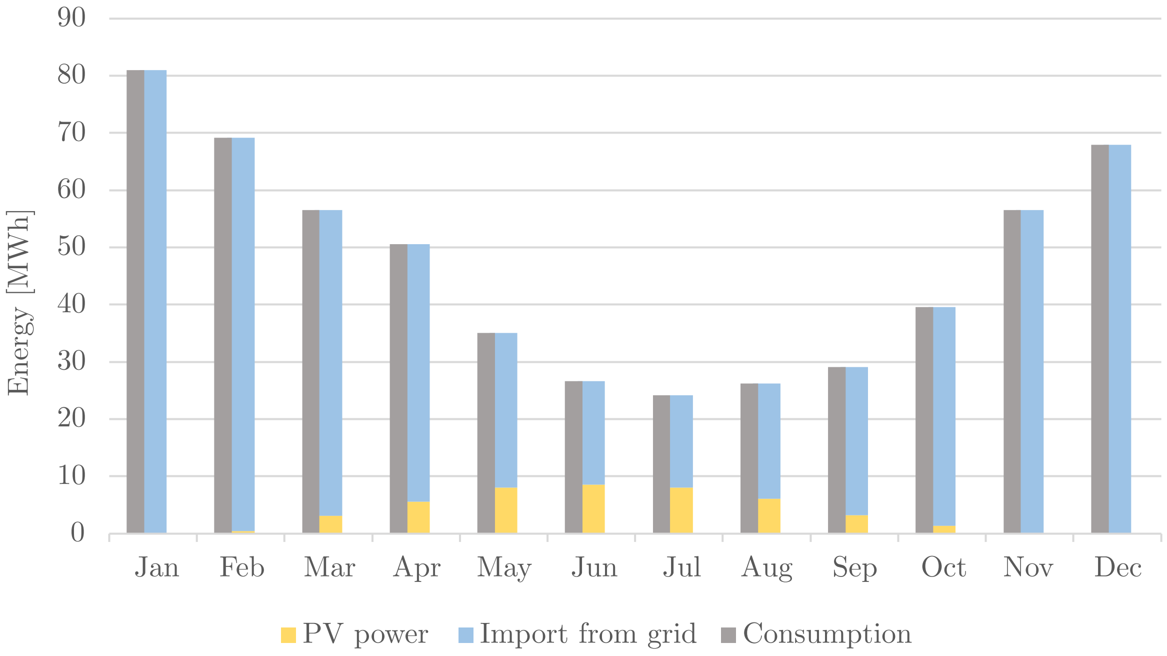

*Figure 4.6: PV production of the EW-system. Data from PV*SOL.*

The month with the biggest coverage from PV production is July, when 33,3 % of the energy consumption could be covered by the PV production. This can be seen in Figure 4.6. The winter months all have a low amount of energy production. December is the month with the lowest share of PV coverage, as only 0,01 % of the energy consumption is covered by the PV system. As December is a month where temperatures are typically low, and there is not much sunlight, this result is not surprising. The soiling losses are also big in the winter months.

The EW-system had 4 months that had export of electricity to the power grid, which can be seen from the blue bars in Figure 4.7. This occurred during May, June, July and August. July was the month with the largest amount of energy export, with a total of 0,348 MWh. June was the month with the largest total production, where the PV system produced 8,630 MWh. The month with the lowest PV production was December, with a production of 0,0126 MWh.

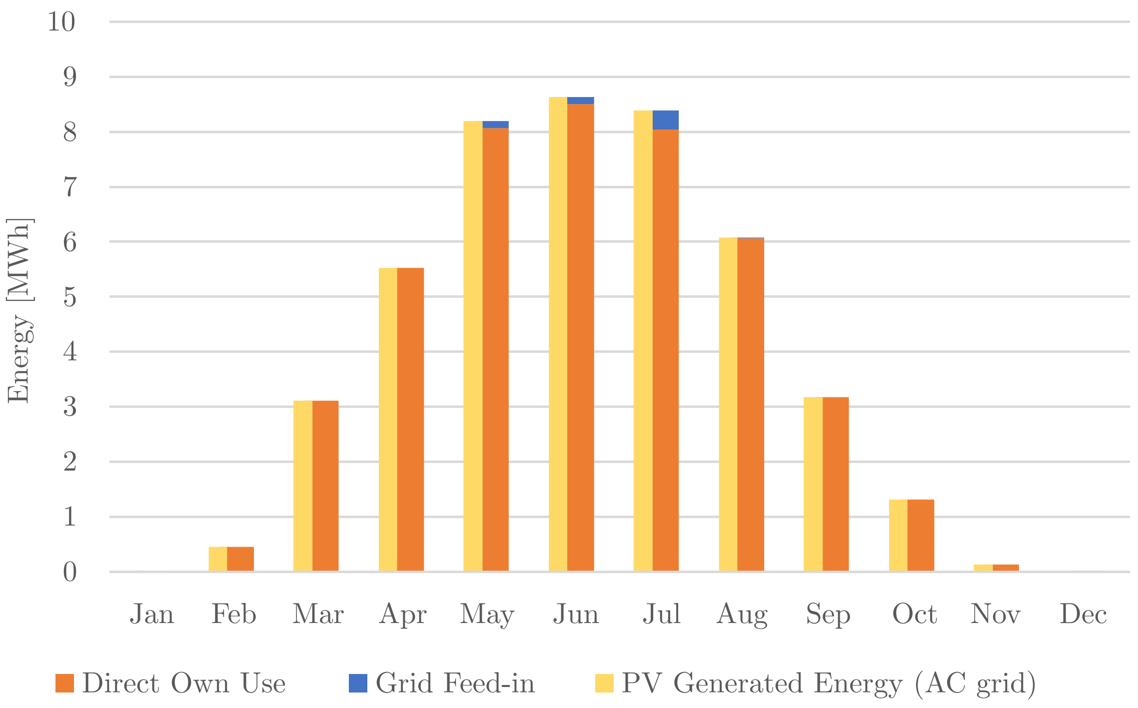

*Figure 4.7: Utilization of the energy production from the EW-system. Data from PV*SOL.*

The EW system has a production of 662,5 kWh per kWp. This is approximately 100 kWh per kWp less than in the S system.

The losses due to shading for the EW system are 17,5 %/yr, which is lower than for the S system.

Figure 4.8 shows the cash balance for the EW PV system. The price of the EW system is calculated using a price of 14 NOK per Wp installed. This system has a capacity of 67,94 kWp, and will have a total investment cost of approximately 950 000 NOK. The costs of the system will break even in year 29, and the balance at the estimated end of life in year 30 is 38 960 NOK.

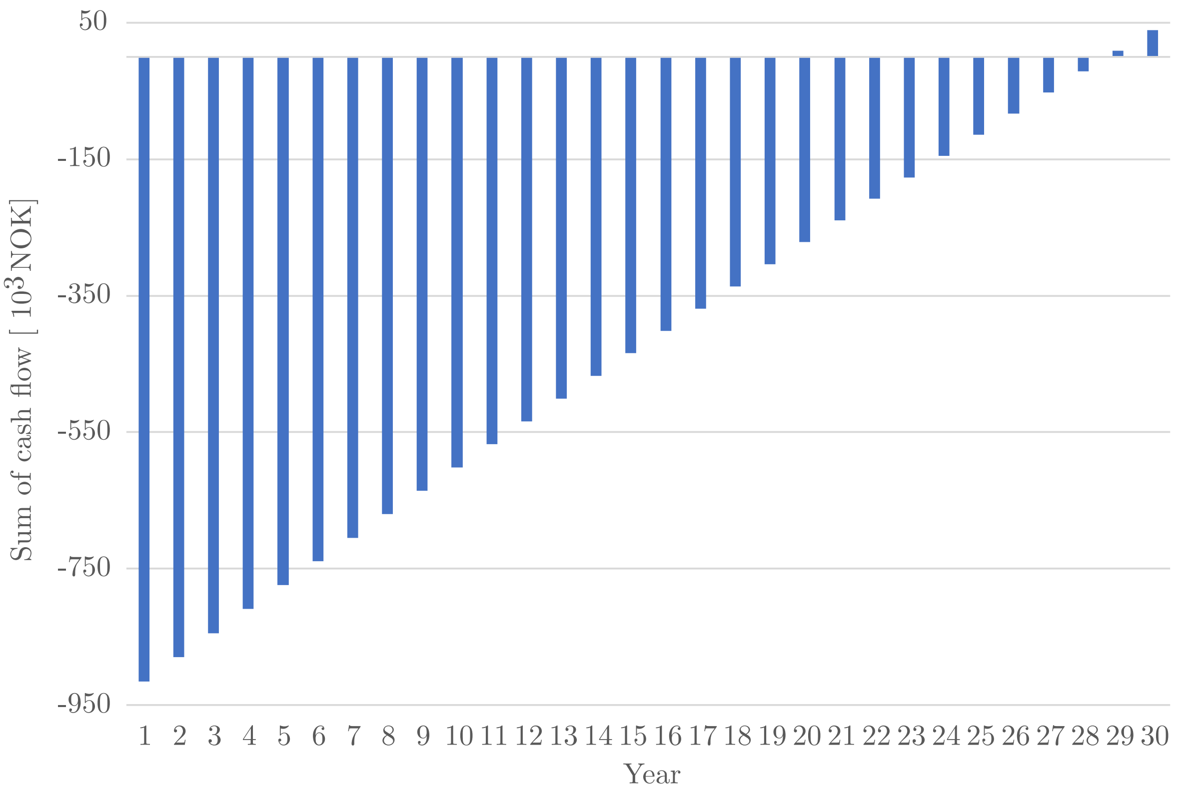

*Figure 4.8: Cash balance of the EW system, in thousand NOK. Data from PV*SOL.*

4.4.3 Comparing the two systems

As the results in chapters 4.4.1 and 4.4.2 show, the differences between the two systems are generally quite small. The EW system generates more energy than the S system, which is not surprising considering the different number of PV panels. This also in turn influences the financial aspect of the systems, making the EW system more profitable over the course of 30 years. The S system ends up with a small negative cash balance of 3908 NOK, while the EW system ends up with a positive cash balance of 38 960 NOK.

The calculation of the total cash flow for both systems does not include any maintenance or other type of expenses after year 1, and therefore the cash balance is only increasing in the following years. The positive cash flow can be split into two parts. The largest contributor to the positive cash flow is money saved on the electricity bill due to the building using the produced energy, and therefore not needing to import as much energy from the grid. The second part of the positive cash flow is the income of electricity sold to the grid. As seen in figure 4.4 and 4.7 the energy exported is a lot smaller than the energy produced and is therefore a small part of the positive cash flow every year. The positive cash flow will decrease every year, due to the 0.55 % annual degradation on the panels, which results in a decrease in energy production. These results are shown in detail in Appendix *F*.

The Solaredge inverters used in both systems have a warranty of 12 years, and must be expected to be replaced before year 30. The power optimizers have a warranty of 25 years, while the Jinko solar panels have a warranty of 15 years. The system is expected to work longer than the warranty, but some expenses must be conceivable before year 30. [74, 75]

The S system has performance ratio (PR) of 69,7 % which is noticeably lower compared to the EW PV system which has a PR of 76,6%. A performance ratio of about 80 % is considered good [70]. The EW system is not far from this value, and has a fairly good performance ratio. The PR will decrease as the degradation occurs on the panels.

5 Batteries

The results from PV*SOL regarding OFV1 show a solution that is quite straightforward, in that the building uses the produced electricity directly. As shown in figures 4.3 and 4.6, the proposed PV systems cover only a small portion of OFV1's energy consumption. This gives an incentive to look at other options for the energy use of the building and its facilities.

In the world's transition to a sustainable energy system, electric energy storage in batteries can be a key technology. A wide range of renewable energy sources can be used in a more convenient way by combining them with energy storage. One type of renewable energy source that can be appropriate for energy storage is roof-top solar power [51]. A report from DNV-GL discussed that batteries for EV charging can be a safe source of energy in case of power failure or voltage issues [21]. As mentioned in chapter 1.3.1, EV charging is seen as an important contribution to an increase in power peaks, and a battery can in some cases contribute to lower power peaks.

Because of this, a battery solution primarily used for EV charging will be considered for OFV1. The idea of how to do this is to install a battery solution in the parking garage belonging to OFV 1-4, that will be used to power EV chargers and is charged with energy from the PV system combined with some import from the grid. The motivation for this is further explained in the following chapters.

When a battery solution for EVs is included in the system, there are multiple components that need to communicate in order for the system to work efficiently. A schematic of the system components is shown in Figure 5.1.

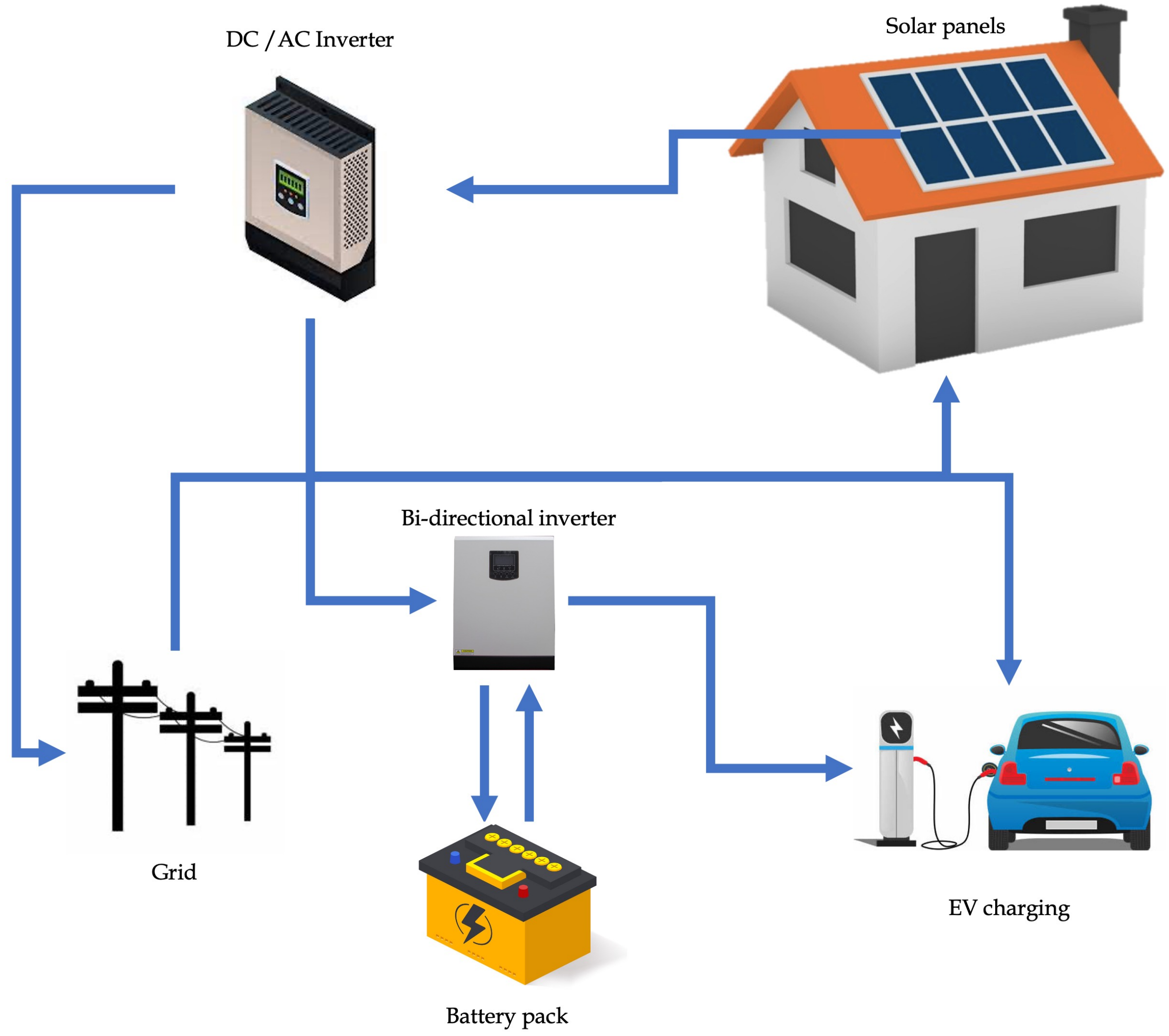

Figure 5.1: A schematic of the whole system. Figures taken from: [1, 2, 3, 4, 5, 6]

5.1 The selected battery technology

As mentioned in the Introduction, LiBs are the most used battery technology for storing energy nowadays. Also, due its high performance, this battery technology will be the selected technology for the energy storage in this PV and EV system. More details about LiBs are mentioned in chapter 2.6.

For this battery solution, the calculations will be based on a specific model of a battery system. The choice fell on battery solutions designed by a Norwegian company named “Pixii”, who collaborate with a Swedish company called “Polarium” to jointly develop and market energy storage solutions. This energy storage system includes Pixii inverters and related equipment, and Polarium’s LiBs. [76, 77]

The design choices of the battery system were made based on STS’ recommendations, as this system is a convenient and compact system for PV self-production. The recommended system is delivered by “Pixii” and is named “PowerShaper 30kW / 65kWh”. The PowerShaper from Pixii is a grid connected energy storage system. It is a complete modular energy solution with up to 30 kW power conversion and 65 kWh energy storage capacity. The Pixii PowerShaper is designed as a cabinet consisting of an inverter called Pixiibox, a communication center called Gateway and LiBs from Polarium. In this solution, all components are integrated and ready to be connected to the grid. The PowerShaper can be used in applications from 10 kW up to 300 kW or 650 kWh. Several cabinets can be combined in a system according to the need for power or energy. [76]

The PowerShaper provides a variety of grid-supporting services and energy saving functions. It supports a wide range of functions, and some of them are [78]:

- PV self-consumption
  - Instead of curtailing or feed in the solar energy generation to the grid, batteries are charged. Batteries discharge when there is no or little solar energy generation.
- Time of use cost reduction
  - Discharge the batteries when electricity rates are high. And reversed, charge the batteries when electricity rates are low.
- Power tariff cost reduction
  - To reduce power tariff costs, the battery can limit grid power peaks

These functions can be performed manually, or they can be executed autonomously, if they are programmed to do so.

The core in the PowerShaper is the inverter, Pixiibox. The Pixiibox is an advanced bi-directional power conversion unit. Bi-directional means that the same inverter can be used in both directions, through the same power electronics. This means that the energy flow can go from the grid to the battery, and back to the grid again. The Pixiibox is a 3,3 kW AC/DC converter module. In one cabinet, there is room for up to 9 Pixiibox modules, configured in single or three-phase for IT or TN networks. [78]

The “brain” and communication center in the PowerShaper is the “Pixii Gateway”. For system advanced monitoring and control applications, the Gateway communicates with all elements in the system, as well as the outside world. This component enables local flexibility. The PowerShaper can provide various services to minimize the electricity bill or support the grid. This is done by set timing or external signals based on own internal measurements in the Gateway or the modules. [78]

The batteries in the system have a voltage of 48 V and capacity of 5 kWh. Each cabinet can hold 13 batteries, which can be connected in parallel so the voltage remains the same, with a total capacity of 65 kWh. [76]

5.1.1 Price of LiBs in the future

The price for LiBs has dropped dramatically the last 9 years, as shown by the blue bars in Figure 5.2. Since 2013, the price dropped from 684 $/kWh to 132 $/kWh in 2021, which is a total price reduction of 80,7 %.

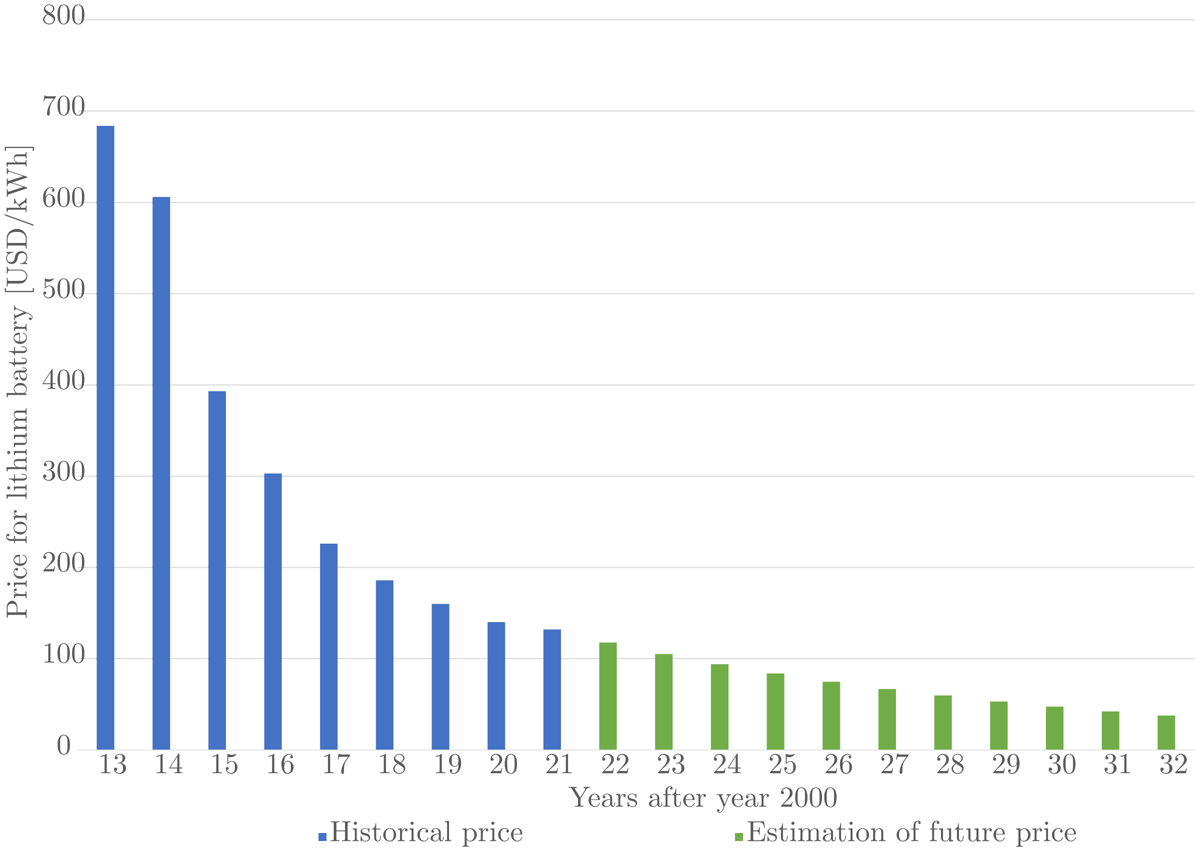

Figure 5.2: Price for lithium ion battery. Data from Bloomberg [79]

As shown in figure 5.2, the battery price reduction has been smaller the past few years. There are many opinions about the prices for LiBs in the future, but for this thesis, the average decline for the last 4 years will be used as a calculation for the development of the future price. With an annual decline of 10,73 %, the green bars show the annual development in a 10 year perspective. According to these calculations, the prices per kWh in 2032 will be 37,87 $/kWh [79].

5.2 Battery for OFV1

When including batteries in a system, it is necessary to be certain of the purpose of the battery. This way, it is possible to decide the right battery technology and the right specifications for the battery. In the following scenarios, the purpose of the battery is to make use of the produced solar energy from the PV systems to charge the EVs in the building. If in one instant, the PV production is equal to the consumption to charge the EVs, there is no need to go through a battery. But as figure 5.5 shows, the need of charging will not always correspond to the solar production, and a method of storing this energy will make it possible for later use.

5.3 Driving and charging habits

Data of the electricity consumption for the EV chargers in OFV1 was not successfully obtained from Ohmia charging, the EV charging supplier in OFV1. Data from a study about EV charging for a housing cooperative called Risvollan borettslag in Trondheim has therefore been used for the analysis in this project [80]. The data found from Risvollan was the plug-in and -out time for the cars, and also the total consumption for the charging session. The data contains this information about every charging session from December 2018 to January 2020. In total, 6787 charging sessions were analysed. The data does not provide information about the charging speed or time of charging start.

In OFV1, Ohmia charging has installed chargers with 32 ampere fuses, the grid is 230 volt IT net, and the maximum power delivered to every charger is about 11 kW if all of the three phases are used. Most of the EVs today will only charge using one phase and will therefore only consume about 7,2 kW.

The data only provides information about the time the car was plugged in, and had no information about the start time of charging. For the calculation in this thesis, the start time of charging is set to the plug in time. With these assumptions it is possible to estimate the energy used on different times of the day during this period.

For the hour when the charging session starts, the energy used will correspond to the time left of that hour times the power input that is assumed to be 7,2 kW. For example, if a charging session starts at 17:30, hour 17 will have a consumption of $0,5h \cdot 7,2kW = 3,6kWh$. The total amount of energy per hour for the given period is shown in Figure 5.3. This figure shows that most of the charging takes place in the afternoon, and then it is more than ten times bigger than it is during the morning hours.

Data from OFV1 containing the mileage or consumption for each EV was also not possible to obtain, which means that some more assumptions needed to be made to find the consumption for the EVs in OFV1. An average EV in Trondheim drove 12 800 km in 2021 [81]. The consumption from an EV varies with the type of car and condition. By assuming an average consumption of 0,19 kWh/km [82], the total electricity consumption for a car with an average mileage will be 2432 kWh/year. This equals $\frac{2432kWh}{365days} = 6,66kWh/day$ per EV. According to the data from Risvollan borettslag [80], the average charging session was 12,72 kWh. Based on these numbers, if an EV uses 6,66 kWh per day, it appears that the average charging routine is charging about every other day.

5.4 Scenarios

The following chapter will describe different scenarios, and will analyse the effects of implementing an external battery bank to the system, to take more use of the solar energy.

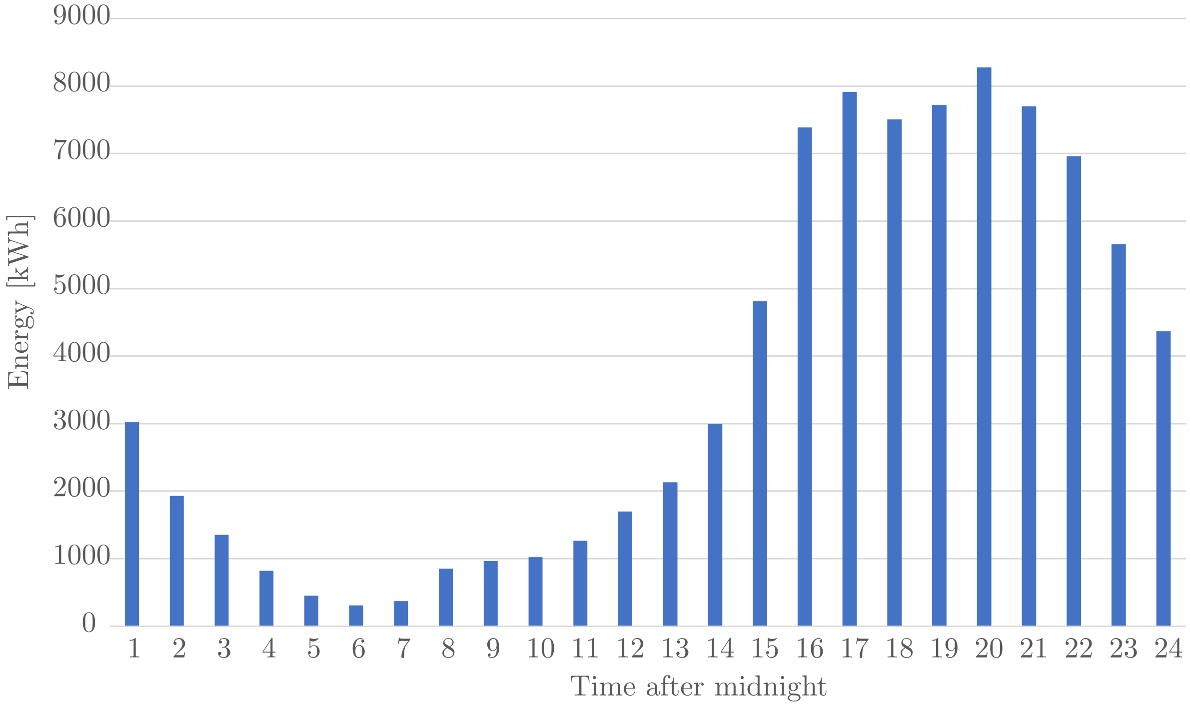

Figure 5.3: Total electricity consumption for EV at Risvollan boretslag. Data from Risvollan [80]

First, the base case is described, meaning what the system is like today.

There are many choices to consider when designing a battery system for storage of energy. The two most important specification is the capacity of the battery and the power that the battery can import and export. An LiB has good abilities to deliver high power, but draining the battery too fast can lead to shorter lifetime, as mentioned in section 2.12. The system needs a bi-directional inverter to convert from AC to DC as this is what the battery can store, and DC to AC as this is what the EV charger needs. The bi-directional inverter's position in the system is shown in Figure 5.1. The capacity of an inverter is often the limiting factor when it comes to import and export power from the battery. The capacity of the bi-directional inverter must handle two processes, the first one is capacity for charging the battery at a rate that corresponds to the battery size and solar production speed. The other process is when delivering the power to the EV chargers that need power.

The assumptions that are the basis for the scenarios are shown in Table 5.1, and are based on information from different platforms. The grid electricity price for scenario 1 is based on an average value of prices per hour for the period October-February the past five years, as these are the months that the electricity import from the grid will be the most significant due to lack of solar production. The grid electricity price for scenario 2 is based on an average value of hour-prices for the whole calendar year over the past five years, as the assumption is made that this scenario will need to import electricity throughout the whole year.

Table 5.1: The assumptions that the scenarios are based on.

Assumptions	**Amount**	**Unit**
Consumers price for charging	2,5	NOK/kWh
Grid electricity price scenario 1	0,8253	NOK/kWh
Grid electricity price scenario 2	0,8142	NOK/kWh
Average daily consumption per car	6,66	kWh
Charge speed per car	7,2	kW
Number of cars scenario 1	9	pcs
Number of cars scenario 2	90	pcs

5.4.1 Base case for EV charging

The base case is the situation today. As mentioned previously, the parking garage in OFV1 has 94 parking spaces, where all of them offer the possibility of EV chargers. In addition to the parking garage, the tenants in OFV1 have the opportunity to park in a parking lot outdoors. The price for renting a parking spot in the parking garage is higher than at the outdoor parking lot [83]. Because of this, it is reasonable to assume that renters of parking spots might rather want to rent and park at the outdoor parking lot, unless they have an EV and want to charge while the vehicle is parked. It is therefore assumed that EV owners will choose to use the parking garage and charge there.

If the tenants have an EV and want to rent a parking spot in the parking garage, it is possible to start a subscription to EV-charging services. This is needed in order to use the chargers that are available. The subscription for EV charging goes through Ohmia Charging. The subscription is separate from both the apartment's rent and renting a parking spot, and includes the electricity for the EV, insurance and service for the facilities. When subscribing to the EV charging service, there are different options to customize the service to the subscriber's needs. For an average EV that requires 12 000 km in annual range and charges at home most of the time, the average price for a subscription is around 2,5 NOK/kWh, including a 25 % VAT. [84]

It is assumed that there are 9 EVs in use in OFV1. This number is based on information from Ohmia's website, as the website allows possible subscribers to order a charging subscription and in that way see the number of occupied parking spots. Nine EVs with a daily consumption of 6,66 kWh each will have a annual consumption of 21878,1 kWh for charging. Comparing this number with the consumption for Risvollan borettslag, which had a total consumption of 87486 kWh during the time period of the collected data, gives $\frac{87486}{21878,1} \approx 4$. This shows that data from Risvollan includes approximately the same as 4 times the annual consumption of the nine EVs in OFV1. By scaling the consumption from Risvollan borettslag shown in Figure 5.3 down by $4 \cdot 365\, days$, the outcome will be an estimation of the daily power demand for charging nine EVs in OFV1. This is shown in Figure 5.4.

As this data is average data for another building and involves some assumptions, is it reasonable to imagine that these numbers will differ from a real scenario. This will be discussed further in chapter 6.

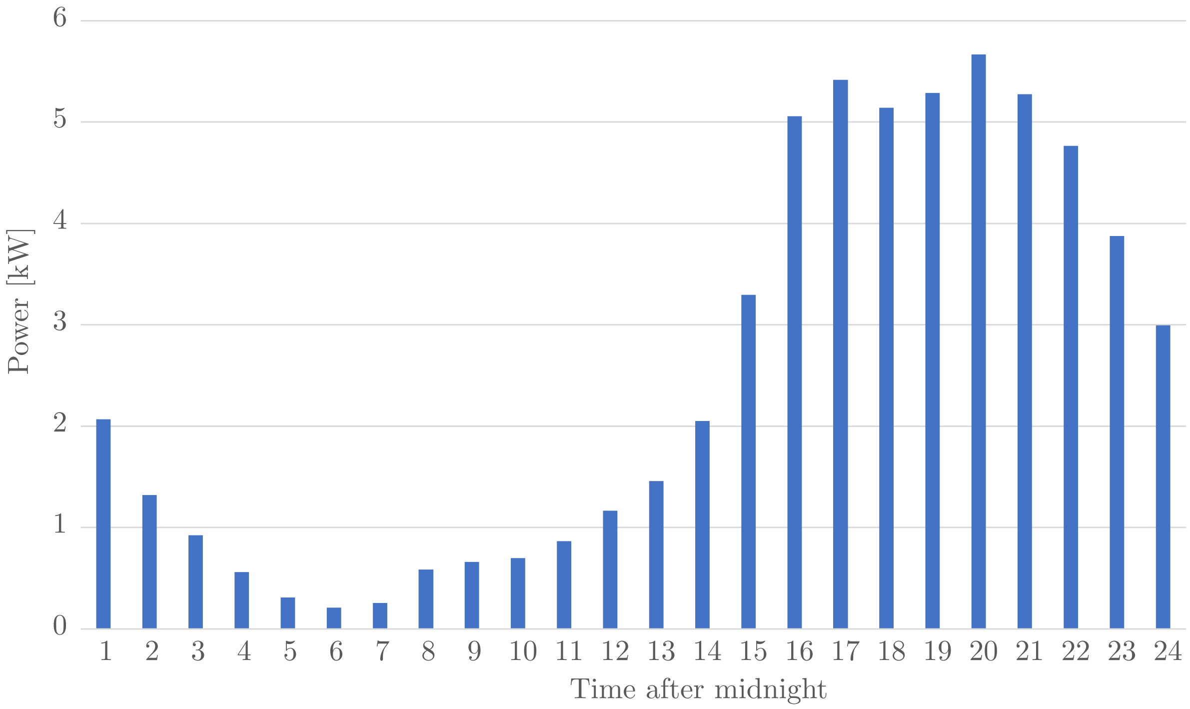

Figure 5.4: Estimated power curve for OFV1, base case and scenario 1. Data scaled from Risvollan [80]

5.5 Scenario 1

Scenario 1 has the same conditions as the base case, and will be an analysis of implementing an external battery if the solar facilities and PV production are as estimated for the EW system, as this had the biggest energy production.

5.5.1 Battery design scenario 1

The purpose of designing a battery is to make the solar energy from the PV systems be used to charge the EVs. The size of the battery is based on the needed capacity, while also taking the cost into consideration.

Scenario 1 has 9 EVs that are assumed to do all of their charging in the parking garage of OFV, as home charging usually is the cheapest option for charging EVs. A daily average consumption of 59,94 kWh for charging the EVs is assumed. Figure 4.6 shows the estimated solar energy produced from the EW PV system. From that figure it can be seen that all of the months from March to September have an average daily production of more than 100 kWh/day. Some days will have less energy production, and other days will have more. Designing a battery around 100 kWh allows the EVs to charge with energy from the sun on days with low production of solar energy, as the battery can store more energy than what the average energy consumption for an EV each day is. This will also allow the battery to not be deep cycled as much, and will extend its lifetime.

To find the right capacity for the inverters, it is convenient that the inverters can deliver enough power to the EV chargers as well as it can charge fast enough from the PV system. The EW PV system has an installed power peak at 67,94 kWp at STC. These conditions will never appear at the building's location, and the panels will not all produce their maximum at the same time, as they are tilted in different directions. Assuming a maximum power output of 75 % of the installed power is assumed to be appropriate. This will give an output of $67,96kW \cdot 0,75 = 50,97kW$, which corresponds to the selected inverter for the EW system in chapter **??** which had a capacity of 50 kW.

If all of the 9 cars plugged in at the same time and started charging with a power of 7,2 kW, a total of 64,8 kW would have to be delivered. It is reasonable to think that some of these 9 cars will have different charging habits, so a 64,8 kW power consumption will be a very unusual incident. If $\frac{1}{3}$ of these 9 EVs charged at the same time, they would consume $3 \cdot 7,2kW = 21,6kW$. This power consumption is likely to occur at some point, and can be a rough estimate for the maximum power consumed from the EVs. If more EVs are connected, the power for each EV would be reduced and then lead to longer charging time. An inverter capacity of around 21,6 kW is also enough power to fully charge the battery with an average day of sun in the summer months.

On the basis of the information in chapter 5.1, the chosen battery system is a Pixii Powershaper cabinet. The design in scenario 1 requires 2 PowerShaper cabinets with 20 Polarium batteries and 7 Pixiiboxes as inverters. The design and ratio of dimensions are shown in Table 5.2. The final battery for Scenario 1 will then have a power conversion capacity of 23,1 kW and a 100 kWh energy storage capacity. This will lead to a maximum C rate of $\frac{1}{\frac{100}{23,1}} = 0,23$.

Table 5.2: Prices of the parts for the battery system in Scenario 1.

Product/part	Price from installer	Amount	Net out	Sum	Unit
Battery com cable	50	20	1000		
Polarium 48V/5kWh	13 900	20	278 000	100	kWh
Pixiibox 48V/3300W	12 600	7	88 200	23,1	kWp
PowerShaper 30kW/65kWh	70 000	2	140 000		
Acquisition cost	4 600	1	4 600		
Sum			511 800		

5.5.2 Economic aspects of scenario 1

The economic benefit of Scenario 1 is dependent on the assumptions that are made. It is also dependent on the price for an EV-charging subscription and how much and what time the PV panels generate enough electricity. This affects the total annual income. The calculations are shown in Appendix *A*.

Considering that one EV on average draws 6,66 kWh electricity each day, and with 9 cars in the parking garage, the total electricity demand for EV charging in one day will be 59,94 kWh. The yellow column in Figure 4.7 shows the PV generated energy from the EW oriented panels. The Figure shows that the EW PV panels generate too little energy in the months October to February. In these months, the parking garage needs to import electricity from the grid to have enough power. This price is calculated to 0,8253 NOK/kWh including VAT.

In the period October to February, very little solar energy is generated, and thereby the production is too low to power all of the EVs with charging each day. During these five months, the total generated solar energy corresponds to 1915,8 kWh, which can be sold to the EVs and give an income of 3592,13 NOK. The amount of imported energy during this period is 7135,14 kWh. The income of the imported electricity that is further sold to the EVs in this period then becomes 7489,79 NOK.

In the remaining months, the period from March to September, the PV panels generate enough energy to charge the EVs in the parking garage without electricity from the grid. The income for the generated solar energy sold to the EVs in this period corresponds to 24 051,03 NOK. In total, the annual income for the generated solar energy sold to the EVs is 27 643,45 NOK. By adding the 7489,79 NOK that is earned by selling the imported electricity to a higher price gives a total income from charging EVs to be 35 133,24 NOK.

In the period March to September, the PV panels generate more electricity than the battery system and EVs require. The surplus electricity will then be sold to the tenants in OFV1. The price is calculated for each of these months in this period based on the average electricity price the last 5 years. During one year, this income will be 24 387,58 NOK. In total for Scenario 1, the income of sold, generated and imported energy is 59 520,82 NOK in one year. All of these calculations are shown in Appendix *A*

To analyze the full economical consequences of the EV charging solution, the cost of investing in the battery system also has to be included. Table 5.2 shows an overview of the prices for and number of the different components in the battery system. The table indicates that the total price for two Pixii Powershaper cabinets with all equipment included will cost approximately 511 800 NOK. To estimate the total price for the battery system, the installation costs also need to be considered. Based on STS' experience, the price for installing one cabinet is approximately 260 000 NOK. As it is designed for two cabinets, the total installing price will be 520 000 NOK. The investment costs for the whole battery system will be around 1 031 800 NOK.

Altogether, to analyze the economic benefit of the battery system and the assumed/calculated income of sold electricity to the consumers, it is possible to evaluate the profitability of this system. The years it will take for this investment to break even is $\frac{1031800\, NOK}{59520{,}82\, NOK/year} = 17,34 years$.

This means that after approximately 17 years, the charging and battery system in the garage will be profitable.

5.6 Scenario 2

The second scenario aims to look at possible future developments. The scenario in question will look at the system if OFV1's parking garage were to have 90 EVs that want the opportunity to charge.

It is difficult to say for certain when this might become reality, but based on chapter 1.4, it is deemed likely to happen sometime in the future. The number of vehicles that will use Frost Eiendom's parking services in OFV is unknown. Even though all new cars should be electric in 2025, it is hard to estimate when the amount of EVs is big enough to say for certain that there will be 90 EVs parked in the parking garage. To be able to estimate other factors, the time frame is estimated to 10 years.

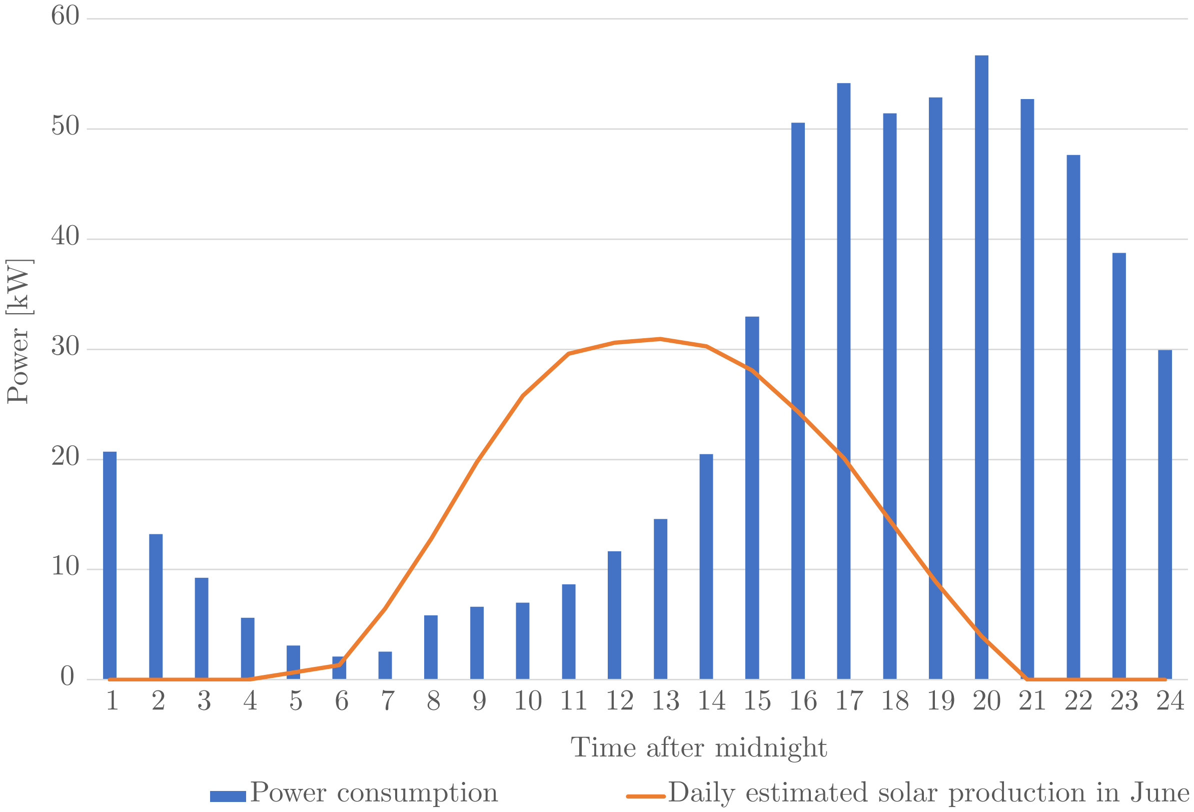

Figure 5.5: Scenario 2, estimated daily power curve for EV charging and estimated solar production for an average day in June. Based on data from Risvollan and research in Oslo. [80][85]

5.6.1 Battery design scenario 2

If there in 10 years will be 90 EVs in OFV1's parking garage, the need for energy will increase. It is assumed that the consumption will increase with a factor of 10 from scenario 1. By assuming the same average consumption of energy and the same charging habits as in scenario 1, the power curve for charging the EVs will be as shown by the blue bars in figure 5.5. The orange line is the line of expected solar production each hour for an average day in June based on data from a research project in Oslo [85]. The data is adjusted to the conditions in OFV1 by doing the following: The EW PV system design for OFV1 has its maximum production of 8630 kWh in June, this will in average be $\frac{8630\,kWh}{30\,days} = 288\,kWh/day$. Some days will yield more, and others less. The solar production per installed peak power in Oslo is therefore scaled down to fit the production of 288 kWh for one day.

For an average day where all 90 EVs charge 6,66 kWh, the energy needed will be 599,4 kWh. As the average EV consumption is much larger than the solar energy produced in the month with the maximum production, it can be assumed that all the energy produced will go to charging the EVs. The capacity of the battery will then be limited by the energy production from the PV system.

As shown in Figure 5.5, on an average day there will not be need of storing energy after hour 14, as all the energy produced by the PV system can go straight to charging the EVs. The capacity for the battery should be big enough to store all the solar energy that is not directly used to charge the EVs. This is the area in figure 5.5 between the blue bars and the orange line. This corresponds to approximately 109 kWh. These calculations are shown in Appendix *B*. As some days will have a higher energy production, and some days will have a different power demand, it will be convenient to scale up the battery system. This will also extend the batteries' lifetime, as less deep cycles are needed. A battery capacity of 150 kWh therefore appears to be an appropriate size for this scenario, as it gives the battery system a buffer.

When it comes to the capacity of the inverters, it is important that they can handle the power that the PV panels produce at their maximum, as well as being able to deliver enough power to the EVs. Maximum power produced by the PV system is assumed to be the same as in Scenario 1, which is 50,87 kW. The capacity of the chargers is also assumed to be the same as Scenario 1, at 7,2 kW. Figure 5.5 shows that the maximum average power needed to charge the cars will be around 55 kW. 55 kW corresponds to the capacity of 7,64 chargers of 7,2 kW. There will in some instances be more than 7 cars connected and therefore also a need for more than 55 kW, but since the PV system only produces in average 109 kWh more than what is used in June, there is in this scenario no economic beneficial of having an inverter bigger than the PV production. An inverter capacity of around 50 kW appears to be a large enough capacity to store all of the solar energy, this equals the inverter capacity that is chosen in chapter 4.3.2 for the PV system and will be sufficient even in the rare situation where the PV system produces its maximum and no cars are charging.

Like in scenario 1, the chosen battery system is a Pixii PowerShaper cabinet. The design in Scenario 2 requires 3 PowerShaper cabinets with 30 Polarium Li-ion batteries and in total fifteen Pixiiboxes as inverters. The design and ratio of dimensions is shown in Table 5.3. The final battery for scenario 2 will then have a power conversion of 50 kW and 150 kWh energy storage capacity. This will lead to a maximum C rate of $\frac{1}{\frac{150}{50}} = 0,33$

Table 5.3: Data for battery design

Product/part	Price from installer	Amount	Net out	Sum	Unit
Battery com cable	50	30	1500		
Polarium 48V/5kWh	3989,3	30	119 679	150	kWh
Pixiibox 48/3300	12 600	15	189 400	50	kWp
PowerShaper 30kW/65kWh	70 000	3	210 000		
Acquisition cost	4 600	1	4 600		
Sum			525 179		

5.6.2 Economic aspects of scenario 2

The economic benefit of Scenario 2 is dependent on the assumptions made for this scenario. The assumed price for Polarium LiBs is based on the data given in Figure 5.2. Compared to the prices today, the cost is estimated to be reduced with 71,3 % in 10 years. The calculations are also dependent on the amount of generated solar energy and how much supplemental electricity that is necessary to import from the grid to have enough to charge the EVs. The calculations are shown in Appendix *A*.

Since one EV draws 6,66 kWh of electricity each day, and with 90 EVs in the parking garage, the total electricity demand for EV charging during one day will be 599,4 kWh. The price for grid electricity is assumed to to be 0,8142 NOK/kWh including VAT.

The estimated required electricity demand in the parking garage is 218 781 kWh in one year. The generated solar electricity covers 45 005,8 kWh of this. Therefore it is necessary to import 173 775,3 kWh from the grid to charge all the 90 EVs. The cost of imported electricity from the grid is around 141 487,77 NOK and the income of selling this energy to the subscribers of the charging service is 325 828,5 NOK. The income from selling the generated solar electricity during one year is 84 385,88 NOK. This makes the total income from selling electricity to the subscribers valued to 268 726,61 NOK.

The full economical benefit of the EV-charging solution has to consider the cost of investing in the battery system. Table 5.3 shows an overview of the prices for and number of the different components in the battery system. This table indicates that the total price for three Pixii PowerShaper cabinets with all equipment included will cost approximately 525 179 NOK. The installation costs also have to be considered when estimating the total price for the battery system. The price for installing one cabinet is approximately 260 000 NOK, based on STS's experience and recommendations. Since the battery system is designed for three cabinets, the total installation price will be 780 000 NOK. The investment of the whole battery system will cost around 1 305 179 NOK.

Altogether, the analysis of the economical benefit of the battery system and the calculated income of electricity sold to the consumers makes it possible to evaluate the profitability of this system. The years it will take to make this system break even is $\frac{1305179\,NOK}{268726{,}61\,NOK/year} = 4,86 years$. This means that after approximately 5 years, the charging and battery system in the garage will be profitable.

5.7 Comparison of Scenario 1 and 2

Table 5.4: Summary of Scenario 1 and Scenario 2

Product/part	Scenario 1	Scenario 2
Battery capacity	100 kWh	150 kWh
Inverter capacity	23,1 kW	49,5 kW
Consumption from EV	21 878,1 kWh/year	21 8781 kWh/year
Energy from solar used	14 742,96 kWh	45 005,8 kWh
Imported energy from grid	7135,14 kWh	173 775,2 kWh
Battery system investment cost	1 031 800 NOK	1 305 179 NOK
Earnings each year	59 520,82 NOK	268 726,61 NOK
Financial profit	17,34 years	4,86 years

The differences between the batteries in Scenario 1 and 2 are shown in Table 5.4. The size of the battery in Scenario 2 is just 1,5 times bigger than in Scenario 1, even though the energy needed to charge the EVs is 10 times more than in Scenario 1. The reason for this is that the PV production is not sufficient to charge a bigger battery with more energy, since the energy demand for all of the EVs in Scenario 2 is exceeding the PV production by a large amount. While in Scenario 1, there can be an advantage to charging the battery and then take advantage of a fully charged battery in longer periods with no sun.

The inverter capacity is more than twice as big in Scenario 2. Since it in Scenario 2 is important to be able to store all of the solar energy, a high power inverter would be beneficial. In Scenario 1, the battery bank will in most cases in the spring, summer and autumn be fully charged before the evening rush of charging. There is not a need for the same import capacity as in Scenario 2, since the daily drain from 9 EVs in Scenario 1 is about $\frac{1}{5}$ of the daily PV production for June.

As shown in figure 5.4, the energy used in Scenario 1 is estimated to be 67,7 % supplied from the PV system. In Scenario 2, only 20,6 % of the energy comes from the solar facilities. The EW PV system is estimated to produce 45005,8 kWh/year, and Scenario 1 will then use 32,0 % of the produced solar energy. Meanwhile, Scenario 2 uses all of the produced solar energy to charge the EVs.

When looking at the financial aspects for the battery and charging system in the scenarios, it is clear that one is more profitable than the other. For Scenario 1, the total annual income of selling electricity to the consumers/subscribers was around 59 520,82 NOK, and for Scenario 2 the annual income was around 268 726,61 NOK. The costs of investing in the battery systems were 1 031 800 NOK for Scenario 1 and 1 305 179 NOK for Scenario 2. The period of time to make the investment break even is 17,34 years for Scenario 1 and 4,86 years for Scenario 2. These numbers are shown in Table 5.4.

5.8 Peak shaving

A battery installed can have other benefits than just to make use of the solar energy. As described in the Introduction, peaks in the power grid are a growing problem. Batteries can be used to counteract to the peaks or smooth out some of the power consumption.

Scenario 2 is further analyzed to show the benefits of peak shaving with a given external battery. As shown in Figure 5.5, the power curve is well pushed towards the evening, and with a peak power of 52,75 kW.

To smooth this curve, a battery bank can be very useful. The gray bars in figure 5.6 show the energy that has to be imported from the grid if no battery is used. There is no need of import from hour 7-14, as the solar production for an average day in June covers the energy demand in these hours.

The same battery that was designed for Scenario 2 is used for this analysis. This battery has a capacity of 150 kWh and the purpose of the battery is now to shave the peaks in the power imported from the grid.

The battery then has to be fully charged going into hour 16. This is done with the surplus production from the PV system, that is calculated to be approximately 109 kWh, as shown in Appendix B. The last 41 kWh have to be imported from the grid to charge the battery over the hours where the import from the grid is lowest, which is from hour 5-14. As the battery now has 150 kWh of energy, this energy can be used to relieve the grid. This can be done by finding the average power consumption over the hours with maximum import, which is from hour 16-24 and corresponds to an average power consumption of 40,34 kW. By distributing the 150 kWh over these 9 hours, it is possible to find the average power that now has to be imported from the grid. As shown in the following calculation, the average power imported from hour 16-24 is then 23,67 kW. As no other value on the graph exceeds this number, this is the maximum power peak shaving for this scenario. This will lower the peak import from the grid with $52,75kW - 23,67kW = 29,08kW$ for this parking garage. The result of this peak shaving is shown by the green bars in figure 5.6. The battery then has to go through a full cycle and the SoC is at 0 at midnight. Detailed calculations are shown in Table 7.5 in Appendix E.

$$Average\, power\, imported\, from\, hours\; 16\; to\; 24 = 40,34 - \frac{150}{9} = 23,67$$

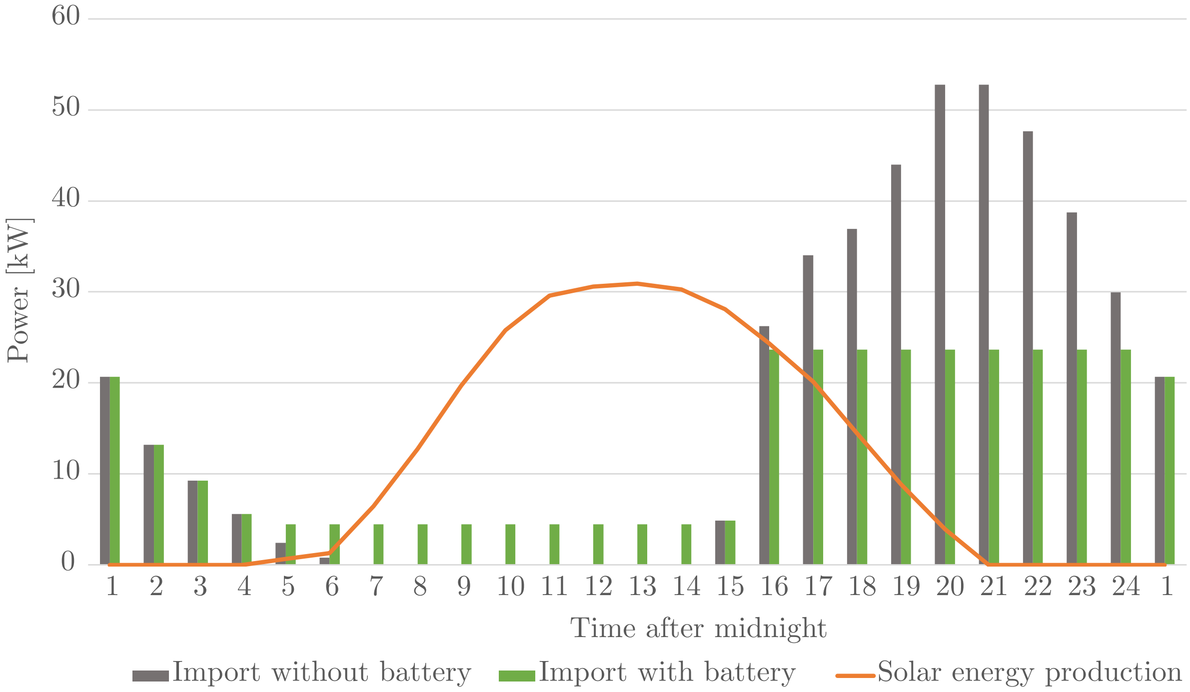

Figure 5.6: Scenario 2: Electricity imported from grid without battery, and with a battery installed. Based on data from Risvollan and research in Oslo. [80][85]

As shown in Figure 4.7, there is almost no energy production from the EW PV system from start of November until February. However, the battery of 150 kWh for Scenario 2 can still be useful for peak shaving. The blue bars in figure 5.7 indicate the estimated consumption for charging EVs in Scenario 2. If the battery is used for maximum shaving of the power peaks, the green bars in Figure 5.7 show the import of energy for each hour after midnight. The battery will then charge 150 kWh from 0 SoC to 100 SoC between hour 2 and 13. It will then use this energy to shave the peaks from EV charging during the evening hours. The minimum and maximum power imported from the grid without a battery is 2,11 kW and 56,69 kW. With the use of a 150 kWh battery, the minimum and maximum power from grid will be 20,02 kW and 31,99 kW. The inverter capacity must then equal the largest gap between the power import from the battery and the power consumption, to be able to deliver enough power. The gap between the maximum values is the largest and equals $56,69kW - 31,99kW = 24,70kW$. This is what the minimal inverter capacity must be. The inverter estimated for Scenario 2 is larger than this number and can be used for this application, and relieve the grid by 24,70 kW. Detailed calculations are shown in Table 7.6 in Appendix E.

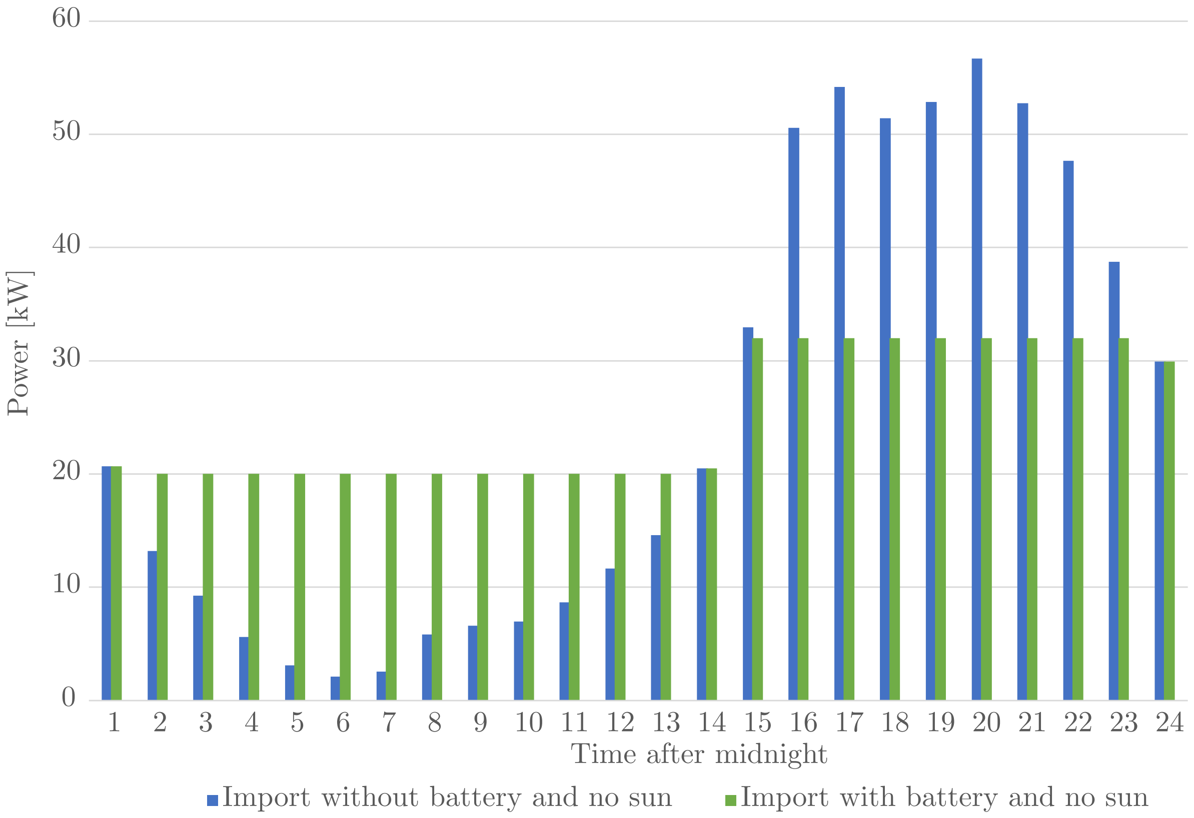

Figure 5.7: Scenario 2: Electricity imported from grid without battery, and with a battery installed when no PV energy is produced. Based on data from Risvollan [80]

If the battery bank was designed with the purpose of the smallest possible battery for the maximum peak shaving in Scenario 2, a battery with more capacity would be preferred. The green bars in figure 5.8 show that the average power import which is 12,97 kW for the given scenario. The external battery must contain the capacity of 246,23 kWh to accomplish this curve. Then the battery would charge from hour 3-15 and deliver power to the EVs from hour 16-2. The inverter capacity must be the difference between the average value and the peak value demand, which equals $52,75kW - 12,97kW = 39,78kW$. A battery system with a capacity of 246,23 kWh and 39,78 kW would for this scenario lead to a completely even load on the grid. Detailed calculations are shown in Table 7.7 in Appendix E.

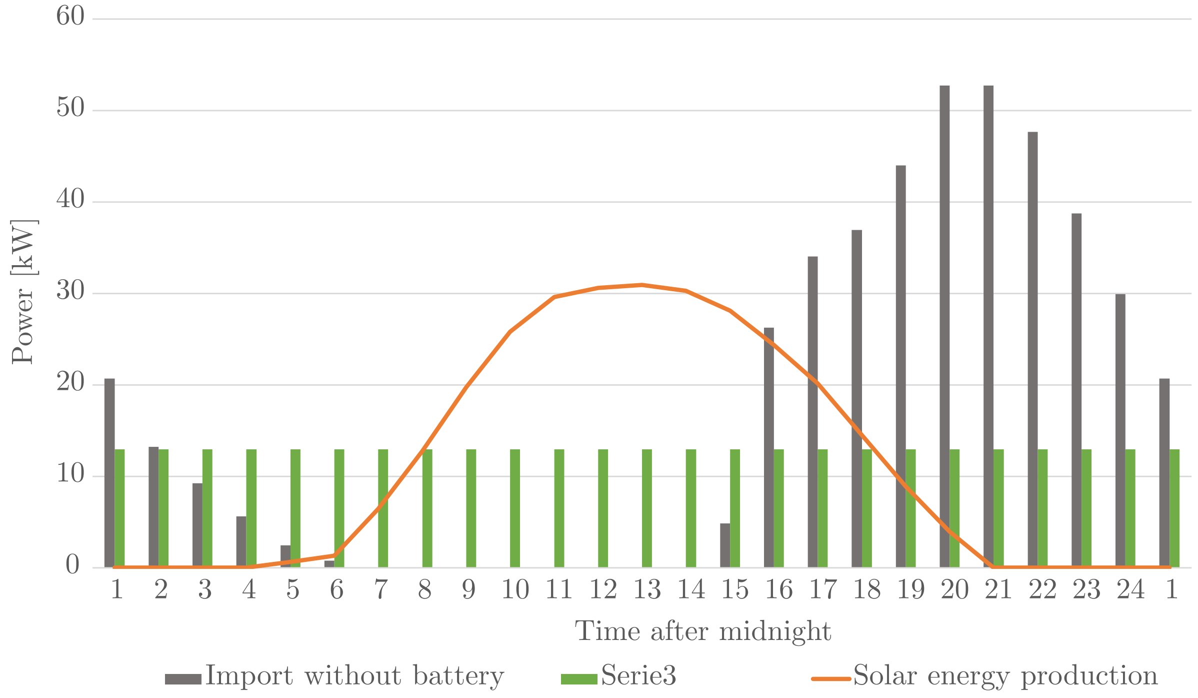

Figure 5.8: Scenario 2, optimal peak shaving: Electricity imported from grid without battery, and with a battery optimal for peak shaving. Based on data from Risvollan and research in Oslo. [80][85]

5.9 Cost of the total system

When realizing a combined system, one must look at the financial benefit of the total system. This includes the PV and battery system, and the estimated income each year. The cost of the EW system is calculated from 14 NOK per Wp installed. The system capacity is 67,94 kWp and gives a total cost of 951 160 NOK.

For Scenario 1, the total investment cost of the battery system is 1 031 800 NOK. When the cost of the PV system is added, it leaves a total investment cost of 1 982 960 NOK. The total income for Scenario 1 is 59 520,82 NOK each year.

For Scenario 2, the total investment cost of the battery system is 1 305 179 NOK. Since it is necessary to add the cost of the PV system, the total investment cost for Scenario 2 is 2 256 339 NOK. The total income for Scenario 2 is 268 726,61 NOK each year.

To evaluate the point where the two scenarios financially break even, it is reasonable to look at the payment period of each scenario. For Scenario 1, the payment period with an income of 59 520,82 NOK each year will be $\frac{1982960NOK}{59520{,}82NOK} = 33,32$years. For Scenario 2, the payment period with an income of 268 726,61 NOK each year will be $\frac{2256339NOK}{268726{,}61NOK} = 8,39$ years. This means that Scenario 2 will be financial beneficial after around 8,5 years, which is approximately 25 years before the system in Scenario 1. The comparison of the two Scenarios are shown in Table 5.5.

Table 5.5: Comparison of the investment cost and earnings of the two systems with PV and batteries included.

	Investment cost [NOK]	**Earnings each year [NOK]**	**Payment period [years]**
Scenario 1	1 982 960	59 520,82	33,32
Scenario 2	2 256 339	268 726,61	8,39

6 Discussion

When writing a thesis, it is important to reflect on the method and the results the thesis leads to. By doing this, one can get a good view of the accuracy of the results, as well as being able to take a look at what could have been done differently. This section will look into the results and discuss what consequences they might bring.

For any calculation or simulation, there are possible sources for errors. In some cases, making assumptions is necessary to be able to perform certain processes, such as calculations. In general, it can be argued that all assumptions are possible sources of error. Some of the choices made in this thesis had a significant impact on the results. Several assumptions were made for the PV system and especially for the battery design, and this can lead to some uncertainties in the results. Even if it is attempted to make educated assumptions based on research and solid data, wrong assumptions can be made.

6.1 The PV systems

The results of the PV system simulations are shown in chapter 4.4. The two systems that were designed had some different qualities, but generally their performance was quite similar.

OFV1's energy consumption is based on data from the electricity meter and the external heating meter. While the electricity meter is separate for OFV1, the external heating meter is shared with OFV2. The external heating energy for OFV1 is based on Frost Eiendom's assumptions that OFV1 uses 30% of the total energy measured in the common external heating meter. This number can differ from real life since this number is only an estimate that Frost Eiendom has made.

Both of the PV systems cover only a small part of OFV1's energy consumption with their production. The EW system has a larger estimated production, so this system then covers a bigger portion. However, the difference in how big parts of the consumption they cover is small: the EW system covers8,00 % of the energy consumption, while the S system covers 6,84 %.

Both systems have the biggest energy production in the summer, which comes to no surprise. The S system had only one summer month where the production was at any point bigger than the energy consumption of OFV1, while the EW system could export small amounts of energy from May to August. However, as figures 4.3 and 4.6 show, the production is high when the consumption is low, and vice versa. This is unfortunately a common issue for PV systems that supply energy to a specific installation, as the winter brings colder temperatures and therefore increases the heating demand. For PV installations that are not built for supplying energy to a specific installation this does not matter as much, as they always feed the energy onto the grid.

The S system had the lowest energy production out of the two systems. However, it had a higher energy production per kWp of installed capacity than the EW system had. The S system produced 767,6 kWh/kWp, and the EW system produced 662,5 kWh/kWp. This is a difference of more than 100 kWh/kWp. When the average production for a PV system in Norway is 650-1000 kWh/kWp, like mentioned in the Introduction, these numbers are on the lower end of that range. But considering the location of Trondheim, which is relatively far north in Norway, being on the lower end of the range is not surprising. This result indicates that the panels in the S system were more efficiently utilized than the panels in the EW system.

The performance ratio of the two systems were 69,7 % for the S system and 76,6 % for the EW system. As mentioned in chapter 4.4.3, a performance ratio of 80 % is considered good. Neither of the PV systems quite meet this criteria, but the EW system does come close to this. A high performance ratio shows that the installation of the PV systems is well suited for the conditions.

The S system had shading losses of 22,8 %/year, and the EW system had 17,5 %/year. As mentioned in chapter 3, OFV2 and OFV3 are much taller buildings than OFV1, and are positioned close enough to create shade on OFV1. A large fraction of the shading losses can therefore likely be attributed to the neighboring buildings. Based on the conditions, one can assume that the shading from the surrounding buildings is the same for the two systems. This way, the percentage of loss that is created by the other buildings is likely the same for both systems, although this is not known for certain. What is likely creating the biggest difference in the shading between the two systems, is the angle and placement of the PV panels. The south-facing panels are placed with a larger inclination angle in order to capture more sunlight, but this will also create some shade. The EW system's panels are not placed at such a steep angle, plus the "wasted" space behind/underneath each panel is used for a panel that faces the opposite direction.

There are a few factors that can influence the energy production from the PV panels that might make the simulations inaccurate. Firstly, the whole simulation of the physical conditions is created by selecting objects on an image of the roof that the PV system will be mounted on. This gives a large chance of human errors. If the height of objects, such as the ventilation ducts on the roof, is incorrect, this would also give inaccurate simulations. Soiling of the PV panels is another source for uncertainty. The values for soiling were based on advice from STS and their experience. However, it is still an assumption, and soiling conditions can vary to a large extent based on a number of factors, such as the weather. However, as long as the conditions are the same for the two systems, they will have the same point of reference, which is important in order to compare the systems. This is the case for the two PV systems, which strengthens the credibility of the results.

Worth considering is also whether the PV systems are practically feasible. STS' evaluation was that the systems seemed to be fine in regards to practical concerns. Even so, the simulations are still only simulations. The answer to whether the systems are practically feasible would only be clear if one were to actually build the systems in real life. This would show how the layout functions, and if it is possible for example for a person to move between the panels, perform maintenance on the systems, and so on. It could be possible that a real-life installation would have to be scaled down to fit on the roof of OFV1, but it could also turn out that it is possible to increase the size of the system further.

The energy consumption data from OFV1 is data from 2021. In the big picture, this is possibly not the most typical year regarding energy consumption. Due to the Covid-19 pandemic, many people spent a lot of time working or attending school remotely, from their home. This lead to a different pattern of energy consumption than in “normal” years. It is hard to tell if this is the case for OFV1, as the residents’ occupations and habits are unknown. If a person’s job did not allow for them to work remotely for example, they would still have had to go to work. Also, as long as 2021 is the consumption data that was available, it was not possible to compare with pre-Covid years.

6.1.1 Possible improvements of the PV systems

A way to further increase the performance ratio and energy production could be to install technology that tracked the sun’s path and made the PV panels rotate accordingly. This would not give a system that is oriented in any one direction, but it would always be pointed in the direction that gives the most sunlight. However, a rotating solution would involve more complicated technology and a lot of moving parts, which makes the system far more complicated. It would also have a higher cost. A system with moving parts would also likely need more maintenance, which would further increase the costs. A solution like this would also most likely take up more space so that fewer panels would be able to fit.

The energy production would also increase if one were able to reduce the soiling on the PV panels. This could be attempted in a couple of ways. Table 4.1 shows the output losses due to soiling of the PV panels, and the soiling is much higher in the winter months, indicating that this is likely due to snow. As snow is the largest single source for soiling, reducing the amounts of snow on the PV panels would likely be an effective measure. This could for example be done by manually removing snow by shoveling it when it is an issue. The effect that this solution could have is unknown, and it would lead to costs related to the labor. This also relies on how easy it is to access the panels. It could also lead to extra wear and tear on the solar panels. Another way to remove snow could be by using technology that heats up the solar panels and melts away the snow. However, this would require using electricity for heating, which would consume electricity and make the total effect of the measure smaller, perhaps even negative.

Additionally, the soiling is assumed to be the same for the two PV systems. However, as the S system has an inclination angle of 40°, it is possible that this is steep enough for snow to slide off of the panels. This has not been taken into consideration. The snow is not likely to slide off of the panels in the EW system, as these are mounted at only 10°.

6.1.2 OFV1 as a location for PV systems

Out of the properties that Frost Eiendom owns, OFV1 did not particularly stand out as a more optimal choice for a PV system than the other options. The choice was based on Frost Eiendom's wishes to explore the possibility of building a PV system on OFV1, and to see what effects this may have.

As a location for PV energy systems, Trondheim is not the place in Norway that gives the highest energy production per year. This is due to Trondheim being far north, and other factors like longer periods of weather with less than optimal sun conditions. This means that OFV1's suitability as a location for PV production is lowered to begin with, just by being located in Trondheim.

It should also be discussed whether OFV1 is the best option for a PV system out of the four buildings that Frost Eiendom owns in Ola Frosts veg. OFV1 is surrounded by OFV2-4, which are all taller buildings. Figure 3.2 shows how they are located compared to each other. OFV4 is far enough away from OFV1 to not be an issue for PV production regarding shading, but OFV2 and OFV3 are closer to OFV1, and significantly taller, respectively 36,6 m and 41,0 m. Therefore, they cause shading on the PV panels, as mentioned previously in the Discussion. Would one of the other buildings in Ola Frosts veg be better suited for a PV installation, since there would not be surrounding buildings that create shade? This is a difficult question to answer without performing an equally thorough analysis of each of these buildings as has been done to OFV1. However, avoiding the direct shading is a good indicator that panels on one of the other buildings could have a higher energy production per square meter. Placing PV systems on the roofs of OVF2-4 could have its own issues though, such as difficult layout and height variations on the surface.

It can also be argued that apartments located in a large complex should have a somewhat lower energy consumption used for heating, since the apartments are usually a lot smaller, and they are surrounded by other heated units and therefore have less heat loss to the surroundings. OFV1 has an average energy consumption of 10 413 kWh per apartment per year, including district heating. This is about half of the consumption of a single-family home. Sources have different numbers for what an average apartment in an apartment building should have in energy consumption, but up to 10 900 kWh per year seem to be within normal range [86]. This puts the apartments in OFV1 at the higher end of the range that is considered normal, but still within the range. Had the apartments in OFV1 had a lower average energy consumption, the PV systems would have been able to cover a larger fraction of it with their energy production.

As OFV1 has four storeys, it does not have a large roof area per square meter of living space in the building. This ratio becomes smaller and smaller the more storeys a building has, which makes it more difficult for a PV system on the roof to supply enough energy for the building it is located on. OFV2-4 have more storeys than OFV1, so a PV system would likely have a bigger problem with supplying enough electricity in these buildings.

As mentioned, the proposed PV systems' energy production did not cover a large part of OFV1's consumption. The example with 20 panels on a family home in the Introduction said that a PV system with 20 panels would be able to supply around 25 % of the energy consumption of 20 000 kWh. The EW system has $\frac{172}{54} \approx 3,2$ panels per apartment in the building. If one considers 3,2 panels per apartment, and an energy consumption of 10 413 kWh per apartment per year, compared to 20 panels for one single-family home with a consumption of 20 000 kWh per year, each panel in the EW system would have to produce about 3 times more than the panels of the single-family home in order to cover the same fraction of the building's consumption. This shows that OFV1 has a small amount of space on the roof per residential unit compared to what is estimated for a single-family home.

In order to increase the degree of coverage from the PV systems' production, the building's energy consumption would need to decrease. There are numerous ways this could be done. One way to motivate the residents to decrease their electricity use is to install individual electricity meters for each apartment. The existing solution where the whole building shares one meter and distributes the cost based on apartment size is not beneficial if the wish is to cut down on electricity consumption, because each individual's actions has so little influence on the electricity bill that they receive each month. The same thing could be possible for the district heating, although it is not certain that the residents would choose to turn the heat in their apartment down in order to save money. There is also the option to refurbish OFV1 to make it more energy efficient, to prevent heat loss and to minimize energy consumption for ventilation, for example. This is an option that would come with high costs.

6.1.3 PV*SOL as a tool

While performing simulations for this project, several options in PV*SOL were not used. The thought was to "keep it simple", and to only include information that was available or could be estimated with a certain degree of accuracy. This evaluation of the software is therefore only based on the group's experience, as the program has functions that were not utilized for this thesis.

For the purpose PV*SOL had for this thesis, the software worked well. It gave the desired results, and was practical in use. Based on the background information provided on the software company's website, the program's sources of information also seem to be accurate and to follow a high standard. This gives the results from PV*SOL an impression of being accurate based on the input that was provided.

A downside to PV*SOL is the low level of detail in the results. As the energy production results were only given on a monthly basis, this reduced the level of accuracy that was possible to achieve when using the software. This means that it is unknown how much the PV production varies day-to-day. Had the level of detail been higher, the data could have made it possible to conduct a more detailed analysis of both the PV systems and the combined PV and battery solution. The day-to-day variation in PV energy production in Trondheim can be large. The battery system was dimensioned to be able to store the average energy produced in a day, in the month where the EW PV system had the highest production. Some extra capacity was added, in an attempt to have enough capacity for the days with above average energy production. There is no way to tell if this extra storage capacity would be enough however, since PV*SOL does not offer a simulation that has daily production data. If one considers an example where the weather is very sunny for a whole week straight, it is not unlikely that more energy would be produced in this period than what the battery could store. However, detailed predictions are difficult to make accurately, especially when the predictions are dependant on an unpredictable phenomenon like the weather. So, if the data had provided numbers for the energy production each day, using these numbers for calculations could easily lead to inaccurate results as well.

Something that PV*SOL does not include, is the option to enter the grid voltage accurately for Norwegian conditions. As described in chapter 2.5, the most common grid type in Norway is the 230 V IT network, while the 400 V TN network is the most common grid type in the EU. Likely as a result of this, PV*SOL only offers the 400 V option for the power grid. However, as mentioned in chapter 4.1, this is mostly an issue regarding inverters for the PV system. Most suppliers have inverters made for 230 V IT networks and otherwise the same specifications, and therefore this was not seen as a significant issue when using PV*SOL. Any losses this could cause are assumed to be irrelevant, and the results are not considered to be affected by this.

6.2 The battery system

The following chapters will discuss the results and possible consequences of the battery system.

6.2.1 EV consumption

For the charging, it is assumed that all EVs charge with 7,2 kW of power at all times they are charging. This is done to simplify the calculations, because the power that the EVs are charged with might vary due to different factors. This can be factors such as how many vehicles are being charged at the same time, the SoC of the EV and the safety fuse of the charger's electricity supply, as well as the on-board charger capacity for each EV. These assumptions will inevitably lead to the calculations being less accurate. A parking garage such as the one in OFV1 often has one common main fuse, which again limits the garage's power supply. If many cars are plugged in at the same time, the total available power will be split evenly to the cars plugged in. This can make the power to each charger drop, and then make the charging session last longer.

7,2 kW is estimated from 1 phase 32 ampere and 230 V, since most of the grid in Norway is 230 V IT. For 400 V TN grid, it is safer and more common to use all 3 phases. If the fuse is 32 A and the on-board charger is compatible with high power, an EV will get 22 kW from that charger.

The 400 V TN power grids that make up a lot of the newly built grids in Norway might lead to higher peaks in the grid as the cars can consume electricity faster, but on the other hand, the EVs will be done charging in a shorter time due to higher speed AC charging.

For the battery scenarios, an important assumption that is made is that all of the EVs start charging as soon as they are plugged into a charger. This might not be the case for all vehicles, and it is a simplification to say that the charging works in this way. As of today, many chargers and cars are compatible and use smart charging. This makes it possible to plug in the car, and the car will automatically start to charge at a given time, or when the electricity price is at its lowest depending on what is programmed for the EV. Looking at the case in Risvollan, if a lot of the users are using smart charging, the power curve in Figure 5.3 will not accurately describe the real case. Based on Figure 5.3, the afternoon is the most common time to plug in the car, which makes sense considering the time people come home from work or school. The actual charging might not happen until later though, if the EVs have smart charging.

Since the average charging session is 12,72 kWh, the average charging session will be done in just under 2 hours if a 7,2 kW charging rate is assumed. A smart way to lower the costs of charging is to make use of smart charging. Figure 5.6 shows the average price per hour for the last 5 years. In an average scenario, use of smart charging will lead to charging occurring between hour 2-5 after midnight. However, as seen in Figure 5.6, the price varies little in a day, and there is not that much to save by charging at night. It is not easy to assume how many that are making use of smart charging, but it is reasonable to think that more users will start to use it if the price of electricity starts to vary more throughout the day, and there is more money to save by using smart charging.

The EV charging pattern is based on the case study for the large apartment complex in Risvollan borettslag, [80]. This case is much larger than Scenario 1 that is considered for OFV1. This might be an issue when the situation is scaled down, because smaller groups do not necessarily behave the same way an average does. The number of cars in Scenario 1 is as low as 9, as described in chapter 5.5. When the “population” is this small, the behavior of each individual car owner becomes much more important. This way, it can easily impact the power consumption pattern if just a couple of the 9 EV owners deviate from the average behavior. If this small group of EV owners has different habits than the average of the large population that the data from Risvollan is based on, the charging predictions for Scenario 1 will be inaccurate.

Scenario 2, on the other hand, might have more similar conditions to Risvollan. Scenario 2 involves 90 EVs that need parking and charging. The total energy consumption in Scenario 2 is 218 781 kWh. This corresponds to approximately 2,5 times higher consumption in Scenario 2 than in the study from Risvollan. Due to the high number of vehicles, the deviation caused by one user will be less noticeable than in Scenario 1.

A further analysis could have been made by going more into the details about the consumption, by for example analyzing differences in the consumption on the weekdays compared to the weekend. That way, one could see if holidays or other things like the weather would affect the consumption. If the consumption would have been different in these situations, it is reasonable to think that also the design of the battery could be different.

In the larger picture, EVs are relatively new as a mainstream vehicle. This is reflected in society, where charging of this sort is a new necessity. For owners of EVs in Norway, it is common to have a charger installed at home, where most of the charging takes place. As EVs are a relatively new technology, the charging habits may change over time. In the future, it is possible that EV charging may take place more like fueling a car with gasoline takes place today, in the sense of time and place. Most gas stations today offer charging for EVs, but this can be time consuming to use. Therefore, charging at home when the car will not be used can be an easier option for many. If charging in gas stations and other locations is made easier and more convenient in the future, this might increase in popularity and change where people choose to charge their car. There is also the option that people might choose to a larger extent to charge while they are at work, which is already somewhat popular today. If people were to no longer charge at home, the battery system would have to be repurposed and could be used for the building OFV1 instead.

It is assumed that Scenario 2 will take place in about 10 years' time. Considering the development that has happened in the field of EV technology in the past 10 years, it is hard to tell where the charging technology is at in another 10 years. For this analysis, it was assumed that the charging habits are the same in the future. However, the charging habits are likely to change.

This analysis has mostly viewed the PV system and battery solutions as two separate systems that do not affect each other to a significant degree. This has lead to ignoring the degradation of the PV system when analyzing Scenario 2. The time frame of this scenario might lead to some degradation of the PV system that produces power for the battery system. This would make the system less beneficial, since the self-produced electricity would decrease. The battery will also experience some sort of degradation. The degree of degradation depends on different factors like temperature, depth of cycles, number of cycles, quality of the battery and annual degradation. For this analysis, the degradation was set to zero which is unlikely to be the case, even with the technology that is available in ten years' time. The efficiency of the battery is set to 100 % which means that if 100 kWh is used to charge the battery it is possible to take 100 kWh out of the battery. In a real life scenario, this is not the case. Both the external battery and the EV batteries have losses and the losses increase as the charging speed goes up and more heat is generated. This means that the energy you put into the battery is somewhat more than the energy you can extract from it. This means that the analysis of the battery systems can be seen as the most accurate at the time that the systems are installed, and less accurate as time passes.

6.2.2 Usage of battery

The main purpose of the designed batteries was to utilize the solar energy production from the EW PV system. A convenient size for the battery in Scenario 1 was calculated to 100 kWh. This capacity is larger than the daily consumption for the 9 EVs in Scenario 1. The calculation is based on average values, but in a real life scenario there will be periods of low production or periods of high consumption, and in these periods a larger battery capacity would be beneficial. To calculate how much these periods will affect the production and consumption is hard to say, and more data would be needed to calculate these situations. A bigger battery would result in a more expensive system, and the price of the system is desired to be as low as possible.

If a sufficiently large battery was installed in Scenario 1, it could be possible to have the system charging the EVs off-grid. The battery could then store energy during the summer, and with a low self-discharge rate have enough energy to supply the 9 EVs during the winter when the solar production is low. This would have been an expensive investment and is not a likely solution in a building like OFV1, that already has a grid connection. In short terms, there is no limit to how large a battery system can be built, so it is important to have the battery system's purpose in mind when determining its size.

For Scenario 2, a battery pack of 150 kWh was calculated to be an appropriate capacity for the battery. Even though the daily consumption from the EVs exceeds this, there is no need for a larger battery, as the solar energy is not sufficient to fully charge this battery on an average day. As described earlier, there will be periods where low production or low consumption occurs. If data was available about these periods, it would be possible to adjust the size of the battery or numbers of inverters to better suit the system. This would then lead to a more complex analysis, but on the other hand might give a result with fewer uncertainties.

A battery bank can also give other opportunities for the building than just to take more advantage of the solar production. A battery bank can be helpful in cases of a power outage. A charged battery can then be used to deliver power to the building or the EV chargers, depending on the need. It can be hard to predict when a power outage will occur, and therefore also hard to make sure to have a fully charged battery when a power outage strikes. This could lead to the worst case scenario of having a power outage and no available energy in the battery. If the battery had some sort of a buffer which did not allow the battery to drop below a 20 % SoC, the battery would be able to at least have some energy for the most necessary activities during a power outage.

As described in chapter 1.3.1, it can be a challenge to deliver energy to the grid in regards to voltage quality. A battery will absorb the surplus solar energy, and in that way reduce what is needed to be exported to the grid. Little information is known about the grid surrounding OFV1, therefore it is hard to give information about the voltage quality and if delivering power from the PV system to the grid will be a problem for this case. A three phase inverter is chosen for the PV systems, and this will help keep the phases equally balanced at the output of the inverter, which is preferable to avoid unbalanced phases. However, it is possible that the storage of the PV production might be sparing the power grid from some instability.

6.2.3 Peak shaving

Earlier in the thesis, it has been shown that the battery can be used to shave the power peaks. For Scenario 2, the battery can be used to lower the import peaks with up to 29,08 kW for the average day in June. Figure 5.7 shows how the import will be smoothed out in the winter when the production from the PV system is zero. The battery will for this incident lower the import peaks with 24,7 kW.

As of today, is there no financial payback for shaving the power peaks, but a power tariff can lead to saving money from peak shaving. This will be discussed later in the thesis. By reducing the import peaks, the building can have a smaller main fuse, which can result in a lower price [87]. Scaling the power peaks will in a larger scale avoid or simplify the grid improvements and in that case avoid unnecessary expenses for society.

The EVs will charge at the highest speed as possible, but if several cars plug in at the same time, so the main fuse exceeds its total limit, the power for each car will be limited. To avoid this, the battery can provide more power to the EVs than what is possible without a battery.

If the battery should allow the imported power on the average day for June to be constant, the battery would have to have a bigger capacity. It is calculated that the capacity of the battery had to be 246,23 kWh and the capacity of the inverter 39,78 kW. As mentioned previously in the discussion, this average is not likely to occur each day, and a battery of this size will only allow the power import to be constant for that day and days with lower consumption.

The batteries are calculated to have a SoC at 100 % before the shaving of the peaks starts and a SoC of 0 % after the peaks have been flattened. This is a full cycle for the battery, and if this happens everyday, the batteries' lifetime will be shorter. To avoid this, it can be an option to design a bigger battery that can provide the same amount of energy without having to do a full cycle. Alternatively, the battery can be used for only the largest peaks, which allows the battery to not go deep in SoC as this might cause irreversible losses for the battery, as explained in chapter 2.6.2.

To find the right time for a battery to charge and to discharge is challenging. In most scenarios, the future consumption is not given, and an estimation based on historical data and assumption must try to distribute the energy as accurately as possible. Due to this, in a real life scenario it would be very difficult to have a constant import from the grid as shown in Figure 5.8.

6.2.4 Choice of battery system

Based on information in chapter 2.6, the selected battery technology for this system was LiBs. Today, this is the most used battery technology due to its longer lifetime and high efficiency. However, with the rapid development of technologies it is reasonable to believe that in the future an even better battery technology, perhaps a flow battery, could be more suited for this purpose.

Flow batteries are an alternative battery solution that was considered for OFV1. As mentioned in chapter 2.6, flow batteries have advantages such as being safe in residential use, a long lifetime, and separate power and energy constrains. The downside of flow batteries is their high cost and large space requirements. The space requirements would likely not be an issue for a flow battery solution in OFV1, but considering the needed energy storage capacity, the costs were assessed as being too high. Had OFV1 needed a larger storage capacity, a flow battery system might have become a more viable option.

6.2.5 Degradation and lifetime

Pixii does not have any information about the lifetime of their battery system, nor for the inverter or cabinet. The component with the shortest lifetime is assumed to be the battery.

Usually, it is said that if the battery capacity is somewhat lower than 70-80 % of its original capacity, it is at the end of life. How long it will take for a lithium battery to get to that point is dependent on factors like temperature, depth of cycles, number of cycles, quality of the battery, storage conditions and time dependent degradation, as explained in chapter 2.6.2.

Polarium, the producer of the batteries, do not state anything about the lifetime of the battery. The cabinet's surrounding temperature should be around room temperature. It is unknown if the cabinet has some sort of temperature regulation to keep the battery at a stable temperature. This could be a useful option, as the battery can heat up both when charging and discharging and cause irreversible losses.

The battery will have a relatively low charging rate with a maximum charging and discharging rate of about 0,23C for Scenario 1 and 0,33C for Scenario 2. A low charging rate is beneficial for the lifetime of the battery, but in some instances a higher charging rate can be valued higher than a long lifetime.

The battery is dimensioned so that its full capacity will not be used on an average day. The battery can be used to store solar power, but also for peak shaving. In the calculation of peak shaving, the full capacity of the battery is used every day. This will lead to one full cycle pr day, and a deep discharge to 0 SoC. As shown in Figure 2.12, a deep charge will shorten the lifetime. Based on similar conditions as the figure, there is a chance of the battery only managing around 2000 days before the SoH is around 80 %. This corresponds to around 5,5 years. This may vary a lot, since the battery's SoH is also effected by a lot of other factors. Alternatively, the battery can be set to only flatten the highest peak, and in that way reduce the usage of the battery capacity to obtain a longer lifetime. The balance between how much the battery should be spared and not used due to shortening the lifetime is a balance between its benefits and lifetime.

As mentioned earlier in the thesis, the battery is assumed to have a SoH of 100 %. This will only be the case in the beginning of the battery's lifetime, and the scenarios will be different as the SoH drops. When the 100 kWh design for Scenario 1 is closing in on the end of its life and has a SoH of 70 %, the available capacity will only be 70 kWh. If an available capacity of 100 kWh is desired when the SoH is 70 %, the battery must then be designed with 142,86 kWh as the initial capacity.

6.3 Alternative energy storage solutions

The reasons for why a LiB was chosen as a solution for OFV1 have been explained previously, in chapter 2.6. However, one could consider using an energy storage technology that is not strictly a battery.

One option for this could have been hot water storage. As OFV1 uses district heating, hot water production and storage could be a good supplement to the system. The PV system could then be programmed to produce hot water when the production is higher than the electricity consumption. Figure 3.3 shows the energy consumption of OFV1, divided into electricity consumption and district heating consumption. The water heater would then turn on the moment the PV production exceeded the electricity consumption, represented by the blue column. The hot water could then either be used directly instead of buying district heating off the supply grid, or it could be stored and used later. On the few occasions when the PV system produces more than the electricity and district heating consumption combined, storing the hot water could be a good option, although thermal storage comes with some losses.

Another alternative could be to use the EVs in the parking garage for energy storage. The EVs could store electricity from the grid, for use in the building OFV1. If the EVs were connected to a smart charger, the user could for example input what time an EV needs to be fully charged when it is plugged in. Up until this time, the EV could be used for supplying the building with electricity, importing, storing and exporting energy the most optimal way according to prices and consumption. This would require a large degree of programming to create a functioning smart control system. Something like this would also be complicated to implement in a building where the residents rent their apartments instead of owning them as well as sharing an electricity meter. A solution like this would lead to faster degradation of the EV batteries, so the probable way something that like this could work in OFV1 is if the EV owners were paid to "rent out" their car's battery. As of now, this option is not seen as realistic for OFV1.

6.4 Costs

The profitability of a project is usually the deciding factor on whether it should be carried out or not. This chapter will elaborate and discuss the financial aspects of the system solutions that are proposed in this thesis.

6.4.1 Financial aspects of the PV systems

As the results show, the PV systems could do better in terms of profitability. The S system ends up with a small negative cash balance of 3908 NOK at the end of its estimated lifetime, and the EW system ends up with a positive cash balance of 38 960 NOK. The financial analysis includes an estimated cash balance for the two PV systems, shown in Figures 4.5 and 4.8.

The S system is close to breaking even financially, and as Figure 4.5 shows, it is not unlikely that the cash balance would have been positive, had the simulation gone on for even just one additional year. Another aspect worth noting is that a negative cash balance of 3908 NOK is a rather small amount for a system with investment costs of 850 000 NOK. While the S system has a negative cash balance at the end of life, it is also worth pointing out that the investment costs of this system are 100 000 NOK less than that of the EW system, which is a considerable amount of money for an investment of this size. Also, the investment costs are the most dependable figure in these calculations, while the cash flows are to some degree unpredictable.

The EW system does end up with a positive cash balance at the end of its estimated lifetime. The positive cash balance of 38 960 NOK in year 30 is just the second year of a net positive cash balance. A positive cash balance of 38 960 NOK is arguably not a large sum compared to the initial investment of 950 000 NOK.

The reason for the PV systems' poor profitability, is that the savings that the PV energy systems provide are not big enough. This is mostly dependent on the price the consumers would have paid for electricity if it was imported from the grid. The prices that were input in PV*SOL for the economic calculations are based on data from 2017-2021 and with a annual inflation of 2 %. If the electricity prices increase faster than this in the future, the savings from the PV systems will be larger than what the results show.

The cash balances show the investment costs in the beginning of the period, and the estimated accumulated system values as time goes on. The cash balances increase steadily, and the reason that the cash balance increases, is the previously mentioned savings on electricity, which are uncertain predictions. Not included in the cash flows of the system is any cost related to maintenance. These are costs that would most likely need to be taken into account every few years.

The financial analysis has not included what happens at the end-of-life for the PV systems. In the current system in Norway, PV panels that are waste are sorted along with general electric waste. Recycling schemes meant specifically for solar panels are currently not in place in Norway, at least not in a large scale [88]. The estimated lifetime is 30 years, and it is hard to predict what recycling schemes will be in place for disposing of PV systems when that time comes. One option is that it will cost money to dispose of the PV systems, which would obviously have a negative impact on the profitability. If the PV system could be sold however, either to a recycling scheme or to be repurposed for another facility, the financial impact would be positive. There is also a third option; that the system ends up having a longer lifetime than anticipated, which would mean that it could stay in its place and keep producing PV energy even longer. The system would degrade over time, so after enough time has passed, the benefit of keeping the PV panels in place would shrink significantly.

To put it shortly, PV systems such as the ones analysed in this thesis become more profitable the higher electricity prices are. This could mean that if placed in another location where electricity costs are higher, it is possible that these systems would be more profitable investments.

6.4.2 Financial aspects of the battery system

The battery system solution is provided by Pixii, and this choice is based on recommendations from STS. The prices for the system in Scenario 1 and 2 are shown in Tables 5.2 and 5.3. In addition, the price for the installation of the battery system is significant. The batteries themselves constitute to only 26,94 % of the total price for the battery system in Scenario 1 and 9,17 % in Scenario 2, where the price per battery is assumed to be lower.

For the installation cost, this is 50,40 % of the cost for Scenario 1 and 59,76 % of the cost for Scenario 2. The installation includes everything that needs to be done before the battery is successfully operative. The installation price is assumed to double if there are two cabinets of batteries compared to one. Possibly, the amount of work does not double by installing two cabinets, which can mean that the cost of this is in fact lower. The cost of connecting the cabinets to the chargers and grid, and programming the software will be a non-recurring cost. The cables connecting the battery to the rest of the system might be a bit thicker if more current is going through them, but twice the price, which has been used, might be an exaggeration. In the calculations, it is accounted that the price of one cabinet is independent of the number of cabinets installed. Installing several cabinets could possibly lead to some kind of quantity discount that would make the price for 2 and 3 cabinets lower than first calculated. This would make an impact on the total cost of the battery system.

A key specification to make use of energy storage is to charge the batteries when the electricity prices are low, and discharge when prices are high. Often, the price of electricity is high when the demand is high, and low when the demand is low. The high demand can usually occur in the daytime, and low demand in the nighttime. Figure 1.4 shows the electricity prices during one day. As seen in the figure, the price difference between day and night is not that large. If there would have been larger variation between day and night, a battery system would probably have been more profitable, due to larger savings on electricity expenses. This will be most important for Scenario 2, as in Scenario 1, the PV system generates enough electricity to avoid importing electricity from the grid. During a short period of time, a considerable price difference in the electricity would lead to larger savings on electrical power, which is a benefit of the battery system. This would also contribute to making the system in Scenario 2 profitable after a shorter period of time.

Especially for the cost estimates, it is a difficult task to predict the future. Figure 5.2 illustrates the price trends for LiBs, and the price of the battery technology might change significantly in the next 10 years. This might change both in capacity and price. This is also a field that has seen tremendous changes in the past few years. The prices do show signs of stagnating, but are still decreasing. This gives a clue that a lot might change in the next few years as well and makes it even harder to estimate an exact price of the battery.

The price for the designed battery system in Scenario 1 and 2 is only based on one source for a given model. This means that some uncertainties follow for the total costs for the battery system. Since the cost of the battery is based on STS' previous projects and their estimated price range for one system, it is possible that the price could differ from the actual price when realizing such a system. In addition to the potential source of error of the costs, it is also reasonable to think that there are other models from different suppliers with other prices. These may have been cheaper, and would make an impact on the total cost of the battery system.

The recycling industry for batteries has been lagging for a long time, but now there are solutions to handle a battery after end service life. In the future this will probably be more extended. The financial analysis has not included what happens after end-of-life for the battery system. If this was included, the battery either could have been sold to a third party for recycling, which could re-purpose the materials. This would make an impact on the profitability of the battery system. Or, the battery could be delivered to recycling either for free or at a cost.

Table 5.4 shows how long it takes before the investments made for the battery system becomes profitable. For Scenario 1, the payment period is 17,34 years and for Scenario 2, the payment period is 4,86 years. In these calculations, the earnings each year are identical for all the years after the installation, and no other maintenance cost is included. This might not be the case as the variables will change in the future. The fact that the payback time on the battery in Scenario 1 is longer than the assumed life of the battery means that this is not a profitable investment with the given assumptions.

The payback time for Scenario 2, on the other hand, is under 5 years and is a better investment than Scenario 1. This is mostly due to the fact that 10 times more energy is consumed in Scenario 2, and the calculations are only based on money earned from sold energy. The calculations also include profit on the energy that does not go through the battery.

There has not been done any calculations about the annual profit if the energy was imported and then sold to the user for 2,5 NOK/kWh, without any PV production or battery storage. This is the case for Ohmia charging's business case, but it includes other costs that Ohmia has, such as investment, maintenance and costumer support.

6.4.3 Financial aspects of PV and batteries combined

A summary of the financial aspects of the combined PV and battery system is shown in Table 5.5. It illustrates the investment costs, earnings each year and the payment period of making the total system profitable. These values are dependent on several assumptions and estimations.

The electricity produced in Norway is renewable and mostly consists of hydro power, and the production of this can vary a lot due to its weather dependence. Norway's power grid is connected with the power grid in other European countries, and the prices in Europe will to some extent affect the prices in Norway. The demand of electricity will also influence the electricity price. These factors makes it difficult to estimate the electricity price in the future [89]. This will affect the amount of money saved from the production of solar power.

As mentioned for the financial aspects of the PV system, the electricity prices used in the calculations in PV*SOL are based on average values in the period 2017-2021. The same applies to the estimated costs for the imported electricity from the grid in the scenarios. The annual income of sold electricity is highly dependent on the amount of imported electricity and the cost of it. This means that the financial aspect of the total system might be different in the future depending on the grid electricity price. Additionally, the annual income in the scenarios is deeply dependent on the amount of users and the size of the system. In Scenario 2, the annual income is much higher than in Scenario 1 and this is precisely for that reason. A big part of the income is due to increased sales of imported electricity, which brings a lot of income without increasing the size and cost of the system, as all of the electricity used for EV charging gives an income.

As for the income of the system, the price and amount of sold electricity constitutes the main source of income. The price Ohmia takes for charging is 2,5 NOK/kWh, and this is the same price used in the calculations. When discussing the price per kWh charged, it should be mentioned that Ohmia does not require any start-up fee for the charging subscription and installation of a charger. If there was a fee to subscribe and to get the charger installed, the price of the electricity sold to the consumer could perhaps be decreased. This could make their electricity prices lower, but would probably be more beneficial for the consumers than the service provider. The desired outcome for the service provider is to make the system become profitable in a shorter period of time. To reach that goal, the annual income is a factor that would have to increase. In relation to this, another aspect that could increase the annual income is if the price of sold electricity could rise because the consumers consider it worth paying more for in-house production of renewable energy.

The system shown in Figure 5.1 has two inverters. A hybrid inverter which can do the same tasks as both the current inverters could potentially be a better match for the system. This could also make the system cheaper, as the system then would require only one inverter.

For both of the scenarios within a combined system, and especially for Scenario 2, the power based tariff will influence the total price of the system. Since this tariff is based on pricing the electricity provider charges from the moment of highest load on the grid, it may be an advantage to store in-house produced electricity in batteries. Storing the energy and delaying/decreasing the required amount of electricity consumed will impact the tariff and then affect the total price of imported electricity from the grid. This will also effect the profitability of the total system if the tariff cost gets decreased.

6.4.4 Subsidies

To invest in a combined PV and battery system can turn out to require a high investment cost. For the majority, this is a significant reason to not invest in such a system. Due to this, there are several agencies/authorities that provide subsidies to invest in systems like this for private installations. As mentioned in the Introduction, Enova is an example of such an agency that contributes to big or small projects, and has focus on innovation and technological development.

Also, due to goals about renewable and sustainable solutions, the Norwegian authorities may be willing to subsidise projects and investments like this even more in the future, including those for commercial buildings. If the cost calculations could include subsidies, it would have an impact on the total cost of the system. Potential subsidies could contribute to decreased investment costs, which also would lead to the system becoming profitable in a shorter period of time. The assumption was made that subsidies were not relevant for the system that could be built in this case. But, like with so many other things, this can change in the future.

7 Conclusion

The goal of this thesis was to explore what an in-house renewable energy production and storage system could look like for an apartment complex in Trondheim, and how this might function. This analysis has been conducted based on a number of simplifications and assumptions, which can make the results less accurate.

The results from the simulated PV systems in PV*SOL showed some different performances, but also many similarities. Both of the systems could only cover up to approximately 8 % of the annual energy consumption in OFV1. This was one of the main reasons for looking into a battery system to utilize the generated solar energy even better. The S system had a higher energy production per kWp of installed capacity, but the EW system had the highest annual energy production. For both the performance ratio and the shading losses of the two systems, the EW system turned out to be better. When the production from the EW system is higher, this would also lead to better relieve of the grid than with the S system.

As for the financial aspects of the two systems, they turn out to be quite similar. The S system ends up with a small negative cash balance of 3908 NOK at the estimated end of life in year 30, and the EW system ends up with a positive cash balance of 38 960 NOK. The EW system has a higher investment cost, but will in return give a higher annual positive cash flow, so this will be more beneficial if the system turns out to last more than 30 years. All over, the results indicated that the EW system was the most optimal PV system for OFV1. Therefore, the EW system laid the basis for the battery system calculations.

The uncertainties about the future are significant, and installing any of these PV systems does not seem like a good investment decision, if making a large profit is the motivation. In fact, it is uncertain if the location is suitable for a PV system at all.

Data from “Risvollan borettslag” was used, along with assumptions regarding EV charging. These estimates are most likely not sufficient information to build a real case on, but it gave the opportunity to consider how a battery bank could function in a fictitious situation. The lifetime of the battery system is assumed to be shorter than the lifetime of the PV system. In a real scenario, both the PV production and the EV consumption will vary from day to day, and result in different use of the battery.

On the other hand, the battery system contributes to other useful consequences that can have value in a different sense than money for the user. This includes peak shaving and storing of surplus solar energy, which will reduce the grid load, and therefore also contribute to reducing the need for upgrading the power grid. The battery can also give the EVs a higher charging speed, and in case of a power outage, the battery has the potential to give energy to the building and EVs.

The proposed battery system also results in several other valuable aspects. The battery solution is especially good for utilizing the generated solar electricity, in that the demand and production do not directly correspond to each other. The results indicate that Scenario 2 is more profitable than Scenario 1, because Scenario 2 has a large income from importing cheap electricity and selling it at a higher price.

As of today, neither of the system options appear to be a solid financial investment. However, they will contribute to more renewable energy production that again can push in the right direction in order to reach the goals for sustainable development. Development in technology that reduces the price for systems like this will make it more favorable for consumers. How much time it will take before this evolution has come far enough, or if it ever will come far enough, is a difficult fact to predict.

To conclude, the total system has its shortcomings, and will financially not be a project one would likely want to carry out. However, the hopes are that the analysis can bring insight, inspiration and benefits for a potential real case system.

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Appendix A

Equations used for economic calculations for batteries

Scenario 1

Consumers electricity price without VAT. Earnings per charged kWh for the owners:

$$2,5NOK/kWh \cdot (1 - 0,25) = 1,875NOK/kWh$$

Income from consumed electricity during one day:

$$59,94kWh \cdot 1,875NOK/kWh = 112,39NOK$$

Total income during the months March to September:

$$\begin{aligned}(112,388NOK \cdot 31days) \cdot 4months \\ +(112,388NOK \cdot 30days) \cdot 3months \\ = 24051,03NOK\end{aligned}$$

Total generated solar energy in the months October to February:

$$1307,5kWh + 134,3kWh + 12,6kWh + 18,2kWh + 443,2kWh = 1915,8kWh$$

Expected income for generated solar energy in the period October to February:

$$1915,8kWh \cdot 1,875NOK/kWh = 3592,13NOK$$

Amount of necessary energy to import from the grid in the period October to February:

$$\begin{aligned}(59,94kWh \cdot 31days - 1307,5kWh) \\ +(59,94kWh \cdot 30days - 134,3kWh) \\ +(59,94kWh \cdot 31days - 12,6kWh) \\ +(59,94kWh \cdot 31days - 18,2kWh) \\ +(59,94kWh \cdot 28days - 443,2kWh) \\ = 7135,14kWh\end{aligned}$$

Income from imported electricity in the period October to February:

$$7135,14kWh \cdot 1,875NOK/kwh = 13378,39NOK$$

Total price for imported electricity from the grid in period October to February:

$$7135,14kWh \cdot 0,8253NOK/kWh = 5888,6NOK$$

Total income from imported electricity:

$$13378,39NOK - 5888,6NOK = 7489,79NOK$$

Income of the generated solar energy for EV charging during one year:

$$24051,032NOK + 3592,13NOK = 27643,45NOK$$

Income from imported electricity and generated solar energy for EV charging during one year:

$$27643,45NOK + 7489,79NOK = 35133,24NOK$$

Monthly income from the surplus electricity sold to OFV1:

$$\begin{aligned}
(3112,4 - (59,94 * 30))kWh \cdot 0,7213NOK/kWh &= 904,77NOK\\
(5527,3 - (59,94 * 31))kWh \cdot 0,7763NOK/kWh &= 2894,76NOK\\
(8190,9 - (59,94 * 31))kWh \cdot 0,7979NOK/kWh &= 5052,76NOK\\
(8629,7 - (59,94 * 30))kWh \cdot 0,7633NOK/kWh &= 5214,49NOK\\
(8390,3 - (59,94 * 31))kWh \cdot 0,8277NOK/kWh &= 5406,89NOK\\
(6071,7 - (59,94 * 31))kWh \cdot 0,8817NOK/kWh &= 3715,12NOK\\
(3167,7 - (59,94 * 30))kWh \cdot 0,8753NOK/kWh &= 1198,78NOK
\end{aligned}$$

Total income from the surplus electricity sold to OFV1 during one year:

$$\begin{aligned}
&(904,77 + 2894,76 + 5052,76 + 5214,49 + 5406,89\\
&\quad +3715,12 + 1198,78)NOK = 24387,58NOK
\end{aligned}$$

Total income during one year for Scenario 1:

$$35133,24NOK + 24387,58NOK = 59520,82NOK$$

Scenario 2

Total amount of generated solar energy during one year:

$$\begin{aligned}
&(18,2 + 443,2 + 3112,4\\
&+5527,3 + 8190,9 + 8629,7\\
&+8390,3 + 6071,7 + 3167,7\\
&+1307,5 + 134,3 + 12,6)kWh\\
&= 45005,8kWh
\end{aligned}$$

Income from solar production during one year:

$$1,875 NOK/kWh \cdot 45005,8 kWh = 84385,88 NOK$$

Amount of required electricity during one day:

$$6,66 kWh \cdot 90 cars = 599,4 kWh$$

Amount of required electricity during one year:

$$599,4 kWh \cdot 365 days = 218781 kWh$$

Amount of required electricity to import from the grid:

$$218781 kWh - 45005,8 kWh = 173775,2 kWh$$

Price for imported electricity from the grid:

$$173775,2 kWh \cdot 0,8142 NOK/kWh = 141487,77 NOK$$

Income from imported electricity in one year:

$$1,875 NOK/kWh \cdot 173775,2 kWh = 325828,5 NOK$$

Income from imported electricity without price for imported electricity from the grid:

$$325828,5 NOK - 141487,77 NOK = 184340,73 NOK$$

Total income during one year:

$$84385,875 NOK + 184340,73 NOK = 268726,61 NOK$$

Cost for the total system

Battery system for Scenario 1 including EW PV system:

$$951160 NOK + 1031800 NOK = 1982960 NOK$$

Battery system for Scenario 2 including EW PV system:

$$951160 NOK + 1305179 NOK = 2256339 NOK$$

Appendix B

Table 7.1: Energy calculations of PV production and consumption in Scenario 2 for EW system

Time after midnight	**EV consumption Scenario 2 [kW]**	**PV production [kW]**	**EV consumption Scenario 2 [kW] - PV production [kW]**	**Power imported [kW]**	**Surplus power [kW]**
1	20,692	0	20,692	20,692	0
2	13,215	0	13,215	13,215	0
3	9,260	0	9,260	9,260	0
4	5,615	0	5,615	5,615	0
5	3,107	0,658	2,449	2,449	0
6	2,113	1,316	0,797	0,797	0
7	2,542	6,448	-3,906	0	3,906
8	5,844	12,765	-6,921	0	6,921
9	6,613	19,740	-13,126	0	13,126
10	6,988	25,793	-18,805	0	18,805
11	8,664	29,609	-20,945	0	20,945
12	11,656	30,596	-18,940	0	18,940
13	14,590	30,925	-16,336	0	16,336
14	20,502	30,267	-9,765	0	9,765
15	32,968	28,096	4,872	4,872	0
16	50,595	24,345	26,250	26,250	0
17	54,178	20,134	34,044	34,044	0
18	51,420	14,476	36,944	36,944	0
19	52,867	8,883	43,984	43,984	0
20	56,693	3,948	52,745	52,745	0
21	52,749	0	52,749	52,749	0
22	47,662	0	47,662	47,662	0
23	38,754	0	38,754	38,754	0
24	29,932	0	29,932	29,932	0
SUM	599,220 kWh	288,000 kWh	311,220 kWh	419,964 kWh	108,745 kWh

Appendix C

Table 7.2: Rounded prices for the electricity price per hour for each month given in NOK/kWh

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Jan	0,75	0,75	0,75	0,75	0,75	0,77	0,77	0,81	0,83	0,83	0,85	0,83	0,83	0,83	0,83	0,83	0,85	0,85	0,83	0,83	0,81	0,79	0,79	0,77
Feb	0,73	0,71	0,71	0,71	0,73	0,73	0,75	0,79	0,83	0,81	0,81	0,79	0,77	0,77	0,77	0,77	0,79	0,81	0,81	0,79	0,77	0,75	0,75	0,73
Mar	0,71	0,71	0,71	0,71	0,71	0,71	0,71	0,75	0,79	0,77	0,75	0,75	0,73	0,73	0,71	0,71	0,71	0,73	0,75	0,75	0,73	0,71	0,71	0,71
Apr	0,75	0,75	0,75	0,75	0,75	0,75	0,77	0,81	0,83	0,81	0,81	0,79	0,79	0,77	0,77	0,77	0,77	0,77	0,79	0,79	0,79	0,79	0,77	0,75
May	0,77	0,75	0,73	0,73	0,73	0,75	0,79	0,83	0,85	0,85	0,83	0,83	0,83	0,81	0,79	0,79	0,79	0,81	0,83	0,83	0,83	0,81	0,81	0,77
Jun	0,73	0,73	0,71	0,71	0,71	0,73	0,75	0,79	0,79	0,81	0,79	0,79	0,79	0,79	0,77	0,77	0,77	0,77	0,79	0,79	0,77	0,77	0,77	0,73
Jul	0,83	0,83	0,81	0,79	0,79	0,81	0,81	0,83	0,85	0,85	0,85	0,85	0,83	0,83	0,83	0,83	0,83	0,83	0,85	0,85	0,83	0,83	0,83	0,83
Aug	0,85	0,85	0,83	0,83	0,83	0,85	0,87	0,89	0,91	0,91	0,91	0,91	0,89	0,89	0,89	0,89	0,89	0,91	0,91	0,91	0,91	0,89	0,89	0,87
Sep	0,83	0,83	0,81	0,81	0,83	0,85	0,87	0,89	0,91	0,91	0,91	0,91	0,89	0,89	0,89	0,89	0,89	0,89	0,89	0,91	0,89	0,89	0,87	0,85
Oct	0,75	0,73	0,73	0,73	0,75	0,77	0,79	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,81	0,83	0,83	0,81	0,81	0,79	0,77
Nov	0,79	0,79	0,77	0,77	0,79	0,81	0,83	0,87	0,89	0,89	0,89	0,87	0,89	0,89	0,89	0,91	0,91	0,91	0,89	0,87	0,85	0,83	0,83	0,79
Des	0,87	0,85	0,85	0,85	0,85	0,87	0,89	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,91	0,89	0,89	0,87

Appendix D

Table 7.3: Total energy consumption for OFV1 in 2021, S PV production, direct own use of S PV energy and energy export each month

	Energy consumption OFV1 [kWh]	**S PV production [kWh]**	**Direct own use [kWh]**	**Grid feed-in [kWh]**
Jan	80944	39,6	39,6	0
Feb	69143,8	645	645	0
Mar	56471,5	3536,3	3536,3	0
Apr	50506,6	5310,7	5310,7	0
May	35075,8	6558,7	6507	51,7
Jun	26644,9	6367,6	6367,6	0
Jul	24119,6	6318,9	6318,9	0
Aug	26188,7	5029,7	5029,7	0
Sep	29094,5	3111,9	3111,9	0
Oct	39574,3	1391,6	1391,6	0
Nov	56547,5	198,3	198,3	0
Dec	67949,8	6,3	6,3	0
SUM	562261	38514,6	38462,9	51,7

Table 7.4: Total energy consumption for OFV1 in 2021, EW PV production, direct own use of PV energy and energy export each month

	Energy consumption OFV1 [kWh]	**EW PV production [kWh]**	**Direct own use [kWh]**	**Grid feed-in [kWh]**
Jan	80944	18,2	18,2	0
Feb	69143,8	443,2	443,2	0
Mar	56471,5	3112,4	3112,4	0
Apr	50506,6	5527,3	5527,3	0
May	35075,8	8190,9	8063,8	127,1
Jun	26644,9	8629,7	8502,6	127,1
Jul	24119,6	8390,3	8042,1	348,2
Aug	26188,7	6071,7	6064,4	7,3
Sep	29094,5	3167,7	3167,7	0
Oct	39574,3	1307,5	1307,5	0
Nov	56547,5	134,3	134,3	0
Dec	67949,8	12,6	12,6	0
SUM	562261	45005,8	44396,1	609,7

Appendix E

Peak shaving in Scenario 2 with 150 kWh battery and PV production. Describing Figure 5.6 and data in Table 7.5.

To maximize the peak shaving, the full capacity of the 150 kWh battery is used. This must be fully charged when going into hour 16. This means that the battery has to charge when the consumption is low, which is between hour 5-14. The PV system provides 108,745 kWh of surplus energy, and the last 41,255 kWh has to be imported from the grid. Since hours 5 and 6 import some energy, this will be included. So the average energy that will have to be imported over the 10 hours is $\frac{(41{,}255kWh+2{,}449kWh+0{,}797kWh)}{10h} = 44,501kW$. Then 150 kWh can be distributed over the 9 hours with the highest estimated import, which are hours 16-24. This results in an average output from the battery at $\frac{150kWh}{9h} = 16,66kW$. The average consumption over the same 9 hours is 40,340 kWh, so the average import over these 9 hours will be approximately $40,34kW - 16,66kW = 23,68kW$, as shown in Table 7.5.

Peak shaving Scenario 2 with 150 kWh battery and without PV production. Describing Figure 5.7 and data in Table 7.6.

For Scenario 2, when no PV energy is produced, the initial import of energy is equal to the consumption. When having the same 150 kWh battery, this has to be fully charged when going out of hour 15. To do so, all the energy must be imported from the grid, as no PV energy is available. The hours with the lowest consumption are hours 2-13. The average consumption over these hours is 7,517 kW. To charge 150 kWh over 12 hours, the average charging speed must be $\frac{150kWh}{12h} = 12,5kW$. The average energy import is therefore $7,517kW + 12,5kW = 20,017kW$. The battery is then fully charged and the 150 kWh can be distributed over the 9 hours with the highest estimated import, which are hours 15-23. The average consumption over these hours is 48,654 kW, and the average output from the battery is at $\frac{150kWh}{9h} = 16,667kW$. The import from hours 15-23 is therefore $48,654kW - 16,667kW = 31,987kW$, which is shown in Table 7.6

Peak shaving Scenario 2 with optimal battery capacity and with PV production. Describing Figure 5.8 and Table 7.7.

The optimal level of power peak shaving would be to have a constant import of electricity every hour during the day. For Scenario 2 with an average PV production for June, that constant import will be $\frac{(419{,}964kWh-108{,}748kWh}{24h} = 12,967kW$. The battery capacity must then equal 246,233 kWh, as shown in Table 7.7.

Table 7.5: Imported energy for Scenario 2 with average solar production for June. 150 kWh battery is applied with the purpose of maximum power peak shaving

Time after midnight	Consumption [kW]	EW PV prod [kW]	Import of energy without battery [kW]	Surplus energy [kW]	Battery energy [kWh]	Import with battery [kW]
1	20,692	0,000	20,692	0,000	0,000	20,692
2	13,215	0,000	13,215	0,000	0,000	13,215
3	9,260	0,000	9,260	0,000	0,000	9,260
4	5,615	0,000	5,615	0,000	0,000	5,615
5	3,107	0,658	2,449	0,000	2,001	4,450
6	2,113	1,316	0,797	0,000	5,654	4,450
7	2,542	6,448	0,000	3,906	14,010	4,450
8	5,844	12,765	0,000	6,921	25,381	4,450
9	6,613	19,740	0,000	13,126	42,958	4,450
10	6,988	25,793	0,000	18,805	66,213	4,450
11	8,664	29,609	0,000	20,945	91,608	4,450
12	11,656	30,596	0,000	18,940	114,999	4,450
13	14,590	30,925	0,000	16,336	135,784	4,450
14	20,502	30,267	0,000	9,765	150,000	4,450
15	32,968	28,096	4,872	0,000	150,000	4,872
16	50,595	24,345	26,250	0,000	147,424	23,674
17	54,178	20,134	34,044	0,000	137,053	23,674
18	51,420	14,476	36,944	0,000	123,783	23,674
19	52,867	8,883	43,984	0,000	103,472	23,674
20	56,693	3,948	52,745	0,000	74,401	23,674
21	52,749	0,000	52,749	0,000	45,327	23,674
22	47,662	0,000	47,662	0,000	21,339	23,674
23	38,754	0,000	38,754	0,000	6,258	23,674
24	29,932	0,000	29,932	0,000	0,000	23,674
SUM	**599,220 kWh**	**288,000 kWh**	**419,964 kWh**	**108,745 kWh**		**311,220 kWh**

Table 7.6: Imported energy for Scenario 2 when no PV energy is produced. 150 kWh battery is applied with the purpose of maximum power peak shaving.

Time after midnight	**Consumption [kW]**	**Battery energy [kWh]**	**Import with battery [kW]**
1	20,692	0	20,692
2	13,215	6,802	20,017
3	9,260	17,559	20,017
4	5,615	31,961	20,017
5	3,107	48,871	20,017
6	2,113	66,776	20,017
7	2,542	84,251	20,017
8	5,844	98,424	20,017
9	6,613	111,828	20,017
10	6,988	124,858	20,017
11	8,664	136,211	20,017
12	11,656	144,572	20,017
13	14,590	150,000	20,017
14	20,502	150,000	20,502
15	32,968	149,020	31,987
16	50,595	130,412	31,987
17	54,178	108,221	31,987
18	51,420	88,788	31,987
19	52,867	67,908	31,987
20	56,693	43,203	31,987
21	52,749	22,442	31,987
22	47,662	6,767	31,987
23	38,754	0,000	31,987
24	29,932	0,000	29,932
SUM	**599,220 kWh**		**599,220 kWh**

Table 7.7: Optimal battery for peak shaving Scenario 2 with solar energy. The import load can be constant during the whole day.

Time after midnight	**Consumption [kW]**	**EW PV prod [kW]**	**Import of energy with sun [kW]**	**Surplus energy [kW]**	**Battery energy [kWh]**	**Import for peak shaving [kW]**
1	20,692	0,000	20,692	0,000	0,248	12,967
2	13,215	0,000	13,215	0,000	0,000	12,967
3	9,260	0,000	9,260	0,000	3,707	12,967
4	5,615	0,000	5,615	0,000	11,060	12,967
5	3,107	0,658	2,449	0,000	21,578	12,967
6	2,113	1,316	0,797	0,000	33,749	12,967
7	2,542	6,448	0,000	3,906	50,622	12,967
8	5,844	12,765	0,000	6,921	70,510	12,967
9	6,613	19,740	0,000	13,126	96,604	12,967
10	6,988	25,793	0,000	18,805	128,377	12,967
11	8,664	29,609	0,000	20,945	162,290	12,967
12	11,656	30,596	0,000	18,940	194,197	12,967
13	14,590	30,925	0,000	16,336	223,500	12,967
14	20,502	30,267	0,000	9,765	246,233	12,967
15	32,968	28,096	4,872	0,000	254,329	12,967
16	50,595	24,345	26,250	0,000	241,047	12,967
17	54,178	20,134	34,044	0,000	219,970	12,967
18	51,420	14,476	36,944	0,000	195,993	12,967
19	52,867	8,883	43,984	0,000	164,977	12,967
20	56,693	3,948	52,745	0,000	125,199	12,967
21	52,749	0,000	52,749	0,000	85,418	12,967
22	47,662	0,000	47,662	0,000	50,724	12,967
23	38,754	0,000	38,754	0,000	24,937	12,967
24	29,932	0,000	29,932	0,000	7,973	12,967
SUM	**599,220 kWh**	**288,000 kWh**	**419,964 kWh**	**108,745 kWh**		**311,220 kWh**

Appendix F

Table 7.8: Annual cash flow for S PV system.

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Investments	-kr 852 805,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 112,25	kr 109,46	kr 106,74	kr 104,08	kr 101,48
Electricity Savings	kr 30 561,21	kr 30 426,53	kr 30 262,93	kr 30 099,34	kr 29 935,74
Annual Cash Flow	-kr 822 131,54	kr 30 535,99	kr 30 369,67	kr 30 203,42	kr 30 037,23
Accrued Cash Flow (Cash Balance)	**-kr 822 131,54**	**-kr 791 595,55**	**-kr 761 225,88**	**-kr 731 022,46**	**-kr 700 985,24**
	Year 6	**Year 7**	**Year 8**	**Year 9**	**Year 10**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 98,95	kr 96,48	kr 94,06	kr 91,71	kr 89,41
Electricity Savings	kr 29 772,16	kr 29 608,55	kr 29 444,97	kr 29 281,36	kr 29 117,79
Annual Cash Flow	kr 29 871,11	kr 29 705,03	kr 29 539,04	kr 29 373,07	kr 29 207,20
Accrued Cash Flow (Cash Balance)	**-kr 671 114,13**	**-kr 641 409,10**	**-kr 611 870,07**	**-kr 582 497,00**	**-kr 553 289,80**
	Year 11	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 87,16	kr 84,97	kr 82,83	kr 80,74	kr 78,70
Electricity Savings	kr 28 954,17	kr 28 790,58	kr 28 627,00	kr 28 463,41	kr 28 299,82
Annual Cash Flow	kr 29 041,34	kr 28 875,55	kr 28 709,83	kr 28 544,15	kr 28 378,52
Accrued Cash Flow (Cash Balance)	**-kr 524 248,47**	**-kr 495 372,91**	**-kr 466 663,08**	**-kr 438 118,93**	**-kr 409 740,41**
	Year 16	**Year 17**	**Year 18**	**Year 19**	**Year 20**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 76,71	kr 74,77	kr 72,88	kr 71,03	kr 69,22
Electricity Savings	kr 28 136,21	kr 27 972,63	kr 27 809,02	kr 27 645,43	kr 27 481,84
Annual Cash Flow	kr 28 212,93	kr 28 047,40	kr 27 881,90	kr 27 716,46	kr 27 551,06
Accrued Cash Flow (Cash Balance)	**-kr 381 527,48**	**-kr 353 480,08**	**-kr 325 598,18**	**-kr 297 881,72**	**-kr 270 330,65**
	Year 21	**Year 22**	**Year 23**	**Year 24**	**Year 25**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 67,46	kr 65,75	kr 64,07	kr 62,43	kr 60,83
Electricity Savings	kr 27 318,24	kr 27 154,65	kr 26 991,07	kr 26 827,46	kr 26 663,87
Annual Cash Flow	kr 27 385,71	kr 27 220,40	kr 27 055,14	kr 26 889,90	kr 26 724,71
Accrued Cash Flow (Cash Balance)	**-kr 242 944,94**	**-kr 215 724,55**	**-kr 188 669,41**	**-kr 161 779,52**	**-kr 135 054,81**
	Year 26	**Year 27**	**Year 28**	**Year 29**	**Year 30**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 59,28	kr 57,75	kr 56,27	kr 54,82	kr 53,41
Electricity Savings	kr 26 500,28	kr 26 336,69	kr 26 173,09	kr 26 009,50	kr 25 845,91
Annual Cash Flow	kr 26 559,56	kr 26 394,44	kr 26 229,36	kr 26 064,32	kr 25 899,32
Accrued Cash Flow (Cash Balance)	**-kr 108 495,25**	**-kr 82 100,81**	**-kr 55 871,46**	**-kr 29 807,13**	**-kr 3 907,81**

Table 7.9: Annual cash flow for EW PV system.

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Investments	-kr 951 160,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 188,46	kr 183,77	kr 179,20	kr 174,74	kr 170,38
Electricity Savings	kr 35 621,36	kr 35 443,70	kr 35 253,12	kr 35 062,55	kr 34 871,97
Annual Cash Flow	-kr 915 350,18	kr 35 627,47	kr 35 432,32	kr 35 237,28	kr 35 042,35
Accrued Cash Flow (Cash Balance)	**-kr 915 350,18**	**-kr 879 722,72**	**-kr 844 290,39**	**-kr 809 053,11**	**-kr 774 010,76**
	Year 6	**Year 7**	**Year 8**	**Year 9**	**Year 10**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 166,13	kr 161,98	kr 157,92	kr 153,97	kr 150,10
Electricity Savings	kr 34 681,40	kr 34 490,81	kr 34 300,26	kr 34 109,66	kr 33 919,11
Annual Cash Flow	kr 34 847,53	kr 34 652,78	kr 34 458,18	kr 34 263,63	kr 34 069,21
Accrued Cash Flow (Cash Balance)	**-kr 739 163,23**	**-kr 704 510,45**	**-kr 670 052,27**	**-kr 635 788,65**	**-kr 601 719,43**
	Year 11	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 146,33	kr 142,65	kr 139,06	kr 135,56	kr 132,14
Electricity Savings	kr 33 728,51	kr 33 537,94	kr 33 347,38	kr 33 156,81	kr 32 966,23
Annual Cash Flow	kr 33 874,84	kr 33 680,59	kr 33 486,44	kr 33 292,36	kr 33 098,36
Accrued Cash Flow (Cash Balance)	**-kr 567 844,59**	**-kr 534 164,00**	**-kr 500 677,56**	**-kr 467 385,19**	**-kr 434 286,83**
	Year 16	**Year 17**	**Year 18**	**Year 19**	**Year 20**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 128,80	kr 125,54	kr 122,36	kr 119,25	kr 116,22
Electricity Savings	kr 32 775,64	kr 32 585,08	kr 32 394,49	kr 32 203,92	kr 32 013,34
Annual Cash Flow	kr 32 904,44	kr 32 710,62	kr 32 516,84	kr 32 323,17	kr 32 129,57
Accrued Cash Flow (Cash Balance)	**-kr 401 382,39**	**-kr 368 671,78**	**-kr 336 154,93**	**-kr 303 831,76**	**-kr 271 702,20**
	Year 21	**Year 22**	**Year 23**	**Year 24**	**Year 25**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 113,26	kr 110,38	kr 107,56	kr 104,82	kr 102,13
Electricity Savings	kr 31 822,76	kr 31 632,19	kr 31 441,63	kr 31 251,04	kr 31 060,47
Annual Cash Flow	kr 31 936,03	kr 31 742,57	kr 31 549,19	kr 31 355,86	kr 31 162,60
Accrued Cash Flow (Cash Balance)	**-kr 239 766,17**	**-kr 208 023,60**	**-kr 176 474,41**	**-kr 145 118,55**	**-kr 113 955,95**
	Year 26	**Year 27**	**Year 28**	**Year 29**	**Year 30**
Investments	kr 0,00	kr 0,00	kr 0,00	kr 0,00	kr 0,00
Feed-in / Export Tariff	kr 99,52	kr 96,96	kr 94,47	kr 92,04	kr 89,67
Electricity Savings	kr 30 869,90	kr 30 679,32	kr 30 488,74	kr 30 298,17	kr 30 107,60
Annual Cash Flow	kr 30 969,42	kr 30 776,28	kr 30 583,21	kr 30 390,21	kr 30 197,27
Accrued Cash Flow (Cash Balance)	**-kr 82 986,53**	**-kr 52 210,25**	**-kr 21 627,04**	**kr 8 763,17**	**kr 38 960,45**

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