Marit Bratlie, Iselin Ørbek Eide and Zeineb Moter

Solar Powered Sport Arenas Incorporated Into Residential Areas

The Case Study of Skagerak Arena in Skien, Norway

Bachelor's thesis in Engineering, Renewable Energy
Supervisor: Alemayehu Gebremedhin
May 2022

Bachelor's thesis

NTNU
Norwegian University of Science and Technology

NTNU
Kunnskap for en bedre verden

Marit Bratlie, Iselin Ørbek Eide and Zeineb Moter

Solar Powered Sport Arenas Incorporated Into Residential Areas

The Case Study of Skagerak Arena in Skien, Norway

Bachelor's thesis in Engineering, Renewable Energy
Supervisor: Alemayehu Gebremedhin
May 2022

Norwegian University of Science and Technology

NTNU
Kunnskap for en bedre verden

TITLE :			
Solar Powered Sport Arenas Incorporated Into Residential Areas			
DATE:	**CODE:**	**GROUP:**	**PAGES/APPENDIX:**
20.05.2022	FENG2900	1	57/xxvi
CANDIDATES:			
Marit Bratlie, Iselin Ørbek Eide and Zeineb Shaker Moter			
SUPERVISOR:			
Alemayehu Gebremedhin			
EXTERNAL CONTACTS AND SUPERVISORS:			
Signe Marie Oland and Øystein Øvrum			

Preface

This thesis was carried out during the spring semester of 2022 and is concluding for our Bachelor's degree in Engineering, Renewable Energy at the Norwegian University of Science and Technology (NTNU).

The research is an outcome of our cooperation with the Norwegian energy companies Lede AS and Skagerak Energi AS. The main data has been dependent on the company's joint venture of Skagerak Energy Lab, and their skill to collect it. We would like to give special thanks to the representatives in Skagerak Energy Lab, Signe Marie Oland and Øystein Øvrum, for their benevolent priority of time and resources to give us great guidance. The sharing of the pertinent data and other details has made the results of this thesis applicable. Staff at the NTNU, represented by Ian Nordheim and Fredrik Ege Abrahamsen should also be commended for significant conversations and constructive feedback. We would like to express our deepest gratitude to close family and friends for their support and help. Finally, we would also like to extend our thanks to our supervisor Alemayehu Gebremedhin for his continued guidance and inspiration during the process.

Gjøvik, May 2022

Signatures

Marit Bratlie | Iselin Ørbek Eide | Zeineb Shaker Moter

Abstract

The world is currently experiencing a drastic change in its primary energy sources. In the coming years, solar energy is expected to become one of the most important sources for electricity production in wide parts of the world. This will have a positive impact on the energy challenges and the climate crisis the world is facing. This study aims to determine how solar energy can be incorporated into residential areas. Specifically, it investigates three different scenarios regarding the photovoltaic facilities at Skagerak Arena located in Norway.

Raw data on the consumption and production was provided by Skagerak Energy Lab. The data was organised in vectors and matrices that were further analysed and compared in the software Matlab. The calculations were further based on the specifications of the PV system, with 2 700 solar panels and a battery capacity of 1 000 kWh.

The first two scenarios addressed the existing system under off-grid conditions. Annual consumption and production data for seven different user groups were analysed. Typical findings indicated a skewed distribution of consumption and production. One of the customer groups could barely manage the demand during wintertime, but had an excess electricity production of around 3 000% in the summer. Other findings referred to periods where one of the other consumer groups failed to meet the need with the existing system.

The last scenario dealt with economic and environmental aspects when the system was connected to the electric grid. Estimates based on 190 panels gave a total system price of 1 381 000 NOK with corresponding emissions of 27 g $CO_2\ eq/kWh$. The system was able to provide approximately 50% of the annual electricity demand for the apartment complex in question.

These results suggest that the best solution for utilising solar energy in Nordic conditions, is to connect the system to the electricity grid. Off-grid, under such conditions, requires huge amounts of energy storage which either requires too much space or becomes too expensive to generate economic profit. The calculated emissions were somewhat higher than the Norwegian energy mix, but still much lower than the European energy mix. With this, photovoltaic systems have a great potential to be sustainable under Norwegian conditions.

Sammendrag

Verdens energisektor er i drastisk forandring. I årene fremover forventes det at solenergi vil bli en av de viktigste kildene til strømforsyning i store deler av verden. Dette vil ha en positiv innvirkning på energi- og klimautfordringene verden står ovenfor. Denne studien tar sikte på å undersøke hvordan solceller kan integreres i etablerte boligområder. Konkret tar den for seg tre ulike scenarioer basert på solcelleanlegget til Skagerak Arena i Norge.

Rådata for forbruk og produksjon ble levert av Skagerak Energilab. Dataen var organisert i vektorer og matriser som videre ble sammenliknet og analysert i programvaren Matlab. Videre baserte beregningene seg på spesifikasjonene til solcelleanlegget, med 2 700 paneler og ett batteri på 1 000 kWh.

De to første scenarioene tok for seg det eksisterende anlegget uten tilkobling til det regionale strømnettet. Her ble årlig forbruk- og produksjonsdata for syv ulike brukergrupper analysert. Funnene indikerte en skjevfordeling mellom forbruk og produksjon. En av brukergruppene får så vidt dekket sitt behov om vinteren, men har en overproduksjon om sommeren, på 3 000%. To av brukergruppene får ikke dekt energibehovet sitt fra Skagerak Arena deler av året, når anlegget ikke er koblet til strømnettet.

Det tredje scenarioet tok for seg det økonomiske og miljømessige aspektet ved et solcelleanlegg som er knyttet til strømnettet. Estimatet baserte seg på 190 solcellepaneler med en total systempris på 1 381 000 NOK og utslipp på 27 g CO_2eq/kWh. Systemet var kapabelt til å forsyne 50 % av det årlige elektrisitetsforbruket til leilighetskomplekset scenarioet sentrerte seg rundt.

Resultatene tydet på at den beste løsningen for å utnytte solenergi i nordiske forhold, er å koble systemet til strømnettet. Uten tilknytning til strømnettet kreves det meget store mengder energilagring, som enten tar for mye plass eller blir for dyrt å finansiere. De beregnede utslippene var noe høyere enn den norske energimiksen, men likevel mye lavere enn den europeiske energimiksen. Solceller har med dette et stort potensial for å være bærekraftig under norske forhold.

Contents

List of Figures

List of Tables

List of Abbreviations

AC Alternating current

ADE Azure Data Explorer

API Application Programming Interface

DC Direct Current

DSO Distribution System Operator

IEA International Energy Agency

kW kilowatt

kWh kilowatt-hour

LHS Latent heat storage

LCA Life cycle assessment

NPV Net Present Value

NTNU Norwegian University of Science and Technology

PV Photovoltaics

SAPS Stand-alone Power System

SDGs Sustainable Development Goals

SHS Sensible heat storage

STC Standard Test Conditions

STE Solar Thermal Energy

TCS Thermo-chemical heat storage

UN United Nations

List of Symbols

I_{MPP} Nominal power current

I_{SC} Short circuit current

i Discount rate

P_{MPP} Nominal Power

t Timer periods

V_{MPP} Nominal power voltage

V_{OC} Open circuit voltage

z Maintenance percentage

List of Definitions

Azimuth Orientation The angle along with the horizon coordinates in relation to the sun [1].

Energy mix The term energy mix refers to the mixture of different combinations of energy sources used to meet the energy demand in a region. Energy mix can also be used when referring to the production of a specific energy type such as electricity.

Exotherm Exotherm refers to a compound that releases heat during its formation and absorbs heat while breaking down.

Irradiance Irradiance is the amount of light energy emitted from a source that hits a square meter of a surface area each second [2].

Isothermal An isothermal process is a process that remains at a constant temperature.

Nominal Power Nominal power (P_{MPP}) is the maximum effect a photovoltaic (PV) device can achieve. The nominal power is determined by measuring the electrical current and voltage in a circuit while varying the resistance under STC conditions.

Nominal Power Current Nominal power current, also called Maximum Power Point Current (I_{MPP}) is the current (amps) when the power output is the greatest [3].

Nominal Power Voltage Nominal Power Voltage, also called maximum power point voltage (V_{MPP}), is the voltage when the power output is the greatest [3].

Off-grid system An off grid system is not connected to the utility grid and is self-reliant in the terms of electricity production.

Open Circuit Voltage Open circuit voltage (I_{OC}) is the maximum voltage the solar panel can produce. The maximum voltage occurs when there is no load on the system. The voltage can be measured by attaching a multi-meter across the open ends of the wires attached to the panel [4].

Panel Efficiency Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. The efficiency is measured under STC and depends on the spectrum and intensity of the incident sunlight. The efficiency will vary depending on the location of the solar panel [5].

Short Circuit Current Short circuit current (I_{SC}) is the current that flows out of the panel when the positive and negative leads are shorted together. The short-circuit current is the highest current the solar panels will produce under STC. The current can be measured by passing the current through a multimeter configured to measure amps [6].

Standard Test Conditions Standard test conditions (STC) are used by manufacturers to define the electrical performance of their photovoltaic panels and modules. By standardising the testing conditions all solar panels can be compared and evaluated despite different testing locations and manufacturing methods. Standard test conditions for a photovoltaic solar panel or module is defined as being 1000 W/m^2 irradiance at a standard ambient temperature of 25° C with a sea-level air mass (AM) of 1.5 [7].

1 Introduction

This section introduces the scope of this thesis and presents the background and motivation for this study. The framework is further developed by the research question, objectives, and scope of this study. To give the reader a well-ordered overview, the work structure and outline are furthermore described.

1.1 Background and Motivation

The world is facing an energy challenge. Rising prices of fossil energy, increased climate crisis, and scarcity of fossil energy resources make renewable energy more relevant than ever [8]. The pandemic of COVID-19 had a dramatic impact on energy supply and demand. As other fuels declined, the demand for renewable energy increased by 3% in 2020 [9]. Photovoltaic (PV) and wind contribute to two-thirds of the renewable growth. A possible explanation might be lower investment costs and improved green policies. The International Renewable Energy Agency published a report that found that the price reduction of PV panels dropped by 82% between 2010-2019 [10]. Solar power is a clean, easily accessible, and inexhaustible source. In line with the world's increasing energy need, solar power will play a significant part in the national and global energy system. In 2050, solar power is expected to account for 38% of the world's energy production [11].

The increase in PV facilities in Norway has not been as outstanding as in other European countries. Since Norway is already established with hydropower plants that provide low electricity prices, solar energy has so far not had equal priority. Norway is connected to the European power market through a cross-border connection. Premonitions for higher electricity prices together with an increased share of renewable energy sources, leads to an uncertain market [12]. There are established photovoltaic systems that further research the possibilities for solar production under Nordic conditions, such as Skagerak Energy Lab. They aim to test how local production, new technology, and energy storage can play well together with the existing utility grid. In 2021, solar power accounted for 186 MW of the electric power in Norway. This corresponds to annual power production of around 0.15 TWh, or 0.1% of the total national power production. By including solar cell facilities not connected to the grid, the total is about 205 MW [13].

Skagerak Energi AS is a Norwegian utility company founded in 2001. Their primary business deals with the distribution and production of electrical power and they have invested large resources in solar energy [14]. The company has innovative goals and great ambitions of optimising the utilisation of renewable sources. This involves improving the existing capacity through power equalisation as well as improving delivery security. In 2016 the process of establishing a research facility for test activities started, and Skagerak Energy Lab was created: A full-scale pilot power plant with local solar production and storage of electrical energy. The photovoltaic system barely managed to obtain normal data before the pandemic of COVID-19 occurred.

A research article on the global changes in electricity demand during COVID-19 shows the pandemic's impact on electricity use [15]. The results revealed the global demand to fall by approximately 10% in April compared to a modelled demand, which accounts for weather, seasonal and temporal effects. The findings further showed a significant variation that can be categorised into four groups, ranging from a mild change of 2% to an extreme decrease of 26%. Individuals, municipalities and national governments changed usage patterns and created a profound impact on electricity usage, due to the mandates caused by the pandemic. Electricity consumption in Norway decreased 4-5 % from 2019, while it increased in 2020 from around 134 TWh to about 140 TWh, a noticeable consumption change [16, 17].

On the basis of the crisis, energy analysts see the opportunity to implement lasting political and structural changes to transform existing energy systems and address the climate crisis [15]. There is further potential to increase the share of solar energy in Norway. If cleaner electricity is produced in Norway, it can replace high emission electricity elsewhere [18].

1.1.1 Sustainability

In the most simplified terms, sustainability refers to the ability to maintain or support a process continuously over time. Sustainability is divided into three main sections: economical, social and environmental. Economical sustainability refers to practices that support long-term economic development and growth of a company or nation without negatively impacting social, environmental, and cultural aspects of the community [19]. Social sustainability is sustainability with humanity as the focus, such as human rights and social justice. Social sustainability centres around equality and distributed opportunities for all. This can be applied both to individuals and to organisations [20].

Environmental sustainability refers to responsible interactions with the environment to avoid depletion or degradation of natural resources. By limiting the use of natural resources and finding ways of living within the ecological limit, there will be little to no depletion of natural resources. Future generations will have the same or better quality of life without damaging the earth's supporting ecosystems [21].

Sustainable Development Goals

In 2015 the United Nations (UN) revealed the 17 sustainable development goals (SDGs), also known as the global goals. The goals were a call to end poverty, protect the planet and ensure peace and prosperity for all humankind by the end of 2030.

The sustainability goals include production and consumption, innovation, and industry as well as gender equality and underwater life. The goals are integrated and recognises that positive change in one area can lead to a negative change in another. The goals consider the different forms of sustainability and merge them together into creating the 17 SDGs [22]. The goals can be read from figure 1.

Figure 1: United Nations 17 Sustainable Development Goals [23]

Achieving sustainability goals requires vast interaction between business, government, and civil society. This may involve investments in developing countries, as well as the implementation of sustainable strategies within individual companies. There is a growing interest in innovation initiatives that involve renewable energy and a circular economy.

1.1.2 Sustainable Energy Production

There are several sustainable ways of producing energy. There are renewable energy options, such as solar energy, wind energy, hydro energy, tidal energy, and geothermal energy, and there are carbon neutral options such as bioenergy. The common denominator for the different forms of renewable energy is based on resources that are naturally replenished over time. The carbon-neutral options centre around the fact that the carbon is released from the plant during combustion. Previously, it has been sequestered from the atmosphere and will be sequestered again as the plants regrow.

Renewable energy and carbon-neutral energy are not automatically sustainable and there can be several environmental problems with energy production. The production of the solar cells needed for solar energy production is an example of this. The cells need a large amount of energy in the production phase and if this energy is produced with fossil fuels, the total environmental impact will be greater than if the cells were produced with renewable energy [24]. This is also applicable to wind and hydro-energy. If the components are not well maintained and have to be changed frequently, there will be a much larger carbon footprint than what is achievable with more maintenance and care [25].

The renewable power sources will almost always be more sustainable than fossil fuels. There are ways to make it even more sustainable by taking certain precautions in the production, operating, and waste stage. By doing so, it is possible to minimise the carbon footprint of energy production.

Energy Production Globally

Electricity, transport, and heating are the three main categories of global energy production. There is a slight difference in the energy mix depending on which type of energy is in focus. Generally, low-carbon sources such as nuclear and renewables represent a larger share of the energy mix for electricity than they do for the transport and heat energy mix [26]. The total energy production in 2019, according to the International Energy Agency (IEA), was 617 EJ (171 389 TWh). Fossil fuels accounted for more than 81% of production in 2019, as in the previous years [27]. The electric energy production in 2019 amounted to a total of 95 EJ (26 300 TWh).

A comparison between the energy mix for the total energy production (transport, heat, and electric) and the energy mix for the electric energy production, can be viewed in figure 2.

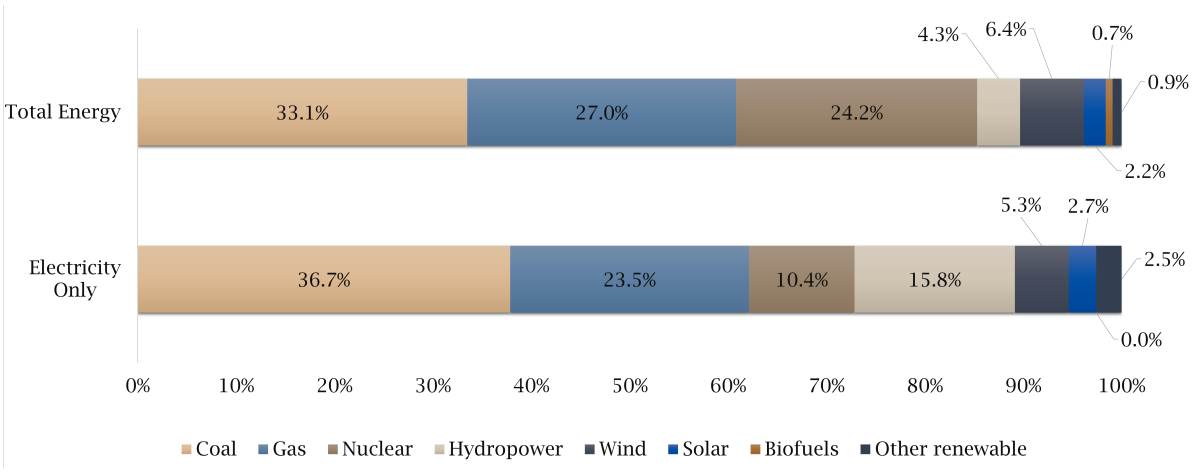

Figure 2: Global Energy Production by Source, inspired by [26]

Norwegian Energy Production

The Norwegian power production relies heavily on hydro-power. In 2020, 98% of the electric energy produced in Norway came from renewable energy sources with hydro-power as the main source. The other forms of energy production were mainly wind and thermal energy. Hydro-power has been the main source of energy in Norway for a long time and has been utilised since the late 1800s [28]. Norway has the highest share of renewable energy as well as the lowest emissions from the power section in all of Europe. In 2021 the installed capacity of the Norwegian power production system was 39 000 MW with an annual power production of 157 TWh. The energy sources are divided into 88% from hydro-power, 10% from wind power, and the remaining 2% from other sources such as thermal and solar [29, 30]. The greenhouse gas emissions directly linked to the electricity production in Norway were 17 gCO_2 eq per kilowatt-hour in 2019. For comparison is the emissions from the European energy mix at about 300 gCO_2 eq per kWh [31].

1.1.3 Previous Studies

The first reported instance of a solar-powered stadium is dated back to Freiburg, Germany in 1995. The Badenova-Stadion (Mage Solar Stadion) was equipped with a 259 kWp photovoltaic system on the roof of the arena [32]. Since the nineties, there has been a growing popularity for low carbon architecture and renewable energy systems. There are now hundreds of stadiums, arenas, and other sports venues that are partly or completely supplied by renewable energy produced on the grounds. While most of the venues are intended for football, the largest venues are those meant for motor racing. The largest reported venue is the Indianapolis motor speedway, the racetrack has an installed capacity of 9 000 kWp and an incredible 39 312 solar panels [33].

There have been several case studies that have looked in detail at the environmental impacts of sports events. In 2018 the Interuniversity Research Centre on Pollution and Environment, based in Italy, published a research paper centered around the Dacia Arena in Udine, Italy. *"Towards Zero Energy Stadiums: The Case Study of the Dacia Arena in Udine, Italy"*. The purpose of the study was to propose an approach to stadium energy enhancement that included several effective and applicable strategies. The strategies were also meant to be applicable for several building typologies, such as residential, commercial academic, etc. The study proposed two different strategies to minimise the energy use in the Badenova-Stadium. The first strategy was to install a PV system on the roof of the arena, for electric supply; the second strategy was to implement a geothermal or a biomass plant for heating and cooling [34].

Another case study was done at the American International University of Bangladesh: *"Optimization of Grid-Tied Distributed Microgrid System with EV Charging Facility for the stadiums of Bangladesh."* The study focused on the ongoing power crisis in Bangladesh and how to utilise renewable energy to power sports stadiums and electric charging of cars. The goal of the study was to lessen the burden on the electric grid as well as the environment. The study resulted in an estimate of the reduction in emissions and the amount of potential energy that could be produced. It was calculated that it was possible to generate 200 kW per year from each micro-grid system. If all of the eight major stadiums joined the cause, more than 1 500 kW power could be supplied to the national grid. This could save up to 4 562 metric tons of CO_2 per year [35].

1.2 Objectives and Scope of The Study

1.2.1 Research Question

After contacting Skagerak Energy lab and discussing different thesis topics and directions, the question that surfaced as the most desirable to get answered was as follows:

"Potential for an off-grid power system supplying a residential area by using the existing PV system at Skagerak Arena.

(i) How many housing units with different energy profiles can be supplied without using additional energy from the grid?

To be able to answer the research question and get a better understanding of the results, it was also decided to look at another scenario where the minimum number of solar panels per customer was used. By finding the minimum number of panels required to cover the annual electricity demand, the results from the original research question can be compared and discussed in broader terms and it will be easier to see the results in relation to the needs of the customers. This resulted in the second scenario of the research question:

(ii) What would the specifications be if each customer had enough solar panels to cover the exact electricity demand throughout the year?

Finally, the economical aspects, as well as the environmental impacts concerning an on-grid scenario, were discussed and the final scenario for the thesis was set:

(iii) If the system were connected to the power grid, what would the economical aspects of self-produced electricity be, and what environmental impact could it lead to? "

Having an off-grid system with only solar-powered energy production is not an optimal solution in Norway. It may not be possible with the few sun hours and low irradiance that is available in the winter. The problem will be considered a hypothetical situation and will not be attempted recreated by Skagerak Energy Lab. The results will instead be used for research purposes and for reference in future endeavours. The on-grid system is also theoretical and is made as a simplified analysis to give an indication of the economical and environmental aspects.

1.2.2 Simplifications and Assumptions

Several simplifications, estimates and assumptions were done during the work due to a lack of data.

The panels installed at Skagerak Arena were purchased at tender, which means the paid price was for the entire system and would be completely different if the number of panels changed. To find the price for a different, much smaller system, the prices from Skagerak could not be used and a different supplier had to be found. Due to this, the data related to the economical calculations were given directly by a solar panel supplier. The prices, estimated production and carbon emissions related to the production of the panels are therefore vulnerable to sales tricks, in the form of lower reported emissions from the production of the panels and higher estimations than what is realistic for the power produced by the panels. The panels, for which economic calculations have been made, are also of a different type than the panels used for the production data. This leads to slightly different results than what would have been if the same panels were used for both. The maintenance cost is calculated by using an estimate that 1% of the total cost goes to maintenance. This is a large assumption. The maintenance cost can vary based on the climate, type of repair that has to be done and other unforeseen problems.

Skagerak Energy lab stated the battery capacity in kilowatt-hours, although the unit usually used is ampere-hour. Since Skagerak uses kilowatt-hour, that is the unit which will be used for battery capacity for the rest of the thesis.

1.2.3 Limitations and Delimitations

The solar panels installed at Skagerak Arena are relatively new. There is not a large amount of data from previous years the data from 2020 can be compared to. There is some data from 2021, but the inverters were down for a large part of the year, so only parts of it can be used. By having no previous years to be compared to, the data will be more vulnerable to atypical weather changes and other unforeseen hindrances to the production.

The production data was from 2020, but the demand data was collected from the year 2021. The year 2020 was a leap year and to be able to compare the production data with the demand data by the same premise, the 29th of February was removed. The consumption data, which was recorded in 2021, was affected by COVID-19 and its abnormal conditions. More people were at home in the daytime, due to the measures taken to reduce the spread of COVID-19. This resulted in an energy profile slightly different than usual, with a higher energy consumption during the day. The year 2021 was also the year with the highest electricity consumption in private homes ever recorded in Norway. This will have a direct impact when looking at the number of solar panels needed to cover the demand.

The production data is received from the transmission system operator, through Skagerak Energy lab, which means there is no data available regarding the system losses. The inverter- and cable losses will therefore be neglected when looking at the overall production.

1.3 Structure of Work

This thesis was developed in cooperation with Skagerak Energy Lab, a project that is part of Lede and Skagerak Energi's investment in new network technology and smart networks. A recapitulation of the workflow is demonstrated in figure 3. The box on the left refers to the process of work done in this thesis and can be used as a starting point for answering the research question. The research was directed to identify consumption data from characteristic consumer groups and production data from the existing solar power system. Point three refers to a literature analysis done of similar existing cases. The aim of this is to summarise the arguments and ideas of existing knowledge within similar studies. Limitations and delimitations in point five were made to narrow the study and make it more manageable and relevant for the established research question in point four.

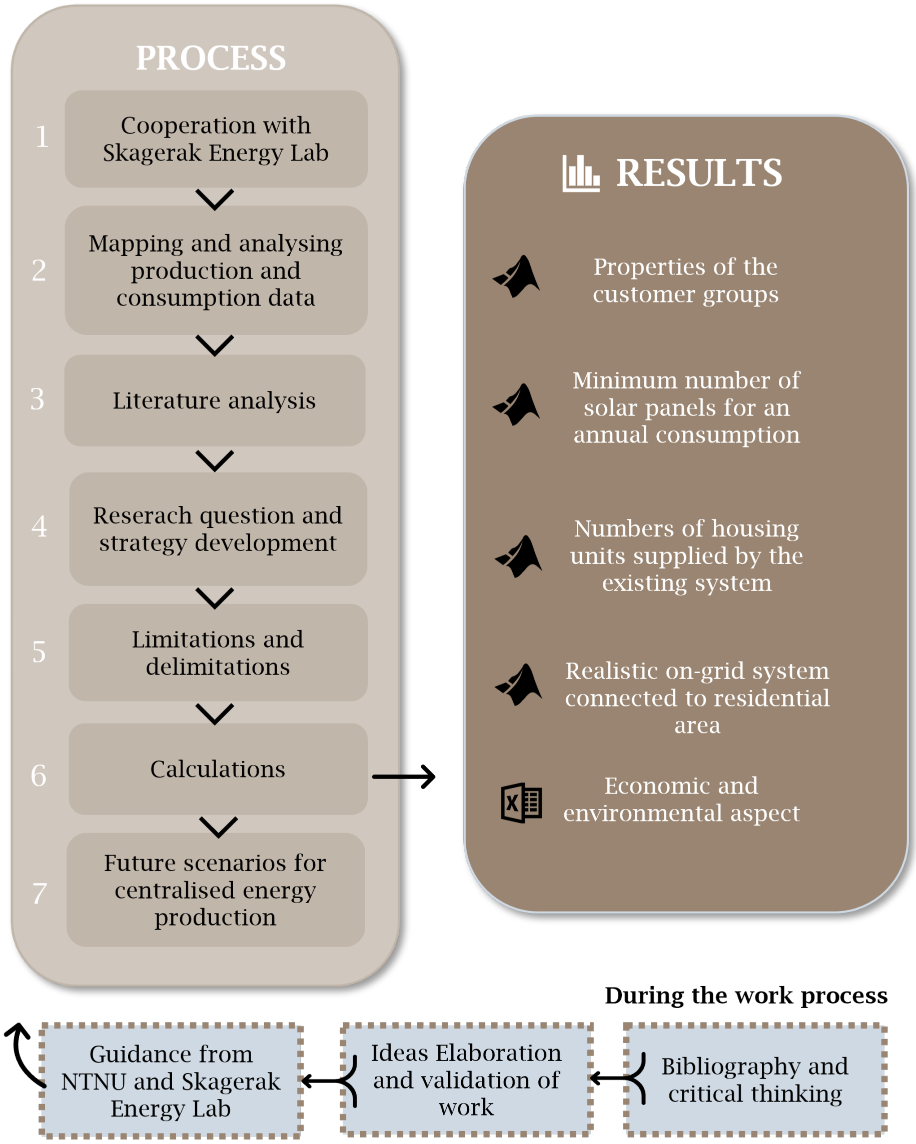

Figure 3: Flowchart of the work process

The right box in figure 3 further presents the results and gives an overview of the main results achieved. As an outcome of several minor results, the processes of four to six were constantly repeated and that would contribute to research on centralised photovoltaic systems under Nordic conditions. The validations done during the process are essential to ensure the high quality of the thesis's results. The supervisor from NTNU, the subject manager as well as the business developer from Skagerak was constantly involved in the processes for elaboration of ideas and quality assuring. Skagerak Energy Lab was consulted on whether the calculations were realistic, and they contributed data and other relevant information. As point seven indicates, the calculations were further used to look at future scenarios for on-grid solar power systems under similar conditions.

1.4 Outline

The structure of this thesis is shaped to give the recipient a most orderly experience of the research and the layout is illustrated in figure 4. The very first section, introduction, forms the foundation of the thesis with a description of the background, research question and scope. Further, theoretical basis substantiates the thesis and provides a supplementary basis for the research. The section goes into depth on the theory related to the thesis and emphasises important aspects such as solar energy, efficient housing, energy storage etc. The following third part embraces the case study where the solar power system of Skagerak Arena is presented. Specifications of the existing system such as batteries, PV panels and setup are given in detail. Section four, methodology, provides a basis for the choices and procedures on the calculations and justifies the choices that have been made along the way. The results of the calculations are presented in section five. To provide a neat and visual experience, the findings are presented with graphs, tables and line charts. Towards the end of the thesis, the results will be discussed in part six. The very last section seven, provides a final conclusion of the research question. Bibliography refers to resources used during the work and are linked to throughout the text. Attached to the assignment are the codes for the calculations done in the Matlab software as well as the calculation units in Excel.

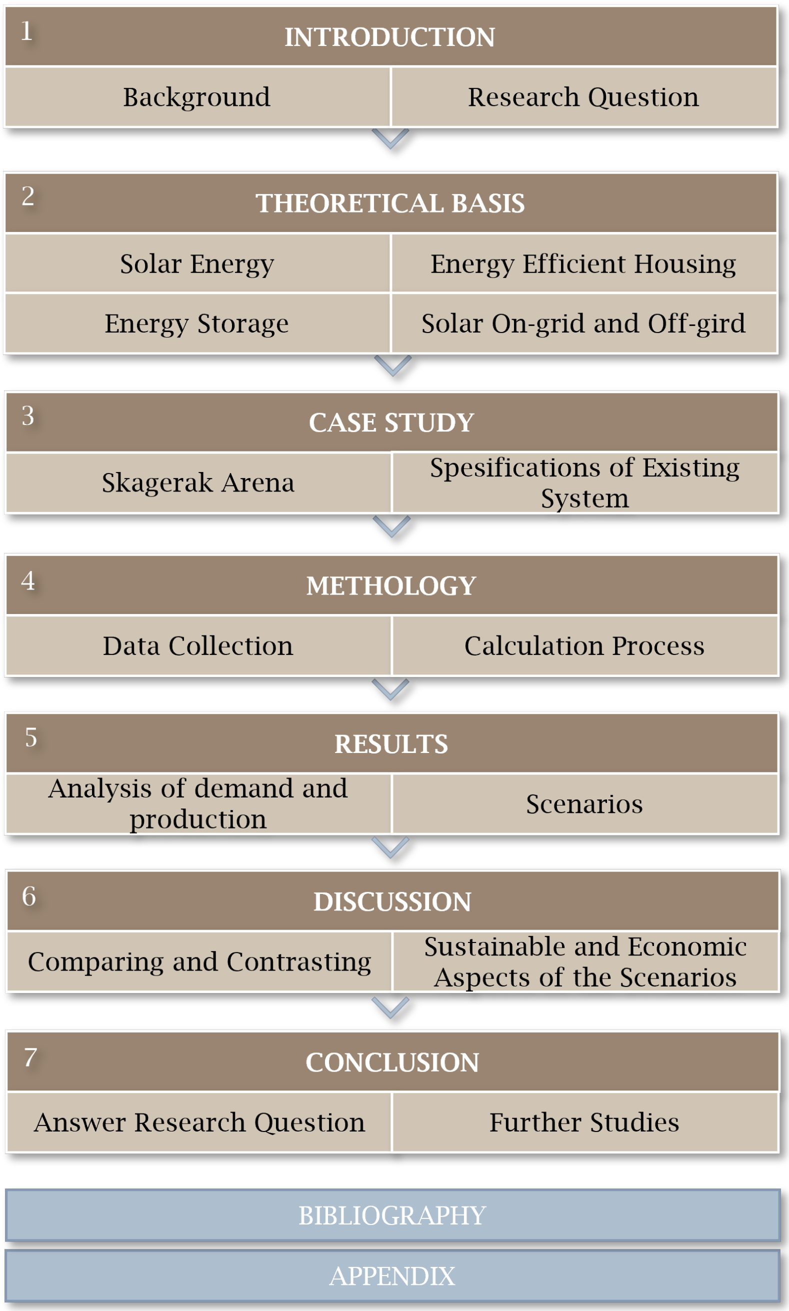

Figure 4: Outline of the thesis

2 Theoretical Basis

This section forms the theoretical basis for the thesis. The most essential phenomena are elucidated and will in further parts be drawn connections to. The groundwork addresses factors such as solar power, energy-efficient housing, energy storage, economic situation, and other crucial elements for the research.

2.1 Solar Energy

Today, several established solutions for solar power are already on the market. The basic elements are all the same, harvesting energy from the sun. However, the methods of collecting the energy into a useful form might differ. There are countless ways to exploit the energy from the sun. Passive solar gain, concentrated sunbeams, photovoltaic and thermal solar power are known forms of accumulating energy [36].

Passive solar gain refers to the sun's ability to heat indoor areas by exposure to the sunlight, typically through big windows facing south. Depending on the design and material of the building, solar radiation will hit, transmit, reflect or absorb solar radiation dissipating the sun's energy. This can advantageously contribute to significant amounts of heat. In Norway, an average house receives around 10-15% of the heating demand from passive solar energy [37]. Furthermore, solar thermal energy (STE) is another way to utilise the sun's heat radiation. This is simply a black surface absorbing light, heated up and the heat is transferred to a working fluid often used to heat swimming pools or buildings. Much higher temperatures can be created if the sun's rays are concentrated by mirrors. The sunlight is focused onto a middle point where a carrier fluid flows through. The carrier fluid, such as oil, heats up to around 400°C and heats the water. The high pressure created can drive a turbine and generate electricity. The big downside, however, is the technology only works well in direct sunshine. By having the mirrors move, the complexity will increase and extra costs will occur. There are other examples of mirror concentrated energy, cut due to high costs, these are not commonly widespread [38]. Photovoltaic solar cells are one of the most known types to harvest the sun by converting light directly into electricity. As economical costs have dropped dramatically and efficiency has increased significantly, this has become one of the most common forms of converting solar energy into electricity. The next section will further go into the details of this technology.

2.1.1 Photovoltaic Types

There are mainly three types of PV panels within commonly reach monocrystalline, polycrystalline, and thin-film solar panels [39]. They capture energy from the sun and turns it into electricity. The mono and polycrystalline are both produced from silicon, a chemical and long-lasting element. At the cellular level, the structures have differences in material, such as mono silicon, polysilicon, or amorphous silicon.

In solar cells, sunlight is absorbed by the silicone. This generates an electrical charge. The cells in a panel are connected and consist of metal conductors similar to a battery. Several cells make up a panel and are connected in series for greater voltage. The total electrical outcome varies based on how much, and how strong sunlight they are exposed to. This varies throughout both a day and which season it is.

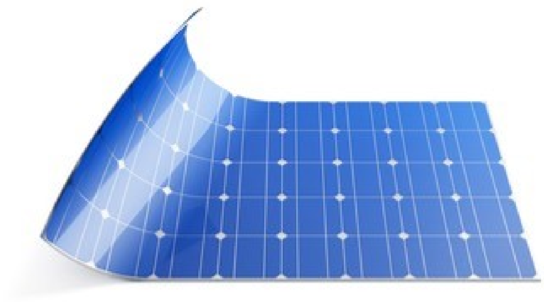

Figure 5: Thin film solar panel [40]

Polycrystalline, also known as multicrystalline, is the most common form of PV panels, even though monocrystalline panels have higher efficiency. The solar cell in monocrystalline panels comes from single-crystal silicon. When the cells are cut from single-cell silicon, the electrons get more room to move and result in a higher efficiency. In a polycrystalline panel, several small crystals are melted together. Although this gives a cheaper manufacturing method, several crystals reduce the electrons' ability to move freely and lower the efficiency. The major difference between monocrystalline and polycrystalline PV panels is how they are manufactured. PV modules are mainly produced in the same way and consist of the same core materials: backsheet, glass, aluminium frame, ethylene-vinyl acetate and solar cells. The latter component, solar cells, separate mono from multi-crystalline. Figure 6 visualises the structure for both types.

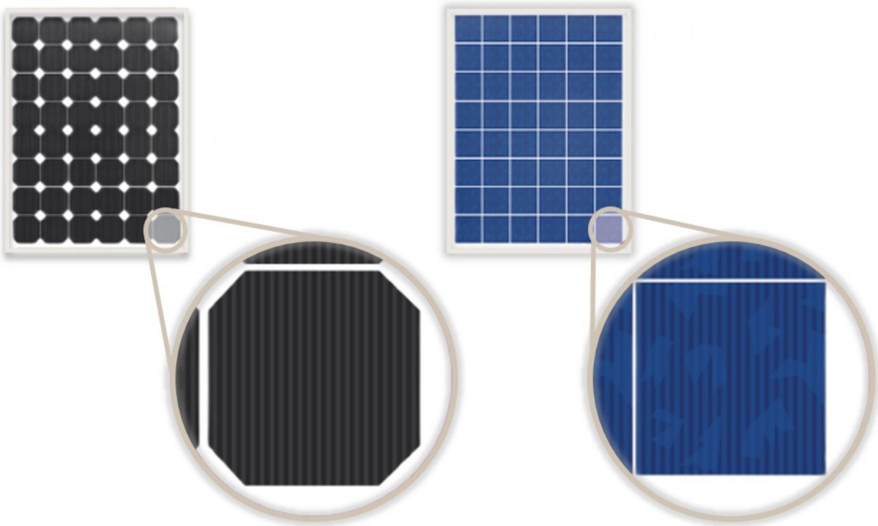

Figure 6: Mono-crystalline and poly-crystalline panels, adapted from [41]

2.1.2 Energy Consumption and Emissions During Production

Energy Consumption

Silicon is, as mentioned in section 2.1.1, used in both mono and polycrystalline PV panels. Silicon is an abundantly available material; it is however extremely energy consuming to convert the raw material into high-grade silicon. To produce the high-purity silicon, quartz sand and an arc furnace at high temperature (1 500-2 000°C) are required [42]. This process makes the silicon have a purity grade of 98-99%. This is high, but not enough and the silicon has to go through several more steps, involving chemical purification, to get the required purity. The steps involving chemicals are not as energy-demanding but can lead to dangerous bi-products such as trichloroacetic acid and silicon tetrachloride, which can be explosive and toxic. The finished purified silicon needs around 200 kWh/kg [43]. When the silicon is purified to a satisfactory purity grade, it is cut into wafers and connected to form the solar cell. The last stage in the production of the PV panel is to assemble the remaining components. The cells are soldered together with metal contacts to form a panel and the metal frame, toughened glass, encapsulation - EVA film layers, polymer rear back-sheet and a junction box with diodes and connectors are connected to create the final product [44].

Emissions

Several life cycle assessment reports have been done on the emissions related to solar power production. The US-based National Renewable Energy Laboratory (NREL) estimated that the lifetime emissions from an average PV panel amounted to 40 grams CO_2eq per kilowatt-hour produced [45]. Another study, published by Nature Energy, estimated a slightly lower value of 21 grams CO_2eq per kilowatt-hour [46]. Even though the reports get slightly different results depending on the different values they use, when compared to fossil fuels the numbers are far superior. For comparison, the NREL also published the life cycle assessment for the coal industry, which resulted in emissions as high as 1 000 grams CO_2eq per kilowatt-hour [45].

2.1.3 Components of a Solar Power System

Inverter is often referred to as a converter when power flows from direct current (DC) into alternating current (AC). The main grid or public utility as well as all households, depend on AC to perform. An inverter's primary function is converting DC power into standard AC.
Combiners in the context of PV panels are frequently used to combine several strings of panels into a single conductor that connects the box to the inverter. Combiners can also have additional integrated features such as disconnect switches, monitoring equipment, and remote rapid shutdown devices [47].
Charge controllers are used to avoid overcharging of the batteries and are used as voltage and/or current regulators. The regulation happens when the energy from the PV panels travels to the battery bank. This is done so the PV panels won't drain the batteries at night when there is no power income from the PV array. The charge controller can have additional features and be used as a display, conveying voltage levels, charge state and current coming in.
Generators provide electrical power, and act as a small power plant. The generator can be connected to the utility grid, or it can be stand-alone. It can generate electricity on the premise, either as a substitute or complement to the electricity from the electric grid.
Battery banks works as a combiner for batteries. It joins several batteries together to make a single output. Attaching several batteries increases the voltage or amperage of the output.
Loads absorb electrical energy and convert it to another form of energy, such as heat, work, light, etc. Customers in an electric grid are often referred to as loads.

2.1.4 System Losses

There are several factors to consider when calculating losses in a PV system. The largest contributor to losses is shading against sunlight, but there are also several other considerable sources. Dirt and dust, reflection, thermal losses, DC and AC cable losses and inverter losses to name a few.

Soiling losses refer to the loss of power connected to the layer of dust, dirt and other physical substances that cover the surface of the PV panel. The particles obstruct the incoming solar irradiation and block the panel from absorbing the solar rays needed to produce energy.
DC and AC cable losses are caused due to the conductor resistance heating that occurs when current flows through the cables, or wires, used throughout the PV plant.
Inverter losses exists because it is not possible to convert power without losing some of it. The efficiency of an inverter is depended on the load. Typically it will be at its highest when the load is at two-thirds of the inverter's capacity. This is called "peak efficiency". The inverter requires power to operate and a large inverter operating small loads will therefore have low efficiency.
Reflection losses occur when the solar radiation bounces back from the surface of the PV panel instead of being absorbed by it. This can be caused by the incidence angle being larger than it was during STC, resulting in higher reflection losses than accounted for in the nominal power rating.

Shadowing Effects

PV panels are constructed from individual cells that are connected in a series string to increase the voltage and electrical energy output. If one of the cells fails to produce the same level of output as the others, it will affect the whole system. Such an instance can occur when part, or all, of the panel, is covered in shadow. This occurrence is called the shadowing effect. The covered cells will receive a lower level of irradiance and will produce a lower output. The solar cells with a higher output will feed current back into the system to make up for the cells with a lower output. As a result, some of the solar cells will function as loads instead of sources. The efficiency of the entire system will decrease disproportionately as a consequence, the panels can get damaged and it can lead to hazardous situations [48].

To reduce the effect of shadowing and protect the panels, bypass diodes are used. Solar panels have built-in bypass diodes which can cut off any of the cells that are experiencing shadowing to decrease the impact the shadowing effect will have on the entire system. This is however not a perfect system. The diodes are expensive to attach to each cell and are therefore attached to a collection of cells. This causes all the connected cells to be cut off even if it is only one cell that is experiencing shadowing [49].

2.2 Energy Efficient Housing

Electricity is used in almost all types of housing units and serves a variety of purposes. While it is common for heating and kitchen utilities to run on gas in other countries, Norwegian homes use electric energy for most of the appliances. This includes heating with electric ovens, electric stovetops and refrigerators [50]. In the winter months, heating can be supplemented with wood-burning stoves, but most homes have electric heating as well. In total 80%, of the heat demand is covered by electricity and 15% is covered by wood-burning stoves. In later years, heat pumps and district heating has become more popular for covering part of the heating demand [51].

2.2.1 Insulation in Housing

Since almost all the indoor heating is done by electricity in Norway, a difference in insulation can make a large impact on the overall electricity consumption. There are several types of insulation with different areas of use. Blanket, concrete block, foam board, spray foam, and loose-fill insulation to name a few [52]. An illustration of blanket, loose-fill and spray foam insulation can be viewed in figure 7.

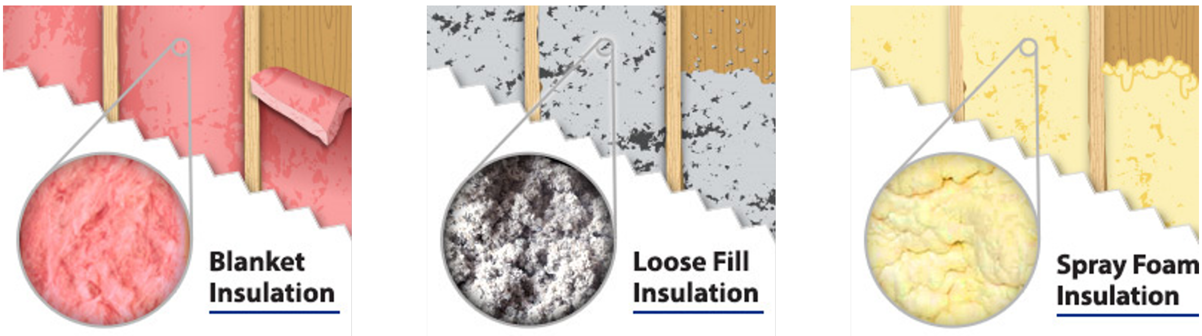

Figure 7: Illustration of blanket, loose-fill and spray foam insulation [53]

Blankets can be supplied as rolls or batts, and are primarily made from fibre glass, mineral wool, plastic fibres and natural fibres. Blanket insulation is often used in walls; including foundation walls, floors and ceilings[54].

Concrete block insulation is made from foam boards and are made to be placed outside or inside of a wall. Some manufacturers incorporate foam beads or air into the concrete mix to increase r-values. Concrete block insulation is used for walls, new constructions, or major renovations [52].

Foam boards or rigid foams use polystyrene, polyisocyanurate, polyurethane or phenolic as material and are used in walls; including foundation walls, floors, and ceilings, as well as unvented low-slope roofs [55].

Loose-fill and blown-in insulation are made up from small particles of cellulose, fibreglass or mineral wool. These small particles form an insulation material that can fit into, and form after, any space without disturbing structures or finishes. Loose-fill and blown-in insulation is most used in existing walls to re-insulate, new wall cavities, attic floors and other hard-to-reach places [56].

Sprayed foam and foamed-in-place insulation is often used in the same way as the loose-fill and blown-in insulation but are made from different materials. The foam is made from cementitious, phenolic, polyisocyanurate and polyurethane. The foam is sprayed into the wall or ceiling as a liquid and as the components mix with the air they instantly expand, foaming to create the insulation [52].

2.2.2 Regulations and Technical Requirements

In Norway, there are regulations and technical requirements for new buildings, which also apply to insulation. The regulations on technical requirements for construction works (TEK17) and the regulations on technical requirements for building works (TEK10) are the regulations which apply to the insulation in private homes [57, 58]. TEK10 was the previous regulation guide, while TEK17 is the current regulation guide. The requirements for new homes, according to TEK10, were 25 cm insulation in exterior walls, 30-35 cm in the ceiling and 25-35 cm in the floors. Nevertheless, a house built in the 1970s and early 1980s can have as little as 10 cm insulation in the walls and 15 cm in the ceiling [59]. TEK17 has minimum requirements for energy efficiency in the walls and ceilings and utilises the U-value to make the requirements. U-value, or the thermal transmittance, is the rate of heat transfer through a structure, divided by the temperature difference across the structure. The lower the u-value gets, the better the insulation in the structure is. The u-value can also be calculated by using the thermal conductivity, also known as the k-value, of the insulation material and dividing it by the thickness of the material. This means the thickness of the insulation is proportional to the thermal transmittance of the structure. The units of measurement for the u-value are W/m^2K. By utilising the u-value, the insulation is not dependent on the thickness, but rather on the type of material the insulation is made of. An illustration of the different forms of insulation that have been the standard from the 1900s to 2007 can be viewed in figure 8.

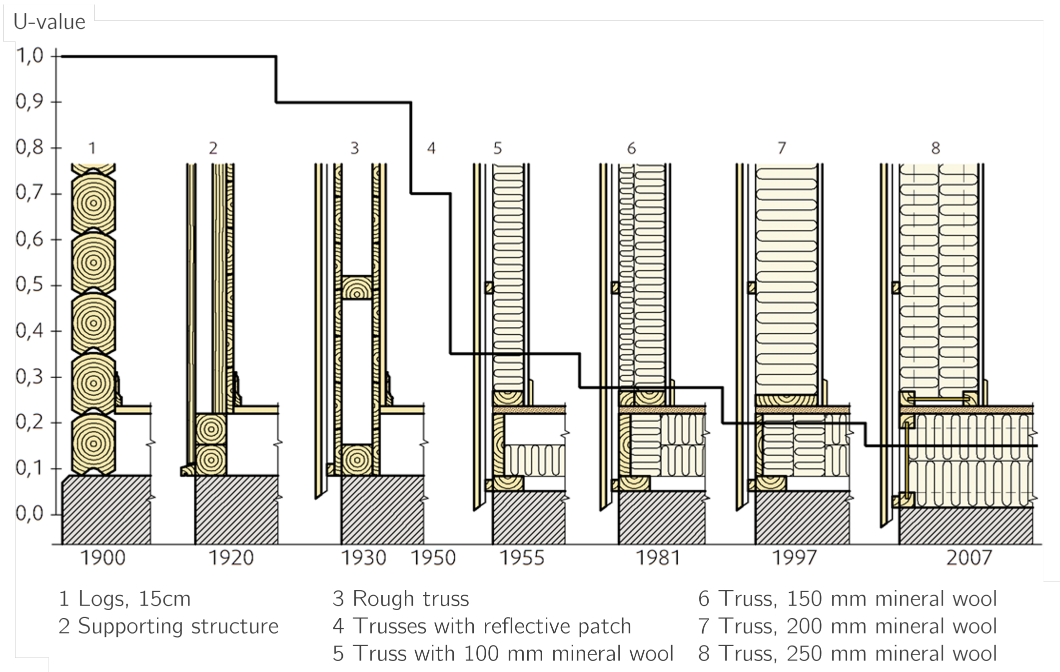

Figure 8: Illustration of average insulation from 1900 to 2007 [59]

2.2.3 Energy Efficient Lighting and Appliances

Elvia is one of the largest Transmission System Operators (TSO) in Norway and has made an overview of what electricity is used for in Norwegian homes. Almost 60% of the electricity is heating, 15-20% is hot water, 15% are for appliances and 10% to lighting [60]. This is the average and there will of course be differences when looking at specific houses. By changing lighting and electric appliances for more energy-efficient versions a lot of energy can be saved.

Efficient Lighting

Energy-efficient lighting is, as the name implies, a more efficient type of light source. Traditional lamps, such as incandescent lamps, use a lot more energy than the newer more efficient lamps to light up the same area. There are several types of energy-efficient lighting: fluorescent lamps, compact fluorescent lamps, and light-emitting diode lamps, to name a few[61]. Efficient lighting also incorporates different kinds of lighting controls such as timers, passive infra-red receivers and ultrasonic sensor-based controls. This makes it possible to have automatic lighting in rooms and outdoor which turns off automatically when not in use, as well as dimmers to control the intensity of the lighting. This can save a lot of energy throughout the year [61].

Efficient Appliances

Since 15% of the electricity in the average household goes to electric appliances, there is a lot to save by reducing the energy consumption of the appliances [60]. The appliances that consume the most energy are normally the stove, the dishwasher, the freezer, the washing machine and the dryer. All these appliances have an energy label. The energy label is an indication of how energy efficient the appliance is. It gives information regarding the electric consumption and rates the appliance on a scale from G to A, with A being the most efficient. Energy labels are required by law on all new appliances in the EU [62]. An explanation for different parts of an energy label can be viewed in figure 9.

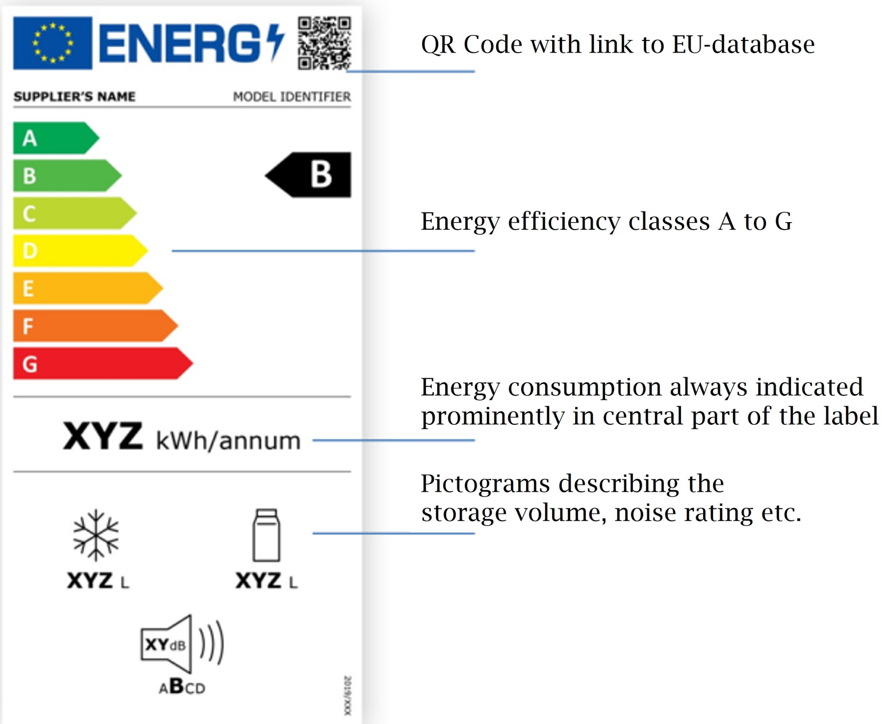

Figure 9: Example of energy label with explaining text for the different symbols [63]

2.2.4 Smart Meters

A smart meter digitises, automates, and simplifies the process of a continuous information transfer of consumption data from the consumer to the Distribution System Operator (DSO). From January 2019, all consumers in Norway are required to install a smart electricity meter in their residential unit or business [62]. As the rest of society is being digitised, it is just as natural to digitise the electricity supply network.
The benefits of smart meters are multifarious. It is a major positive consequence of technology development as DSO can operate more efficiently with far fewer ground faults and

voltage deviations. The supplier can get more information about what is happening in the electricity grid near the customer and can provide faster localisation and correction of faults. The customer will also benefit from such technology economically as lower operating costs will lead to lower transmission tariffs and the consumer has control over their own electricity consumption. There are also electricity meters with more comprehensive factors such as water, gas, temperature, humidity, and heat connected to other smart devices [64]. The data on electrical consumption updates every ten seconds.

2.2.5 Types of Heating Systems

Electric heating is the process in which electrical energy is converted into thermal energy. Electric heating is the most common form of heating in Norway and is used in different forms. The most frequently used form of electric heating is panel heaters. Panel heaters increase the temperature of the air by using convection heat from the surface of the panel. Another form of commonly used electric heating is underfloor heating. Underfloor heating is often used in bathrooms and makes use of electrical cables underneath the floorboard [65].

Heat Pumps is an energy-efficient way of heating and cooling buildings. Heat pumps use electricity to transfer heat from one area to another, the same way a refrigerator does. The air on one side will get cooler, while on the other side it will get hotter. This means the same system can be used for both heating and cooling. Heat pumps transfer heat instead of generating it and can therefore be more efficient than standard electric heating options. There are three types of heat pumps that are considered the main types; air-to-air, water source and geothermal [66]. The most common heat pumps in Norwegian homes are air-to-air heat pumps.

District heating, also known as urban energy, supplies heating and hot tap water to individual buildings or districts. It can be described as a central heating system where the heating system is built up as an underground infrastructure with insulated water pipes, as illustrated in figure 10. The energy is based on waterborne heating systems that take advantage of available local sources. It utilises energy sources that would otherwise be wasted and are therefore considered a renewable source. The heat is extracted from energy sources such as waste heat from industry, waste incineration, heat pumps, bioenergy or others. The water maintains a temperature of about 70-120 °C depending on the technology and season.[67] Via the infrastructure, the hot water is led each building as shown in figure 10.

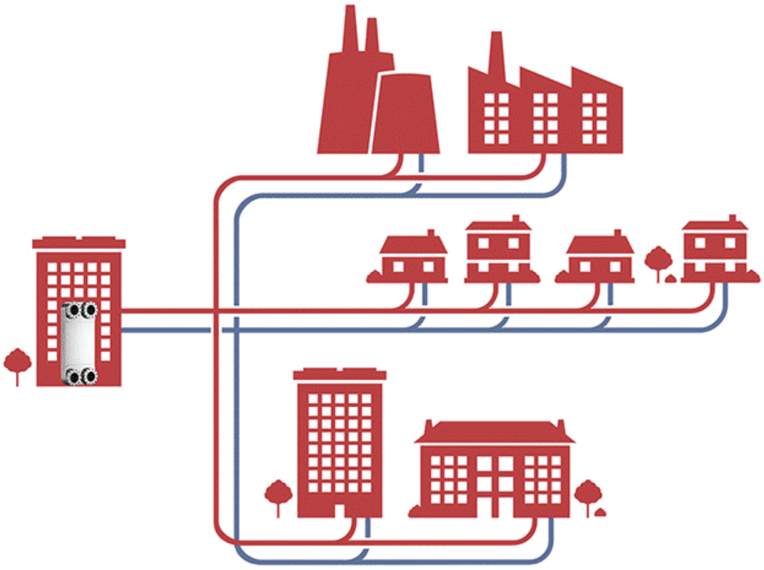

Figure 10: District heating illustated [68]

2.3 Energy Storage

A critical part of the grid is energy storage. Energy storage is used to store energy for later use. Energy storage is often used to reduce imbalances between energy demand and production and can also be used to even out the power peaks that occur in the grid. Another large utilisation of energy storage has to do with renewable energy. There are several great sources of renewable energy, such as wind and solar power. There is however a large problem in the fact that most renewable sources cannot produce energy steadily, the production rates change with season, months, days, hours and even by the minute. For renewable energy to become a completely reliable source of energy, there is a crucial need for stable energy storage. There is a large interest in energy storage and extensive public and private research is being carried out to achieve technological breakthroughs in the area [69].

2.3.1 Different Types of Energy Storage

There are various types of methods designed to capture and store energy, for it to be utilised when required. The energy is converted into a different type for easier storage. Pumped hydroelectric, flywheels, compressed air and thermal energy storage are examples of this. Batteries also change the type of energy but in a slightly different way. A battery converts the electricity into chemical energy, but can also convert back into electricity through electrochemical oxidation-reduction. Batteries can consist of lithium-ion, lead-acid, lithium iron or other battery technologies [70]. Energy storage can be used for different purposes and for different periods. It can be used to store energy from one season to another or for shorter time intervals, such as from day to night.

Pumped hydroelectric can be used to store energy in the form of potential energy. Electricity is used to pump water to a reservoir on higher ground for it to be released later and flow through a turbine to once again generate electricity. Pumped hydroelectric storage can store energy for a long time. In Norway, it is most used for seasonal storage, but in other countries, it is normally used for day to night storage. The water gets pumped into the reservoir at night when the demand is low and released in the day when the demand is high [71].

Flywheels use kinetic energy in the form of rotational energy as the storage type. Electricity is used to spin a flywheel (rotor) and when the energy is needed, a generator is attached and the spinning force of the rotor generates electricity. Ideally, a flywheel will store energy indefinitely. In reality, there is wheel air drag and bearing losses so there will be a practical limit to the time it can store energy. To reduce the loss of energy due to drag, the flywheel can be placed in a vacuum [72].

Compressed air at a pressure of up to 7 000 kilopascal gets stored, often in underground caverns, as a way of energy storage. The air is compressed using electricity and when the demand is high it will get released into an expansion turbine generator to get turned back into electric energy [73].

Thermal energy storage uses heating or cooling as a medium for storage. By heating or cooling a substance when the demand is low, the substance can be used for heating or cooling during periods of high electricity consumption [74]. The heating of a medium requires a lot more energy than maintaining a certain temperature. This means the substance can be brought up to the desired temperature when the production is high and when the production is low the energy can be spent on maintaining the temperature, rather than rising it. Thermal storage consists of three categories: sensible heat, latent heat, and thermo-chemical heat storage. Sensible heat storage (SHS) is the most common form of thermal storage. The medium usually consists of water which is heated or cooled to serve the intended purpose. Molten salts or metals can also be used. This is more expensive, but can obtain a higher storage capacity [75]. Latent heat storage (LHS) uses the phase change that occurs in the medium when heat is added. By utilising the phase change, large amounts of heat can be stored without a significant temperature change in the medium. There are several phase-changing materials to choose between, such as salts, polymers, gels and paraffin waxes. All the materials are isothermal at the melting point and it is therefore normal to choose the material based on the desired temperature of the medium. LHS usually has a higher storage capacity than SHS [76]. Thermo-chemical heat storage (TCS) uses thermo-chemical materials which are capable of reversible exotherm/endotherm chemical reactions. Depending on the material, TCS can achieve a higher storage capacity than SHS and LHS. Thermal energy storage can store energy for a long time and can work as seasonal storage, storing heat from the summer into the winter [77]. Thermal energy storage can also be combined with district heating and can serve as a heat reservoir when the heating demand is high [78].

2.3.2 Batteries

There are several different types of batteries. Alkaline, nickel-metal hydride (NIMH), and lithium-ion batteries are the most common form of batteries readily available in the consumer market.

Essentially, the different types of batteries work in the same way. They store the energy as chemical energy and convert it back into electricity when discharged. The chemical reaction uses the flow of electrons from one electrode compound to another through an external circuit to create an electric charge. The flow of electrons is balanced by charged ions that flow through an electrolyte solution that is connected to both electrodes. By using different materials for the electrode and electrolyte compounds the different battery types can have different kinds of chemical reactions that affect how much energy the batteries can store and how high voltage they can hold [79].

Alkaline batteries uses zinc as the negative electrode and magnesium dioxide as the positive electrode. As the battery discharges both of the compounds get consumed, resulting in the battery losing charge. Alkaline batteries are disposable batteries and can not be safely recharged once used.
Nickel-metal hydride batteries use an intermetallic compound that includes nickel as the negative electrode and a nickel hydroxide as the positive electrode. The compounds of a nickel-metal hydride do not get consumed during discharge and the batteries are rechargeable.
Lithium-Ion Batteries, also called Li-ion batteries, are the newest form of battery on the common market. The positive electrode is often an intercalated lithium compound and for the negative electrode, a graphite compound is common. Li-ion batteries are rechargeable [80].

Lithium-ion batteries consist of a cathode, anode, electrolyte, separator and a positive-negative current collector. Lithium is stored in the anode and the cathode, while the electrolyte is the one carrying the positively charged lithium ions from one pole to the other, transported through the separator component. This transportation of the positively charged ion is the reason for the free electrons in the anode pole that will generate a charge at the positive current collector. Electrical current will be flowing from the current collector through a device and into the negative collector. The separator also functions as a wall to block the flow of electrons inside the battery. [81]

Lithium-ion battery uses lithium ions as the main component of its electrochemistry. While in its discharge cycle, the anode directs the ionisation of the lithium ions for separation from their electrons. The transportation of the ions is directed from the anode, through the electrolyte to the cathode, so they can be recombined with their electrons and electrically neutralise. Because of the small size of the Li-ion, the transportation from anode to cathode happens through a micro-permeable separator[82].

The Li-ion batteries have a no memory effect, which means that in production and storage the repeated partial discharge/charge cycles will not cause the battery to 'remember' a lower capacity.[82]

Since the beginning of the 90s, Lithium-based batteries have been commercialised. Over 50% of the small portable battery market was overtaken by lithium-based batteries in a short period, the batteries have been entering the industrial markets successfully since the 2000s. The battery has tons of different features including, high energy density, high efficiency, maintenance-free design, versatility, state of charge- (SOC) and state of health (SOH) indication, this makes lithium-ion batteries a popular choice in the battery market. [83]

2.4 On-Grid and Off-Grid Solar Power Systems

2.4.1 On-Grid Solar Power System

On-grid systems refer to a power system connected to the local utility grid as illustrated in figure 11. It is commonly used in residential homes due to the security of energy supply. More specifically it infers that any overabundance or shortage of power can be fed to the grid through net metering [84]. There will always be power supplied to the consumer without any interruptions caused by the varying production from the solar panels.

A benefit of having an on-grid system is the economical aspects and gains. There will be no need for batteries which would otherwise be a major expense for the system. Especially during the summer season, when there is a large amount of excess production from the solar panels. By directing the overflow of production to the grid, rather than having it as an input to a battery bank. An on-grid solution ensures energy contributions all year around.

Due to the lack of batteries, an on-grid solar system can not function or generate electricity during a blackout. Blackouts usually transpire when the utility grid is disfigured, and that leads to the solar inverter feeding into a damaged grid, which may lead to safety risks and major energy and economical losses [84]. Another disadvantage would be less incentive provided for conserving energy.

Figure 11: On-gird solar system attached to electricity grid, adapted from [85]

By having some of the consumption covered by self-produced energy, the current can travel a lot shorter than what it would have if it came from the grid. Due to this, the cable losses caused by the high voltage in the utility grid will be reduced.

2.4.2 Off-Grid Solar Power System

Off-grid is a common way of utilising solar power systems. As the term off-grid implies, it is a system not connected to any other electrical utility grid. It is also known as a stand-alone power system (SAPS) and provides an independent power supply to a home or business [86]. This type of system allows electricity to be used by solar panels and stored inside a battery without a direct connection to the utility as illustrated in figure 12.

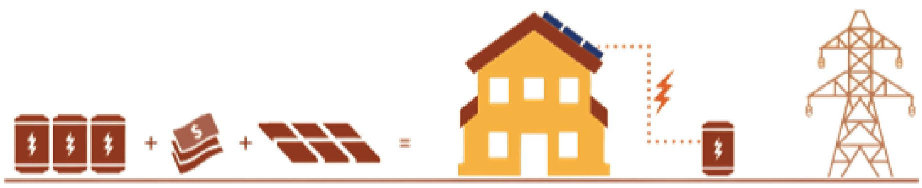

Figure 12: Off-gird solar system adapted from [85]

The off-grid solar power system is slightly more complicated than standard solar power systems. Despite the complexity, the basics still depend on energy from the sun and allow for local and sustainable self-sufficiency. There is an advantage of off-grid operation in remote locations as the national electricity network is not sufficient. The sunlight is captured by the solar panels where an inverter turns DC into AC. The most uniqueness about this system is the battery that stores electricity until needed. During the day the battery will collect energy, and throughout the day and night, the consumer will benefit from this. To emphasise, the battery is the extraordinary component that distinguishes the system from other photovoltaic systems.

2.4.3 Connections Under Nordic Conditions

The Nordic climate varies and consists of long dark winters of snow, bright summer days, rainfall, and considerably strong sunshine. The duration of the day varies with great differences over the year. Figure 13 presents data on the average day lengths in Oslo, Norway. The light area represents the twilight phase while the dark zone represents the sunshine duration. Summertime refers to significantly longer days with around 12 hours of sun compared to wintertime with around just three hours of sun a day. (The variation also takes place within the northern globe.)

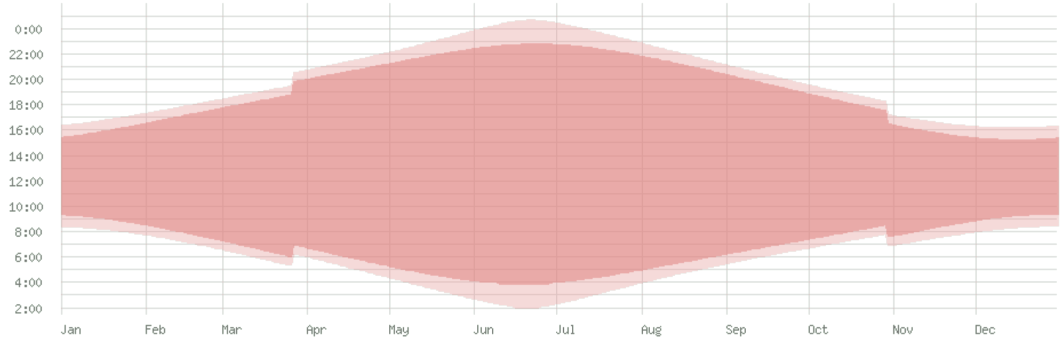

Figure 13: Average day length in Oslo, Norway [87]

According to an investigation done by the Norwegian independent research organisation SINTEF, solar cells have the opportunity to succeed in the Nordic climate despite the cool climate [88]. The experiment addresses a solar system exposed in a weather chamber. Typical weather phenomena such as light rain or heavy rain, snow, sleet, and freezing rain (that turns into ice) showed the efficiency of the solar cells under the different conditions. One of the findings showed the cold snowy weather is advantageous as the panels avoid overheating while the snow reflects extra sunshine. This scenario takes into account the solar panels not covered by the snow.

The experiment seems promising for solar energy in the north, but an independent solar cell plant is not yet technically or economically profitable [88]. Due to the predominance of solar energy production during the summer months, off-grid solar cells will not be particularly optimal in Nordic conditions. It is normal to compensate with several energy sources as a counterweight. Predicated on this, on-grid will be the primary most reasonable way of connection in Nordic conditions. Off-grid is a possible solution where the national power network is not easily accessible.

2.5 Economic Aspects

In this section the most relevant economic concepts will be presented. That includes description of terms and equations used in regards of calculations and the understanding of it.

2.5.1 Spot Price

The spot price refers to the current price in the market. The product is bought or sold for immediate delivery [89]. The instant settlement is negotiated concerning prices of currency, security or commodity [90]. The trade is done "on the spot" - hence the name spot price. The price varies greatly and changes from day to day and from hour to hour.

There is no mathematical equation for the spot price. The price will thus be affected by the supply and demand for electricity, which changes throughout the year. The price is defined by the number of buyers and sellers interested in the product [91]. In other words, it is the price the sellers and buyers value an asset to right now from an economic point of view.

2.5.2 Net Present Value

Net present value (NPV) [92]assesses the profitability of a specified investment on the basis that the money differs in value in the future. NPV is also presented as the outcome of computation used to find the day value of a future stream of payments. The present value of cash inflows and outflows over a period of time differs, and is presented as an NPV. Due to value losses in currency over time caused by inflation, NPV is used in capital budgeting and investment planning to survey the effectiveness of a projected investment or project [92].

It seeks to regulate the current value of an investment's future cash flows exceeding the investment's commencing cost. If the NPV is positive, the discounted present value of all future cash flows will be positive too, and therefore very attractive. If negative it will result to only losses [92].

$$NPV = -B_0 + \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} \tag{1}$$

[93]

NPV is used to calculate present total value of a future stream of payments, and is calculated by the use of equation 1. Starting by the value of invested money (B_0) deducted the value of the expected cash flows. The cash flows is composed of the sum of the net cash inflow-outflows during a period of time (R_t) divided by percentage in discount rate

(i) [94]that could be earned in alternative investment and to the power of timer periods (t)[93].

2.5.3 Maintenance Cost

The ongoing fee of maintaining the system, is called the maintenance cost. By investing in an installation, the buyer must arrange costs for repairs and replacement parts for the system [95].

$$Maintenance = \sum_{t=1}^{N} \frac{(System\ Price * z)}{(1+i)^t} \tag{2}$$

The maintenance cost is calculated by equation 2, using the system price, a constant representing the part of the total price designated for maintenance (z), the estimated lifetime of the system (t) and the discount rate (i).

2.5.4 Cost of Tender

When large quantities of a product are to be bought or large projects are to be built, different companies can be contacted. The different suppliers can bid on the project by making different offers to the company or customer in need of their services. This is called an invitation to tender. A key feature of tender is that it is not allowed to change the offer after the tender deadline is expired[96] .

By having different potential suppliers or contractors' competition over the customers, the prices will be significantly lower than what is achievable in a normal market. The supplier is usually willing to go for a much lower price when there are a lot of products to be sold[97].

3 Case Study

The solar plant at Skagerak Arena will be explained and described in the coming section. The characteristics regarding the residential units will be presented, in addition to the specifications of the existing facility and the software used by Skagerak Energy Lab for collecting and analysing the data.

3.1 Skagerak Arena

Skagerak Arena is a football stadium located in Skien, Norway. The stadium was built in 1923, but had extensive renovations that begun in 2006. The stadium is completely renovated and only a small section of the original building is still intact. The Norwegian power company "Skagerak Energi AS" became a major sponsor in 1995 and is the source for the arena name [98]. In 2016 Skagerak Energy Lab, a subsidiary of Skagerak Energi AS, started the planning of a large scale pilot plant at Skagerak Arena. The project's main goal was to install a large number of solar panels at the stadium and supply the arena with power during matches and other arrangements [99]. Today, the plant is fully operational and has a large battery that is able to supply the arena in case of a power failure that may occur in the grid. The plant is also connected to an apartment complex and a store that is located on the arena grounds. Figure 14 is a picture of Skagerak Arena. The corner of the building, facing the picture, shows the apartments located at the arena while the grocery store is placed on the corner to the left.

Figure 14: Picture of Skagerak Arena [100]

3.1.1 Specifications of the Plant

2700 polycrystalline solar panels, of the types REC295TP2 and REC300TP2, are installed on the roof above the stands at Skagerak Arena. The panels are placed onto the different roofs and are divided into 1 020 panels above the stands on the west side as well as the east side of the stadium, while the south stand has 660 panels. The solar panels have a total nominal power of 800 kWp and produce roughly an average of 660 000 kWh each year. An overview of the panel placement can be viewed in figure 15, the overview was obtained directly from Skagerak Energy Lab. All of the panels are produced using locally sourced silicon.

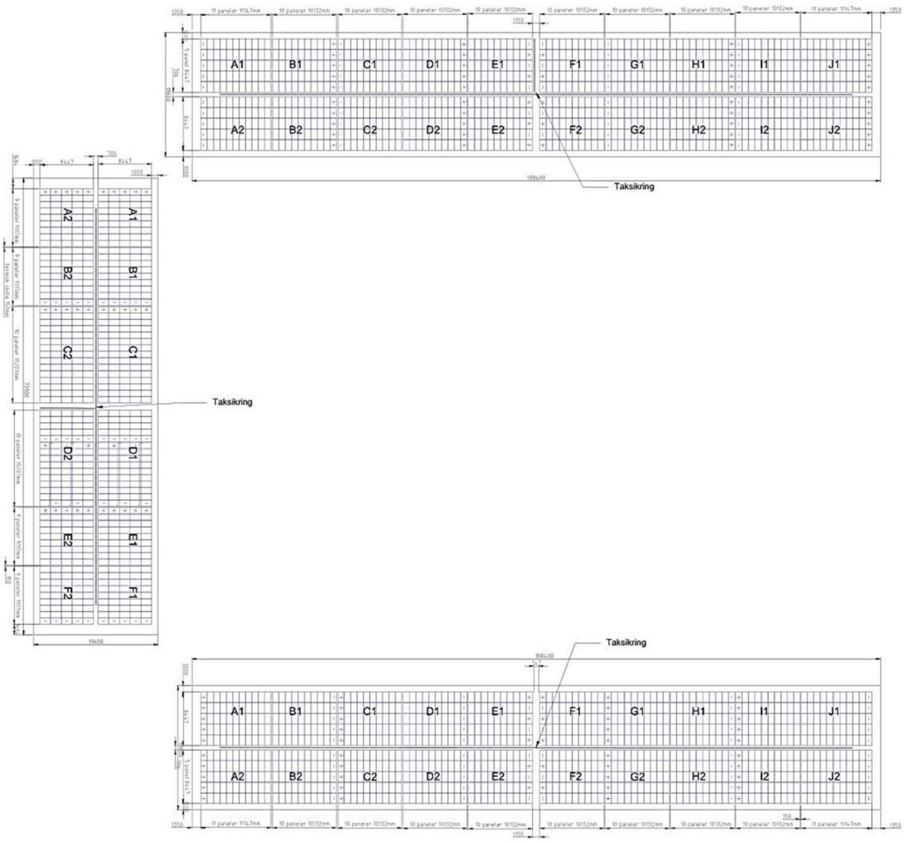

Figure 15: Overview of the panel placement at Skagerak Arena

The panels are arranged in 135 strings. The western roof contains strings 1 to 50 and has a nominal power of 300.9 kWp, the southern roof contains strings 51 to 85 and has a nominal power of 198 kWp and lastly, the eastern roof contains strings 86 to 135 and has a nominal power of 300.9 kWp. All the panels are of the same size and the measurements of the panels can be viewed in figure 16. The electrical data for the panels can be read from table 1. Both the measurements and the electrical data were obtained directly from Skagerak Energy lab. The nominal power of the panels is 295 Wp and 300Wp due to their specifications. The panels are connected to inverters that convert the 1000V DC from the panels into 400V AC that is used in the main power grid.

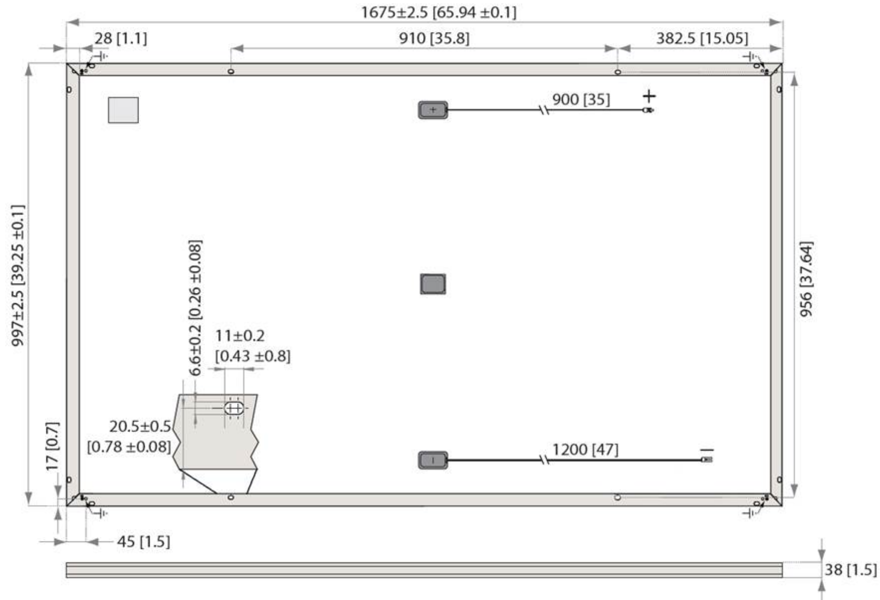

Figure 16: Measurements of the solar panels

Table 1: Electrical data for the solar panels

Nominal Power - $P_{MPP}(WP)$	275	280	285	290	295	300
Watt Class Sorting (W)	-0/+5	-0/+5	-0/+5	-0/+5	-0/+5	-0/+5
Nominal Power Voltage - $V_{MPP}(V)$	31.5	31.7	31.9	32.1	32.3	32.5
Nominal Power Current - $I_{MPP}(A)$	8.74	8.84	8.95	9.05	9.14	9.24
Open Circuit Voltage - $V_{OC}(V)$	38.2	38.4	38.6	38.8	39	39.2
Short Circuit Current - $I_{SC}(A)$	9.52	9.61	9.66	9.71	9.76	9.82
Panel Efficiency (%)	16.5	16.8	17.1	17.4	17.7	18

The panels have different orientations depending on where they are installed. They all have the same tilt at 8°, but different azimuth orientations depending on the roof they are installed on. The panels at the southern roof have a azimuth of $-20°$, The western roof 70° and the eastern roof has a $-110°$ azimuth.

A principal sketch of the energy system with solar cells, energy storage and local customers are demonstrated in figure 17. The energy supply of the football stadium is connected to two transformer kiosks: The local production to the first one and energy storage to the other. To achieve power equalisation, energy storage is connected to the second kiosk, which further carries the spotlight during the matches. Both transformer kiosks are connected via the electrical substation connected to the regional grid.

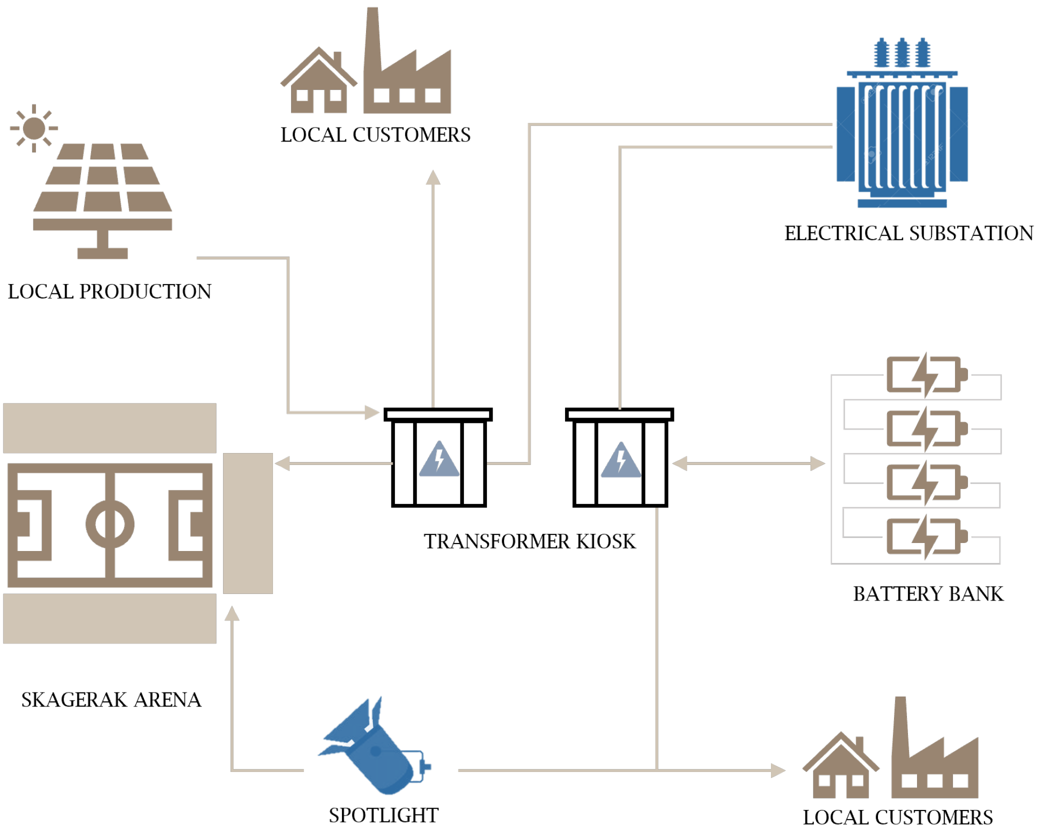

Figure 17: Principal sketch, adapted from [101, 102]

3.1.2 Energy Storage Specifications

The energy storage for Skagerak Arena is located in a building adjacent to the the arena. The energy storage is manufactured by Samsung and is made up of lithium-ion batteries that in total can provide 800 kW with a total storing capacity of 1000 kWh. The building where the batteries are located contains the control system for the entire plant. The batteries are connected to combined inverters and rectifiers which enables both charging and discharging of the batteries to the main power line. The main objective of the energy storage is to store surplus production and even out the power peaks that can occur when all the lights in the arena are turned on and the power consumption in the arena is at the highest. The specifications regarding the batteries are received directly from Skagerak Energy Lab.

3.2 Information Regarding the Residential Area

Skagerak Energy Lab has access to the consumption data for several of the housing units in the residential area surrounding the arena. There are different kinds of living facilities such as detached houses, care homes, apartments and townhouses, and they all have different energy profiles. For the research question, seven different customer groups were selected by Skagerak Energy Lab. The different categories of customer groups are described in table 2 and visualised in figure 18.

Table 2: The seven different consumer groups provided by Skagerak Energy Lab

Group	Type of housing	Amount	Specification
1	Apartment	19	With district heating
2	Apartment	20	
3	Townhouse	18	From the 1970s
4	Care home	18	
5	Detached house	5	Old building, without electric cars
6	Detached house	3	Old building, with electric cars
7	Detached house	1	New building, with electric cars

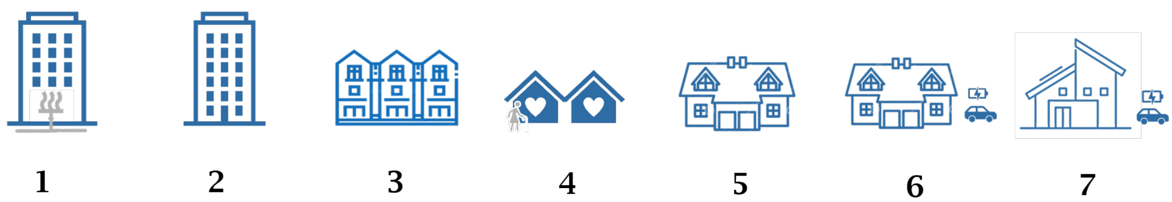

Figure 18: Visualisation of the seven different consumer groups, adapted from [102]

The provided housing units are all anonymous, so the location and number of residents are unknown. This does not apply for group one, which is the apartments connected to the stadium. Their location is known, but not the number of tenants. The specifications regarding the houses are rather vague. It is estimated by Skagerak Energy Lab that the old houses are built in the 1960s and 70s, while the new houses are built later than the year 2000.

3.3 Software and Data Collection Methods Used by Skagerak Energy Lab

Skagerak Energy Lab takes advantage of smart meter technology as it is a useful analysis tool for optimising the electricity grid and collecting data for further analysis.

3.3.1 Azure Data Explorer

Data extraction of the production is mostly done through the software Azure Data Explorer (ADE). This is a service for real-time analysis of large data volumes that, among other things, identifies patterns, trends and deviations. ADE has the great trait of storing as well as improving products [103]. Data is internally stored at Skagerak in Avro format in ADE [104].

Data that includes solar production, consumption, and the battery can be available to third parties via Application Programming Interface (API) solution. API can be used to exchange data between different systems or apps. The systems can communicate through an API integration even without humans involved [105]. Avro files provide a smooth transition for data exchange between programs regardless of language. The storage is kept efficient and compact.

3.3.2 Micro Scada X

MicroSCADA X is created by Hitachi Energy, established in 2018. The control system of Skagerak Energy lab uses MicroScada for network control and full utilisation of present and future potential. The software has the features of visualising the power network, guarding the safety and gives a great insight into the operations anywhere at any time. The operating system controls all interactions across the electrical utilities, renewable sources, infrastructure, industries and transportation [106]. On an overall basis, it gives an oversight of functionalities integrated within a single platform.

The program is formed on logical navigation and data handling based on algorithms. Developed on the same configurations, the systems software also has the qualification of fast troubleshooting in operations. The attribution of information collection of photovoltaic solar cells, power inverters and meteorological sensors are counted. With all functions integrated into one platform, the algorithms also optimise the scheduling of equipment. Comprehensively, this provides a clean and safe delivery and the greatest possible efficiency in the generation and maintenance of the electrical infrastructure.

4 Methodology

The description of what was done and how it was done is carried out in this segment and is aimed to give a deeper understanding of the procedure. The evaluation of reliability of the methodological approach is regularly followed during this process to justify methodological choices. The introduction of instruments used for data collection and calculations is further explained. Further, this part highlights the most relevant approach for the research question while the more detailed procedures with accurate calculations can be found appendix A.

4.1 Empirical Analysis and Quantitative Research

The study is written as an empirical analysis with an evidence-based approach and interpretation of information. The study is based on real-world data, metrics and results, rather than theories and concepts. The data received from Skagerak Energy lab is perceived to be reliable and factual from satisfactory sources. The research is quantitative and although the entire data can't be compared to previous years, the amount of data that is comparable is satisfactory. The data can also be compared to data from different locations in Norway and nationwide averages.

4.2 Data Collection and Processing Methods

4.2.1 Data collection

The collection of data provided by Skagerak has been processed since 2018. Due to several challenges with the inverters, the most stable production data is retrieved from 2020 while the steadiest data of consumption is from 2021. A large amount of data is required to answer the research question. To be able to collect and analyse the data several tools, smart meters, and programs were used.

Data collection was an ongoing process throughout the project. Skagerak Energy Lab started by giving the data regarding the electricity demand and production. While the data was being analysed several questions arose and additional data and information were needed. This resulted in a request regarding the specifications of the solar panel's electrical data and measurements, as well as the details regarding the energy storage. When writing the theoretical basis there were different kinds of information that were deemed necessary. The data collection methods needed to be elaborated on, and different information regarding the residential area and the housing units was needed.

The data regarding electricity production and demand comes directly from Skagerak Energy Lab which is a reliable source.

4.2.2 Matlab

To process and analyse the large amounts of data Skagerak Energy Lab provided, Matlab was used. Matlab is a widely used software tool for numerical mathematics. The software can be used to solve problems such as linear equations, differential equations, polynomials and integration. The functionality of Matlab can be expanded by adding toolboxes that are designed to solve more specific problems. It is also possible to construct self-made functions designed for highly specific tasks to make problem-solving easier. In this specific study, Matlab has been mostly used for matrix calculations to different degrees and plotting in different forms. Matlab contains commands for plotting and graphing in two and three dimensions and all images can be exported for use in publications [107].

4.3 Electricity production and Demand

4.3.1 Average Electricity Demand

Seven different consumer groups, with a different number of individual houses, and their yearly energy consumption in an hourly-based resolution were provided by Skagerak Energy Lab. By combining the energy consumption from the different houses in each group and dividing them by the number of housing units, an average customer from each group was created, still in an hourly-based resolution.

By summing the consumption vectors for the different average customers, the total consumption for each group was calculated. All of the calculations were done in Matlab, the codes that were used can be viewed in appendix A.1.

4.3.2 Electricity Production at Skagerak Arena

Skagerak Energy lab provided the total production data from 2020 for all the solar panels in an hourly-based resolution. By summing up the individual hour based production the total production at Skagerak Arena could be calculated. By finding the hours belonging to the different months of the year the production could be divided into seasons to be further analysed and compared. Spring is set from March to May, summer is June to August, autumn is set from September to November and winter is December to February. The hours of the year, with the corresponding month, can be read from table 3. The production was also divided into six months intervals that stretched from April to September and October to March.

Table 3: Hours of the year distributed to the corresponding month

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of hours	744	672	744	720	744	720	744	744	720	744	720	744
Cumulative dist.	744	1 416	2 160	2 880	3624	4 344	5 088	5 832	6 552	7 296	8 016	8 760

4.4 Code to Calculate the Battery Capacity

Several different battery capacities needed to be found to answer the research question. The solution to this was a code that could handle large amounts of data and with a few inputs would have the battery capacity as an output. The code needed the yearly energy demand as well as the electricity production, both in an hourly-based resolution. By creating a ”reduced demand vector”, which is the demand vector subtracted from the production vector, it was possible to see when the demand was higher than the production. Whenever the demand is larger than the production, a battery is needed to cover the difference. If the production is too low for several hours, the needed battery capacity increases. The code created a cumulative distribution of the reduced demand vector, that would stop adding value if the sum went above zero, this represented zero battery capacity. By analysing the cumulative distribution and finding the lowest value in the vector, the needed battery capacity could be set. The code used to calculate the different battery capacities can be seen in appendix A.4. A visualisation of the needed battery capacity can be viewed in figure 19. The shaded part represents the period when the demand is larger than the production. The capacity of the battery needs to be equal or larger than the area of the shaded zone.

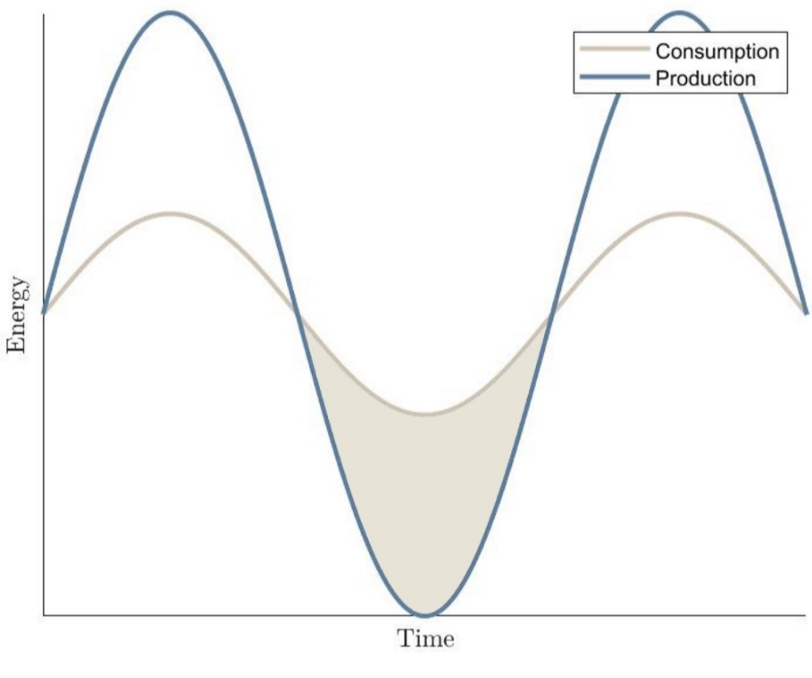

Figure 19: Visualisation of the required battery capacity

4.5 Off-Grid Scenario

4.5.1 Minimum Number of Panels to Cover Yearly Electricity Demand

To find the minimum number of panels to cover the yearly electricity demand, the total electricity demand for the average customer was used. By dividing the total electricity demand by the production from one solar panel and rounding the result up, the minimum required number of panels could be found.

4.5.2 Battery Capacity Required For the Minimum Number of Panels

The code from section 4.4 was used to find the required battery capacity for the minimum number of panels. By using the production from the previously calculated number of minimum panels for each group. The code could utilise the reduced demand and delivered the required battery capacity for each group.

4.5.3 Housing Units Supplied by Skagerak Arena

To find the number of housing units from each customer group that could be supplied off-grid with the existing system at Skagerak Arena, the Matlab code from section 4.4 was used. By a process of elimination it was possible to see how many customers there could be at one time. The process started off by looking at one customer from a given group. In the first calculation the costumer would have access to all of the panels and the entire battery capacity. If the battery never emptied throughout the year, it meant it was possible to increase the number of customers. When there were two customers, the number of panels and battery capacity would be divided by two. The calculation would still revolve around one costumer, now with access to half of the panels and half of the battery capacity. If the battery still never went completely empty throughout the year, yet another customer could be added. When there were three customers, the number of available panels and the battery capacity would be divided by three and so on. When the battery was emptied and presented as a negative number in the code, there was too many customers and the number of supplied housing units had to be reduced. The graph representing the number of panels and battery capacity per costumer is a decreasing exponential graph.

4.6 On-Grid scenario

4.6.1 System Specifications

The scenario regarding the on-grid system took into consideration the consumption data for costumer group one, the apartments with district heating. The aim of the scenario was to have a system which could supply all of the apartments in the building with enough electricity to be self-sustainable for the two sunniest months of the year, June and July. To be able to achieve this the consumption data and the production data had to match for June and July.

4.6.2 System Pricing

To get realistic prices for the different components of the on-grid system, extensive research were done. Several estimates and assumptions were made based on the research. After several online searches, e-mails and telephone conversations with relevant Norwegian companies and suppliers, the company with the most complete and accessible deals and prices was Otovo AS [108].

With constant conversations and follow-ups, the needed data was obtained. Values such as number of panels and panel type, estimated annual production, savings and total system cost was received directly from Otovo AS. The data received from the firm was used for all of the economical and environmental calculations. The received values are presented in table 4.

Table 4: Economical and technical information received from Otovo AS

Nominal Power of the Panels	360 W_p
Number of Panels	60
Yearly Production	14 100 kWh
Savings	25 000 NOK/Year
Carbon Footprint	600-800 $kgCO_2$/kWp

By utilising the values received from Otovo AS and the production data from Skagerak Energy Lab, an estimate for the expenses associated with the panels at Skagerak Arena could be made. The values regarding production, savings and carbon footprint received from Otovo AS were related to 360 Wp panels, and the panels at Skagerak Arena are 300 Wp.

The price is a comprehensive amount for the whole system and is given by tender. Exact prices for the components are not commonly given, but for an indication of the distribution of expenses, a master's thesis regarding cost evaluation of photovoltaic solar cell integration in a Norwegian commercial building was used [109].

4.6.3 Direct Income

Income was made directly by selling the overproduction to the electricity grid. Spot prices had to be collected, considering the electricity prices changes hourly. The spot prices were obtained from Nord Pool AS, a pan-European power exchange [110]. The data was hourly based and had to be assembled into a vector.

First, to find the direct income calculations, calculations were made on the overproduction. The overproduction was found by subtracting the consumption vector from the vector representing the production data from the calculated number of required PV panels, both in an hour based resolution. Then the positive numbers of the overproduction vector was multiplied with the spot price vector, to make an income vector. In comparison to the consumption data, the production is quite small so the income vector will not be substantial before being added up. The final sum of the income vector is the direct income of the system.

4.6.4 Economy final values

The net present value was calculated using equation 1. The calculation is repeated with an increasing number of time periods until a positive value is achieved. The number of times the calculation has to be repeated, until it turns positive, is the number of years it takes before the system is paid off. The calculations were done in Excel spreadsheet containing the discount rate.

When the payback period was set, the net income after said period could be calculated. The net income was calculated by subtracting the system cost and the maintenance cost from the final net present value.

The maintenance cost was calculated by using equation 2. The already estimated system price was multiplied by a constant, with the value of 1%, an assumption given from a professor's work experience. The equation was repeated for each year of the expected lifetime of the system. The lifetime of the system was set to thirty years.

4.7 Carbon Footprint of the System

Information regarding the carbon footprint of the system was given by the supplier of the PV panels Otovo AS. The CO_2 equivalents per kilowatt peak produced were stated to be in an interval between 600 to 800 kg CO_2/kWp. By this premise, it was possible to calculate grams CO_2eq per kilowatt-hour. By multiplying the emissions per nominal power (Wp) produced, by the total nominal power of the system, the total emissions related to production were calculated. By then dividing the production emissions by the amount of energy produced in the entire lifetime of the system, the emissions in CO_2eq per kilowatt-hour could be calculated.

5 Results

This section interprets the results of this study. The outcome commences with an overall view and visualisation of the analysis of consumption and demand data, further presenting the results of the research question. The general order of the results is based on the sequence of the calculations as shown in the methodological chapter. Predominantly, the most compelling results are presented in charts, tables, graphs and other figures. The visual presentations will form a better understanding at the same time as they correspond to the central research questions.

5.1 Electricity Demand and Production

5.1.1 Electricity Demand

The sum of the yearly energy demand from the different consumer groups can be viewed in figure 20. The detached houses have by far the largest energy consumption and the apartments with district heating have the lowest. It can also be viewed that the older detached houses *without* electric cars (group five) have a larger energy consumption than the newer houses *with* electric cars (group seven).

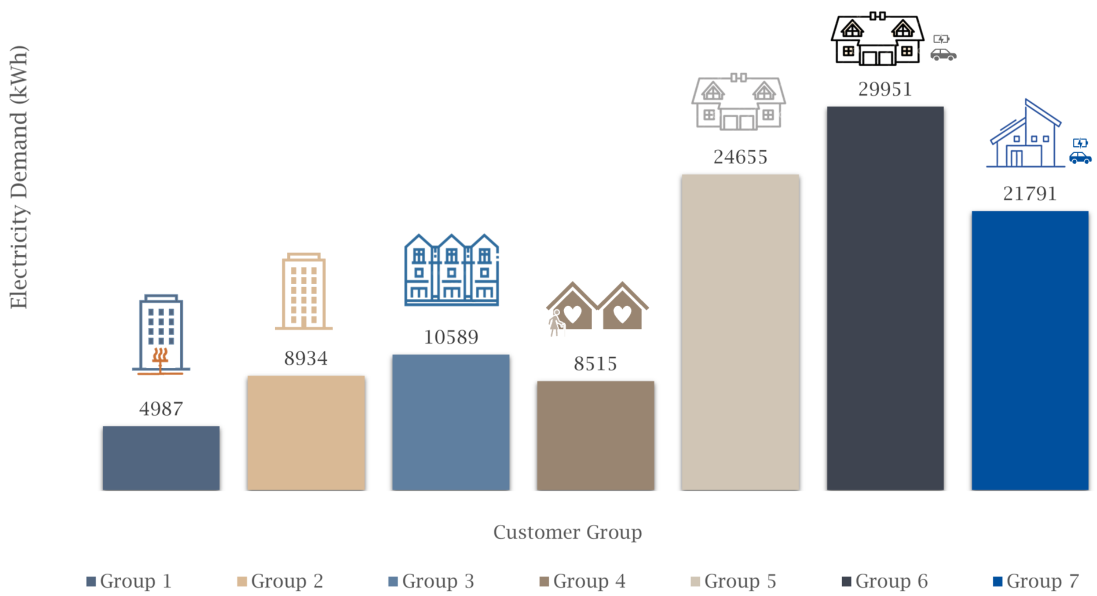

Figure 20: Sum of the average electricity demand per household from the different customer groups

There is a large difference in the electricity demand throughout the year. Figure 21 visualises the electricity demand for the different months of the year. The detached houses have a much larger variation in demand depending on the season than the smaller apartments and townhouses. The apartments utilising district heating have the most stable energy demand. The increase in electricity demand in the winter months stems from the rising heating demand, which does not heavily affect group one since almost all of the heating demand is covered by district heating and thereby the more stable curve. All of the calculations done regarding the demand can be viewed in appendix A.1.

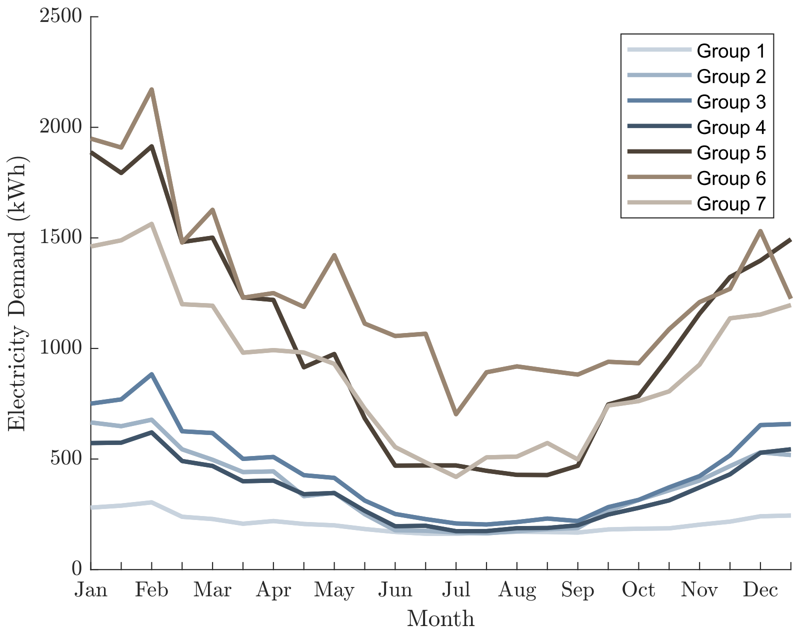

Figure 21: Average electricity demand per household for the different customer groups

5.1.2 Electricity Production

The solar panels at Skagerak Arena produced roughly 680 000 kWh in 2020. The main part of the production naturally occurred in the summer when there were the most sun hours. The percentage of the total production divided into the different seasons as well as in the summer half of the year and the winter half can be viewed in figure 22. The calculations done regarding the electricity production can be viewed in appendix A.2.

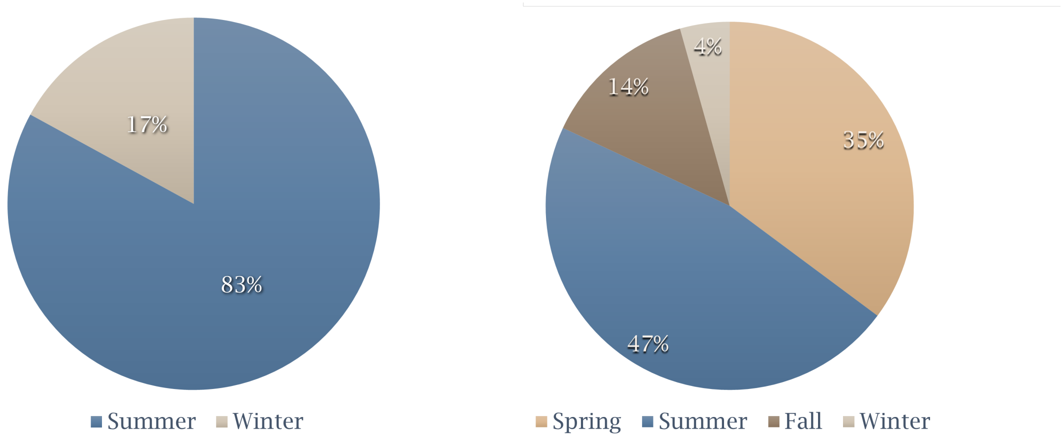

Figure 22: Electricity production divided by six months intervals and by seasons

By dividing the total produced energy by the number of solar panels (2 700), it could be calculated that the average production from one solar panel was 250 kWh a year.

5.2 Off-Grid scenarios

5.2.1 Minimum Number of Required Panels

The minimum number of required solar panels to cover the yearly electricity demand for the average customer from each group was calculated using the code in appendix A.3. The required number of panels for an average customer from each group can be read from table 5.

Table 5: Panels needed to cover exact energy consumption per average customer

Group	1	2	3	4	5	6	7
Panels	20	36	42	34	98	119	87

Between the months of March to September, 83% of the energy is produced. In opposition, the energy consumption reaches the highest point in the winter when it is cold and a larger need for heating. The curve describing the production and consumption of energy for the one customer in the first customer group, with 20 panels, can be viewed in figure 23.

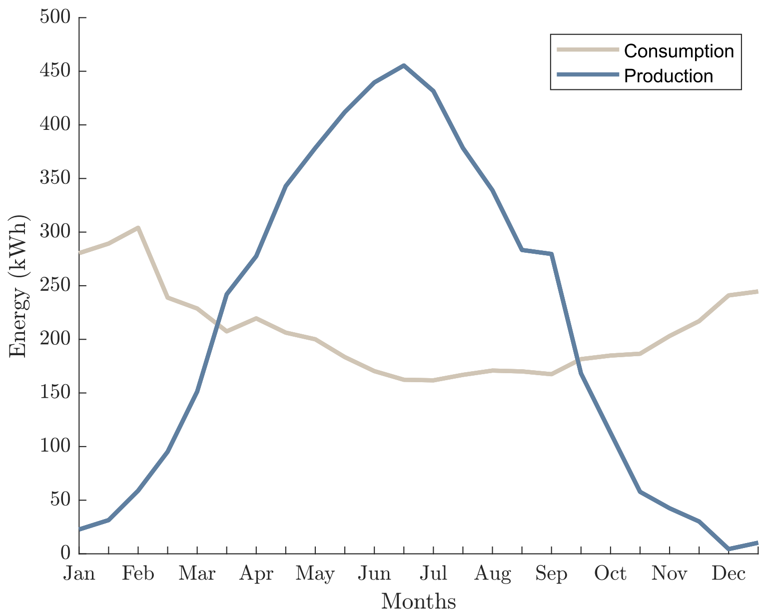

Figure 23: Comparison between produced electricity and electricity consumption for the average customer in group one

The panels cover the exact amount of electricity needed throughout the year, but the amount of overproduction in the summer is too large for any battery to handle and the energy available in the winter ends up being too low. This will be further elaborated on in section 6.2.

If the different housing units were to have the number of panels described in table 5, the batteries would have to be able to store an unreasonable magnitude of energy to be able to supply the houses throughout the winter. The required capacity for the batteries can be read in table 6.

Table 6: Capacity needed to cover exact energy consumption per group

Customer Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Minimum panels	20	36	42	34	98	119	87
Capacity (kWh)	2 070	4 600	5 370	4 220	12 900	13 000	10 400

5.2.2 Housing Units Supplied by Skagerak Arena

To answer the research question of how many housing units from each group that could be supplied by Skagerak Arena without additional electricity supply from the grid, the code from appendix A.5 was used. The number of housing units, solar panels per customer, actual battery capacity per customer, and required battery capacity per customer can be read from table 7. The battery capacity and the number of panels which correspond to the different numbers of supplied housing units can be viewed in figure 24.

Table 7: Number of housing units that can be supplied by the existing system.

Customer Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Supplied Housing Units	5	2	2	2	0	0	1
Number of Panels per Housing Unit	540	1 350	1 350	1 350	2 700	2 700	2700
Actual Battery Capacity (kWh)	200	500	500	500	X	X	1 000
Required Battery Capacity (kWh)	173	330	490	347	1 187	1 216	783

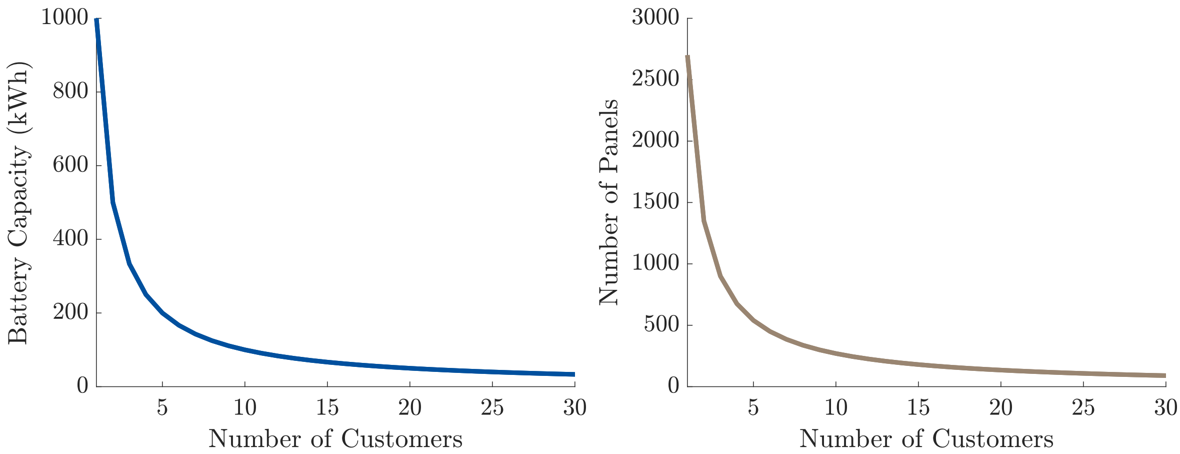

Figure 24: Number of panels and battery capacity per customer

Customer groups five and six resulted in zero houses supplied. The large demand in the winter is simply too big for the system to handle.

If an average customer from the different groups was to have the number of panels described in table 7, the overproduction throughout the year would be substantial. Table 8 shows the overproduction for the different average customers and how much of the total yearly electricity demand it covers, in percentage.

Table 8: Over production for the different customer groups

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Over prod. (kWh)	131 250	331 650	329 990	332 070	656 510	651 210	659 370
Pct. of demand (%)	2 732	3 812	3 216	3 999	2 763	2 274	3 125

Figure 25 describes the electricity demand and production for an average customer in group five. The graph on the right is a magnified figure of the graph on the left and shows the period where the production is lower than the demand for the longest time. This period is what decides the required battery capacity as explained in section 4.4. The period stretches from the 30th of November to the 30th of December.

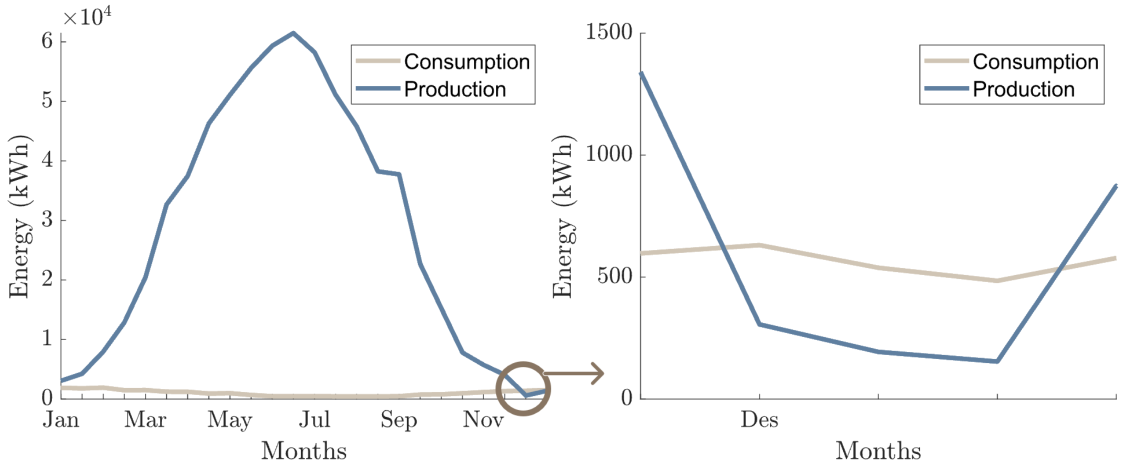

Figure 25: Electricity demand for group five and production from 2 700 solar panels

5.3 On-Grid Scenario

5.3.1 Structure of the System

Figure 26 illustrates the most significant components of the on-grid system. To be able to utilise the electricity produced by the solar panels, the current has to go through several components. First, the different wires attached to the different solar panels have to be combined into one output cable. This is where the combiner comes in. The combiner is connected to a charge controller which throttles any danger or cut-offs in the circuit. When there is one single cable of power the line goes into the inverter, which changes the current from DC into AC. From there, the current can go directly to the customer or to the utility grid.

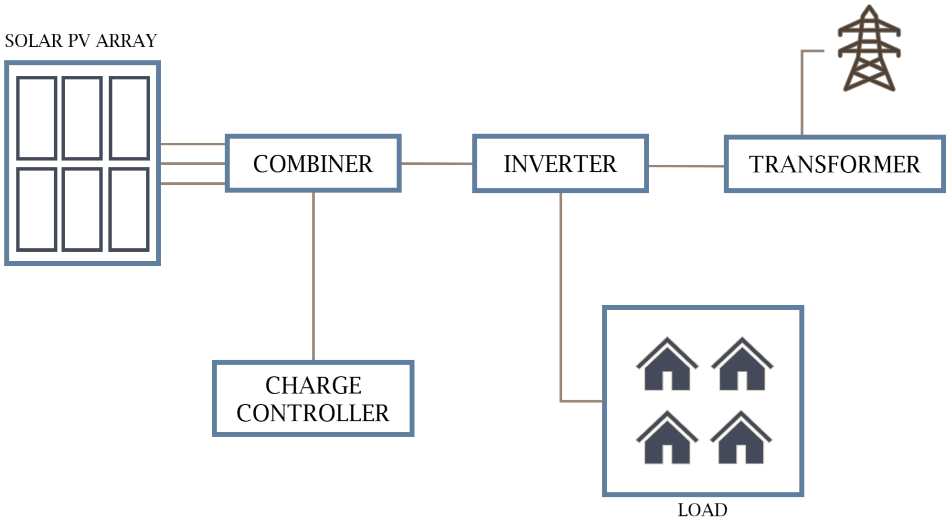

Figure 26: Simplified sketch of on-grid system, adapted from [102]

The system was able to produce roughly 50% of the annual electricity demand for the apartment complex. A visualisation of the consumption from the 19 apartments and the production from 190 PV panels can be viewed in figure 27. There is some overproduction during the summer, which gets sold to the grid.

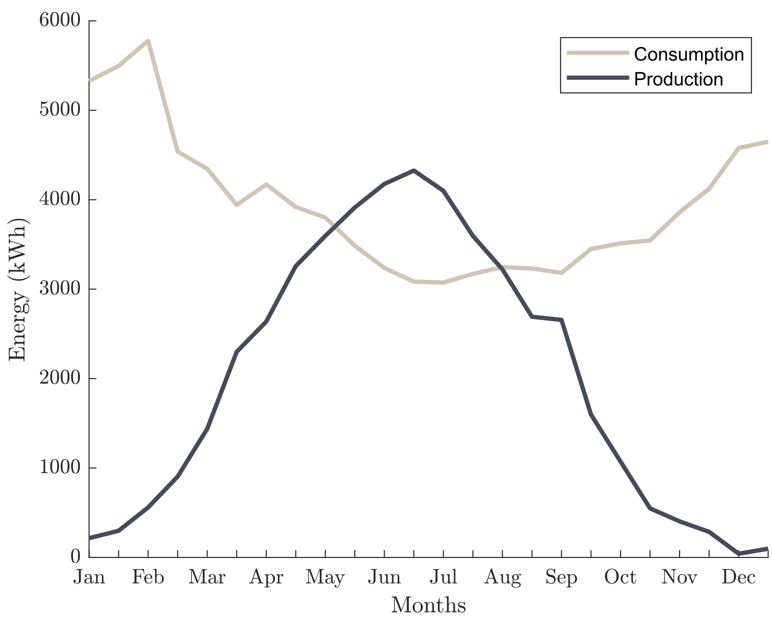

Figure 27: Electricity consuption from 19 apartments and production from 190 PV panels

5.3.2 System Cost

The total cost for the entire system, with 190 installed solar panels and an on-grid connection, is 1 381 000 NOK. The price for the different components, as well as the corresponding percentage of the overall system costs, can be seen in table 9. Approximately 50% of the total expenses consist of the solar cell modules and the assembly.

Table 9: System Cost

Cost Type	Cost Item	Price (NOK)	Share of Price
Material	Solar Cell Module (190) + assembly	635 000	46%
	Power Cables	28 000	2%
	Inverter	193 000	14%
	Operation Monitoring Equipment	165 000	12%
Installation	Connection to the Fuse Box and Grid	360 000	26%
Total	System Price	1 381 000	100%

5.3.3 Earnings

With a number of 190 PV panels and an electricity price of 1.65 NOK/kWh, the direct income due to overproduction, was calculated to be 2 012 NOK/year. The net cost saved data retrieved from the supplier was estimated to be 93 500 NOK and the net present value, after the calculated payback period of thirty years was 3 250 NOK. The maintenance cost resulted in 238 000 NOK during the lifetime of the system. All of the data retrieved directly by mail from Otovo AS can be viewed in appendix B.1.

5.3.4 Environment Impact

The carbon emissions related to the production of the solar panels was set to be between 600 to 800 kg CO_2eq per kilowatt peak. An estimate of 700 kg CO_2eq per kilowatt peak was used for the calculations. The corresponding emissions related to the production was calculated to be 27 g CO_2eq per kilowatt-hours.

6 Discussion

The discussion reflects the different topics and aspects presented in the previous chapters and assembles them together to form a comprehensive understanding for the different results. The different scenarios get reflected upon and are further looked into by being compared and considered in a broader perspective.

6.1 Electricity Production and Demand

To be able to get a better understanding of the different scenarios, the electricity demand and production had to first be analysed. The electricity production was at its highest in the summer months and hit peak production in June. This is logical when compared to the graph in figure 13. The amount of sun hours during the day is directly linked to the amount of produced electricity from solar panels.

In regard to electricity demand, the year 2021 was unlike previous years. When the pandemic hit a lot of people were told to work from home. This resulted to a different energy profile in the daytime. When people normally would go to work and turn off several appliances at home, they would now instead work from the home office. The consequence of this was a higher electricity demand throughout the day.

The different customer groups, provided by Skagerak Energy Lab, had vastly different electricity demands. This was expected as the housing units were of different types, sizes and ages. The detached houses used the most electricity. This is reasonable as they have larger space for domestic heat and likely more residents than the smaller apartments. All of the housing units, apart from customer group one, are anonymous for privacy reasons. Due to this, it has not been possible to verify the different sizes in indoor areas and numbers of residents. Assumptions were made regarding how the electricity was utilised. However, there was some information regarding the different customer groups, and assumptions were made based on those. Customer groups five, six and seven are detached houses. Customer groups five and six are to be placed under the category of old houses, estimated to be built somewhere in the 60s or 70s. Customer group seven was based on a single house which is regarded as a new house built after the year 2000. The groups containing the old houses used more electricity than the new house, even though the new house has a home charging station for their car and one of the groups (group five) of old houses does not.

A reason for the difference in electricity consumption, could be the insulation in the houses. Figure 8 describes the difference in insulation from the 60s to 2000s. As mentioned in section 2.2.2, the insulation in buildings has gotten thicker and better as the standards have improved and can have a large impact on the overall energy consumption in a house. If the old houses never got new insulation in their walls or roofs after the houses got constructed, there could be a large potential for energy savings in form of reduced heat transfer through the walls and roofs. Another factor that can contribute to larger electricity demand, is the appliances and lighting choices. New houses have a higher chance of having appliances and lighting that are made to conserve energy, seeing as this is a more important feature now than what it used to be. The old houses might have appliances that are quite old and do not follow the modern requirements described in section 2.2.3. New appliances could save a lot of energy in comparison to the old. However, it is not automatically a greener choice to switch to a new and more energy-efficient appliance. The new appliance has to be made, and a lot of energy and materials have to be produced to do so.

As mentioned earlier, are all things considered made up of assumptions as to why customer groups five and six have a higher electricity demand than group seven. The old houses might cover a much larger indoor area and have double the amount of residents compared to the house in group seven. From previous research, it is a probable estimate that the old houses have thinner insulation.

Groups one and two are both apartments, estimated to be built in the same decade, with the key difference of heating type. Group one has district heating and group two has electric heating. With an assumption that the average size of the apartments is relatively similar, the difference in electricity consumption is quite large. From figure 21 it is possible to see that the electricity demand in the summer is almost identical for groups one and two, but in the winter the demand for group two increases twofold. While the demand for group one has only a small increase and is much more stable throughout the year. This is due to the district heating and it is safe to assume that almost the entire increase in group twos electricity demand is caused due to electric heating.

6.2 Assessment of Off-Grid Scenarios

The different scenarios regarding an off-grid system were related to the minimum number of required solar panels to cover the electricity need, and how many housing units which could be supplied by the existing system at Skagerak Arena.

The minimum number of required solar panels to cover the annual electricity demand resulted in batteries with unreasonable high capacities for all of the different customer groups. This is caused due to the Nordic climate and the restricted amount of sun hours in the winter. Figure 22 shows that 83% of the production happens between the beginning of April and end of September when compared to the graph in figure 21, which describes the electricity demand for all of the different groups; It can be observed that peak production and peak demand are at completely different times of the year. The consequence of this is that the electricity produced in the summer has to be stored until the winter when it is needed. From table 6 the different battery capacities for the minimum number of panels can be viewed. If the average customer from group one was to have the number of panels that produce exactly the amount of electricity that is required throughout the year, the batteries would have to be twice the capacity of what Skagerak Energy Lab uses to supply

Skagerak Arena (1 000 kWh). A customer from group six would need batteries thirteen times the size. This would neither be economical nor environmentally sustainable. The batteries would need a large space to be stored safely and would cost more than all of the solar panels combined. Skagerak Energy Lab has a small building designated for their battery bank, so their battery capacity is by no means small.

Compared to the scenario involving the minimum number of required panels, the existing system at Skagerak Arena can supply a large number of panels, but with a much smaller battery capacity. The battery capacity at Skagerak Arena is not small by any means, but the demand is simply too large. As explained in section 4.5.3, when the number of housing units increases, the number of solar panels and battery capacity per customer will decrease. Since the number of solar panels, that are available at the arena, is relatively large and produces enough total electricity to supply all of the housing units, the battery capacity causes the problem. Once again the Nordic condition has to be mentioned as to why there is so little production in the winter. There are simply not enough sun hours to maintain enough production. This means there has to be a large number of panels to compensate for the capacity. The panels have to produce enough electricity to cover a substantial amount of the demand in the winter.

Table 7 shows how many housing units from each group that can be supplied. Group five and six had such a high demand in the winter that not even one house can be supplied. They do, however, have an enormous overproduction in all of the other months of the year. This means a large amount of energy get lost as the housing units are not connected to the grid and there are no other energy storage facilities that can be used. Figure 25 shows how much overproduction there is for a single customer in group 5 throughout the year and how it is of no use in the winter when the battery capacity is too small. This is in no way economically or environmentally sustainable. The sheer amount of energy that is needed to purify the silicon for the solar panels is immense, as explained in section 2.1.1. It is simply not a good option to only have one source of electricity production, especially when the source is solar power and the system is located far north. None of the 17 SDGs set by the UN would be achieved by the off-grid system. The energy would come from a renewable source, but would not be sustainable due to the inefficient way of using it.

If the system had another source of power, such as wind or district heating, the houses might get through the winter with a lot fewer solar panels than what is necessary today. District heating could even out the electricity demand and lower the electric heating demand drastically. This can be observed in figure 21, where group one has district heating and the electricity demand throughout the year is a lot more even than that for any of the other groups. Another option would be to look at different energy storage options. If a solution was found regarding seasonal energy storage, the off-grid option could have the potential to be profitable. This can be quite challenging, as energy storage is one of the major challenges concerning renewable energy. Flywheels, as described in section 2.3.1, can be utilised to store energy from day to night, but it will not solve the seasonal storage problem. Seasonal storage is usually done on a much larger scale, such as with pumped hydroelectric storage or compressed air. To be able to use these methods a large area is needed as well as a substantial amount of equipment and the necessary facilities, which is not a realistic scenario for a small scale off-grid plant.

A possible solution can be an integration of thermal storage and district heating. By utilising the large surplus of electricity in the summer and heating a storage medium by the use of heat pumps or electric heaters, the energy can be stored for months and utilised when the demand is higher. Considering the fact that the heating demand is the largest part of the energy demand during the winter, the energy does not have to be converted back into electricity. Converting thermal energy into electricity can be difficult and some of the energy will be lost to the surrounding. By utilising thermal storage a large part of the energy demand in the winter is covered and the demand is split into different forms of energy. By not solely relying on one form of energy, the energy supply is not as vulnerable to sudden changes and downtime in production. The batteries can still be used for the parts of the energy demand which can not be met with thermal energy. By using sensible or latent heat storage, as explained in section 2.3.1, it might be possible to store some of the energy generated in the summer and bring it into the winter. This can be a costly project, and might not be realistic for a single house.

6.3 On-grid scenario

The on-grid scenario is a more realistic scenario when compared to the off-grid options. It is becoming more popular in Norway to produce electricity privately, as the price for electricity climbs and solar panels are becoming cheaper, as mentioned in section 1.1. The scenario builds on the idea that an apartment complex has bought enough solar panels to cover almost all of the consumption during the sunniest summer months for the 19 apartments. To be able to achieve this, 190 panels were required, as well as an inverter and some other components. The total system price came to be 1 381 000 NOK. This is a considerable sum of money and if the price of electricity remains on the same level, it will take thirty years before the investment is financially profitable. There are, however, predictions that the electricity price will continue to rise as the difference between supply and demand continue to grow in the European market. If this happens, it will become more profitable to produce electricity privately.

The maintenance cost was based on an assumption that 1% of the total system cost would go towards maintaining the system. This is a broad assumption considering all the different factors that can affect maintenance. changes in the climate can lead to damage caused by weather, such as hail and lightning, high humidity can lead to rust, different types of roofs can lead to different expenses related to repairs etc. The maintenance costs can be higher or lower than the estimated value and would have a direct effect on the overall costs.

Another aspect of the on-grid scenario is the environmental impact. The company that supplied the solar panels stated that the emissions related to the production were around 600-800 $kgCO_2eq/kWp$. By some calculations, the units could be changed to

CO_2eq/kWh, which is the unit used to evaluate the energy mix and its sustainability. The solar panels in the on-grid scenario resulted in emissions of 27 gCO_2eq/kWh. Compared to the Norwegian energy mix, which is at 17 gCO_2eq/kWh, the on-grid system has slightly higher emissions during its lifetime, that do not mean they are not environmentally sustainable. The Norwegian energy mix is simply *too* clean to beat. Section 1.1.1 mentions that 98% of the electricity produced in Norway comes from hydro-power and that Norway has the largest share of renewable energy as well as the lowest emissions from the power section in all of Europe. Comparing to the Norwegian energy mix is simply therefore not equitable. However, when compared to the European energy mix, the situation of the panels look quite good. The European energy mix is at about 300 gCO_2eq/kWh and is a lot worse than 27 gCO_2eq/kWh, which the panels produce. In a different country, an on-grid system could be a great way of working towards the 7th sustainable development goal, affordable and clean energy for all.

7 Conclusion

The purpose of this thesis is to answer the different scenarios related to the research question:

"Potential for an off-grid power system supplying a residential area by using the existing PV system at Skagerak Arena.

(i) How many housing units, with different energy profiles, can be supplied without using additional energy from the grid? (ii) What would the specifications be if each customer had enough solar panels to cover the exact electricity demand through out the year? (iii) If the system were connected to the power grid, what would the economical aspects of self produced electricity be, and what environmental impact could it lead to? "

The data regarding the electricity consumption from the different housing units as well as the production data from Skagerak Arena was, provided by Skagerak Energy Lab.

The data for the electricity demand and production showed that the production and consumption are widely different throughout the year. When the production was at its highest, the demand was at its lowest. The different types of housing units showed large variations in electricity demand, both regarding difference in building type and in age. The old detached houses used far more electricity than the newer houses. This was discussed to be due to difference in insulation and appliances. The two groups which represented apartments, had a large variation in the energy profile. The apartments with district heating had a stable electricity demand throughout the year, while the apartments without district heating had a much larger electricity demand during the winter. The addition of thermal energy, in the form of district heating in the winter, made the electricity demand noticeably more stable throughout the year.

The scenario regarding the minimum number of required solar panels to cover the yearly electricity demand resulted in a sensible number of panels, but an unreasonable battery capacity. The amount of energy that had to be seasonally stored in the batteries from summer to winter was deemed unrealistic.

When looking at the existing system available at Skagerak Arena, the number of housing units from each group supplied was relatively small. Groups five and six had such a large electricity consumption in the winter that not even one housing unit could be supplied. The group that could have the largest number of housing units supplied was group one, the only group with district heating. For an off-grid plant to work during Nordic conditions, there has to be several sources of energy as well as energy storage that can hold the energy generated in the summer until it is needed during the winter. Having several energy sources will make the energy supply more stable and less vulnerable to abnormal weather and unforeseen hindrances in production. Having more than one way of storing energy is important to ensure a reliable supply even when there is no production.

Seasonal storage of energy is a challenge. A possible solution is thermal energy storage combined with district heating. By utilising the surplus electricity production in the summer, it is possible to make use of sensible or latent heat storage to store the energy as heat until it is needed. By combining the thermal energy storage with district heating it could be possible to cover parts, or all of the heating demand in the winter with energy generated in the summer.

The final scenario was focused on the economical and environmental aspects of self produced power with an on-grid system. The economical results were made using a large amount of assumptions and estimates, which has to be considered when looking at the results. The system had a payback period of thirty years, which barely made the system economical profitable. If the electricity prices keep rising, as they are predicted to, the system would become profitable at a faster rate. The environmental impact of the system amounted to 27 gCO_2eq/kWh, slightly worse than the Norwegian energy mix, but a lot better when compared to the European mix. An on-grid system have the potential of being a great way to achieve the 7th sustainable development goal, affordable and clean energy for all.

Bibliography

[1] Willem Gabriel Le Roux. "Optimum tilt and azimuth angles for fixed solar collectors in South Africa using measured data". In: *Renewable Energy* 96 (2016), pp. 603–612.

[2] Science Direct. *Irradiance*. URL: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/irradiance. (accessed 12.05.2022).

[3] Electrical Volt. *Difference between Rated,Nominal and Operating Voltage*. URL: https://www.electricalvolt.com/2019/12/difference-between-ratednominal-and-operating-voltage/. (accessed 30.03.2022).

[4] PV Education. *Open-Circuit Voltage*. URL: https://www.pveducation.org/pvcdrom/solar-cell-operation/open-circuit-voltage. (accessed 30.03.2022).

[5] PV Education. *Solar Cell Efficiency*. URL: https://www.pveducation.org/pvcdrom/solar-cell-operation/solar-cell-efficiency. (accessed 30.03.2022).

[6] PV Education. *Short-Circuit Current*. URL: https://www.pveducation.org/pvcdrom/solar-cell-operation/short-circuit-current. (accessed 30.03.2022).

[7] Alternative Energy Tutorials. *Standard Test Conditions*. URL: https://www.alternative-energy-tutorials.com/photovoltaics/standard-test-conditions.html. (accessed 29.03.2022).

[8] Statkraft. *Statkrafts Lavutslippsscenario 2020*. URL: https://www.statkraft.no/globalassets/0/.no/barekraft/var-rapportering-om-barekraft/nedlastningsarkiv/2020/statskrafts_lavutslippsscenario_2020_digital.pdf. (accessed 14.05.2022).

[9] International Energy Agency. *Global Energy Review 2021*. URL: https://iea.blob.core.windows.net/assets/d0031107-401d-4a2f-a48b-9eed19457335/GlobalEnergyReview2021.pdf. (accessed 15.05.2022).

[10] Molly Lempriere. *Solar PV costs fall 82% over the last decade, says IRENA*. URL: https://www.solarpowerportal.co.uk/news/solar_pv_costs_fall_82_over_the_last_decade_says_irena. (accessed 18.05.2022).

[11] Statkraft. *Solkraft*. URL: https://www.statkraft.no/var-virksomhet/solkraft/. (accessed 15.05.2022).

[12] The Government of Norway. *Syv spørsmål og svar om strømprisen*. URL: https://www.regjeringen.no/no/tema/energi/stromnettet/syv-sporsmal-og-svar-om-stromprisen/id2873517/a. (accessed 18.05.2022).

[13] NVE. *Solkraft*. URL: https://www.nve.no/energi/energisystem/solkraft/f. (accessed 15.05.2022).

[14] Knut A. Rosvold. *Skagerak Energi AS*. URL: https://snl.no/Skagerak_Energi_AS. (accessed 18.05.2022).

[15] Elizabeth Buechler et al. "Power and the pandemic: exploring global changes in electricity demand during COVID-19". In: *arXiv preprint arXiv:2008.06988* (2020).

[16] Statnett. *Vi brukte mer strøm i 2021*. URL: https://kommunikasjon.ntb.no/pressemelding/vi-brukte-mer-strom-i-2021?publisherId=89853&releaseId=17924322. (accessed 15.05.2022).

[17] Ann Christin Boeeng. *Varmt vær og pandemi førte til mindre energibruk*. URL: https://www.ssb.no/energi-og-industri/energi/statistikk/produksjon-og-forbruk-av-energi-energibalanse-og-energiregnskap/artikler/varmt-vaer-og-pandemi-forte-til-mindre-energibruk. (accessed 14.05.2022).

[18] NVE. *Hvor kommer strømmen fra?* URL: https://www.nve.no/energi/energisystem/kraftproduksjon/hvor-kommer-strommen-fra/. (accessed 18.05.2022).

[19] University of Mary Washington. *Economic Sustainability*. URL: https://sustainability.umw.edu/areas-of-sustainability/economic-sustainability/. (accessed 11.05.2022).

[20] Adec Innovations. *What is Social Sustainability?* URL: https://www.adecesg.com/resources/faq/what-is-social-sustainability/. (accessed 11.05.2022).

[21] James Meadowcroft. *Sustainability*. URL: https://www.britannica.com/topic/sustainable-society. (accessed 11.05.2022).

[22] United Nations Development Programme. *The SDGS in action*. URL: https://www.undp.org/sustainable-development-goals. (accessed 11.05.2022).

[23] Hong Kong University Common Core. *Sustainable Development Goals*. URL: https://commoncore.hku.hk/sustainable-development-goals/. (accessed 11.05.2022).

[24] Dustin Mulvaney. *Solar energy isn't always as green as you think*. URL: https://spectrum.ieee.org/solar-energy-isnt-always-as-green-as-you-think/. (accessed 19.04.2022).

[25] LI Cui Lin; LIU Jie; prof. LU Jin Yu; Vice prof. ZHU Yun. *Turbine protection at Gezhouba*. URL: https://www.waterpowermagazine.com/features/featureturbine-protection-at-gezhouba/. (accessed 19.04.2022).

[26] Hannah Ritchie and Max Roser. *Electricity Mix*. URL: https://ourworldindata.org/electricity-mix. (accessed 25.04.2022).

[27] International Energy Agency. *World Energy Balances: Overview, World*. URL: https://www.iea.org/reports/world-energy-balances-overview/world. (accessed 25.04.2022).

[28] Norwegian Ministry of Petroleum and Energy. *Renewable energy production in Norwayk*. URL: https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/. (accessed 19.04.2022).

[29] The Norwegian Water Resources and Energy Directorate. *Kraftproduksjon*. URL: https://www.nve.no/energi/energisystem/kraftproduksjon/. (accessed 19.04.2022).

[30] Energy Facts Norway. *Electricity Production*. URL: https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/. (accessed 19.04.2022).

[31] The Norwegian Water Resources and Energy Directorate. *Stromforbruk i Norge har lavt klimagassutslipp*. URL: https://www.nve.no/nytt-fra-nve/nyheter-energi/stromforbruk-i-norge-har-lavt-klimagassutslipp. (accessed 15.05.2022).

[32] Luis G Monteiro et al. "One-year monitoring PV power plant installed on rooftop of mineirao FIFA world cup/olympics football stadium". In: *Energies* 10.2 (2017), p. 225.

[33] Solar Plaza. *Top 50 Solar Stadiums Worldwide*. URL: https://www.solarplaza.com/resource/11879/top-50-solar-stadiums-worldwide-2018-world-cup-edition/. (accessed 28.04.2022).

[34] Mattia Manni et al. "Towards zero energy stadiums: The case study of the Dacia arena in Udine, Italy". In: *Energies* 11.9 (2018), p. 2396.

[35] Sourav Barua, Chowdhury Akram Hossain, and Md Mahfuzur Rahman. "Optimization of grid-tied distributed microgrid system with EV charging facility for the stadiums of Bangladesh". In: *2015 International Conference on Electrical Engineering and Information Communication Technology (ICEEICT)*. IEEE. 2015, pp. 1–6.

[36] Viridian Sola. *Solar Technology*. URL: https://www.viridiansolar.co.uk/resources-2-0-different-forms-solar-energy.html. (accessed 03.05.2022).

[37] Norsk Solenergiforening. *Passiv Solvarme*. URL: https://www.solenergi.no/passiv-solvarme. (accessed 18.05.2022).

[38] Monika Agrawal, Avinash Kumar, and Amartya Chowdhury. "A detailed simulation-based study on the effect of mirror integration on PV Module (s) with analysis of different wind flow scheme". In: *Solar Energy* 222 (2021), pp. 129–144.

[39] Greemmatch. *How are solar panels made*. URL: https://www.greenmatch.co.uk/blog/2014/12/how-are-solar-panels-made. (accessed 24.04.2022).

[40] Blue Sol Energia Solar. *Painel Solar Flexível: Conheça A Nova Invenção do Mercado*. URL: https://blog.bluesol.com.br/painel-solar-flexivel/. (accessed 18.05.2022).

[41] American Solar Energy Society. *Monocrystalline vs Polycrystalline Solar Panels*. URL: https://ases.org/monocrystalline-vs-polycrystalline-solar-panels/. (accessed 02.03.2022).

[42] PV Education. *Refining Silicon*. URL: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/refining-silicon. (accessed 19.05.2022).

[43] PV Education. *Refining Silicon*. URL: https://www.pveducation.org/pvcdrom/manufacturing-si-cells/refining-silicon. (accessed 10.05.2022).

[44] Clear energy reviews. *Solar panel construction*. URL: https://www.cleanenergyreviews.info/blog/solar-panel-components-construction. (accessed 30.04.2022).

[45] NREL. "Life cycle greenhouse gas emissions from solar photovoltaics". In: *Renew. Sustain. Energy Rev.* 50 (2012), p. 80.

[46] Michaja Pehl et al. "Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling". In: *Nature Energy* 2.12 (2017), pp. 939–945.

[47] Joshua Smalley. *What is a combiner box?* URL: https://www.solarpowerworldonline.com/2015/06/what-is-a-combiner-box/. (accessed 19.05.2022).

[48] Neelkanth G Dhere and Narendra S Shiradkar. "Fire hazard and other safety concerns of photovoltaic systems". In: *Journal of Photonics for Energy* 2.1 (2012), p. 022006.

[49] Sonia Veerapen and Huiqing Wen. "Shadowing effect on the power output of a photovoltaic panel". In: *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*. IEEE. 2016, pp. 3508–3513.

[50] Benjamin Roussey. *Where is Natural Gas Mostly Used?* URL: https://energycentral.com/c/gn/where-natural-gas-mostly-used.. (accessed 20.04.2022).

[51] The Norwegian Water Resources and Energy Directorate. *Varme*. URL: https://www.nve.no/energi/energisystem/termisk-energi/varme/. (accessed 20.04.2022).

[52] Energy Saver. *Types of Insulation*. URL: https://www.energy.gov/energysaver/types-insulation. (accessed 20.04.2022).

[53] Madeline Hagaman. *Insulation*. URL: https://www.bestpickreports.com/blog/post/need-new-insulation-learn-about-the-best-types-and-placement/. (accessed 20.04.2022).

[54] OJ Insulation. *What is Blanket Insulation?* URL: https://www.ojinc.com/what-is-blanket-insulation/. (accessed 19.05.2022).

[55] Building with Chemistry. *Rigid Foam Insulation in Building and Construction*. URL: https://www.buildingwithchemistry.org/building-future/materials-science/rigid-foam-insulation/. (accessed 19.05.2022).

[56] Nick Connor. *What is Blown-In and Loose-Fill Insulation – Definition*. URL: https://www.thermal-engineering.org/what-is-blown-in-and-loose-fill-insulation-definition/. (accessed 19.05.2022).

[57] National Office of Building Technology and Administration. *Byggteknisk forskrift (TEK10)*. URL: https://dibk.no/regelverk/tek/3/14/14-2/. (accessed 01.05.2022).

[58] National Office of Building Technology and Administration. *Byggteknisk forskrift (TEK17) med veiledning*. URL: https://dibk.no/regelverk/byggteknisk-forskrift-tek17/14/14-3//. (accessed 01.05.2022).

[59] SINTEF. *Er huset ditt klart for en ny vinter?* URL: https://www.sintef.no/siste-nytt/2017/er-huset-ditt-klart-for-en-ny-vinter/. (accessed 19.04.2022).

[60] Elvia. *Hva bruker mest strøm?* URL: https://www.elvia.no/nettleie/alt-du-ma-vite-om-ny-nettleie-for-2022/hva-bruker-mest-strom/. (accessed 01.05.2022).

[61] Electrical Technology. *What is Energy Efficient Lighting and Techniques to Implement It*. URL: https://www.electricaltechnology.org/2016/12/energy-efficient-lighting-techniques-to-implement-it.html. (accessed 19.05.2022).

[62] The Norwegian Water Resources and Energy Directorate. *Smarte strømmålere (AMS)*. URL: https://www.nve.no/reguleringsmyndigheten/kunde/strom/stromkunde/smarte-strommalere-ams/. (accessed 19.05.2022).

[63] Label2020. *Energy Label*. URL: https://www.label2020.eu/. (accessed 11.05.2022).

[64] Smart Maic. *Smart meters for any kind of consumptions!* URL: https://smart-maic.com/en/. (accessed 02.05.2022).

[65] Great Norwegian Encyclopedia. *elektrisk oppvarming i bolig*. URL: https://snl.no/elektrisk_oppvarming_i_bolig. (accessed 15.05.2022).

[66] U.S. Department of Energy (DOE). *Heat Pump Systems*. URL: https://www.energy.gov/energysaver/heat-pump-systems. (accessed 05.05.2022).

[67] Norsk Fjernvarme. *Fjernvarme*. URL: https://www.fjernvarme.no/fakta/fjernvarme. (accessed 19.04.2022).

[68] SWEP. *District heating*. URL: https://www.swep.net/campaigns/district-energy/. (accessed 27.03.2022).

[69] Tarik Kousksou et al. "Energy storage: Applications and challenges". In: *Solar Energy Materials and Solar Cells* 120 (2014), pp. 59–80.

[70] United States Environmental Protection Agency. *Electricity Storage*. URL: https://www.epa.gov/energy/electricity-storage. (accessed 12.05.2022).

[71] Shafiqur Rehman, Luai M Al-Hadhrami, and Md Mahbub Alam. "Pumped hydro energy storage system: A technological review". In: *Renewable and Sustainable Energy Reviews* 44 (2015), pp. 586–598.

[72] R Pena-Alzola et al. "Review of flywheel based energy storage systems". In: *2011 International Conference on Power Engineering, Energy and Electrical Drives*. IEEE. 2011, pp. 1–6.

[73] Laijun Chen et al. "Review and prospect of compressed air energy storage system". In: *Journal of Modern Power Systems and Clean Energy* 4.4 (2016), pp. 529–541.

[74] Ioan Sarbu and Calin Sebarchievici. "A comprehensive review of thermal energy storage". In: *Sustainability* 10.1 (2018), p. 191.

[75] Gang Li. "Sensible heat thermal storage energy and exergy performance evaluations". In: *Renewable and Sustainable Energy Reviews* 53 (2016), pp. 897–923.

[76] Hussam Jouhara et al. "Latent thermal energy storage technologies and applications: A review". In: *International Journal of Thermofluids* 5 (2020), p. 100039.

[77] Tianrun Yang et al. "Seasonal thermal energy storage: A techno-economic literature review". In: *Renewable and Sustainable Energy Reviews* 139 (2021), p. 110732.

[78] Elisa Guelpa and Vittorio Verda. "Thermal energy storage in district heating and cooling systems: A review". In: *Applied Energy* 252 (2019), p. 113474.

[79] Australian Academy of Science. *How a battery works*. URL: https://www.science.org.au/curious/technology-future/batteries. (accessed 15.05.2022).

[80] Tom Bishop. *3 Main Battery Types*. URL: https://paleblueearth.com/blogs/news/3-main-battery-types. (accessed 15.05.2022).

[81] Office of Energy Efficiency and Renewable Energy. *How Does a Lithium-ion Battery Work?* URL: https://www.energy.gov/eere/articles/how-does-lithium-ion-battery-work. (accessed 19.04.2022).

[82] UNIVERSITY OF WASHINGTON. *What is a lithium-ion battery and how does it work?* URL: https://www.cei.washington.edu/education/science-of-solar/battery-technology/. (accessed 19.04.2022).

[83] Rainer Bussar et al. "Battery energy storage for smart grid applications". In: *Association of European Automotive and Industrial Battery Manufacturers* (2013).

[84] Amplus Solar. *What is On-Grid Solar?* URL: https://amplussolar.com/blogs/what-is-on-grid-solar. (accessed 26.04.2022).

[85] Jacob Marsh. *Going off-grid with solar: what does it mean and how much will it cost? (Part 2)*. URL: https://news.energysage.com/going-off-grid-with-solar-examples/. (accessed 11.05.2022).

[86] Dr.Lana El Chaar. *Stand-Alone Photovoltaic Systems?* URL: https://www.sciencedirect.com/topics/engineering/stand-alone-photovoltaic-systems. (accessed 01.04.2022).

[87] World Data. *Smart meters for any kind of consumptions!* URL: https://www.worlddata.info/europe/norway/sunset.php. (accessed 12.04.2022).

[88] Christina Benjaminsen. *How well do solar cells really work in the Nordic climate?* URL: https://www.worlddata.info/europe/norway/sunset.php. (accessed 10.04.2022).

[89] The Economic Times. *What is 'Spot Price'*. URL: https://economictimes.indiatimes.com/definition/spot-price. (accessed 19.05.2022).

[90] IG. *Spot price definition*. URL: https://www.ig.com/uk/glossary-trading-terms/spot-price-definition#information-banner-dismiss. (accessed 10.05.2022).

[91] JAMES CHEN. *Spot Price*. URL: https://www.investopedia.com/terms/s/spotprice.asp. (accessed 10.05.2022).

[92] JOHN JAGERSON. *What Is the Formula for Calculating Net Present Value (NPV)?* URL: https://www.investopedia.com/ask/answers/032615/what-formula-calculating-net-present-value-npv.asp. (accessed 10.05.2022).

[93] CFI Education Inc. *What is the NPV Formula?* URL: https://corporatefinanceinstitute.com/resources/knowledge/valuation/npv-formula/. (accessed 10.05.2022).

[94] Regjeringen.NO. *NOU 2012: 16 Samfunnsøkonomiske analyser*. URL: https://www.regjeringen.no/no/dokumenter/nou-2012-16/id700821/?ch=6. (accessed 10.05.2022).

[95] Taylor Freitas. *What are the hidden costs of solar panels?* URL: https://www.cnet.com/home/energy-and-utilities/what-are-the-hidden-costs-of-solar-panels/. (accessed 10.05.2022).

[96] Designing Buildings Ltd. *Tender Cost*. URL: https://www.designingbuildings.co.uk/wiki/Tender_cost. (accessed 10.05.2022).

[97] JULIA KAGAN. *Cost of Tender*. URL: https://www.investopedia.com/terms/c/costoftender.asp. (accessed 10.05.2022).

[98] ODDs ballklubb. *SKAGERAK ARENA*. URL: https://www.odd.no/om-stadion/Skagerak-Arena. (accessed 07.05.2022).

[99] Skagerak Energilab. *Tekniske data Skagerak Energilab*. URL: https://www.skagerakenergilab.no/teknisk/category2187.html. (accessed 07.05.2022).

[100] ABB. *ABB technology powers soccer club's Skagerak Arena in Norway*. URL: https://new.abb.com/news/detail/25902/abb-technology-powers-soccer-clubs-skagerak-arena-in-norway. (accessed 07.05.2022).

[101] Enova. *Skagerak EnergiLab - Sluttrapport konseptutredning*. URL: https://www.skagerakenergilab.no/getfile.php/1323228-1556091429/Energilab/Sluttrapport. (accessed 16.05.2022).

[102] Microsoft. *Make your own custom shapes in PowerPoint*. URL: https://www.microsoft.com/en-us/microsoft-365/blog/2015/08/20/make-your-own-custom-shapes-in-powerpoint/. (accessed 11.05.2022).

[103] Microsoft. *About Azure Data Explorer*. URL: https://docs.microsoft.com/en-us/azure/data-explorer/. (accessed 22.04.2022).

[104] Microsoft. *Apache Avro*. URL: https://www.ibm.com/topics/avro. (accessed 20.04.2022).

[105] Thomas Skjorten. *Hva er API og API-integrasjon?* URL: https://www.visma.no/blogg/hva-er-api-sporsmal-og-svar/. (accessed 24.04.2022).

[106] Hitachi Energy. *Real-time monitoring and control of primary and secondary equipment in transmission band distribution substations*. URL: https://search.abb.com/library/Download.aspx?DocumentID=1MRS756064&LanguageCode=en&DocumentPartId=LoRes&Action=Launch. (accessed 12.04.2022).

[107] Sourav Barua; Chowdhury Akram Hossain; and Md. Mahfuzur Rahman. *Matlab; Math. Graphics. Programming*. URL: https://se.mathworks.com/products/matlab.html?s_tid=hp_products_matlab. (accessed 28.04.2022).

[108] Otovo AS. *Om oss*. URL: https://www.otovo.no. (accessed 09.05.2022).

[109] Magnus Østbye. "Kostnadsevaluering av photovoltaiske-solceller integrert i fasade på Norske næringsbygg". MA thesis. Norwegian University of Life Sciences, Ås, 2014.

[110] Nord Pool AS. *Day-ahead prices*. URL: https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/NO/Hourly/?view=table. (accessed 09.05.2022).

Appendix

A Matlab Codes

A.1 Electricity Demand Codes

```
clc, clear
set(0,'DefaultFigureVisible','off')

demand_data = xlsread('NTNU_31.01.22.xlsx');

%% Demand for each individual house in hourly based resolution (kWh)
group_1 = demand_data(:,1:19);  % 19 apartment with district heating
group_2 = demand_data(:,22:41); % 20 apartments
group_3 = demand_data(:,44:61); % 18 townhouses from the 1970s
group_4 = demand_data(:,64:81); % 18 care homes
group_5 = demand_data(:,84:88); % 5 detached houses, old without electric cars
group_6 = demand_data(:,91:93); % 3 detached houses, old with electric cars
group_7 = demand_data(:,96:96); % 1 detached house, new with electric car

% Demand for each group in hourly based resolution(kWh)
sum_group_1_vec=sum(group_1,2);
sum_group_2_vec=sum(group_2,2);
sum_group_3_vec=sum(group_3,2);
sum_group_4_vec=sum(group_4,2);
sum_group_5_vec=sum(group_5,2);
sum_group_6_vec=sum(group_6,2);
sum_group_7_vec=sum(group_7,2);

% sum demand (kWh)
sum_group_1=sum(sum_group_1_vec);
sum_group_2=sum(sum_group_2_vec);
sum_group_3=sum(sum_group_3_vec);
sum_group_4=sum(sum_group_4_vec);
sum_group_5=sum(sum_group_5_vec);
sum_group_6=sum(sum_group_6_vec);
sum_group_7=sum(sum_group_7_vec);

%% Average customers from each group
```

```
%Average customer group 1, apartment with district heating
ave_customer_1=sum_group_1_vec/19;
sum_ave_customer_1=sum(ave_customer_1);

%Average customer group 2, apartment
ave_customer_2=sum_group_2_vec/20;
sum_ave_customer_2=sum(ave_customer_2);

%Average customer group 3, townhouse from the 1970s
ave_customer_3=sum_group_3_vec/18;
sum_ave_customer_3=sum(ave_customer_3);

%Average customer group 4, Care home
ave_customer_4=sum_group_4_vec/18;
sum_ave_customer_4=sum(ave_customer_4);

%Average customer group 5, detached house Old without electric
    cars
ave_customer_5=sum_group_5_vec/5;
sum_ave_customer_5=sum(ave_customer_5);

%Average customer group 6, detached house Old with electric cars
ave_customer_6=sum_group_6_vec/3;
sum_ave_customer_6=sum(ave_customer_6);

%Average customer group 7, detached house new with electric car
ave_customer_7=sum_group_7_vec/1;
sum_ave_customer_7=sum(ave_customer_7);

%% Demand divided by season
Demand_group_1_spring = ave_customer_1(1417:3624,:); % Hours
    belonging to March-May
Demand_group_1_summer =ave_customer_1(3625:5832,:); % Hours
    belonging to June-August
Demand_group_1_fall = ave_customer_1(5833:8016,:); % Hours
    belonging to september-november
Demand_group_1_winter=[ave_customer_1(1:1416,:);ave_customer_1
    (8017:8760,:)]; % tHours belonging to Desember-February.


sum_group_1_spring=sum(Demand_group_1_spring);
sum_group_1_summer=sum(Demand_group_1_summer);
sum_group_1_fall=sum(Demand_group_1_fall);
sum_group_1_winter=sum(Demand_group_1_winter);
```

A.2 Electricity Production Codes

```
%% Production
%clc , clear

prod_data = xlsread('SkagerakEnergilab_2020.xlsx');
prod_data(1,:) = [];
prod_data(1417:1440, :)= [];
prod_data(:,1) = [];
sum_prod=sum(prod_data);
antall_panel=2700;
gjen_ett_panel = prod_data/antall_panel;
sum_ett_panel= sum(gjen_ett_panel);
paneler_gruppe_1=144;
prod_gruppe_1=gjen_ett_panel*paneler_gruppe_1;

% Production divided into months (three months)


timer_jan=744;
timer_feb=672;
timer_mar=744;
timer_apr=720;
timer_mai=744;
timer_jun=720;
timer_jul=744;
timer_aug=744;
timer_sep=720;
timer_okt=744;
timer_nov=720;
timer_des=744;

prod_data_spring = prod_data(1417:3624,:);
prod_data_summer = prod_data(3625:5832,:);
prod_data_fall = prod_data(5833:8016,:);
prod_data_winter=[prod_data(8017:8760,:);prod_data(1:1416,:)];
sum_prod_spring=sum(prod_data_spring);
sum_prod_summer=sum(prod_data_summer);
sum_prod_fall=sum(prod_data_fall);
sum_prod_winter=sum(prod_data_winter);

andel_summer=sum_prod_summer/sum_prod;
andel_spring=sum_prod_spring/sum_prod;
andel_fall=sum_prod_fall/sum_prod;
andel_winter=sum_prod_winter/sum_prod;
```

```
% Production six months

prod_summer_half= prod_data(2191:6570);
prod_winter_half= [prod_data(1:2190);prod_data(6571:8760)];

sum_prod_summer_half=sum(prod_summer_half);
sum_prod_winter_half=sum(prod_winter_half);

share_summer_half=sum_prod_summer_half/sum_prod;
share_winter_half=sum_prod_winter_half/sum_prod;
```

A.3 Minimum Number of Required Panels codes

```
%% Production and demand

%Required amount of panels to cover the yearly energy demand for
    each
%average customer
panels_group_1 = ceil(sum_ave_customer_1/sum_one_panel);
panels_group_2 = ceil(sum_ave_customer_2/sum_one_panel);
panels_group_3 = ceil(sum_ave_customer_3/sum_one_panel);
panels_group_4 = ceil(sum_ave_customer_4/sum_one_panel);
panels_group_5 = ceil(sum_ave_customer_5/sum_one_panel);
panels_group_6 = ceil(sum_ave_customer_6/sum_one_panel);
panels_group_7 = ceil(sum_ave_customer_7/sum_one_panel);

% Vector for the amount of energy produced by the minimum amount
    of panels
prod_vec_group_1=panels_group_1*avg_one_panel;
sum_prod_group_1=sum(prod_vec_group_1);
prod_vec_group_2=panels_group_2*avg_one_panel;
sum_prod_group_2=sum(prod_vec_group_2);
prod_vec_group_3=panels_group_3*avg_one_panel;
sum_prod_group_3=sum(prod_vec_group_3);
prod_vec_group_4=panels_group_4*avg_one_panel;
sum_prod_group_4=sum(prod_vec_group_4);
prod_vec_group_5=panels_group_5*avg_one_panel;
sum_prod_group_5=sum(prod_vec_group_5);
prod_vec_group_6=panels_group_6*avg_one_panel;
sum_prod_group_6=sum(prod_vec_group_6);
prod_vec_group_7=panels_group_7*avg_one_panel;
sum_prod_group_7=sum(prod_vec_group_7);
```

A.4 Battery Capacity Code

```

panel=1; %Amount of panels
reduced_demand=((Demand−(production_one_panel.∗panel)));
%The reduced demand created from the demand and the production
    from one panel times the amount of panels

rng default
reduced_demand_negative = −reduced_demand;
Capacity = 0;  %Battery Capacity
cumulative_reduced_demand=zeros(1,length(reduced_demand_negative
    ));
for i = 1:length(reduced_demand_negative)
    cumulative_reduced_demand(i)=reduced_demand_negative(i);
    if i > 1
        cumulative_reduced_demand(i)= min(Capacity,
            cumulative_reduced_demand(i)+
            cumulative_reduced_demand(i−1));
    end
end

cumulative_reduced_demand=cumulative_reduced_demand';

min_required_capacity=min(cumulative_reduced_demand); %Describes
     the needed battery capacity
```

A.5 Housing Units Supplied by Skagerak Arena Codes

```
%% group 1
clc
panel_1=540; %amount of panels
reduced_demand_1=((gjen_kunde_vek_1−(avg_one_panel.∗panel_1)));

reduced_demand_1_first = reduced_demand_1(1:4380);
reduced_demand_1_second = reduced_demand_1(4381 : end);
reduced_demand_1_turned=[reduced_demand_1_second;
    reduced_demand_1_first]; %redusert forbruk (forbruk−
    produksjon) som begynner midt pÃě Ãěret for  starte med
    hÃÿyest produksjon

rng default
x_1 = −reduced_demand_1_turned;
thresh_1 = 0;  %battery capacity
xc_1=zeros(1,length(x_1));
```

```matlab
for i = 1:length(x_1)
      xc_1(i)=x_1(i);
      if i > 1
            xc_1(i)= min(thresh_1, xc_1(i)+xc_1(i-1));
      end
end

xc_1=xc_1';

max_kap_1=max(xc_1);
min_kap_1=min(xc_1);
[M,I] = min(xc_1)

%% group 2
clc
panel_2=1350; %amount of panels
reduced_demand_2=((gjen_kunde_vek_2-(avg_one_panel.*panel_2)));

reduced_demand_2_first = reduced_demand_2(1:4380);
reduced_demand_2_second = reduced_demand_2(4381 : end);
reduced1demand_2_turned=[reduced_demand_2_second; reduced_demand_2_first];

rng default
x_2 = -reduced_demand_2_turned;
thresh_2 = 0;  %battery capacity
xc_2=zeros(1,length(x_2));
for i = 1:length(x_2)
      xc_2(i)=x_2(i);
      if i > 1
            xc_2(i)= min(thresh_2, xc_2(i)+xc_2(i-1));
      end
end

xc_2=xc_2';

max_kap_2=max(xc_2);
min_kap_2=min(xc_2);
[M,I] = min(xc_2)

%% group 3
clc
panel_3=1350; %amount of panels
reduced_demand_3=((gjen_kunde_vek_3-(avg_one_panel.*panel_3)));
```

```
reduced_demand_3_first = reduced_demand_3(1:4380);
reduced_demand_3_second = reduced_demand_3(4381 : end);
reduced_demand_3_turned=[reduced_demand_3_second;
    reduced_demand_3_first]; %redusert forbruk (forbruk-
    produksjon) som begynner midt pÃě Ãěret for  starte med
    hÃÿyest produksjon

rng default
x_3 = -reduced_demand_3_turned;
thresh_3 = 0;  %battery capacity
xc_3=zeros(1,length(x_3));
for i = 1:length(x_3)
      xc_3(i)=x_3(i);
      if i > 1
            xc_3(i)= min(thresh_3, xc_3(i)+xc_3(i-1));
      end
end

xc_3=xc_3';

max_kap_3=max(xc_3);
min_kap_3=min(xc_3);
[M,I] = min(xc_3)

%% group 4
clc
panel_4=1350; %amount of panels
reduced_demand_4=((gjen_kunde_vek_4-(avg_one_panel.*panel_4)));

reduced_demand_4_first = reduced_demand_4(1:4380);
reduced_demand_4_second = reduced_demand_4(4381 : end);
reduced_demand_4_turned=[reduced_demand_4_second;
    reduced_demand_4_first]; %redusert forbruk (forbruk-
    produksjon) som begynner midt pÃě Ãěret for  starte med
    hÃÿyest produksjon

rng default
x_4 = -reduced_demand_4_turned;
thresh_4 = 0;  %battery capacity
xc_4=zeros(1,length(x_4));
for i = 1:length(x_4)
      xc_4(i)=x_4(i);
      if i > 1
            xc_4(i)= min(thresh_4, xc_4(i)+xc_4(i-1));
      end
```

```
end

xc_4=xc_4';

max_kap_4=max(xc_4);
min_kap_4=min(xc_4);
[M,I] = min(xc_4)

%% group 5
clc
panel_5=2700; %amount of panels
reduced_demand_5=((gjen_kunde_vek_5-(avg_one_panel.*panel_5)));

reduced_demand_5_first = reduced_demand_5(1:4380);
reduced_demand_5_second = reduced_demand_5(4381 : end);
reduced_demand_5_turned=[reduced_demand_5_second;
    reduced_demand_5_first]; %redusert forbruk (forbruk-
    produksjon) som begynner midt pÃě Ãěret for  starte med
    hÃÿyest produksjon

rng default
x_5 = -reduced_demand_5_turned;
thresh_5 = 0;  %battery capacity
xc_5=zeros(1,length(x_5));
for i = 1:length(x_5)
    xc_5(i)=x_5(i);
    if i > 1
        xc_5(i)= min(thresh_5, xc_5(i)+xc_5(i-1));
    end
end

xc_5=xc_5';

max_kap_5=max(xc_5);
min_kap_5=min(xc_5);
[M,I] = min(xc_5)

%% group 6
clc
panel_6=2700; %amount of panels
reduced_demand_6=((gjen_kunde_vek_6-(avg_one_panel.*panel_6)));

reduced_demand_6_first = reduced_demand_6(1:4380);
reduced_demand_6_second = reduced_demand_6(4381 : end);
reduced_demand_6_turned=[reduced_demand_6_second;
```

```
    reduced_demand_6_first]; %redusert forbruk (forbruk-
    produksjon) som begynner midt pÃě Ãěret for  starte med
    hÃÿyest produksjon

rng default
x_6 = -reduced_demand_6_turned;
thresh_6 = 0;  %battery capacity
xc_6=zeros(1,length(x_6));
for i = 1:length(x_6)
     xc_6(i)=x_6(i);
     if i > 1
         xc_6(i)= min(thresh_6, xc_6(i)+xc_6(i-1));
     end
end

xc_6=xc_6';

max_kap_6=max(xc_6);
min_kap_6=min(xc_6);
[M, I] = min(xc_6)

%% group 7
clc
panel_7=2700; %amount of panels
reduced_demand_7=((gjen_kunde_vek_7-(avg_one_panel.*panel_7)));

reduced_demand_7_first = reduced_demand_7(1:4380);
reduced_demand_7_second = reduced_demand_7(4381 : end);
reduced_demand_7_turned=[reduced_demand_7_second;
    reduced_demand_7_first]; %redusert forbruk (forbruk-
    produksjon) som begynner midt pÃě Ãěret for  starte med
    hÃÿyest produksjon

rng default
x_7 = -reduced_demand_7_turned;
thresh_7 = 0;  %battery capacity
xc_7=zeros(1,length(x_7));
for i = 1:length(x_7)
     xc_7(i)=x_7(i);
     if i > 1
         xc_7(i)= min(thresh_7, xc_7(i)+xc_7(i-1));
     end
end

xc_7=xc_7';
```

```
max_kap_7=max(xc_7);
min_kap_7=min(xc_7);
[M, I] = min(xc_7)
```

A.6 Economy Codes

```
%%Economy

Production_data190 = (prod_data/amount_panels)*190;
consumption = sum(group_1,2); % Apartments with /district heating (Stadium_turn Skagerak Arena âĂŞ 19 PCs), total consumption in hourly resolution(kWh)


Spotprice_vek = xlsread('Spotprice.xlsx');
Spotprice_MWh = Spotprice_vek(:,2); %NOK/MWh
Spotprice = Spotprice_MWh/1000; %NOK/kWh


figure(1)
s = plot(Spotprice);

Overproduction_vec = (Productiondata190 - consumption) .* (Spotprice);

Overproduction = Overproduction_vec(Overproduction_vec>0);

v = sum(consumption);
z = sum(Productiondata100);
Overproduction_sum = sum(Overproduction)
```

B Excel Calculations and Tables

B.1 Economy Calculations and Tables

Table 10: System components and cost

Cost Type	Cost Item	Total Price
Material	Solar Cell Module (100) + assembly	Included
	Power Cables	Included
	Inverter	Included
	Operation Monitoring Equipment	Included
Installation	Connection to the Fuse Box and Grid	Included
Total	System Price	1.38E+06

Table 11: System income and savings

Current Price	1.648	NOK/kWh
Net Cost Saved Current	93 500	NOK
Direct income	2 012	NOK

Table 12: Final economical results

Gross Income	2.41E+05	NOK
Profitability in kroner (present value)	3.25E+03	NOK
Years before earning the investment	3.00E+01	Year
Maintenance	2.38E+05	NOK

Table 13: Discount rate and maintenance cost

Discount rate	0.04	
Maintenance Percentage	0.01	(from compendium)
Year	Maintenance (NOK)	Net Present Value (NOK)
1	13 227.61	89 903.85
2	12 718.86	86 446.01
3	12 229.67	83 121.16
4	11 759.30	79 924.19
5	11 307.02	76 850.18
6	10 872.13	73 894.41
7	10 453.98	71 052.32
8	10 051.90	68 319.53
9	9 665.29	65 691.86
10	9 293.55	63 165.25
11	8 936.10	60 735.82
12	8 592.41	58 399.82
13	8 261.93	56 153.68
14	7 944.16	53 993.92
15	7 638.62	51 917.23
16	7 344.82	49 920.41
17	7 062.33	48 000.40
18	6 790.70	46 154.23
19	6 529.52	44 379.07
20	6 278.39	42 672.18
21	6 036.91	41 030.94
22	5 804.72	39 452.83
23	5 581.46	37 935.41
24	5 366.79	36 476.36
25	5 160.38	35 073.42
26	4 961.90	33 724.44
27	4 771.06	32 427.35
28	4 587.56	31 180.14
29	4 411.11	29 980.91
30	4 241.45	28 827.80
	237 881.63	1 616 805.11