Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Marie Hefte

Energy system planning of Zero Emission Neighborhood in Bodø combined with hydrogen ferries

Master's thesis in Energy and Environmental Engineering
Supervisor: Magnus Korpås
January 2021

NTNU
Norwegian University of Science and Technology

Marie Hefte

Energy system planning of Zero Emission Neighborhood in Bodø combined with hydrogen ferries

Master's thesis in Energy and Environmental Engineering
Supervisor: Magnus Korpås
January 2021

Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

NTNU
Norwegian University of
Science and Technology

Summary

The Bodø airport redevelopment project aims to turn today's airport area into a smaller airport and a Zero Emission Neighborhood with a new generation of buildings that are environmentally friendly and energy efficient. 15000 new homes and 20000 working places are planned to be build. This is a pilot project for Zero Emissions Neighborhoods, the goal for the pilot project is to develop an urban and environmentally friendly neighborhood, whit minimized energy demand, and with zero greenhouse gas emissions. Renewable energy sources are needed to achieve a low carbon society, and decarbonization of the transportation sector is a major part of reaching the goal of a low carbon society. The sea transportation sector is a major means of transportation in the Bodø area and has a considerable emission reduction potential.

The main contribution of this thesis is an investigation of the power system choice in the new zero emission neighborhood in Bodø in a combination with hydrogen ferries. The neighborhood will have local and nearby power production as wind power and PV power, and a hydrogen storage system will be included. This thesis uses the Matlab model windhydtool to calculate the sizing of the power system for the Zero Emission Neighborhood in Bodø combined with three hydrogen ferries from Bodø, one to Røst, one to Moskenes, and one to Værøy. The ferries run two times a day, and in the summer months June, July, and August the ferries run four times a day, due to all the tourists visiting the area in the summer. These ferry routes are the longest and most difficult in Norway and too long for electricity battery, therefore hydrogen used as the fuel is the right solution. Wind power plant or PV power plant or a combination of both technologies should cover the electrical load of the neighborhood, and also cover the ferries' hydrogen load with hydrogen production. The system has local onsite and nearby power

production, but is grid connected so electricity can be imported and exported when needed.

First, an estimate of the building stock and the neighborhood's hourly electricity demand was made. Furthermore, an estimate of the ferries hourly hydrogen demand was made to do the calculations. Three main scenarios were run: one with only electricity load and with use of hydrogen storage and fuel cell, one with both the electricity demand and the hydrogen demand and the hydrogen stored is only used for the ferries, the last one with both the electricity demand and the hydrogen demand and with use of the fuel cell. Further, each of these three main scenarios is run ; with only wind power, only PV power, and a combination of 80% wind power and 20% PV power.

The results show how the ferries' hydrogen load impacts the power production demand. The hydrogen load each year is 26,5 GWh, and the electricity load is 101,3 GWh. The main goal for the neighborhood is the zero energy goal, and the neighborhood should be as much as possible self supplied with energy. The case where both hydrogen load and electricity load are included and which has the lowest power import from the grid over the year is the case with 43500 kW installed wind power capacity and 10900 kW installed PV power capacity. The power import from the grid for this case is 37 GWh. A combination of wind power and PV power gives an optimized solution, because the wind power plant produces at its maximum during the winter when the wind speed is high and the PV power plant produces at its maximum during summer when the solar irradiance is high. This solution uses the hydrogen fuel cell, so it is beneficial to use the stored hydrogen in the fuel cell and produce electricity to cover a share of the neighborhood's electricity demand.

Sammendrag

Prosjektet "ny by- ny flyplass" i Bodø har som mål å ombygge dagens flyplass til en mindre flyplass, og en nullutslippsbydel med en ny generasjon bygg som er miljøvennlige og energieffektive. 15000 nye hjem skal bli bygd og 20000 nye arbeidsplasser skal bli etablert. Dette er et pilotprosjekt for nullutslippsbydeler, målet med pilotprosjektet er å utvikle en urban og miljøvennlig bydel som minimerer energiforbruket og med null klimagassutslipp. Fornybare energikilder er nødvendige for å oppnå et lavutslippsamfunn, og reduksjon av karbonutslippet i transportsektoren er en viktig del for å nå målet om et lavutslippsamfunn. Sjøtransportsektoren er en viktig del av transportsektoren i Bodøområdet og har et stort reduksjonspotensial i forhold til klimagassutslipp.

Hovedoppgaven til denne masteroppgaven er å undersøke valget av egnet energisystem for den nye nullutslippsbydelen i Bodø kombinert med hydrogenferger. Bydelen vil ha lokal kraftproduksjon i form av vindkraft og solkraft, og et system med hydrogenlager vil bli inkludert. Denne masteroppgaven bruker Matlab programmet windhydtool til å beregne størrelsen av energisystemet som skal dekke nullutslippsbydelen og tre ferger fra Bodø, en til Røst, en til Værøy og en til Moskenes. Fergene kjører to ganger om dagen, og om i sommermånedene juni, juli og august kjører de fire ganger om dagen på grunn av alle turistene som besøker området. Disse fergestekkene er de lengste og mest utfordrende i Norge, og de er for lange for elektriske batteri, derfor er hydrogen nyttet som drivstoff en god løsning. Vindturbiner, eller solcellepanel, eller en kombinasjon av begge teknologiene skal dekke bydelens elektrisitetsbehov og fergenes hydrogen behov. Systemet har lokal kraftproduksjon, men er koblet til strømnettet så kraft kan bli importert og eksportert når det trengs.

Først er størrelsen og sammensetningen på byggningsmassen estimert og bydelens elektrisitetbehov estimert. Videre er fergenes hydrogenlast estimert for å kunne gjøre beregningene. Tre hovedscenarioer ble kjørt: en med bare elektrisitetslasten og med hydrogenlageret og brenselcellen, en med både elektrisitetslasten og hydrogenslasten og hydrogenlageret er bare brukt til hydrogenlasten, den siste med både elektrisitetslasten og hydrogenlasten og hydrogenlageret og brenselcellen. Tilslutt ble alle hovedscenarione kjørt hvor energibehovet ble dekket av: bare vindkraft, bare solkraft og en kombinasjon av 80 % vindkraft og 20 % solkraft.

Resultatene viser hvordan fergenes hydrogenlast påvirker kraftbehovet. Det årlige hydrogenbehovet er 26,5 GWh, og elektrisitetlasten er 101,3 GWh. Hovedmålet til bydelen er null-energi målet, og bydelen skal bli så selvforsynt med energi som mulig. Scenarioet med både hydrogenlasten og elektrisitetslasten inkludert og som har den laveste importen av kraft fra strømnettet er scenarioet med 43500 kW installert vindkraft og 10900 kW installert solkraft. Importen av kraft for dette tilfellet er 37 GWh. En kombinasjon av vindkraft og solkraft gir en optimalisert løsning, dette er fordi vindkraftproduksjonen er høyest på vinteren når vindhastigheten er høyest og solkraftproduksjonen er høyest på sommeren når solinnstrålingen er størst. Denne løsningen bruker brenselcellen til å produsere elektrisitet til å dekke en del av bydelens elektrisitetsbehov.

Preface

This master thesis is the final work of the five year master degree in energy and environmental engineering at the Department of Electric Power Engineering at the Norwegian University of Science and Technology. The master thesis is written the fall of 2020 and is a continuation of my specialization project written about the same topic the fall of 2019.

I would like to thank my supervisor Magnus Korpås for great guidance throughout the semester. This project would not have been possible without your helpful guidance. Your inputs and availability have been highly appreciated.

Trondheim, January 2021

Marie Hefte

Contents

List of Figures

List of Tables

Nomenclature

$\dot{V}_{He}$	Hydrogen production in electrolyzer
$\dot{V}_{Hf}$	Hydrogen consumed in the fuel cell
$\dot{V}_{Hl}$	Hydrogen load
η_e	specific power consumption of electrolyzer plant[kWh/Nm^3]
η_f	specific power generation of fuel cell plant[kWh/Nm^3]
E	Electrical energy
P_d	Dissipated wind and solar power
P_e	Power consumption of electrolyzer
P_f	Power output from fuel cell
P_g	Power exported to the power grid
P_l	Electrical load
P_w	Wind power output
P_{exp}	Power export
$P_{imp,e}$	Power import to electrolyzer
P_{imp}	Power import
P_{pv}	PV power output
V_H	Hydrogen in the tank [Nm^3]
t	Time step[hour]

Chapter 1

Introduction

1.1 Motivation

Climate change and environmental damage are two of the most dramatic challenges the world is facing today. 36 % of the total global final energy use is used in the buildings and construction sectors combined, and nearly 40 % of the total direct and indirect CO_2 emissions are from these sectors.[47] Table 1.1 shows the total greenhouse gas (GHG) emissions in Norway in 2019 from different sectors. The greenhouse gas emissions in Norway are mainly from the oil and gas sector, the industry sector and the transportation sector. To reduce emissions in the building sector, Zero emission neighborhood are a solution. The expected development in the energy sector and the transportation sector both nationally and globally is towards electrification, which will lead to decarbonization of these sectors.

Sector	GHG emissions (Mill.tons CO2 equiv.)
Oil and gas extraction	14.0
Manufacturing industries and mining	11.6
Energy supply	1.6
Heating in other industries and households	1.0
Road traffic	8.5
Aviation, navigation, motor equip. etc.	6.9
Agriculture	4.4
Other	2.3

Table 1.1: Norwegian GHG emissions in 2019 [35]

Internationals agreements are made to combat the climate and environmental challenges the world is facing today. Norway is implementing the Paris Agreement and UNs sustainable development goals. The Paris Agreement is an internationally agreement on climate change that came into force in November 2016, which Norway has ratified. The Paris Agreement aims to hold the increase in the global average temperature to well below 2 °Celsius and pursue efforts to limit the temperature increase to 1,5 °Celsius above pre-industrial temperatures. Norway aims to reduce greenhouse gas emissions by at least 50 % and towards 55 % by 2030 compared to 1990 levels, which is a strengthened ambition from 2020. [28] The Paris agreement also aims to increase the ability to adapt to the adverse impacts of climate change and make economic flows consistent with a pathway towards low greenhouse gas emissions and climate resilience. The Paris agreement was the first international agreement that included all countries to set ambitious goals to decrease the total greenhouse gas emissions in the world. [29] UNs sustainable development goals is the world's common agenda to combat poverty, reduce inequalities, and stop climate change by 2030. The sustainable development goals consist of 17 goals, which Norway has to follow up.

The expected development in energy and transportation globally is towards electrification. To decarbonize the transportation sector, it is natural to electrify using battery and hydrogen fuel cell electric technology and renewable energy charging and refueling infrastructure. The Norwegian Public Road Administration is responsible for the roads and mostly all the connected ferries in Norway, which is an important part of the Norwegian roads. In Norway now, there are about 130 car ferry routes and yearly 20 millions vehicles and 40 millions passengers are using the ferries in total. The Norwegian Public Road Administration expects hydrogen to be the best solution for the longest and most difficult car ferry routes, and electric battery the best solution for the shortest ferry routes. The combinations of electrification with batteries and hydrogen production will leads to a significant reduction in greenhouse gas emissions from the sea transportation sector. [40] Over the past decades the authorities have developed public tenders, commercial competition, and contracts that combine new technology development and system demonstrations. They also follow up with stricter contract award criteria which favoring low greenhouse gas emissions. This leads to a local market in Norway where technology providers are motivated to invest in environmentally friendly and new solutions and products at a price who is cost-competitive. The first fully battery electric car ferry in the world was MF Ampere who has been operating since 2015 at E39 and crossing the Sognefjord. It is expected that by 2022 there will be at least 73 battery electric ferries in operation in Norway. Persistent political interest and awareness are necessary to reach the goal. [41] Figure 1.1 shows the Norwegian Public Road Administration's expected reduction of CO_2 emissions from Norwegian car ferries towards 2030.

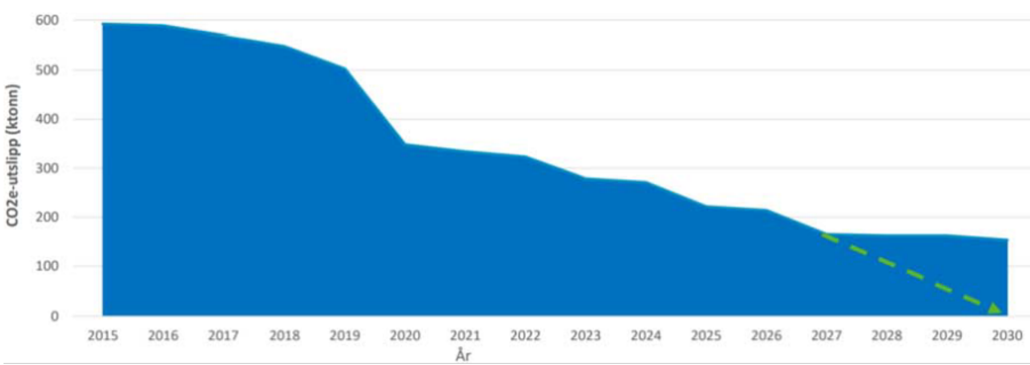

Figure 1.1: Expected reduction CO_2 emissions from Norwegians car ferries towards 2030 [42]

Buildings and the construction sector require a great amount of energy, since nearly 40 % of the total global CO_2 emissions are from this sector it has a great reduction potential both nationally and internationally. The main motivation for Zero Emission Neighborhood is to reduce greenhouse gas emissions. Local energy production in neighborhoods such as photovoltaics can contribute to a higher share of renewable energy production in the power grid. Norway possesses regulatory hydro power, and with well connected power grid, Norway can work as a green battery and supply Europe with clean renewable energy. This stable and predictable source makes room for more renewable power production from variable sources, such as wind and solar. To achieve climate targets, the resources should be utilized efficiently which will reduce the cost for development and operation. [2]

1.2 Description of the thesis

The research center for Zero Emission Neighborhood aims to develop and promote a new generation of buildings and neighborhoods characterized by their efficiency and environmental friendliness. The Bodø redevelopment project is one of the pilot projects at the research center, where the airport area in Bodø will be turned into a smaller airport, which release a large area of land to build a zero emission neighborhood.

In this master thesis, different zero energy scenarios for the pilot project in Bodø will be analyzed. A focus will be on the decarbonization of the ferries in the Bodø area and the opportunities for hydrogen in sea transport, and how this can impact the need for renewable energy sources development in the region to fulfill the requirements. Annual energy use for the new neighborhood and the hydrogen ferries will be estimated to do a calculation of the new needed renewable energy sources to supply the demand.

The goal for this master thesis is to plan the power system for the zero emission neighborhood with local power production as wind power and PV power, in a combination with a hydrogen storage system and hydrogen load from ferries. Wind power and solar power are non-storable energy resources with high variations and low predictability. A hydrogen storage system can therefore utilize surplus wind and solar power. Simulation studies will be done on the variations in generation and demand, and analysis of the need for local storage of electricity and hydrogen. This thesis will compare the different scenarios with each other.

This master thesis will start by presenting the pilot project and the relevant theory in chapter 2. Chapter 3 shows the windhydtools model used in this thesis, and the input data is presented in chapter 4. The result are shown and discussed in chapter 5, before the result are further discussed in chapter 6. The conclusion of the result and work are presented in chapter 7. In chapter 8 possible and recommended future work is presented.

Chapter 2

Background

2.1 About the pilot project

The Zero Emission Neighborhood pilot project located in Bodø is named: New city - new airport. The government of Norway has decided to end the military air activity in Bodø. The runway at the airport is from the early 1950s, and has therefore few years left and need to be replaced by a new one within 2025. The airport development gives the opportunity to develop the city in a new way. When the airport is moved, and a new smaller one is built, it releases a significant amount of area close to the city center. The transformation area is approximately 5 600 000 m^2 and an area of 2 200 000 m^2 will be used to build the civil airport. The new airport will be located 900 m southwest of today's existing one. The remaining size of 3 400 000 m^2, which is the same size as today's city center, will be used to build a new and sustainable city. The planned new multi functional urban area will include both residential and business areas, and will include both re-use and new constructions. 15000 new homes and 20000 new workplaces are planned, and Bodø will have approximately 30000 new inhabitants when the neighborhood is finished. [39] Since the population in Bodø is estimated to increase, more workplaces are needed as well as schools and different healthcare buildings. The project has a long time horizon and the new neighborhood is going to be developed within the next 60 - 80 years. The first construction phase for the neighborhood development is planned for the second part of the 2020's.[3] The new neighborhood will be close to the city center of Bodø and have a good connection with the existing city. Figure 2.1 shows the planned new airport and the new city.

Figure 2.1: Illustration of the new airport and the new city

Bodø is a city located in the northern part of Norway. It is the largest city and the administration center in the County of Nordland and has 52000 citizens. The pilot project is an important development project for Bodø as a city as well as for the northern region of Norway. The ocean surrounds the city on three sides and the city is close to the nature and mountains. The city center is compact, and it is possible to walk and bike between the residential area and the business area. Bodø is one of the few cities in the world with the airport in walk-distance to the city center. The new and smaller airport will lead to noise reduction for the citizens in Bodø. In 2012 the decision about relocating the military airport was made. The civil airport will be in use at least until 2024, and the new airport is assumed to be finished in 2026. [18] The preceding years will be used for the planning and design process. The airport project is estimated to cost approximately 5,7 billion NOK. [25]

The pilot project is one of the most complex and comprehensive area planning projects in Norway. The project's stakeholders are the project group from Bodø municipality with a project manager and members from different departments. The municipality includes both stakeholders and the citizens in the planning process with establishing several platforms for consultation, and a living lab methodology is used where a collaboration between citizen, the research and the business sector in co-creation processes. The defense department is the stakeholder for the military airport and Avinor for the civil airport. Both Bodø Energi and BE Varme are involved in the project and are owned by the municipality, Forsvarsbygg is also represented as well as other stakeholders. [1]

The goal of the pilot project is to develop a sustainable, compact, and smart city, that will make the city more attractive and important as a business center in the region. The neighborhood's energy demand should be minimized and have minimized greenhouse gas emissions. The buildings are planned to be built according to Zero Emission Buildings (ZEB) standards. The goals and guidelines for the project are based on UNs sustainable development goals. The project will be an ideal example internationally in modern environment friendly and sustainable city planning and will be an arena for research and development. A goal is to have good infrastructure and establish an efficient transportation system with environmentally friendly means of transportation.[17]

Today the means of transportation in Bodø are private cars. To reach the climate goals, changes are needed and public transportation have to replace the private vehicles. The height differences in Bodø are small, so the city is ideal for biking. The part of transportation that are biking was 8 % in 2013/2014, the municipality's goal is to reach 25 % in 2025. [23] Bodø municipality aims to have zero growth of private vehicle, and in the city center 75 % of the transportation should be walking and bicycling. Public transportation by bus and train are good and have increasing popularity, but only 4 % of today's transportation are public transportation.[36] The efficiency needs to increase to make public transportation more advantageous, but it is estimated that it will happen when the building density increases.

Due to the location close to the sea in Bodø, ferries and other sea transportation is very important in the region. One of the longest ferry distances in Norway is located between Bodø and Lofoten. A new port is planned to be built at Langstranda when the airport is moved. Bodø has today an efficient junction point where the railways meats the port. The goal is that goods transportation goes from roads to ship and trail transportation. The relocation of the port is expensive, but it will release area close to the city center which is an economic advantage. To have the port, the railway, and the airport close together is a benefit for the goods transportation efficiency.

2.2 Zero Emission Neighborhood

The Research Center on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) was established in 2017 by the research council of Norway and is hosted and led by the Norwegian University of Science and Technology (NTNU) together with SINTEF Building and Infrastructure and SINTEF Energy. The Research Center creates solutions for the neighborhood and buildings of the future and will enable the transition to a low carbon society by developing sustainable neighborhoods with zero greenhouse gas emissions. The ZEN Researcher works with gives advice, test and analyze solutions together with municipalities, industry, and governmental organizations in the pilot project to define goals and define key performance indicators. The Research Center on Zero Emission Neighbourhoods has nine pilot projects spread all over Norway, where one of the pilot projects is the Bodø airport redevelopment project. The pilot project tests the new solutions for development and the pilot areas include both new and well-established areas that will be further developed. The area of the nine pilot projects is more than 1 million m^2 and includes more than 30000 inhabitants in total. The ZEN Research center will last eight years until 2024.

The ZEN research center has defined a neighborhood as a group of interconnected buildings with associated infrastructure located within a confined geographical area. A zero emission neighborhood is a sustainable neighborhood where the greenhouse gas emission is reduced to zero within its life cycle, and aims to reduce both its direct and indirect greenhouse gas emission towards zero. The calculations depend on the chosen ambitions level with respect to which life cycle models, and buildings and infrastructure elements to count in.

A Zero Emission Neighborhood focuses on seven categories: innovation, energy, power, economy, mobility, greenhouse gas (GHG) emissions, and spatial qualities.

a The primary goal of the Zero Emission Neighborhood is to reduce the

GHG emissions towards zero. To achieve this, the neighborhood must plan, design and operate buildings and all the infrastructure components towards zero life cycle GHG emissions. Both direct emissions, which are occuring directly from a source as consequence of an activity, and indirect emissions, which is taking place through indirect pathways needs to be taken in to account.

b The neighborhood should become highly energy efficient and powered by a high share of smart renewable energy in the energy supply system. Energy is the electricity or heating load, and reducing the electricity and heating demand should be the first priority in the transition towards a decarbonized energy system. The focus should be on system optimisation, storage of the energy, load and power management, smart grids and digitization.

c The energy flows should be manage in a smart and flexible way, both within and between the buildings in the neighborhood. The energy exchanges to the surrounding energy system should also manages in a flexible and smart way. To achieve this it is important to have a strong focus on the power flows and especially on power peaks in the system.

d Sustainable transport patterns and smart mobility systems should be promoted. It includes the inhabitants and other users transportation within and to and from the neighborhood. The sustainable transportation goal can be achieved thorough good spatial planning and logistics. These will lead to reduced environmental footprint from transportation and improve the life of the inhabitants in the neighborhood, it will also leads to reduced pollution, congestion and the journey time, and encourage healthier and more sustainable travel choices for the inhabitants and users.

e The planning process, as well as the operating should be done with respect to economic sustainability, by minimising total life cycle costs for buildings, energy and other infrastructure connected to and within the neighborhood.

f A goal is to plan and locate amenities in the neighbourhood to provide good spatial qualities and stimulate sustainable behaviour, and design a public space based on the users of the neighborhoods demands. Spatial qualities cover open and public spaces such as street networks, parks, waterfronts and squares, as well as their interconnections.

g Development of the area should be characterized by innovative processes based on new forms of cooperation between the involved partners leading to innovative solutions. This can include improved or new business models, processes, products and services in order to achieve the goal of zero emission neighborhoods.

Each of these seven categories has a set of one or more assessment criteria, and for each of those a key performance indicator(KPI). Assessment criteria can be either mandatory or voluntary and are requirements that need to be fulfilled for a neighborhood to be considered environmentally, socially and economically sustainable and feasible. KPIs is based on data obtained and measured from a real project and is a set of quantifiable performance measurements that define sets of values, making it easier to measure and track the performance of the neighborhood over time and against other similar projects. [5]

2.2.1 Zero Emission Buildings

The buildings in the zero emission neighborhood are built according to Zero Emission Buildings (ZEB) standards. The national research center on Zero Emission Buildings was a Norwegian research project from 2009 to 2017, and the fundamental purpose was to place Norway in the forefront with respect to innovation, research, and implementation within the field of zero emission buildings which are energy efficient. The research center was organized as a joint by the Norwegian University of Science and Technology and SINTEF. One result from the research center was the ZEB definition, including system boundaries definitions and different ambitions levels, where the levels depending on how many phases of the building's life cycle that are counted in to the calculation. The definition with highest ambition level says that buildings should have zero greenhouse gases emissions over their lifetime, including the production, operation and demolition of the buildings. The buildings should produce enough renewable energy to compensate for their greenhouse gas emissions over a life cycle perspective. The FME ZEN is the successor of ZEB. [48]

Zero energy buildings combine energy efficient buildings and renewable energy onsite production to consume only as much as the onsite energy production over a time period. Zero energy buildings will lead to mitigation of CO_2 emissions and reduce the energy consumption in the buildings. Buildings with renewable onsite energy production will increase the total share of renewable energy.[22]

2.3 Hydrogen

Hydrogen is an energy carrier and can be a part of the solution to reach the UNs climate goals and reduce greenhouse gas emissions in the world. Hydrogen can be produced with different methods. 76 % of the global hydrogen production is from natural gas, which leads to significant greenhouse gas emissions. 23 % of the global hydrogen production is from coal, and only 1 % is from water electrolysis.[30] Today approximately 70 million tons of hydrogen is used globally, most of the hydrogen is used in industrial processes as oil refining and fertilizer production, but hydrogen is getting more attention as an energy carrier for transportation and renewable energy production. Hydrogen can contribute to reduce the CO_2 emissions in several sectors and can be a part of a low emission society. If hydrogen should be a part of an environmentally friendly solution, the production method should be with no emissions, and also the electricity used in the electrolysis production process should be renewable. [10] The popularity of hydrogen globally has increased in the last few years. Norway has great potential and the business sector is ready for an increasing hydrogen market. However, the production price for electrolysis production of hydrogen needs to decrease to make it a more competitive energy carrier.[30] Hydrogen can be used in transportation mainly when the electric battery has too low capacity, or it gets too heavy, and hydrogen is therefore ideal for long distance transportation and transportation on the sea. Hydrogen is a part of a zero emission society and a low carbon society, and is not only crucial in the transportation sector but also in power production, industrial processes and can also be used for heating of buildings.[32].

Electrolysis is the process where the two carbon atoms and the hydrogen atom in water are separated by direct current electricity. The reaction in water electrolysis is:

$$H_2O + energy \rightarrow H_2 + \frac{1}{2}O_2 \tag{2.1}$$

To produce 1 kilogram of hydrogen 9 liters of water is needed in the electrolysis, and the byproduct is 8 kilograms of oxygen and heat. An electrolysis cell consists of two electronic conductors and an ionic conductor. It is mainly two electrolysis technologies that are commercial today that are alkaline electrolysis and acidic electrolysis, and the difference is the type of electrolyte. Both the efficiency and the lifetime are higher for the alkaline electrolysis method. The efficiency for electrolysis of water is about 70 - 80 %. The efficiency is expected to increase as the technology is improved, even though the technology has been long known and used in Norway since 1921 by Norsk hydro. The heat from the electrolysis can be used for district heating, and also the oxygen can be used for medical purposes or in several industrial processes. When the byproduct is used, the production costs are reduced and the efficiency increases. For hydrogen from electrolysis reduction of the costs can be done with decrease the price of production plant, and also increase the total efficiency of the production plant. [30] In Norway, the electricity used to produce hydrogen with electrolysis is exempt from the electrical power tax, which helps to reduce the production costs and makes it more profitable. The electricity price is a cost driver for the total costs of electrolysis. Indirect emissions from the process depend on the electricity production method from the electricity used. Commercial electrolysis units range from a few kW to large scale plants with several MW.

It is cheaper to produce hydrogen from hydrocarbons than with electrolysis. This method is well known from the oil and gas industry. Natural gas is heated and compressed, and the gas which mostly consist of methane(CH_4) reacts with water steam, and CO and H_2 is produced. The byproduct from this process is CO, CO_2 and other greenhouse gasses, so if this is supposed to be an environmentally friendly method carbon capture and storage needs to be combined in the process. [45] The process without carbon capture will produce about 8 ton of CO_2 when producing 1 ton of hydrogen.[30] This method has an energy efficiency of 70 - 85 percent. The gas prices are an major cost driver for the total costs of steam reforming of natural gas.

2.3.1 Fuel cells

A fuel cell converts hydrogen to electrical energy and operates like a battery in the way that it generates electrical energy from an electrochemical reaction. The process in a fuel cell is the reverse reaction of water electrolysis, as shown in equation 2.1. The end product from the fuel cell process is water, electricity, and heat, so the exhaust is just water. Lower heating value, LHV of hydrogen is 2,995 kWh/Nm^3. The lower heating value refers to how much of the heat released by combusting a specific quantity and returning the temperature of the combustion products to 150 °Celsius, and assumes the latent heat of vaporization of water in the reaction products is not recovered. The size of a fuel cell can vary from small devices to large scale power plants. Fuel cells use two electrodes, an anode and a cathode which are separated by liquid or solid electrolyte that carries electrically charged particles between them. [9] Fuel cell system has higher efficiency than internal combustion engines and turbines. The system has few moving components and therefor silent operation. Fuel cell has also low impact on the environment, and flexibility in the fuel choice. Proton Exchange Membrane fuel cell is the best fuel cell solution and is operating at low temperature, and the electrolyte is a proton exchange membrane and therefore can be made very compact. The fuel cells can be connected in series to reach the right power and voltage output.[19]

2.3.2 Storage

Hydrogen can be stored, and therefore it can be used to store energy produced from renewable energy sources, which are unpredictable such as solar and wind power. The density of hydrogen gas is 0.08988 kg/Nm^3, the unit Nm^3 refers to normal cubic meters, which is at 20 °Celsius and 1.01 bars.[19] Since hydrogen has low energy density at normal pressure compared to other energy carriers the density needs to be increased for efficient storage, transportation, and use. Hydrogen can be stored with the use of different methods. A storage solution is compressed gas, which is most relevant for stationary large scale storage, and is the most common and developed method. It can also be stored as liquid and in solids. These processes require energy, and therefore the total cost is increased. Compressed hydrogen is usually stored in thick- walled cylindrically shaped tanks made of stainless steel. A range of sizes and pressures for the storage system are commercially available. [13]

2.4 Power production

2.4.1 Wind power

Wind turbines uses kinetic energy from the wind speed to produce electrical energy. The main technology for wind power production is the horizontal axis propeller type wind turbine with three rotor blades. The wind turbine consists of the foundation, the tower, nacelle, rotor, and a transformer. The tower is usually the same length as the diameter of the wings. Inside the nacelle mechanical energy from the rotor blade is converted to electricity via the main shaft, gear, high speed shaft and generator. It is two main categories of horizontal axis wind turbine, and that is turbine with gear and gearless. The generator can have a higher ratio than the rotor blades in turbines with gear, but in turbines without gear the generator has the same ratio as the rotor blades. The generator efficiency depends on the physical size and the ratio, so wind turbines with gear can have a smaller generator than without gear, without reducing the efficiency. Large scale wind turbines starts to produce power with wind speed at 3- 4 m/s, and reach maximum production at wind speed at 11-15 m/s. When the wind speed is high, the rotor blades adjust the blades angel to avoid to large forces while keeping the production at its maximum. At wind speed at 25-28 m/s most wind turbines needs to shut down, due to the powerful forces.[26] The wind power production output increases with the cube of the wind. Equation 2.2 shows the electric power output P_el, as a function of the power coefficient C_p, the air density ρ, the rotor area A and the wind speed v^3.

$$P_{el} = C_p \cdot \frac{1}{2}\rho A v^3 \tag{2.2}$$

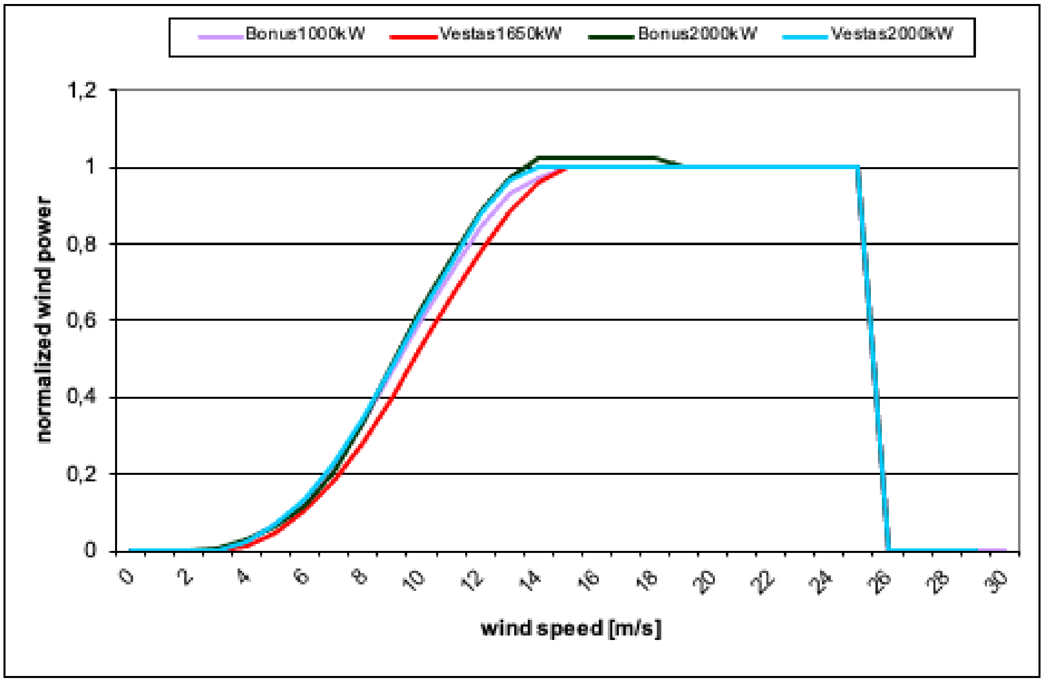

Figure 2.2: Wind turbine power curves

Figure 2.2 shows the normalized power generation at different wind speeds for four different wind turbines: Bonus 1000 kW, vestas 1660 kW, Bonus 2000 kW, and vestas 2000 kW. The figure shows that different wind turbines are designed for different wind speed, and the wind turbines reach its maximum power production at different wind speed. The wind speed increases with the elevation, and therefore the power production depends also on the hub height.

Wind power is a renewable energy source with no emissions and is one of the fastest growing energy sources worldwide. Wind power is suited to large scale power production. The costs of wind farms are dropping, and several places it is cheaper to build wind farms than coal or gas power plants. [37] More than 60 GW wind power capacity was installed in 2019, and the total global installed capacity is over 651 GW. Most of the newly installed wind power capacity was in already established markets.[14] Offshore wind is a newer technology and has considerably higher costs, but 2019 was the year with most new installed capacity of offshore wind. It is estimated that wind power markets will grow further. Often the best wind conditions are located in remote areas where the grid capacity is limited. The grid capacity is often a reason for expensive projects.

Norway has right conditions for wind power production, and is one of the best suited countries in the world for wind turbines. Norway has a long coastline, and has a high average wind speed. Wind turbines are building in Norway even though there is a lot of reluctance from the local inhabitant several places where wind turbines is going to be built. 23.june 2020 there was 42 wind power plant with over 850 wind turbines in Norway, with an installed capacity of 2600 MW. [24] The costs are decreasing, and the CO_2 prices increasing, and this makes wind power plants a more competitive energy source. In 2018 NVE estimated that a new wind power plant has a Levelised Cost of Energy, LCOE of less than 35 øre/kWh, which is lower than gas and coal plants but higher than large scale hydro power plant.[24] Wind power is an energy source that are unpredictable and can not be stored, therefore it is good to combine it with more predictable energy sources as hydro power. The power production in Norway can lead to lower total emissions in Europe, because the European grid is connected. NVE assumes that 10 TWh exported wind power will reduce the CO_2 emissions by 5 million tons. [4]

The area of a wind park depends on the size of the wind turbine and the numbers. 2000 m^2/turbine is the average land use in Norway for large scale wind power plants. Typical hub height range from 60 - 100 m for wind turbines at MW size. A wind power plant needs a great amount of land in the building period, due to the interconnected roads, and therefore this is also a encroachment in the nature. The area is often located at high ground and in untouched natural areas. [21]

2.4.2 Solar power

The radiations from the sun are referred to as solar energy, and the energy received as heat and light can be converted to electricity and other usefull forms. Each year the earth receives 15000 times more energy from the sun than the total energy consumption and is an important energy source.[33] Photovoltaic (PV) cells convert the solar radiations into electricity. Solar power is a renewable energy source with 22 to 46 gram greenhouse gas emissions per kWh during its life cycle, and the emissions are from the production and transportation phase. It is estimated that the life-cycle emissions will decrease in the future due to improved production technologies for the panels. During the operation it is no emissions from PV cells. Solar power sold to the grid can contribute to reduce the CO_2 emission footprint from the grid. Solar power is an unpredictable and nonstorable energy source.

The PV cells consist of semiconductor material and produce DC current. PV cells are made up of two slices of semiconducting materials, usually silicon. To make silicon lead electricity, an electric field is established with manufacturers "dope" silicon with other materials, and it is usually doped with boron and phosphorus. The top layer of silicon gets phosphorus seeded which adds extra electrons, and the bottom layer gets boron which leads to fewer electrons. A positive electric charged p-side and a negative electric charged n-side are occurring. Photons from the sunlight knock free an electron, and the electric field will push the electron out of the silicon junction. A couple of other components of the cell turn the electrons into power that can be usable. On the sides of the cell, there are metal conductive plates that collect the electrons and transfer them to wires, and the electrons can flow like any other source of electricity.[8] PV panels are made of many PV cells, and PV modules are several connected PV panels. The PV cell's efficiency depends on the temperature, radiance and spectrum. PV panels produce DC current, so a converter is needed if the PV panel is connected to the power grid. No encroachment on nature is needed since the panels can be installed on roofs and walls on buildings either as free-standing structures or as integrated into the construction. This can also increase the energy efficiency of the buildings. PV panels can only utilize a small amount of the received sunlight, and most panels have an efficiency between 15- 20 % [43] . The panels can be connected to the power grid, so the power is exported when the power production is higher than the local consumption. Figure 2.3 shows the diagram of PV cell.

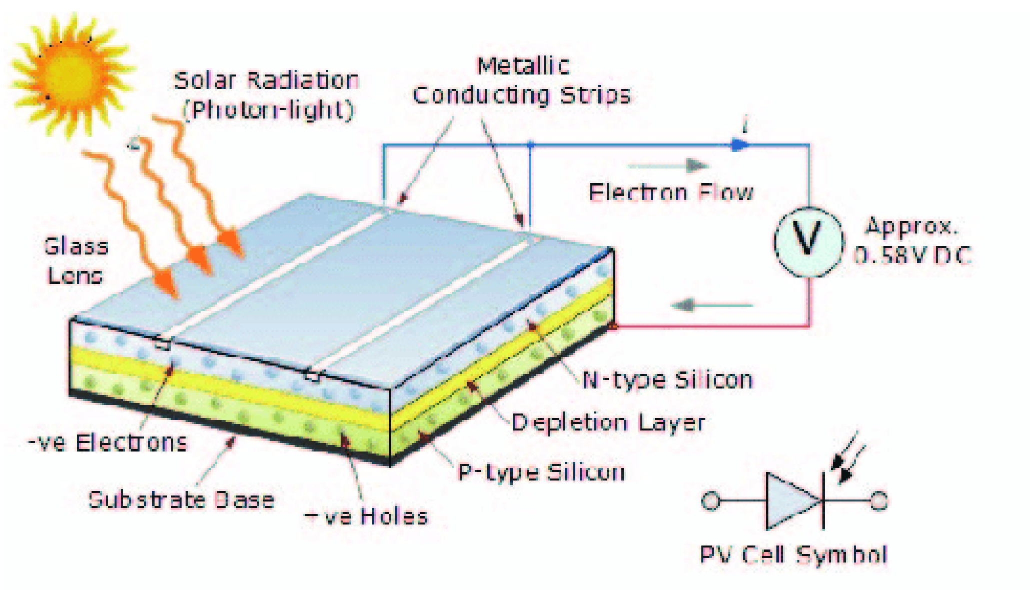

Figure 2.3: PV cell diagram, [12]

The climate in Norway is cold and often rainy and overcast compared to other countries. High temperatures increase the internal energy leakage in the cells because electrons are more active in warm conditions. Low temperatures are therefore more ideal for PV cells. The snow will reflect the sun rays and increase solar radiation. The Nordic climate is well suited for solar power production.[31] Norway has solar radiations on a horizontal surface about 700 - 1000 kWh/m^2 each year.[33] The solar radiation has a great variation throughout the year and is highest during the summer. The angle of inclination of the panels can be optimized to utilize solar radiation. PV cells produce approximately 100-170 kWh/m^2 in Norway, but this depends on factors like the location, the system solution and efficiency. During winter in Norway it can be necessary to remove the snow from the surface of the panels. It is often unnecessary to remove dust and pollution from the solar cell surface, because it often gets washed away when it rains. [34]

The lifetime of a solar cell is about 30 years, and it requires a minimum of maintenance. The costs have fallen, and the electricity from solar power has become competitive in Norway. Previously solar power was only profitable in countries with high electricity prices. At the end of 2019, the total installed PV capacity in Norway was 120 MW. In 2019 new installed capacity globally was 115 GW, and that leads to total globally capacity of 627 GW.[27]

Chapter 3

Method

3.1 Windhydtools

Windhydtools is a Matlab and Excel simulation program for the assessment of a wind-hydrogen energy system. The program is developed by M. Korpås and is derived from the doctoral work, which is documented in M. Korpås "Distribution Energy Systems with Wind Power and Energy Storage", Doctoral thesis at NTNU 2004:39. The program uses time-series for wind speed, electrical load, and hydrogen load to calculate the electrical energy balance and hydrogen balance for each time step of the simulation. Excel is used as the interface for defining input data and for analyzing the simulation results.

Modification in the model is created to include solar power, so one of them or both wind power and solar power in an optimal combination is used to produce the hydrogen and cover the electricity demand from the zero emission neighborhood. The program runs when windhydsim is written in the commandoline and then reads the input data from excel and the time-series for the loads. The figure below shows the schematic illustration of the wind hydrogen system.

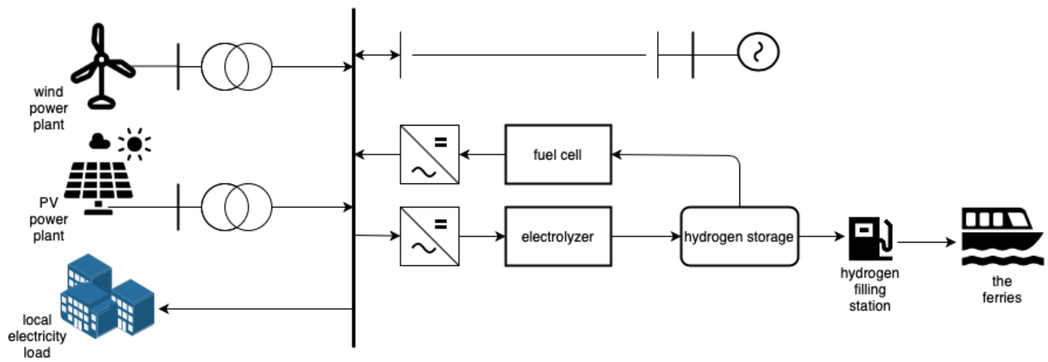

Figure 3.1: Schematic illustration of the wind, PV and hydrogen system

In the model a control strategy is chosen, the four control strategies are:

1. **Self- supplied with electricity and hydrogen.**
   The production of hydrogen starts when the wind and solar power production exceeds the local load. The fuel cell is operating when the local load exceeds the wind and solar power. Production of hydrogen from grid electricity starts if the hydrogen storage level reaches the supply security limit.

2. **Wind and solar power primarily for the hydrogen filling station.**
   The production of hydrogen starts when the wind and solar power exceeds zero. Production of hydrogen from grid electricity starts if the hydrogen storage level reaches the supply security limit. The fuel cell is not in use.

3. **Maximum grid utilization with fuel cell strategy 1.**
   The production of hydrogen starts when the local power production surplus exceeds the grid capacity. The fuel cell is operating when the local load exceeds the wind and solar power. The production of hydrogen from grid electricity starts if the hydrogen storage level reaches the supply security limit.

4. **Maximum grid utilization with fuel cell strategy 2.**
   The production of hydrogen starts when the local power production surplus exceeds the grid capacity. The fuel cell is operating whenever

it is possible, with the highest possible power. Production of hydrogen from grid electricity starts if the hydrogen storage level reaches the supply security limit.

Power exported to the main grid P_g can take both positive values and negative values, and the negative values are occurring when power is imported. The power balance is given below, with the system variables on the left side of the equation sign and the external inputs on the right side:

$$P_e(t) + P_d(t) + P_g(t) - P_f(t) = P_w(t) + P_{pv}(t) - P_l(t) \tag{3.1}$$

Power export and import are constrained by this restriction:

$$-P_g^{max} \leq P_g(t) \leq P_g^{max} \tag{3.2}$$

where P_g^{max} is maximum power transmission to the main grid. If the power production surplus is greater than the transmission capacity, power has to be dissipated.

The power and hydrogen flow rate in the electrolyzer and in the fuel cell are given by these equation:

$$P_e(t) = \eta_e \dot{V}_{He}(t) \tag{3.3}$$

$$P_f(t) = \eta_f \dot{V}_{Hf}(t) \tag{3.4}$$

where η_e is the specific power consumption of the electrolyzer, including rectifier losses and consumption of power for hydrogen compression. η_f is the specific power output of the fuel cell, where inverted losses is included. Electrolyzer and fuel cell operation are limited by:

$$P_e^{max} \leq P_e(t) \leq P_e^{max} or P_e(t) = 0 \tag{3.5}$$

$$P_f^{min} \leq P_f(t) \leq P_f^{max} or P_f(t) = 0 \tag{3.6}$$

where P_e^{max} and P_f^{max} are the maximum power capacity of the components.

The hydrogen storage balance is expressed as:

$$V_H(t+1) - \frac{P_e(t)}{\eta_e}\Delta t + \frac{P_f(t)}{\eta_f}\Delta t = V_H(t) - \dot{V}_{Hl}(t)\Delta t \tag{3.7}$$

where the hydrogen load $\dot{V}_{Hl}$ is an external input with a fixed value for each time step. The stored hydrogen capacity is constrained by:

$$0 \leq V_H(t) \leq V_H^{max} \tag{3.8}$$

where V_H^{max} is the maximum storage capacity of the system.

The net electricity production, consumption and export as well as hydrogen production and consumption in the different system components needs to be calculated. The net electrical energy production or consumption is given by this equation:

$$E = \sum_{t=1}^{T} P(t)\Delta t \tag{3.9}$$

The total hydrogen demand in the system is given by:

$$V_{Hl} = \sum_{t=1}^{T} \dot{V}_{Hl}(t)\Delta t \tag{3.10}$$

where T is the final time step and Δt is the time resolution in hours. The net energy produced exported to the main grid is expressed by:

$$if P_g(t) \leq 0 \tag{3.11}$$

$$P_{imp} = -P_g(t) \tag{3.12}$$

$$P_{exp}(t) = 0 \tag{3.13}$$

$$else$$

$$P_{imp}(t) = 0 \tag{3.14}$$

$$P_{exp}(t) = P_g(t) \tag{3.15}$$

where P_{exp} is power exported to the grid and P_{imp} is power imported from the grid.

The power import used for hydrogen production is found by these equation:

$$if P_{imp}(t) \leq P_l(t) \tag{3.16}$$

$$P_{imp,e} = 0 \tag{3.17}$$

$$else$$

$$P_{imp,e}(t) = P_{imp}(t) - P_l(t) \tag{3.18}$$

Chapter 4

Input data

The model takes in hourly time-series for hydrogen load and electricity load from the zero emission neighborhood, and the analysis period is one year. Hourly data for wind power output and solar power output are collected from renewable.ninjas.

4.1 Zero Emission Neighborhood

The windhydtools model uses hourly time-series for the electricity load. The ZEN profiles database predictor Excel program is used to estimate hourly values for both electricity and thermal demand for the zero emission neighborhood. An estimate about the size of the new city was made in my project thesis, since the Bodø redevelopment project is in an early phase and it is therefore limited information about the size of the planning city and building stock, and assumptions were necessary to make. The ZEN rapport no. 14 has statistic about the average building size in Norway for different buildings types, so this was used to make assumptions about the floor area for the neighborhood.[15] Average areal of buildings in Norway was used, and the fact that 15000 new homes and 20000 job places are planned. The building stock will consist of different buildings type with different demands. The area of the new building stock in Bodø is estimated to be:

Building type	Size [m^2]
Residential buildings	1050000
Offices	180000
Educational buildings	1080000
Health buildings	129000

Table 4.1: Floor area distribution for the zero emission neighborhood

4.1.1 Electrical load and thermal load

The input data in the excel program is the floor area and hourly values for outdoor temperatures in Bodø. The temperature in Bodø in 2019 is shown in figure 4.1 and is obtained from renewables.ninja. The average temperature is -1,6 °C, the maximum temperature is 26,0 °C, and the lowest temperature is -26,3 °C.

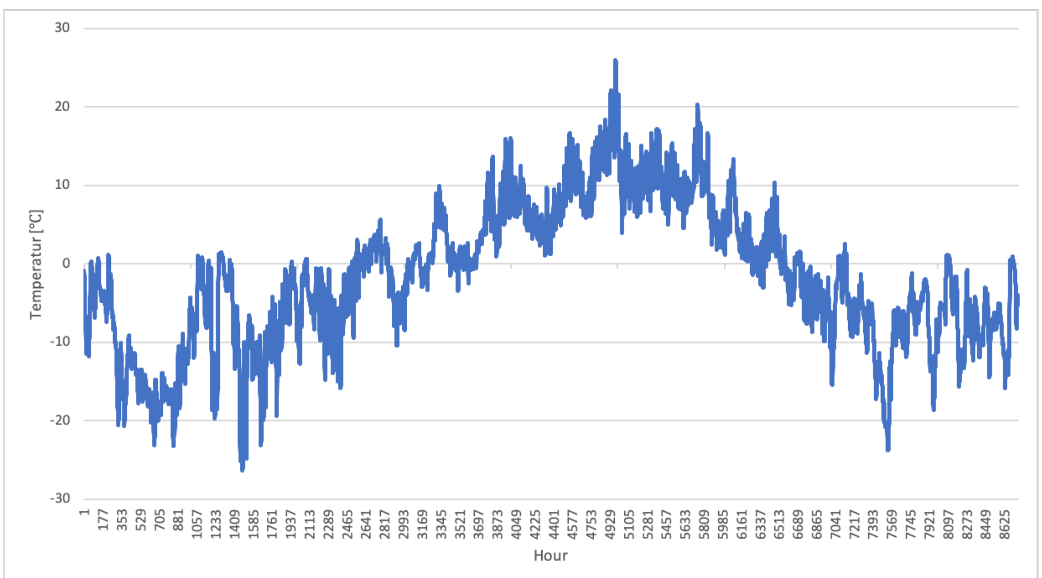

Figure 4.1: Hourly temperatures in Bodø in 2019

The heating demand for the zero emission neighborhood in Bodø is estimated from the excel program. Figure 4.2 shows the thermal hourly load profile for a year. The demand for heat is highest during the winter. During the summer, the demand is minimal due to high outdoor temperatures. The average temperature in Bodø is low, and therefore the average demand for heating is high since the heating demand depends on the outdoor temperatures. The total heating demand for the year is 237864564 kWh, with hourly variations between 4710 kW and 64318 kW. The hourly mean is therefore 27153 kW. Based on research, the best solution to cover the heating demand in Norway is by bio pellets boiler or heat pump.[20]

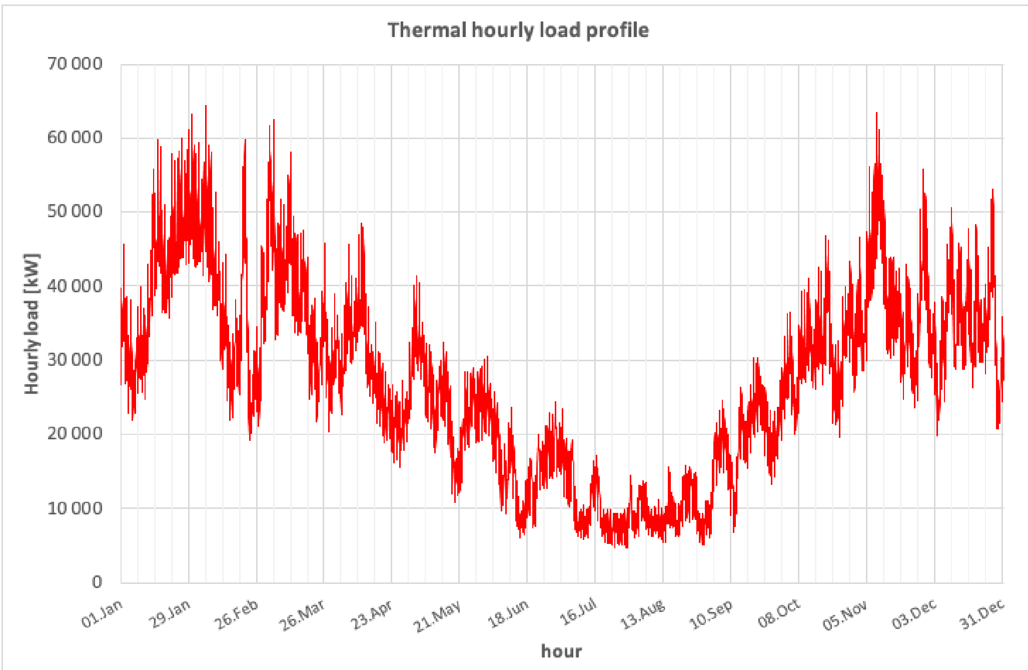

Figure 4.2: Thermal hourly load profile for a year

Figure 4.3 shows the electricity hourly load for a year. The figure shows that the electricity demand is lower during the summer. The variations during the year are smaller compared to the heating demand because the electrical load is not so dependant to the outdoor temperatures. The total electricity demand for the year is 101327482 kWh, with hourly variations between 6503 kW and 15996 kW. The hourly mean is 11687,13749 kW.

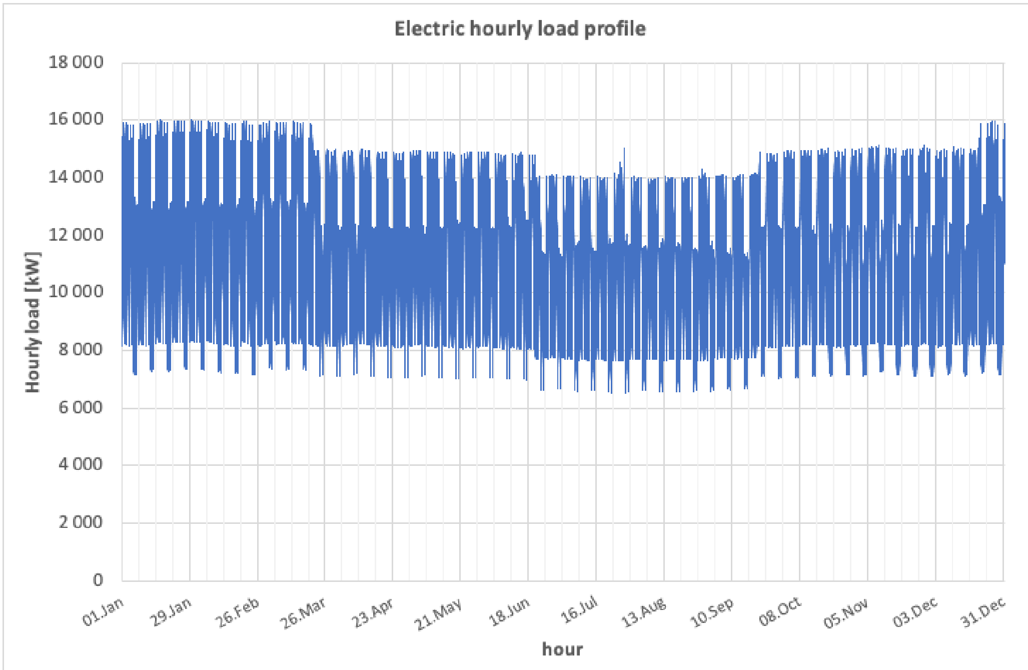

Figure 4.3: Hourly electricity load for a year

4.2 Solar power

Information about the PV power conditions in Bodø is obtained from renewable.ninjas. The model uses normalized hourly values for PV power.

The tilt is the angle of the panels and how far the panel is inclined from the horizontal, an angel of 0°is a panel facing directly upwards. The optimal angle for the panel to maximizing the power output from the panels is dependant on where the location is and the latitude. It is easiest to fix the panels to a tilt and have it there thorough the year. In renewable.ninja, the tilt is set to 35°. The azimuth is the angle measure in a spherical coordinate system, so it is the compass direction the panel faces, an angle of 180°means facing pole-ward. So for latitudes larger than 0 it means they should be facing south-wise, and the azimuth is therefore set to 180°. The capacity factor of the PV system is set to 1 kW, and the output values are therefore calculated from that power capacity.

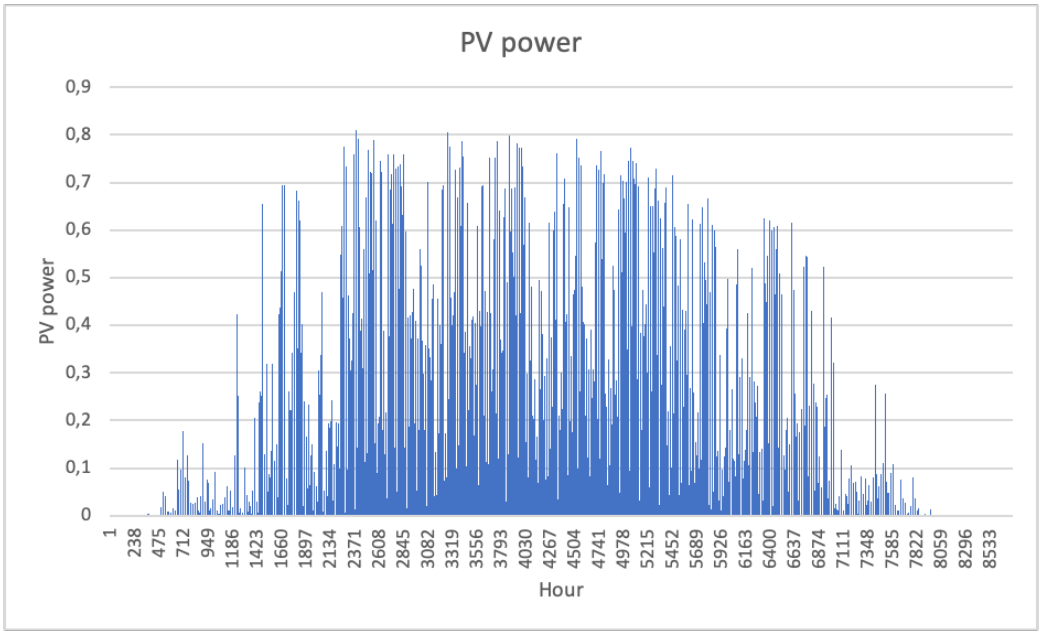

Figure 4.4: Normalized PV power for a year

Figure 4.4 show the normalized PV power output for a year with hourly values.

4.3 Wind power

The wind power produced is estimated from the wind speed in Bodø. Hourly values for the wind speed are obtained from renewable.ninjas, and the data is from 1. January to 31. December 2019.

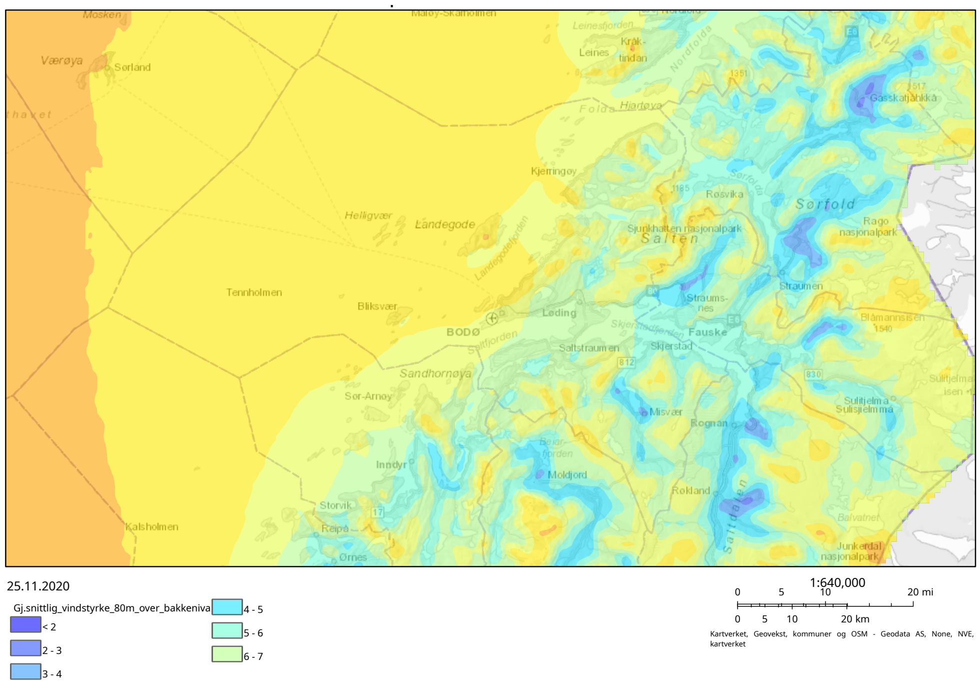

Figure 4.5: Wind at 80 meters in Bodø

Figure 4.5 shows the wind speed at 80 meters height in the Bodø area, and where the best wind conditions are located in the area. Figure 4.6 show hourly wind speed at 80 meters in Bodø in 2019. The wind has an average value of 6,98 m/s, and varies from 2,0 m/s to 25,6 m/s in 2019.

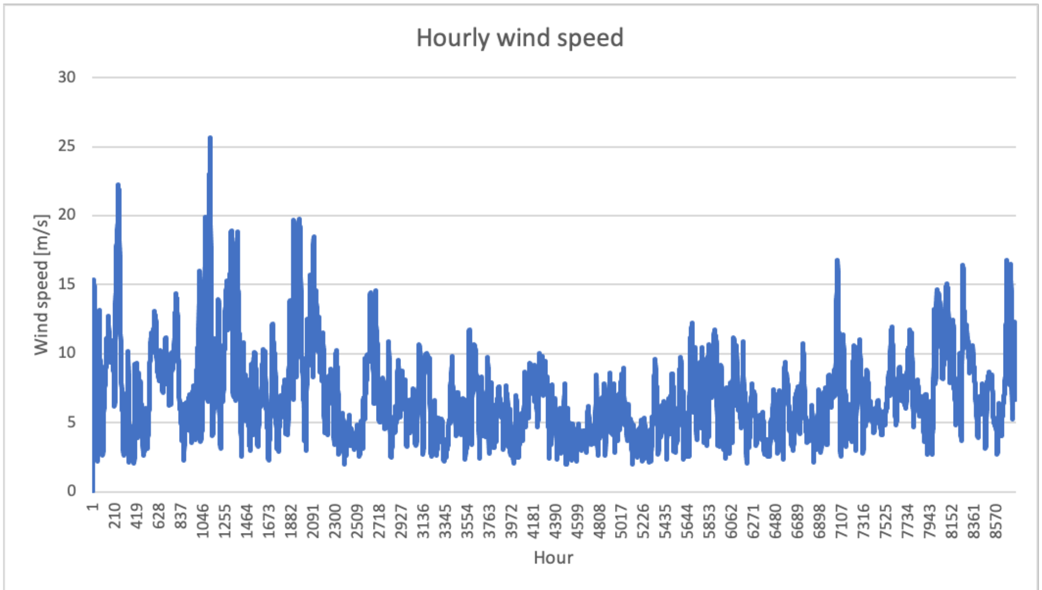

Figure 4.6: Hourly wind speed at 80 meters in 2019

Normalized hourly values for wind power output are obtained from renewable.ninjas. The hub height is set to 80 meters, and the chosen turbine model is Vestas 2000kW. The capacity factor of the wind system is set to 2000 kW, and the output values are therefore calculated from that power capacity. Figure 4.7 shows the hourly normalized wind power output values for a year with the chosen parameters.

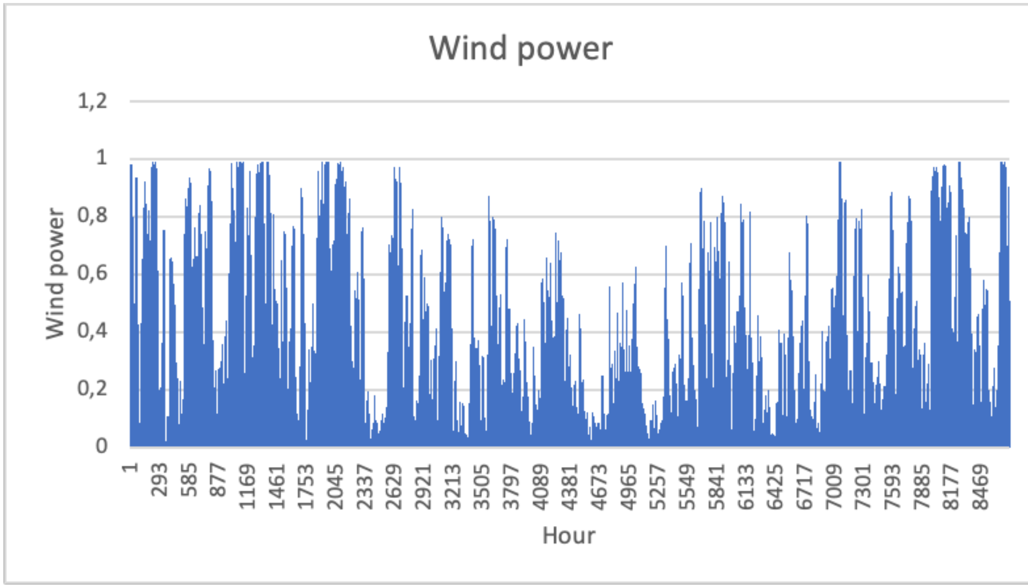

Figure 4.7: Normalized wind power for a year

4.4 Hydrogen load

Hourly values for the hydrogen load are used as input data in the model. The ferries uses hydrogen and are charged when the ferries are at the port. Power from the wind turbines and PV panels are used for the electrolysis and production of hydrogen, and the hydrogen is stored until the ferries charge.

The amount of needed hydrogen is estimated from the power use from the electrical ferry Ampere. Ampere is located at Sognefjorden in the western part of Norway and was the first battery ferry in the world in 2015, the fjord crossing is 6 km and the ferry uses 130-200 KWh for this distance, and therefore uses 25 kWh/km. [46] From this information the energy consumption is estimated for the distances between Bodø and the island Værøy, and the island Røst, and Moskenes which is located in Lofoten. During the summer, many tourists are visiting Bodø and the northern area of Norway, and the ferries need to have multiple departures in a day compared to the winter season. The ferry from Bodø to Moskenes, the ferry from Bodø to Røst, and the ferry from Bodø to Værøy are estimated to run two times a day, and in the summer months June, July and August the capacity is doubled, so they runs four times a day. These are the longest ferry distances in Norway, and the distances are:

	km
Bodø-Røst	109
Bodø-Moskenes	94,3
Bodø-Værøy	86,3

Table 4.2: The ferry distances [44]

Figure 4.8: A map of the ferry distances from Bodø

Figure 4.8 shows a map of a part of the northern area in Norway, and the distances from Bodø to Røst, Værøy, and Moskenes.

The power losses for hydrogen are included in the estimate for electricity needed for the ferries. A fuel cell that uses hydrogen can theoretically have an efficiency of almost 100 % , but real efficiency values are now around 50 %. [7]

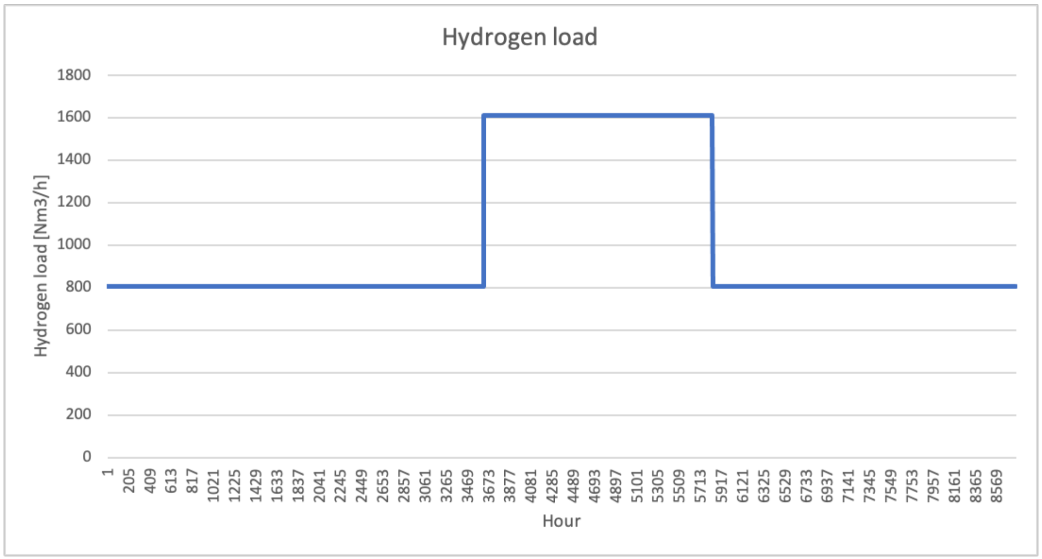

Figure 4.9: The ferries hydrogen load for a year

Figure 4.9 shows the ferries hydrogen load over a year with an hourly average hydrogen load. During the summer, the average hydrogen load is 1611,57 Nm^3/h, and the rest of the year the load is 805,79 Nm^3/h which gives an annual average of 1008,89 Nm^3/h.

The hydrogen load each year is 8837876,42 Nm^3, which is equal to 26469440 kWh. And the electrolyzer efficiency is 70 % and therefor is equal to 37813485,71 kWh directly from the main grid. The amount of demanded power from the grid is equivalent to 37,3 % of the total zero emission neighborhoods electricity demand.

When the ferries are at the port they charge, and it is the hour before they leave they charge all the needed amount of hydrogen. The charging is therefore four times during the summer, and two times the rest of the year. During the summer the three ferries are estimated to have departure at 06.00, 10.00, 15.00, 21.00, and the rest of the year the departure is at 08.00 and 16.00. Each charging requires 9669,56 Nm^3 which is 869,09 kg of hydrogen. Figure 4.10 shows the hydrogen load with four charging at summer and two charging the rest of the year, where each charging requires the same amount of hydrogen. The annual total hydrogen load is 794348,33 kg.

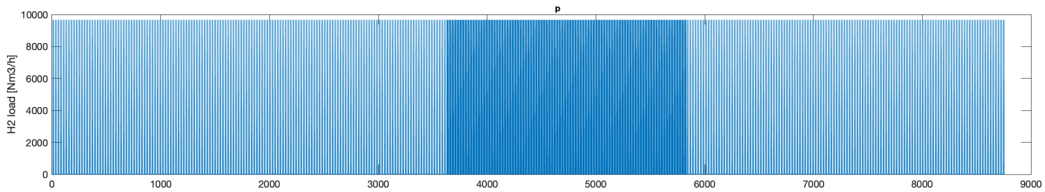

Figure 4.10: The ferries hydrogen load with four charging in the summer and two charging the rest of the year

Chapter 5

Results

The result shows the three main scenarios: one with only electricity load and control strategy 1 is chosen, one with both the electricity demand and the hydrogen demand and control strategy 2, the last one with both the electricity demand and the hydrogen demand and control strategy 1. Further was each of these three main scenarios run with three different supply technologies to cover the demand. One with only wind power, one with only PV power and the last one is a combination of 80% wind power, and 20% PV power.

The defined input values for the component parameters are:

- Electrolyzer rating: 30000 kW
- Hydrogen storage capacity: 100000 Nm^3
- Supply security limit for storage: 50%
- Fuel cell rating: 12000 kW

5.1 Only electricity load and control strategy 1

5.1.1 Case 1: Only wind power

The load is the zero emission neighborhood's electricity load. Control strategy 1 means that hydrogen is produced when the wind power exceeds the local load, and the fuel cell is operating when the local load exceeds the wind power production. Both wind power and the fuel cell cover the electricity demand, and power from the grid is imported when required.

The installed wind power capacity is 35,5 MW.

	MWh
Wind generation	110667,70
Electrical load	101327,48
Electrolyzer load	13461,07
Fuel cell generation	4640,77
Import from grid	29050,27
Export to grid	29570,19
Net export to grid	519,91

Table 5.1: Results when wind power covers the electricity demand with use of the fuel cell

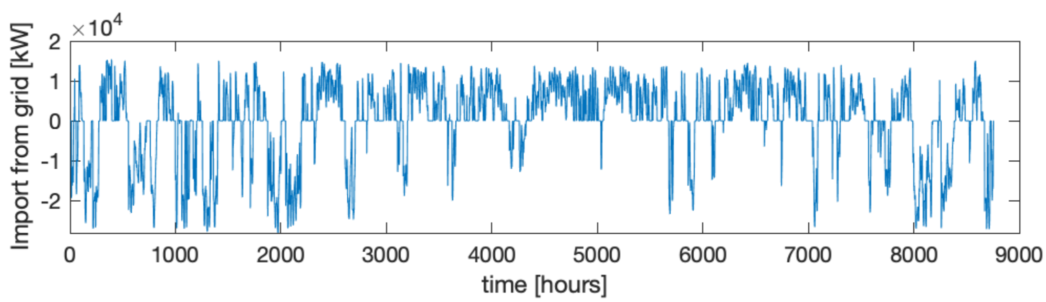

Figure 5.1: Power import from the grid when wind power covers the electricity demand with use of the fuel cell

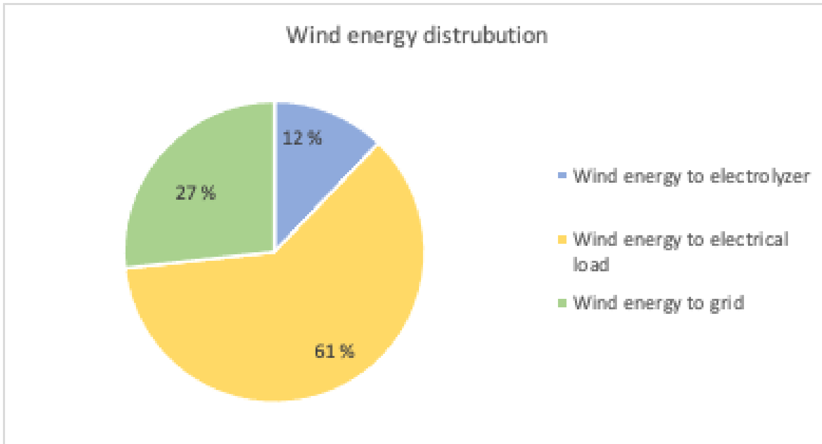

Figure 5.2: Wind energy distribution when wind power covers the electricity demand with use of the fuel cell

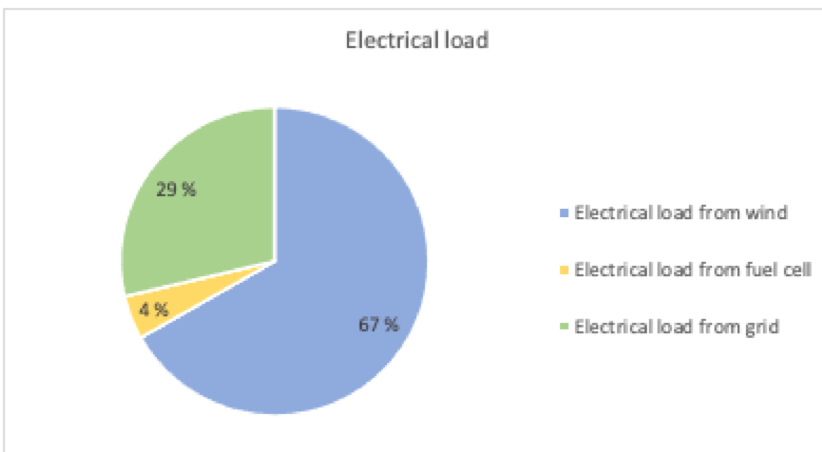

Figure 5.3: Origin of the electricity which cover the electrical load when wind power covers the electricity demand and with use of the fuel cell

Discussion

Wind power together with the hydrogen fuel cell covers the electricity demand, and power from the grid is charged when needed. The installed wind capacity is 35500 kW. The total annual import is 29 GWh, and the total annual net export is 0,52 GWh. Figure 5.1 shows how the power import varies over the year. Most of the import is during the summer when the wind speed is low in Bodø, and the export is high during winter when the wind speed is at its highest. The electrical load is covered and figure 5.3 shows where the energy comes from, 67% of the electrical load is covered by power from the wind power plant. The hydrogen storage and the fuel cell is in use, and 12,16 % of the wind energy produced goes to the electrolyzer, but only 4,58% of the electrical load is covered by the fuel cell. Figure 5.2 shows the wind power distribution.

5.1.2 Case 2: Only solar power

The load is the zero emission neighborhood's electricity load. Control strategy 1 means that hydrogen is produced when the PV power exceeds the local load and the fuel cell is operating when the local load exceeds the PV power production. Both PV power and the fuel cell cover the electricity demand, and power from the grid is imported when required.

The installed PV power capacity is 147 MW.

	MWh
PV generation	127881,62
Electrical load	101327,48
Electrolyzer load	39952,85
Fuel cell generation	13983,5
Import from grid	49720,09
Export to grid	50304,87
Net export to grid	584,79

Table 5.2: Results when PV power covers the electricity demand with use of the fuel cell

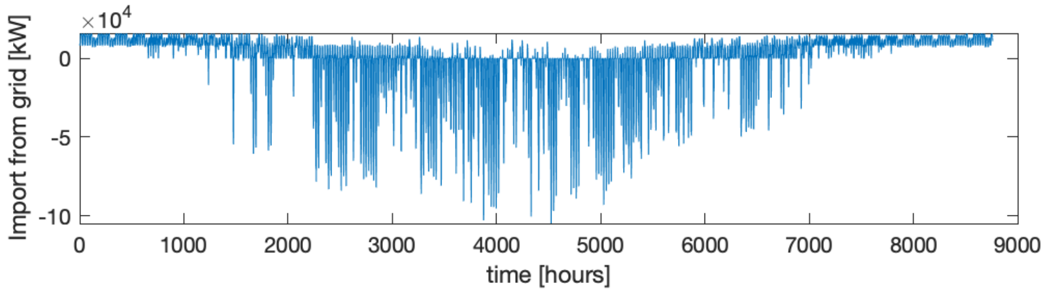

Figure 5.4: Power import from the grid when PV power covers the electricity demand with use of the fuel cell

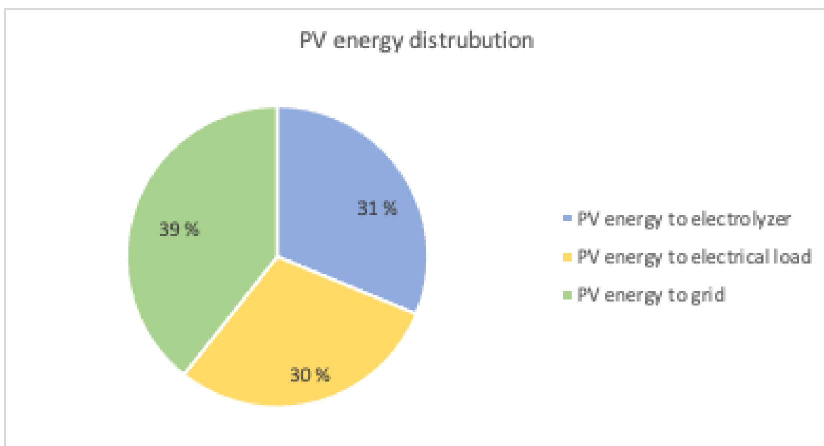

Figure 5.5: PV energy distribution when PV power covers the electricity demand and with use of the fuel cell

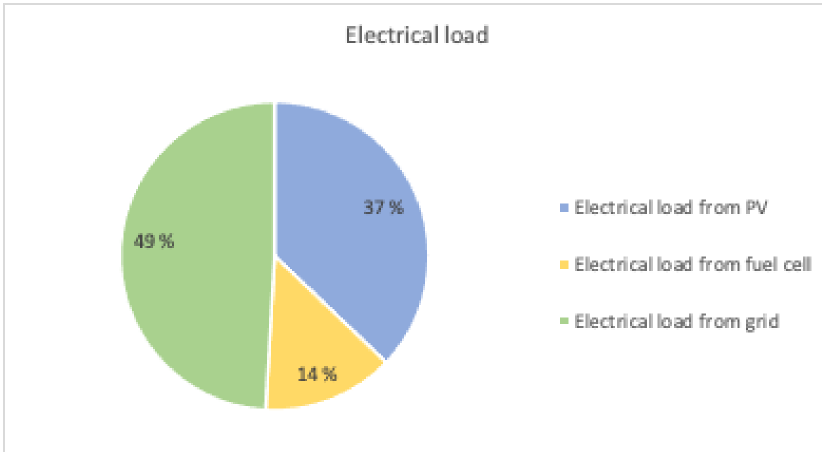

Figure 5.6: Origin of the electricity which covers the electrical load when PV power covers the electricity demand with use of the fuel cell

Discussion

The installed PV capacity is 147 MW. The total annual import is 49,7 GWh, and the net export is 0,58 GWh. Figure 5.4 shows the power import over the year. The PV production is highest during summer, and very low during winter therefore power is exported during summer and imported during winter. Figure 5.5 shows the PV energy distribution. Only 29,42 % of the PV energy produced goes to the electrical load. 39,34% of the PV energy goes to the grid, because when the production is happening, the production is much higher than the electrical load. The grid capacity has to be large due to the high production during the summer time. The electrical load is covered, and figure 5.6 shows where the energy comes from. 37,13% of the electrical load is covered by PV power, and 13,8% of the demand is covered by the hydrogen fuel cell. The rest and nearly half of the electricity demand are covered by power imported from the grid due to the low production during winter.

5.1.3 Case 3: 80% wind power and 20% solar power

The load is the zero emission neighborhood's electricity load. Control strategy 1 means that hydrogen is produced when the PV and wind power exceeds the local load and the fuel cell is operating when the local load exceeds the PV and wind power production. Both PV power, wind power and the fuel cell cover the electricity demand, and power from the grid is imported when required.

The installed PV power capacity is 8,4 MW. The installed wind power capacity is 33,6 MW.

	MWh
Wind and PV generation	112052,16
Electrical load	101327,48
Electrolyzer load	13657,17
Fuel cell generation	4712,4
Import from grid	25002,72
Export to grid	26782,634
Net export to grid	1779,91

Table 5.3: Results when wind and PV power covers the electricity demand with use of the fuel cell

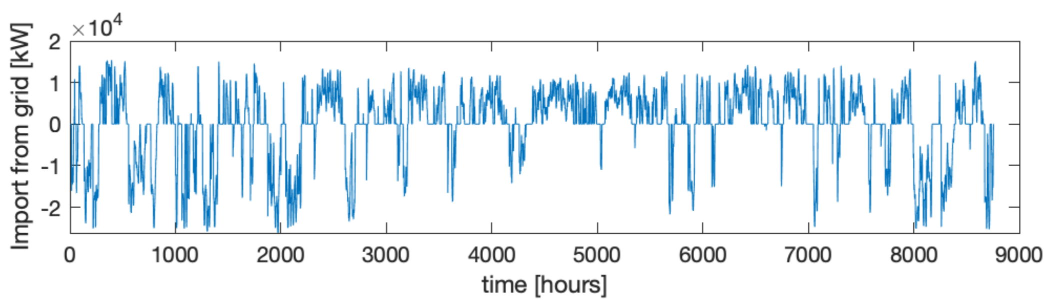

Figure 5.7: Power import from the grid when wind and PV power covers the electricity demand with use of the fuel cell

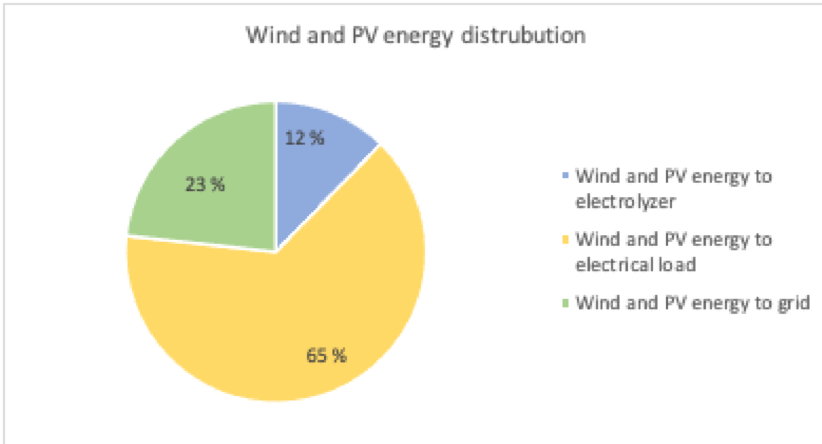

Figure 5.8: Wind and PV energy distribution when wind power covers the electricity demand with use of the fuel cell

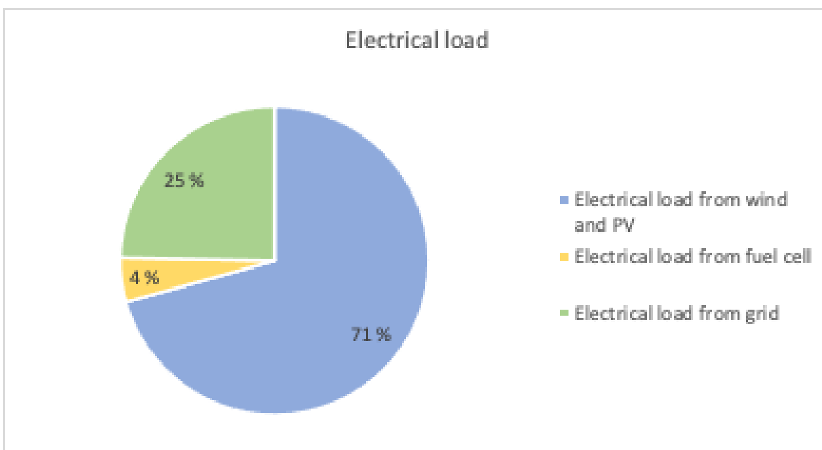

Figure 5.9: Origin of the electricity which covers the electrical load when wind and PV power covers the electricity demand with use of the fuel cell

Discussion

A combination of wind power and PV power, where 80% of the capacity is wind power and 20 % is PV power. The installed wind capacity is 33,6 MW and the PV power 8,4 MW. The annual import from the grid is 25 GWh, and the net export is 1,78 GWh. Figure 5.7 shows the power import over the year. The wind power production is highest during the winter and the PV power production is highest during the summer, therefore a combination will make the import and export over the year more equal. However, the wind conditions in Bodø are better than the solar conditions, and therefore the power export from the grid is lowest during the summer. The power export is highest during the winter when the wind production is high. Figure 5.8 shows the wind and PV energy distribution. 23,09% of the power production goes to the grid, and 24,68% of the electrical load is covered by power from the grid. Only 12,19% of the power produced goes to the electrolyzer. Figure 5.9 shows the origin of the electricity which cover the electrical demand. Only 25 % of the electrical load is powered by power from the grid.

5.2 Electricity load and hydrogen load and control strategy 2

5.2.1 Case 1: Only wind power

The loads are the zero emission neighborhood's electricity load and the ferries hydrogen load. Control strategy 2 means that the production of hydrogen starts when the wind power exceeds zero, and the fuel cell is not in use. Only wind power covers both the electricity demand and the hydrogen demand, and power from the grid is imported when required.

The installed wind power capacity is 45 MW.

	MWh
Wind generation	140283
Electrical load	101327,48
Electrolyzer load	38027,41
Import from grid	55102,3
Export to grid	56030,4
Net export to grid	928,1

Table 5.4: Results when wind power cover the electricity and hydrogen load without use of the fuel cell

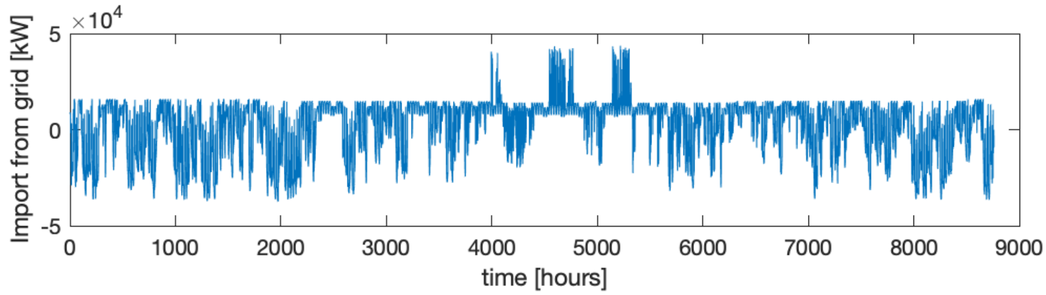

Figure 5.10: Power import from the grid when wind power cover the electricity and hydrogen load without use of the fuel cell

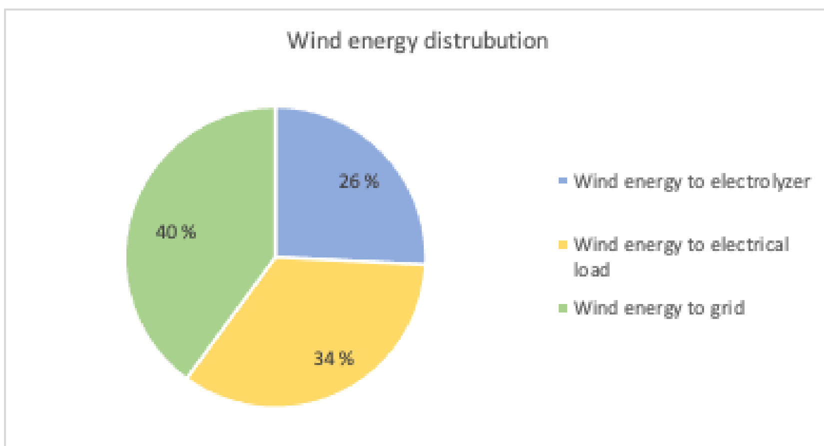

Figure 5.11: Wind energy distribution when wind power cover the electricity and hydrogen load without use of the fuel cell

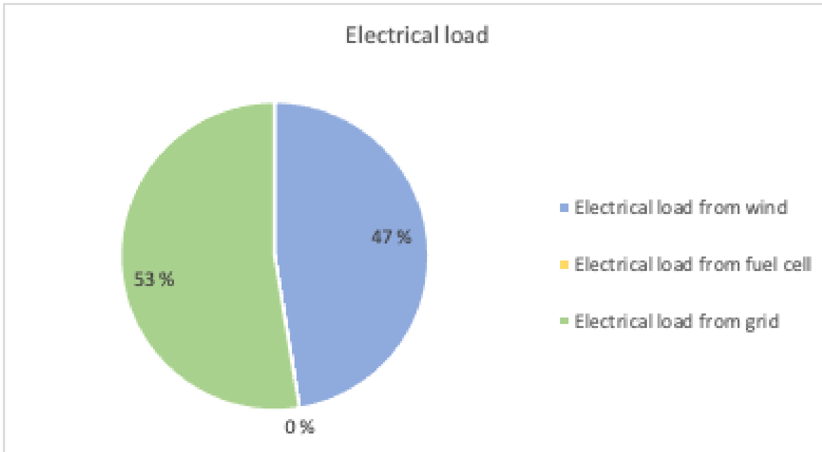

Figure 5.12: Origin of the electricity which covers the electrical load when wind power cover the electricity and hydrogen load without use of the fuel cell

Discussion

Wind power covers the electricity demand and the hydrogen demand, and power from the grid is charged when needed. 45 MW installed wind capacity. The fuel cell is not in use, and therefore the hydrogen produced goes only to the ferries. 25,8% of the wind energy goes to the electrolyzer. The annual import from the grid is 55 GWh, and the net export is 0,93 GWh. Figure 5.10 shows the power import over the year. The power import is happening during summer when the wind speed is at its lowest, in the rest of the year the import is low. The power export is highest during winter time, and a totally 39,94% of the wind energy produced goes to the grid. Figure 5.11 shows the wind energy distribution. Figure 5.12 shows the origin of the electricity which covers the neighborhood's electrical load. 47,42% of the electrical load is covered by wind power, and the rest is covered by power from the grid.

5.2.2 Case 2: Only solar power

The loads are the zero emission neighborhood's electricity load and the hydrogen load of the ferries. Control strategy 2 means that the production of hydrogen starts when the PV power exceeds zero, and the fuel cell is not in use. Only PV power covers both the electricity demand and the hydrogen demand, and power from the grid is imported when required.

The installed PV power capacity is 160 MW.

	MWh
pv generation	139190,88
Electrical load	101327,48
Electrolyzer load	37813,49
Import from grid	81437,3
Export to grid	81487,21
Net export to grid	49,91

Table 5.5: Results when PV power cover the electricity and hydrogen load without use of the fuel cell

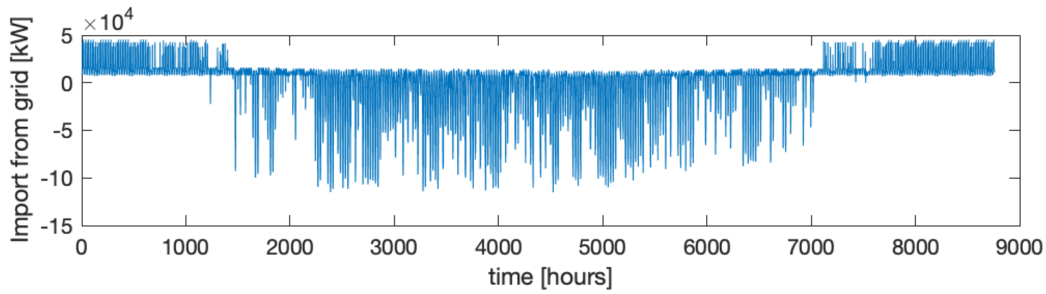

Figure 5.13: Power import from the grid when PV power cover the electricity and hydrogen load without use of the fuel cell

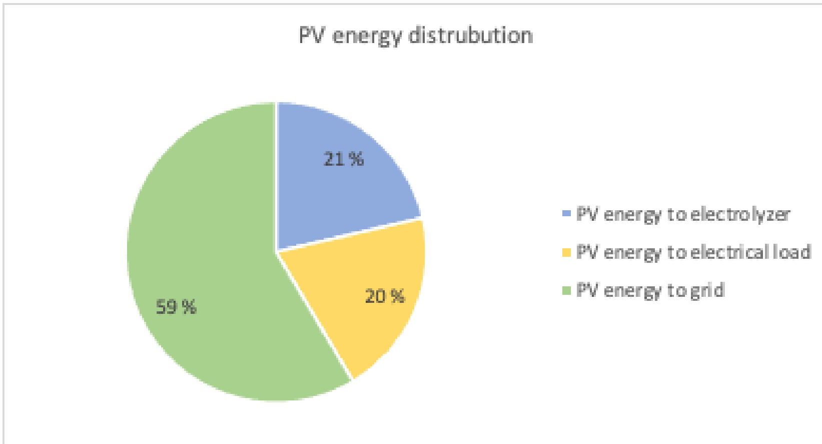

Figure 5.14: PV energy distribution when PV power cover the electricity and hydrogen load without use of the fuel cell

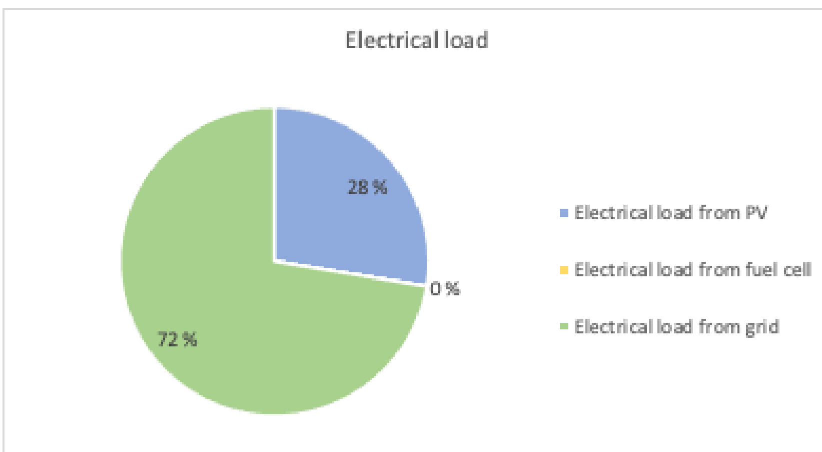

Figure 5.15: Origin of the electricity which cover the electrical load when PV power cover the electricity and hydrogen load without use of the fuel cell

Discussion

PV power covers the electricity demand and the hydrogen demand. The PV installed capacity is 160 MW, and the fuel cell is not in use due to the chosen control strategy. The power import from the grid over the year is 81,4 GWh and the net export is 49,9 MWh. Figure 5.13 shows the power import over the year. The power import is in the winter when the solar radiation is lowest, and the export is in the summer. The power export is very high in the summer when the solar radiation is high due to the large installed PV capacity and therefore requires large grid capacity. Figure 5.14 shows the PV power distribution, and 58,54% of the PV power produced goes to the grid. 20,09% of the PV power goes to the electricity load, and 21,37% goes to the electrolyzer and to the ferries. Figure 5.15 shows the origin of the electricity which covers the electrical load. Only 27,6% of the electrical load is covered by PV power, and the rest is from power imported from the grid.

5.2.3 Case 3: 80% wind power and 20% solar power

The loads are the zero emission neighborhood's electricity load and the hydrogen load of the ferries. Control strategy 2 means that the production of hydrogen starts when the wind power and PV power exceeds zero, and the fuel cell is not in use. Both wind power and PV powers cover both the electricity demand and the hydrogen demand, and power from the grid is imported when required.

The installed wind power capacity is 42 MW. The installed PV power capacity is 10,5 MW.

	MWh
wind and pv generation	140065,2
Electrical load	101327,48
Electrolyzer load	38027,41
Import from grid	51289,21
Export to grid	51999,52
Net export from grid	710,31

Table 5.6: Results when wind and PV power cover the electricity and hydrogen load without use of the fuel cell

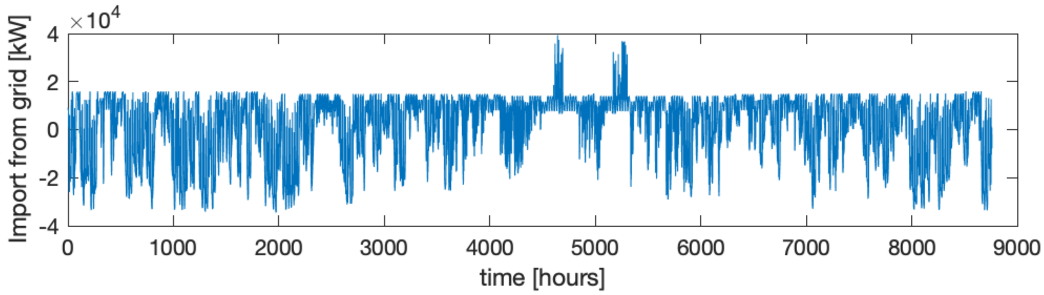

Figure 5.16: Power import from the grid when wind and PV power cover the electricity and hydrogen load without use of the fuel cell

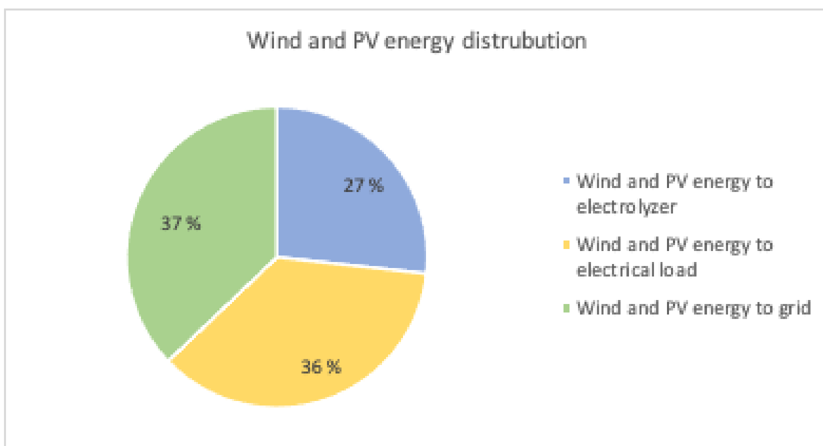

Figure 5.17: Wind and PV energy distribution when wind and PV power cover the electricity and hydrogen load without use of the fuel cell

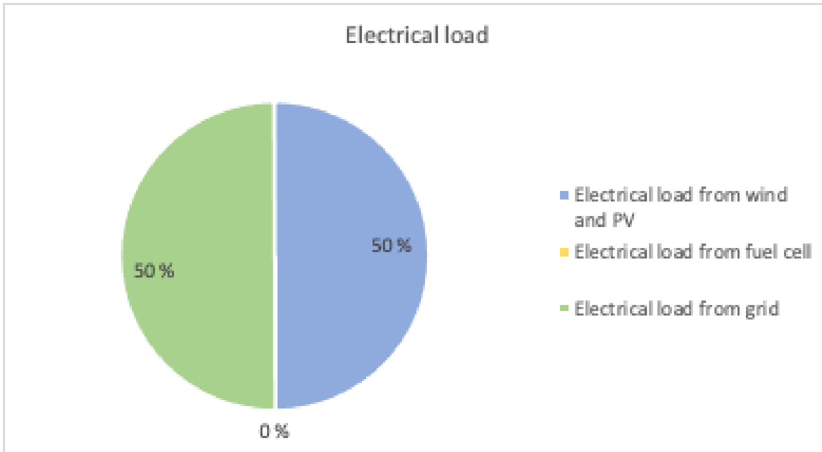

Figure 5.18: Origin of the electricity which cover the electrical load when wind and PV power cover the electricity and hydrogen load without use of the fuel cell

Discussion

42 MW installed wind power, and 10,5 MW installed PV power are installed to cover the electricity and hydrogen demand without using the fuel cell. The power import from the grid over the year 51,3 GWh and the net power export to the grid is 0,71 GWh. Figure 5.16 shows the power import variations over the year. The import is needed during the summer when the hydrogen load is high, and the wind power production is at its lowest and the PV power production is not enough. 37,13 % of the power produced goes to the power grid, and 26,75% goes to the electrolyzer. 49,93% of the electrical load is covered by wind and PV power, and the rest of the electrical load is covered by power from the grid.

5.3 Electricity load and hydrogen load and control strategy 1

5.3.1 Case 1: Only wind power

The loads are the zero emission neighborhood's electricity load and the hydrogen load of the ferries. Control strategy 1 means that hydrogen is produced when the wind power exceeds the local load, and the fuel cell is operating when the local load exceeds the wind power production. Only wind power covers both the electricity demand and the hydrogen demand, and power from the grid is imported when required.

The installed wind power capacity is 47 MW.

	MWh
Wind generation	146517,8
Electrical load	101327,48
Electrolyzer load	47352,29
Fuel cell generation	3263,71
Import from grid	42305,63
Export to grid	43407,37
Net export from grid	1101,74

Table 5.7: Results when wind power cover the electricity and hydrogen demand with use of the fuel cell

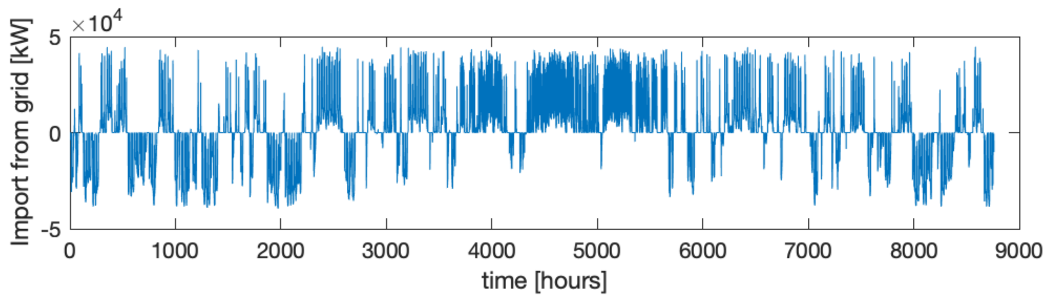

Figure 5.19: Power import from the grid when wind power cover the electricity and hydrogen demand with use of the fuel cell

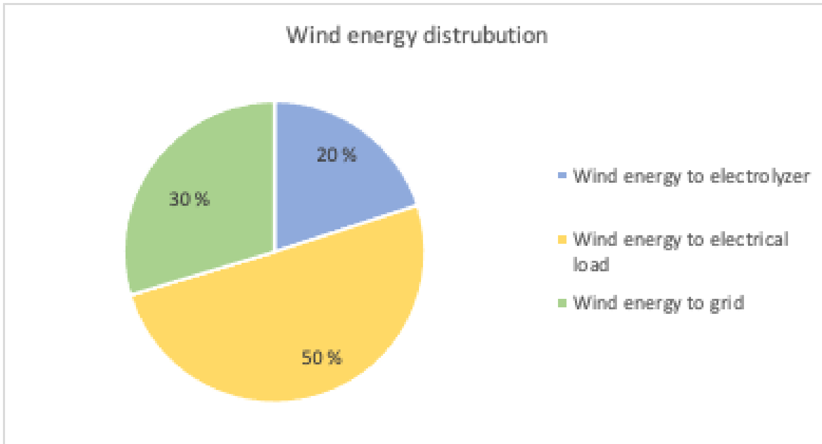

Figure 5.20: Wind power distribution when wind power cover the electricity and hydrogen demand with use of the fuel cell

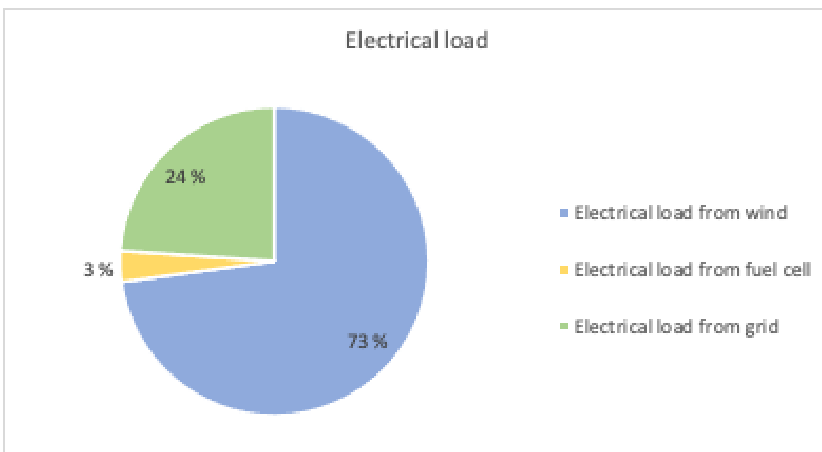

Figure 5.21: Origin of the electricity which cover the electrical load when wind power cover the electricity and hydrogen demand with use of the fuel cell

Discussion

Wind power covers the electricity demand and the hydrogen demand, and power from the grid is charged when needed. The installed wind capacity is 47 MW. The total power import from the grid over the year is 42,3 GWh, and the net power export is 1,1 GWh. Figure 5.19 shows the power import variations over the year. The power import is mostly during the summer when the hydrogen load is high and the wind power production is low and the power export is in the winter when wind power production is high. 29,63% of the wind energy produced goes to the power grid, and 23,93% of the electrical load is covered by power from the grid. 50,38% of the wind energy produced goes to the electrical load. The electrolyzer and the fuel cell is in use, and 20% of the wind energy produced goes to the electrolyzer, and 3,22% of the electrical load is covered by power from the fuel cell. The ferries' hydrogen load is supplied with the rest of the produced hydrogen.

5.3.2 Case 2: Only solar power

The loads are the zero emission neighborhood's electricity load and the hydrogen load of the ferries. Control strategy 1 means that hydrogen is produced when the PV power exceeds the local load, and the fuel cell is operating when the local load exceeds the PV power production. Only PV power covers both the electricity demand and the hydrogen demand, and power from the grid is imported when required.

The installed PV power capacity is 185 MW.

	MWh
pv generation	160939,46
Electrical load	101327,48
Electrolyzer load	70973,84
Fuel cell generation	11606,12
Import from grid	65312,37
Export to grid	65556,63
Net export to grid	244,26

Table 5.8: Results when PV power cover the electricity and hydrogen demand with use of the fuel cell

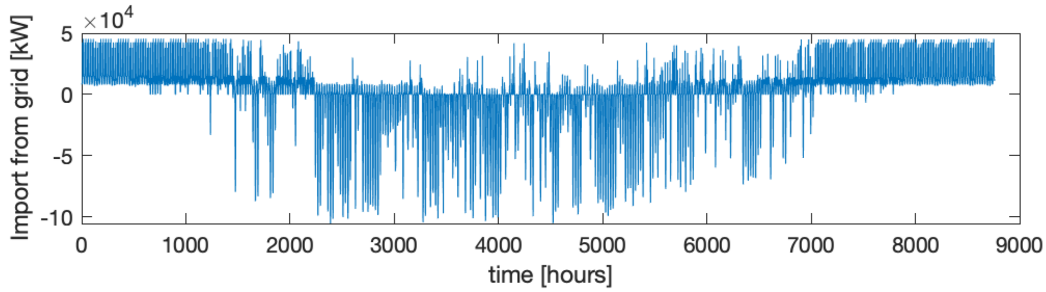

Figure 5.22: Power import from the grid when PV power cover the electricity and hydrogen demand with use of the fuel cell

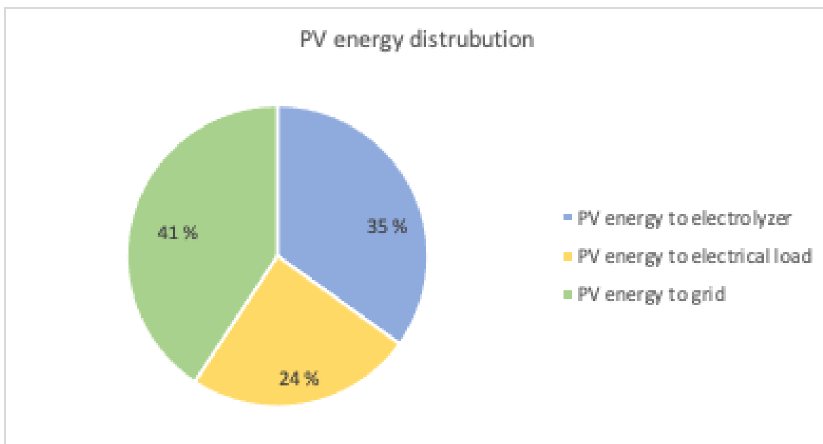

Figure 5.23: PV energy distribution when PV power cover the electricity and hydrogen demand with use of the fuel cell

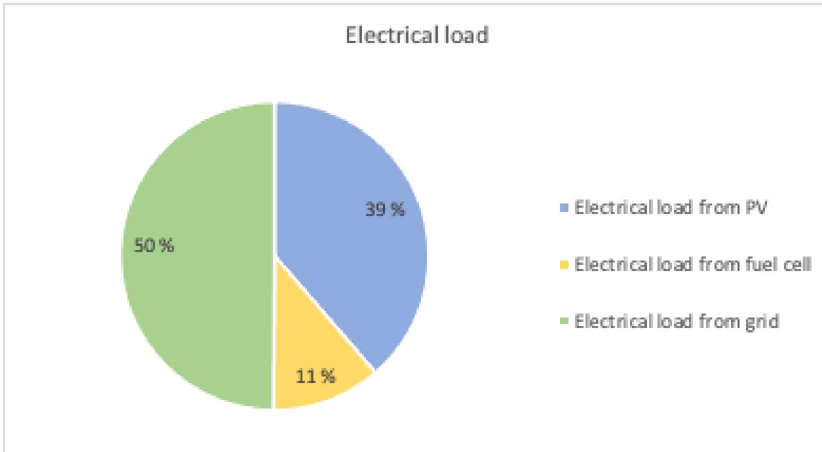

Figure 5.24: Origin of the electricity which cover the electrical load when PV power cover the electricity and hydrogen demand with use of the fuel cell

Discussion

PV power covers the electricity demand and the ferries' hydrogen demand. The PV rating is 185 MW. The total power import from the grid is 65 GWh, and the net power export is 0,24 GWh. Figure 5.22 shows the power import over the year. The power import is mostly during winter time when the sun radiance is low, and the power export is during the summer and is high due to the large PV installed capacity. 40,73% of the PV power produced goes to the grid, because when the sun radiance is high the production is much higher than the load. 24,34% of the PV power produced goes to the electrical load, and 38,66% of the electrical load is covered by PV power. The rest of the electrical load is covered by 11,45% fuel cell power and 49,88% imported grid power.

5.3.3 Case 3: 80% wind power and 20% solar power

The loads are the zero emission neighborhood's electricity load and the ferries' hydrogen load. Control strategy 1 means that hydrogen is produced when the PV and wind power exceeds the local load, and the fuel cell is operating when the local load exceeds the PV and wind power production. Both PV and wind power covers both the electricity demand and the hydrogen demand, and power from the grid is imported when required.

The installed wind power capacity is 43,5 MW. The installed PV power capacity is 10,9 MW.

	MWh
wind and pv generation	145401,02
Electrical load	101327,48
Electrolyzer load	46560,51
Fuel cell generation	2986,58
Import from grid	37443,0
Export to grid	37942,61
Net export to grid	499,61

Table 5.9: Results when wind and PV power cover the electricity and hydrogen demand with use of the fuel cell

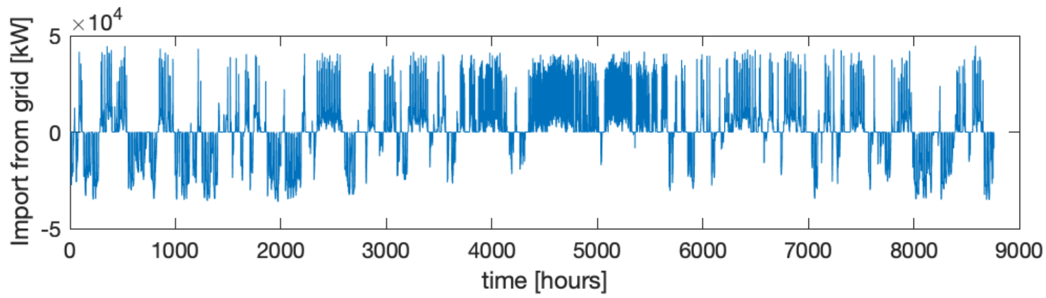

Figure 5.25: Power import from the grid when wind and PV power cover the electricity and hydrogen demand with use of the fuel cell

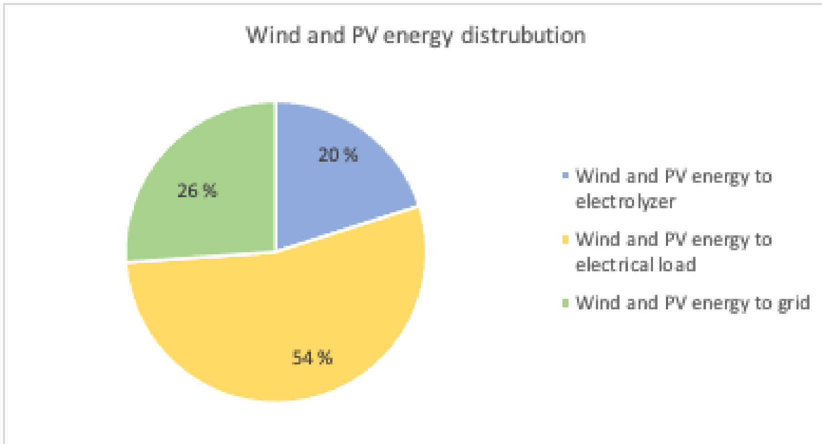

Figure 5.26: Wind and PV energy distribution when wind and PV power cover the electricity and hydrogen demand with use of the fuel cell

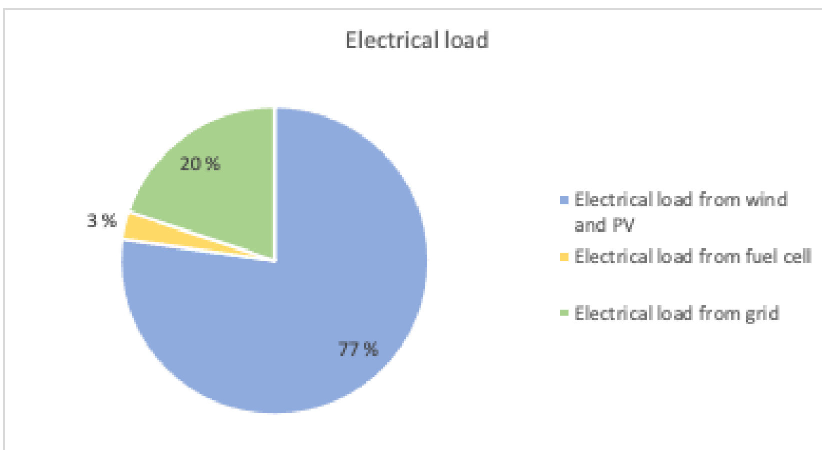

Figure 5.27: Origin of the electricity which cover the electrical load when wind and PV power cover the electricity and hydrogen demand with use of the fuel cell

Discussion

43,5 MW wind power capacity and 10,9 MW PV capacity are installed to cover the electricity load and the hydrogen load. The needed power import from the grid is 37,4 GWh, and the net export to the grid is 0,5 GWh. Figure

5.25 shows the power import over the year. The power import is happening during the year but mostly in the summer when the hydrogen load is higher. 26,1% of the wind PV power produced goes to the grid. Only 19,8% of the electrical load is covered by power from the grid, the rest of the electricity load is covered by 2,95 % with power from the fuel cell and 77,25% with power from the wind and PV power production. 20,07% of the wind and PV power goes to the electrolyzer to produce hydrogen to cover the ferries' demand.

Chapter 6

Discussion

6.1 Results

The zero emission neighborhood should be as much as possible self-contained with energy and independent from the power grid. The case studies show that the case with both the neighborhoods electricity demand and the ferries hydrogen demand are included and which has the lowest power import from the grid is the case with 80% wind power and 20% PV power. The wind power capacity is 43,5 MW and the PV power capacity is 10,9 MW, and the power import from the grid is 37 GWh for that case. The ferries hydrogen demand and the neighborhood's electricity demand together is annually 139,1 GWh, so the power import is equivalent to 27% of the total demand.

The maximum hydrogen storage capacity is set to 100000 Nm^3 to cover the hydrogen demand. The supply security limit for storage is 50% of the capacity, so the storage level never reaches under 50000 Nm^3 before hydrogen production starts again. The electrolyzer rating is set to 30000 kW to produce enough hydrogen to cover the ferries' demand. The fuel cell rating is 12000 kW and can contribute to cover the electricity demand when it is in use. The hydrogen production and the use of the fuel cell do that power produced can be stored when the production is higher than the load and the power can be used when the load is higher than the production. The cases where the fuel cell is in use require a larger installed power capacity compared to the cases with no use of the fuel cell. When the fuel cell is in use, and both electrical and hydrogen load is included for the case where both PV and wind power generates, the electrolyzer load is 46,6 GWh and for the case without the use of the fuel cell the electrolyzer load is 38 GWh. Although the electrolyzer load is higher, the power import over the year is lower when the fuel cell is in use. If the fuel cell technology were further developed and had higher efficiency, the result would be even better.

The scenario with only the electricity load compared to the scenario with both electricity load and hydrogen load shows how the ferries' hydrogen load impacts the power system and the additional need for renewable energy sources when it is included. The power production and therefore the installed capacity needs to be higher due to the higher load. For the case where both wind power and PV power cover the demand and the fuel cell is in use, the case with only the neighborhood's electricity demand is considered needs 33,6 MW installed wind power and 8,4 MW installed PV power to produce 112 GWh. Moreover,the case where both the neighborhood's electricity demand and the ferries'hydrogen demand are considered needs 43,5 MW installed wind power and 10,9 MW installed PV power to produce 145 GWh. 9,9 MW more wind power and 2,5 MW more PV power is needed when the hydrogen load is included. The electrolyzer load is significant higher when the hydrogen load is included. The electrolyzer load is 13,7 GWh for the case where both wind and PV power covers only the neighborhood's electricity demand, and 4,65 % of the electrical load is covered by power from the fuel cell. The electrolyzer load is 46,6 GWh for the case where both wind and PV power covers both the neighborhood's electricity demand and the ferries' hydrogen demand, and 2,95% of the electrical load is covered by power from the fuel cell. The electrolyzer load needs to be much higher to cover the hydrogen load, but due to the capacity of the storage system, the fuel cell cover less of the electricity load when the hydrogen load is included.

A combination of wind and solar power is a good solution both with the hydrogen load included and without. The wind power plant produces at its maximum during the winter when the wind speed is at its maximum. The PV plant produces most during summer when the solar irradiance is highest. So during the year, the result is best when wind and solar power are operating in a combination. When the hydrogen load from the ferries is taken into account, this is still a good solution since the electrical load of the neighborhood is lower during summer when the hydrogen load is higher. Wind and solar power are unpredictable energy sources and can not be controlled and needs to be produced when it is wind and sun, therefore storing the energy produced as hydrogen is a right solution for utilizing the resources. The hydrogen storage can potentially regulate both the power import and export and avoid peaks.

Large wind power plant requires a significant amount of land. The best wind conditions are on higher ground, and the wind power plant should be build close to the Bodø city and where the wind conditions are the best. It can be challenging to find a appropriate and optimal location nearby. Experience from other wind power plant development projects in Norway indicates a significant opposition from the local citizens. The PV panels can be installed on the roof or on the walls of the buildings and is therefore a part of the neighborhood, and they are not so visible for the citizens. If only PV power supply the load, the PV plant will require a large area and maybe a larger area than possible to install on the buildings. Then a PV park located on the ground can be an option as well as the onsite PV panels. The hydrogen storage systems can be located on the port, close to where the charging of the ferries take place, and the system also requires a large area. The hydrogen system includes large tanks to store compressed hydrogen, and if the storage system capacity increases, more renewable power can be stored.

6.2 Uncertain parameters

The input values in the model are historical data based on previous observations, and the given values may not occur in the future. These case studies have taken temperatures, wind speed, and solar irradiance from 2019 as a reference. The results are therefore optimal for the 2019 case. Both the temperature, wind speed, and the solar irradiance varies from year to year, and therefore an average value over several years can be used to get a more average result.

Hydrogen ferry is a relatively new technology, and the technology is not tested out in a large scale. The ferries distances in the Bodø area are one of the longest and toughest distances. The hydrogen load used in the model is estimated from consumption values from the battery ferry Ampere, which is operating on a short distance. The estimated values and real consumption values can considerably deviate. The consumption of hydrogen for the ferries in the Bodø area is therefore an uncertain input parameter.

6.3 Model

Zero energy for the neighborhood is the main focus for this thesis, and therefore the power production in the neighborhood should be as equal as possible to the load in the area. The model is not an optimization model, and the size of the power plant is a chosen parameter before the model is run. Therefore it is uncertainties in the optimal combination of wind and PV power capacity, and the model requires a significant number of attempts to get to the best suited solutions. Another challenge generally with models like this is that electricity, the temperature, the solar irradiance, and the wind speed are assumed to be constant for an hour. In the physical world this will not be the case. These parameters can and probably will change several times within an hour.

Chapter 7

Conclusion

The main contribution of this thesis is an investigation of the power system choice in the new zero emission neighborhood in Bodø. The Bodø airport redevelopment project wants to turn today's airport area into a smaller airport and a Zero Emission Neighborhood with a new generation of buildings. The goal is to develop an urban and environmentally friendly neighborhood, which is energy efficient and minimizes the energy demand, and with zero greenhouse gas emissions. 15000 new homes and 20000 working places are planned to be built. This thesis uses the Matlab model windhydtool to calculate the sizing of the power system for the Zero Emission Neighborhood combined with three hydrogen ferries from Bodø, one to Røst, one to Moskenes, and one to Værøy. The ferries run two times a day, and in the summer months June, July, and August, the ferries run four times a day due to all the tourists visiting the area in the summer. These ferry routes are the longest in Norway and too long for electricity battery, therefore hydrogen used as the fuel is the right solution. Wind power plant and PV plant should cover the electrical load of the neighborhood, and also cover the ferries' hydrogen load with hydrogen production. The system has local power production but is also grid connected, so electricity can be imported and exported when needed.

First, an estimate of the building stock and the neighborhood's electricity demand was made. Also, an estimate of the ferries hydrogen demand was made to do the calculations. Three main scenarios were run: one with only electricity load and control strategy 1 is chosen, one with both the electricity demand and the hydrogen demand and control strategy 2, the last one with both the electricity demand and the hydrogen demand and control strategy

1. Further, each of these three main scenarios runs with only wind power, only PV power, and a combination of 80% wind power and 20% PV power.

The main goal for the neighborhood is the zero energy goal; the neighborhood should produce as much local renewable energy as the neighborhood consumes. The neighborhood should also be as self supplied with energy as possible, so the power import and export should be as low as possible. A research question was to find the additional need for renewable energy when the hydrogen ferries are included in the model.

The case where both the hydrogen load and the electricity load are included and which has the lowest power import from the grid over the year is the case with 43500 kW installed wind power capacity and 10900 kW installed PV power capacity. The power import from the grid for this case is 37 GWh. A combination of wind power and PV power gives an optimized solution, because the wind power plant produces at its maximum during the winter when the wind speed is high and the PV power plant produces at its maximum during summer when the solar irradiance is high. This solution uses the hydrogen fuel cell so it is also beneficial to use the stored hydrogen in the fuel cell and produce electricity to cover a share of the neighborhood's electricity demand. So the need for power import from the grid is smaller when the fuel cell is in use.

The results show how the ferries' hydrogen load impacts renewable power production demand. The hydrogen load each year is 26,5 GWh, and the electricity load is 101,3 GWh. For the case where both wind power and PV power cover the demand and the fuel cell is in use, the case with only the neighborhood's electricity demand is considered needs 33,6 MW installed wind power and 8,4 MW installed PV power to produce 112 GWh. Moreover, the case where both the neighborhood's electricity demand and the ferries' hydrogen demand are considered needs 43,5 MW installed wind power and 10,9 MW installed PV power to produce 145 GWh. 9,9 MW more wind power and 2,5 MW more PV power is needed for this case when the hydrogen load is included.

Renewable energy sources are needed to achieve a low carbon society, and a zero emissions neighborhood is a main part of a low carbon society. A hydrogen storage system can be used to power ferries and in combination with a fuel cell also produce electricity to supply the neighborhood. This will decarbonize the sea transportation sector, and the building and construction sector. This case study shows the energy system choice of the neighborhood in combination with hydrogen ferries. There is a doubt in whether the obtained results can be reliable. The Bodø redevelopment project is in an early phase, and several assumptions were made.

Chapter 8

Further work

Based on the result and the discussion presented in this master thesis, there are several areas that need more research in the future. The planned Zero Emission neighborhood in Bodø is a pilot project who is essential for future neighborhood development. The project is in an early phase and has a long time horizon. In this thesis, assumptions are made on the building stock, both size and building type. When the planning process of the pilot project in Bodø is further developed, and more information is available, more correct results can be made. The pilot project is one of the most complex and comprehensive area planning projects in Norway. The goal of the pilot project is to develop a sustainable, compact, and smart city, that will make the city more attractive and important as a business center in the region. The project includes several stakeholders, and requires cooperation between the stakeholders and the different subject area.

Future work should look more into the heating system of the Zero Emission Neighborhood in Bodø. In this thesis, it is concluded that bio pellets or heat pump are the best solution to cover the heating demand, but different heating technologies should be further investigated.

An aspect that is not considered as a constraint in this thesis is the existing grid capacity in the area. In the case where PV power covers the demand, the power export to the grid is very high and the grid capacity needs to be high. Development of the grid capacity can lead to very high costs. This thesis did not look into the economic perspective of the pilot project, which is also an important part of such a large development project. The best suited energy technologies can be different when other parameters are taking into account like the maintenance and operation cost.

The system can further include more electrification of the transportation sector. Both directly with battery and indirectly with hydrogen production can be used to decarbonize the sector. This thesis included three ferry distances in the model, but several distances can be included to phase out the fossil fuel in sea transportation in the area around Bodø. Other transportation methods can be included and not only the ferries. The transportation on land also has significant emissions, so that sector should also be electrified. Private vehicles and heavy goods vehicle traffic can be included in the model.

Bibliography

[1] Åse Lekang Sørensen Eyvind Fredriksen Harald Taxt Walnum Kristian Stenerud Skeie Inger Andresen. “Initial plans for thermal and electrical use generation distribution and storage”. In: (2017).

[2] Stian Backe and Ann Kristin Kvellheim. “ZERO EMISSION NEIGHBOURHOODS, Drivers and barriers towards future development”. In: (2020). URL: https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/2657684/ZEN%20Report%20no%2022.pdf?sequence=1&isAllowed=y.

[3] Daniela Baer and Inger Andresen. “ZEN pilot projects mapping of the pilot projects within the research center on zero emission neighbourhoods in smart cities”. In: (2018). URL: https://fmezen.no/wp-content/uploads/2019/01/ZEN-Report-no-10.pdf.

[4] Anders Bjartnes. “Fornybar energi kutter klimagassutslipp”. In: (2019). URL: https://energiogklima.no/blogg/fornybar-energi-kutter-klimagassutslipp/.

[5] ZEN Research center. “ZEN REPORT no.7”. In: (2018). URL: https://fmezen.no/wp-content/uploads/2018/11/ZEN-Report-no-7-Bilingual.pdf.

[6] SINTEF Christina Benjaminsen. “Dette må du vite om hydrogen”. In: (2019). URL: https://forskning.no/energi-fornybar-energi-klima/dette-ma-du-vite-om-hydrogen/1359513.

[7] SINTEF Christina Benjaminsen. “Dette må du vite om hydrogen”. In: (2019). URL: https://forskning.no/energi-fornybar-energi-klima/dette-ma-du-vite-om-hydrogen/1359513.

[8] Michael Dhar - LiveScience Contributor. “How do solar panels work”. In: (2017). URL: https://www.livescience.com/41995-how-do-solar-panels-work.html.

[9] Hydrogen Europe. "Fuel Cells". In: (2020). URL: https://hydrogeneurope.eu/fuel-cells.

[10] Asgeir Tomasgard (NTNU) med flere. "Hydrogen i fremtiden". In: (2019). URL: https://www.ntnu.no/documents/7414984/0/Hydrogen+i+framtiden_rapport_A4_web_LR+28-03-2019.pdf/cbcf5251-7a61-41ac-88ea-faef5daf558c.

[11] Trond Strømgren Fredrik G. Aarskog Janis Danebergs and Øystein Ulleberg. "Energy and cost analysis of a hydrogen driven high speed passenger ferry". In: (2020). URL: https://ife.brage.unit.no/ife-xmlui/bitstream/handle/11250/2673418/Aarskog_et_al_International_Shipbuiliding_Progress_67_2020.pdf?sequence=1.

[12] Research Gate. "Basic diagram of Phtovoltaic solar cell". In: (2017). URL: https://www.researchgate.net/figure/Basic-diagram-of-Phtovoltaic-solar-cell_fig1_323354575.

[13] Christopher Johan Greiner. "Sizing and Operation of Wind-Hydrogen Energy Systems". PhD thesis. 2010.

[14] GWEC. "GWEC: Over 60 GW of wind installed in 2019, the second biggest year in history". In: (2020). URL: https://gwec.net/gwec-over-60gw-of-wind-energy-capacity-installed-in-2019-the-second-biggest-year-in-history/.

[15] Nina Holck Sandberg Jan Sandstad Næss Arild Gustavsen Inger Andresen og Helge Brattebø. "Energianalyse for bygningsmassen i Oslo". In: (2019). URL: https://fmezen.no/wp-content/uploads/2019/03/ZEN-Report-no-14.pdf.

[16] Knut Hofstad. "Solenergi". In: (2020). URL: https://snl.no/solenergi.

[17] Bodø kommune. "Mål og retningslinjer for planlegging av den nye bydelen". In: (2018). URL: https://bodo.kommune.no/getfile.php/1313125-1562070394/Plan2C20bygg20og20eiendom/Kart20og20arealplaner/Arealplaner/Planprosesser/2019/Kommunedelplan20for20Ny20bydel/120Oppstart/M%C3%A5l20og20retningslinjer20for20planlegging%20av%20ny%20bydel.pdf.

[18] Bodø kommune. "Ny by - Ny flyplass". In: (2019). URL: https://bodo.kommune.no/utviklingsprosjekter/ny-by-ny-flyplass-article426-1062.html.

[19] Magnus Korpås. "Distributed Energy Systems with Wind Power and Energy Storage". PhD thesis. 2004.

[20] Karen Byskov Lindberg. "Impact of Zero Energy Builings on the Power System, A study of load profieles, flexibility and system investments". PhD thesis. 2017.

[21] Miljødirektoratet. "Arealbehov (typetall) for landbasert vindkraft i Norge". In: (2019). URL: https://www.miljodirektoratet.no/globalassets/dokumenter/fornybar-energi/vindkraft/vindkraft-arealoppsummering010419.pdf.

[22] A.J. Marszal P. Heiselberg J.S. Bourrelle E.Musallc K. Voss I. Sartori A. Napolitanoe. "Zero Energy Building – A review of definitions and calculation methodologies". In: (2010).

[23] Norconsult. "Ny by, ny flyplass - Utviklingsperspektiver for Bodø 2050". In: (2019). URL: https://eu.eu-supply.com/app/rfq/publicpurchase_docs.asp?PID=251511&LID=294901&AllowPrint=1.

[24] Energi Norge. "Dette bør du vite om vindkraft i Norge". In: (2020). URL: https://www.energinorge.no/fagomrader/fornybar-energi/nyheter/2019/dette-bor-du-vite-om-vindkraft-i-norge/.

[25] NRK. "Avinor ser bort fra knusende rapport – anbefaler flyplassprosjekt til milliarder". In: (2020). URL: https://www.nrk.no/nordland/avinors-endelige-anbefaling-i-ny-by-_-ny-flyplass-prosjektet-i-bodo-er-a-bygge-flyplassen-1.15067268.

[26] NVE. "Kraftproduksjon fra vindturbiner". In: (2019). URL: https://www.nve.no/energiforsyning/kraftproduksjon/vindkraft/kraftproduksjon-fra-vindturbiner/.

[27] NVE. "Solkraft". In: (2020). URL: https://www.nve.no/energiforsyning/kraftproduksjon/solkraft/?ref=mainmenu.

[28] Regjeringen. "Climate change and the environment". In: (2020). URL: https://www.norway.no/en/missions/eu/values-priorities/climate-env/.

[29] Regjeringen. "Norway has ratified the Paris Agreement". In: (2016). URL: https://www.regjeringen.no/en/aktuelt/norge-har-ratifisert-parisavtalen/id2505365/.

[30] Regjeringen. "Regjeringens hydrogenstrategi". In: (2020). URL: https://www.regjeringen.no/contentassets/8ffd54808d7e42e8bce81340b13b6b7d/regjeringens-hydrogenstrategi.pdf.

[31] Sintef. "How well do solar cells really work in the Nordic climate". In: (2018). URL: https://www.sintef.no/en/latest-news/how-well-do-solar-cells-really-work-in-the-nordic-climate/.

[32] Sintef. "Hydrogen". In: (2020). URL: https://www.sintef.no/hydrogen/#/.

[33] Norsk solenergiforening. "Hvorfor solenergi?" In: (2020). URL: https://www.solenergi.no/hvorfor-solenergi.

[34] Norsk solenergiforening. "Solceller". In: (2020). URL: https://www.solenergi.no/solstrm.

[35] SSB. "Emissions to air". In: (2020). URL: https://www.ssb.no/en/natur-og-miljo/statistikker/klimagassn/.

[36] SSB. "Kommunefakta". In: (2020). URL: https://www.ssb.no/kommunefakta/bodo.

[37] Statkraft. "Wind power". In: (2020). URL: https://www.statkraft.com/what-we-do/wind-power/.

[38] Bjørn Pedersen Trygve Holtebekk. "Brenselcelle". In: (2020). URL: https://snl.no/brenselcelle.

[39] Tormod Haugstad at tu. "Den nye byen i Bodø skal romme 15.000 boliger og 20.000 arbeidsplasser". In: (2018). URL: https://www.tu.no/artikler/den-nye-byen-i-bodo-skal-romme-15-000-boliger-og-20-000-arbeidsplasser-med-null-utslipp-av-klimagasser-br/451788.

[40] Statens vegvesen. "Ferjesambandene er en del av vegnettet". In: (2020). URL: https://www.vegvesen.no/fag/trafikk/ferje.

[41] Statens vegvesen. "Utviklings kontrakt hydrogen-elektrisk ferje". In: (2020). URL: https://www.vegvesen.no/fag/trafikk/ferje/utviklingskontrakt-hydrogen.

[42] statens vegvesen. "Utvikling CO2 utslipp - ferjesektoren". In: (2020). URL: https://www.vegvesen.no/_attachment/2796219/binary/1341772?fast_title=En+stille+revolusjon+i+norske+fjorder.+Innovasjon+-+utviklingskontrakt.pdf.

[43] Aris Vourvoulias. "How Efficient Are Solar Panels?" In: (2020). URL: https://www.greenmatch.co.uk/blog/2014/11/how-efficient-are-solar-panels.

[44] Wikipedia. “Ferjesambandet Bodø-Røst$_{V}ærøy-Moskenes$”. In: (2020). URL: https://no.wikipedia.org/wiki/Ferjesambandet_Bod%C3%B8%E2%80%93R%C3%B8st%E2%80%93V%C3%A6r%C3%B8y%E2%80%93Moskenes.

[45] Wikipedia. “Hydrogen production”. In: (2020). URL: https://en.wikipedia.org/wiki/Hydrogen_production.

[46] Wikipedia. “MF Ampere”. In: (2020). URL: https://no.wikipedia.org/wiki/MF_%C2%ABAmpere%C2%BB.

[47] FME ZEN. “Report 2019”. In: (2020). URL: https://fmezen.no/wp-content/uploads/2020/04/NTNU_ZEN_AnnReport2019_web.pdf.

[48] The Research Center on Zero Emissions Buildings. “Om ZEB”. In: (2017). URL: https://zeb.no/index.php/no/om-zeb/about-the-zeb-centre.

Appendix A

Windhydtools

The appendix presents part of the matlab code for the windhydtools model and the flowchart for the model.

A.1 windhydsim.m

```
%Script windhydsim

clear all
disp('WINDHYDSIM - Simulator for wind-hydrogen systems');
disp('Remember to save and close corresponding excel file');


%***** READ DATA FROM EXCEL *****

%Get name of excel sheet for data reading and writing
excel_name = input('What is the name of your excel file? ','s');

if excel_name(end-3)~='.'
    excel_name = strcat(excel_name,'.xls');
end

%Read simulation type from excel (single or multiple simulation)
sim_type = whxlsread(excel_name,'Intro','B7');
```

```
sim_type = char(sim_type);

disp('...reading input data from excel.');
[CP,SP,CS,TS,InOutPair,TS_pnorm] = readdata(excel_name,sim_type);

B = createparam(CP);

%***** LOAD TIMESERIES *****
P = whtimeseries(SP,B,TS,InOutPair,TS_pnorm);

%Run the simulator
disp('Starting simulation...number of timesteps is:');
disp(SP(3));

[X,U,W]=simloop(P,SP,B,CS);
disp('Simulation finished!');

tmp = plotdata(excel_name,P,X,U,W,SP,B,CS,TS);

disp('...storing results in Excel file:');
disp(excel_name);

%Calculate and write main results to excel
ResArray = mainresults(P,X,U,W,SP,B,CS);

%Write time series results to excel
tmp  = results2excel(excel_name,P,X,U,W,ResArray,sim_type);

disp('WINDHYDSIM exits. Open the excel file to view results.');
```

A.2 The flowchart

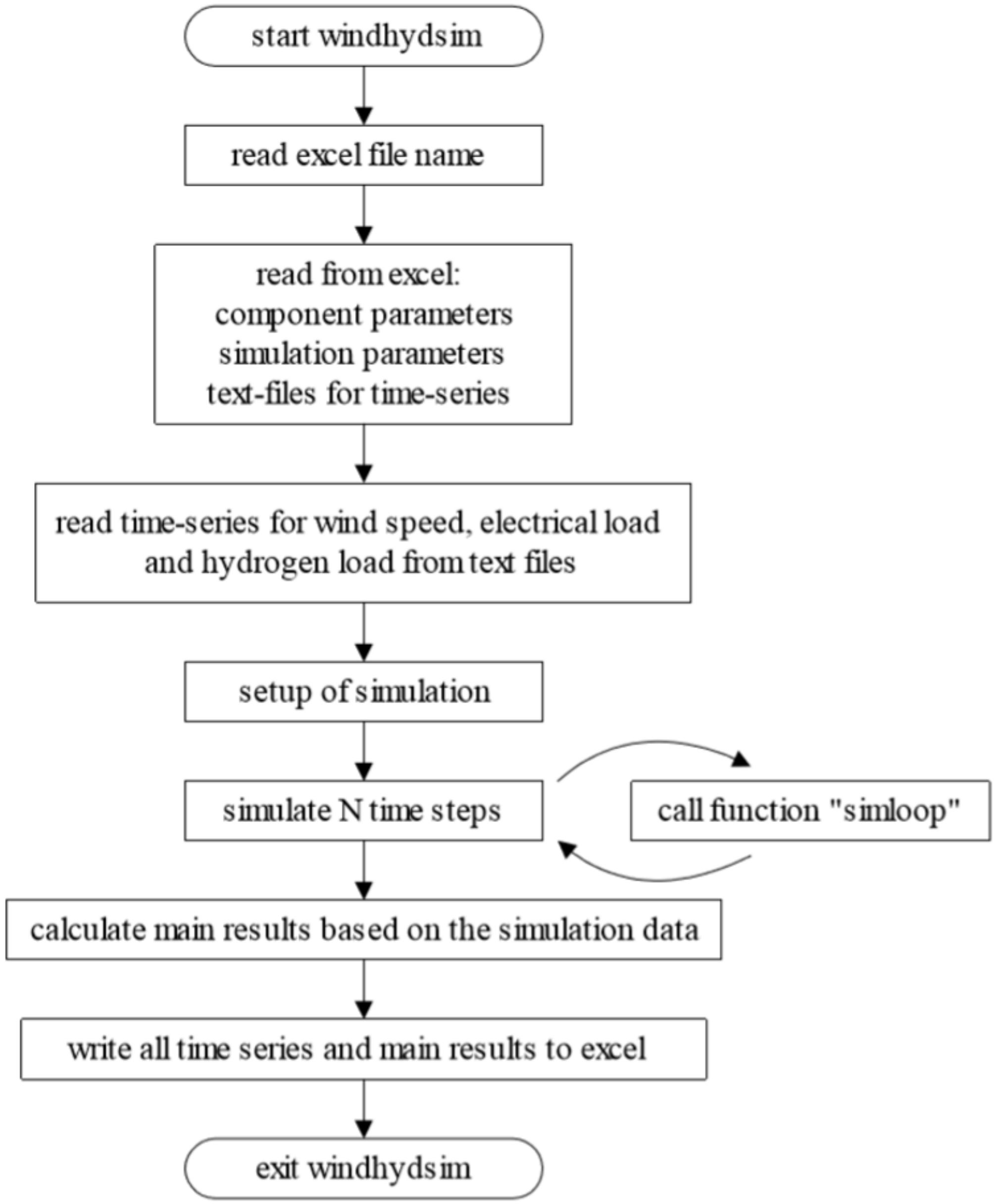

Figure A.1: The flowchart of the operation when windhysim is written in Matlab.

Appendix B

The percentage results

The appendix shows the percentage of the renewable energy distribution, and the percentage of the origin of the electricity which covers the neighborhood's electricity demand for all cases.

B.1 Only electricity load and control strategy 1

B.1.1 Case 1: Only wind power

The installed wind power capacity is 35,5 MW, and B.1 shows the energy distribution for this case, and B.2 shows the origin of the electricity load.

	percent
Wind energy to electrolyser	12,16
Wind energy to electrical load	61,12
Wind energy to grid	26,72

Table B.1: Wind energy distribution when wind power covers the electricity demand with use of the fuel cell

	percent
Electrical load from wind	66,75
Electrical load from fuel cell	4,58
Electrical load from grid	28,67

Table B.2: Origin of the electricity which cover the electrical load when wind power covers the electricity demand and with use of the fuel cell

B.1.2 Case 2: Only solar power

The installed PV power capacity is 147 MW. and B.3 shows the energy distribution for this case, and B.4 shows the origin of the electricity load.

	percent
PV energy to electrolyser	31,24
PV energy to electrical load	29,42
PV energy to grid	39,34

Table B.3: PV energy distribution when PV power covers the electricity demand and with use of the fuel cell

	percent
Electrical load from PV	37,13
Electrical load from fuel cell	13,80
Electrical load from grid	49,07

Table B.4: Origin of the electricity which covers the electrical load when PV power covers the electricity demand with use of the fuel cell

B.1.3 Case 3: 80% wind power and 20% solar power

The installed PV power capacity is 8,4 MW. The installed wind power capacity is 33,6 MW, and B.5 shows the energy distribution for this case, and B.6 shows the origin of the electricity load.

	percent
Wind and PV energy to electrolyser	12,19
Wind and PV energy to electrical load	63,91
Wind and PV energy to grid	23,09

Table B.5: Wind and PV energy distribution when wind power covers the electricity demand with use of the fuel cell

	percent
Electrical load from wind and PV	70,67
Electrical load from fuel cell	4,65
Electrical load from grid	24,68

Table B.6: Origin of the electricity which covers the electrical load when wind and PV power covers the electricity demand with use of the fuel cell

B.2 Electricity load and hydrogen load and control strategy 2

B.2.1 Case 1: Only wind power

The installed wind power capacity is 45 MW, and B.7 shows the energy distribution for this case, and B.8 shows the origin of the electricity load.

	percent
Wind energy to electrolyser	25,80
Wind energy to electrical load	34,25
Wind energy to grid	39,94

Table B.7: Wind energy distribution when wind power cover the electricity and hydrogen load without use of the fuel cell

	percent
Electrical load from wind	47,42
Electrical load from grid	52,58

Table B.8: Origin of the electricity which covers the electrical load when wind power cover the electricity and hydrogen load without use of the fuel cell

B.2.2 Case 2: Only solar power

The installed PV power capacity is 160 MW, and B.9 shows the energy distribution for this case, and B.10 shows the origin of the electricity load.

	percent
PV energy to electrolyser	21,37
PV energy to electrical load	20,09
PV energy to grid	58,54

Table B.9: PV energy distribution when PV power cover the electricity and hydrogen load without use of the fuel cell

	percent
Electrical load from PV	27,60
Electrical load from grid	72,40

Table B.10: Origin of the electricity which cover the electrical load when PV power cover the electricity and hydrogen load without use of the fuel cell

B.2.3 Case 3: 80% wind power and 20% solar power

The installed wind power capacity is 42 MW. The installed PV power capacity is 10,5 MW, and B.11 shows the energy distribution for this case, and B.12 shows the origin of the electricity load.

	percent
Wind and PV energy to electrolyzer	26,75
Wind and PV energy to electrical load	36,12
Wind and PV energy to grid	37,13

Table B.11: Wind and PV energy distribution when wind and PV power cover the electricity and hydrogen load without use of the fuel cell

	percent
Electrical load from wind and PV	49,93
Electrical load from grid	50,07

Table B.12: Origin of the electricity which cover the electrical load when wind and PV power cover the electricity and hydrogen load without use of the fuel cell

B.3 Electricity load and hydrogen load and control strategy 1

B.3.1 Case 1: Only wind power

The installed wind power capacity is 47 MW, and B.13 shows the energy distribution for this case, and B.14 shows the origin of the electricity load.

	percent
Wind energy to electrolyser	20,00
Wind energy to electrical load	50,38
Wind energy to grid	29,63

Table B.13: Wind power distribution when wind power cover the electricity and hydrogen demand with use of the fuel cell

	percent
Electrical load from wind	72,85
Electrical load from fuel cell	3,22
Electrical load from grid	23,93

Table B.14: Origin of the electricity which cover the electrical load when wind power cover the electricity and hydrogen demand with use of the fuel cell

B.3.2 Case 2: Only solar power

The installed PV power capacity is 185 MW, and B.15 shows the energy distribution for this case, and B.16 shows the origin of the electricity load.

	percent
PV energy to electrolyser	34,92
PV energy to electrical load	24,34
PV energy to grid	40,73

Table B.15: PV energy distribution when PV power cover the electricity and hydrogen demand with use of the fuel cell

	percent
Electrical load from PV	38,66
Electrical load from fuel cell	11,45
Electrical load from grid	49,88

Table B.16: Origin of the electricity which cover the electrical load when PV power cover the electricity and hydrogen demand with use of the fuel cell

B.3.3 Case 3: 80% wind power and 20% solar power

The installed wind power capacity is 43,5 MW. The installed PV power capacity is 10,9 MW, and B.17 shows the energy distribution for this case, and B.18 shows the origin of the electricity load.

	percent
Wind and PV energy to electrolyser	20,07
Wind and PV energy to electrical load	53,83
Wind and PV energy to grid	26,10

Table B.17: Wind and PV energy distribution when wind and PV power cover the electricity and hydrogen demand with use of the fuel cell

	percent
Electrical load from wind and PV	77,25
Electrical load from fuel cell	2,95
Electrical load from grid	19,80

Table B.18: Origin of the electricity which cover the electrical load when wind and PV power cover the electricity and hydrogen demand with use of the fuel cel

Marie Hefte

Energy system planning of Zero Emission Neighborhood in Bodø combined with hydrogen ferries

NTNU

Norwegian University of
Science and Technology