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Techno-Economical Analysis of Large-Scale Green Power Self-Sustainability in Norway

- A Case Study using Onshore Wind Power, Battery, and Green Hydrogen Storage

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Preface

This Master's thesis represents the end of five extraordinary years as a student at the Faculty of Science and Technology at the Norwegian University of Life Sciences (NMBU). Motivated by a sustainable future and a keen interest in renewable energy, this thesis provided me with invaluable insight and knowledge into some possible solutions towards achieving net-zero emissions. Throughout the spring of 2023, I have undoubtedly enhanced my academic skills in writing, research, and structural work, all while growing as an individual.

The completion of this thesis would not have been possible without the guidance, encouragement, and support of a number of individuals. My deepest gratitude goes to my supervisor, Jesper Frusig, who has mentored and supported me throughout this process. His understanding, dedication and constructive feedback have significantly contributed to my academic growth and the successful compilation of this thesis, giving me a deeper understanding and appreciation of my field of study. I would also like to extend a special acknowledgment to Michal Kaut at SINTEF. His expertise, guidance, and invaluable insights in HyOpt, have significantly enhanced the technical aspects of this research.

Furthermore, I am grateful to my fellow students, friends and family, who have been an incredible source of inspiration and support. The countless discussions, brainstorming sessions, and collaborative efforts have enriched my understanding and shaped the development of this work. Their insightful perspectives and feedback have undoubtedly contributed to the overall quality of this thesis. Last but not least, thank you to everyone who has made the years at NMBU unique and unforgettable.

Ås - June 15. 2023

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Abstract

The global transition to net-zero emissions requires a complete transformation of our consumption, production, and energy systems. By substituting polluting fuels with renewable sources, it is possible to drastically reduce carbon emissions connected to power. To make this transition possible, the renewable energy sector must enhance efficiency and flexibility, where one solution could be energy storage. This thesis analyses a possible solution, including wind energy and the use of green hydrogen and batteries for power storage, located in coastal areas in Norway. An optimization model developed by SINTEF, named HyOpt, is used to explore technical and economic aspects, and aims to determine the optimal economic and environmental solution.

Three cases are constructed and analyzed. Case 1 involves a reconstruction of a pilot-project that was built to supply 10 households with power, located in the Utsira, an island in the Southern of Norway. Case 2 is constructed to investigate the possibility of making the entire island of Utsira self-sufficient in power. Case 3 involves delivering power to a planned production facility of ammonia, located in Berlevåg in the Northern of Norway.

The model calculated that the green self-sustainability project of Case 1, will deliver a total of 175.5 MWh annually and has a net present cost of 3 million NOK. The project is predicted to have a Levelized Cost of Electricity (LCOE) at 2.363 NOK per produced kWh. In addition, it is calculated that an implementation of this project, will annually reduce a total of 54.6 tons of CO_2-emissions. Case 2 has a calculated net present cost of 169 million NOK, and will deliver a total of 17 555 MWh. Of the three cases, it gives the lowest LCOE, at 1.308 NOK/kWh. The calculated total emissions saved by this project annually, are predicted to 5 450 tons of CO_2. Case 3, the largest case, is expected to have a total net cost of 169 million NOK to annually deliver a total power of 876 000 MWh. The calculated LCOE for this case is estimated to 1.587 NOK/kWh and saves 14 892 tons of CO_2.

Overall, this thesis presents findings that support the technical and economic viability of achieving green self-sustainability in Norway. Nevertheless, it emphasizes the necessity for additional research and development toward the modeling and construction aspects of the proposed cases to ensure successful implementation.

Sammendrag

Den globale overgangen til netto-nullutslipp krever en komplett transformasjon av våre forbruk, produksjon og energisystemer. Ved å erstatte miljøskadelige energiproduksjonsmetoder med fornybare kilder, kan vi drastisk redusere karbonutslippene. For å kunne oppnå klimamålsetningene vi har satt, må de fornybare energiløsningene forbedre effektiviteten og fleksibiliteten den har i dag, hvor bruk av energilagring er et steg i rett retning. Denne oppgaven analyserer en mulig løsning i Norge, som inkluderer vindenergi, hvor grønt hydrogen og batterier blir brukt som energilagringsmetoder. En optimaliseringsmodell utviklet av SINTEF, kalt HyOpt, brukes for å utforske tekniske og økonomiske aspekter, med mål om å bestemme den optimale økonomiske og miljømessige løsningen.

Tre tilfeller er konstruert og analysert. Tilfelle 1 innebærer en rekonstruksjon av et pilotprosjekt som ble bygd for å forsyne 10 husholdninger med tilstrekkelig strøm, og er lokalisert på Utsira, en øy i Sør-Norge. Tilfelle 2 er en konstruert løsning for å gjøre hele Utsira selvforsynt med strøm. Tilfelle 3 omhandler levering av strøm til et planlagt produksjonsanlegg for ammoniakk, som skal være lokalisert i Berlevåg i Nord-Norge.

Modellen beregnet at å være selvforsynt med grønn energi vil i Tilfelle 1, årlig trenge å levere totalt 175,5 MWh og ha en kostnad på 3 millioner NOK. Prosjektet er spådd å ha en elektrisitetskostnad på 2,363 NOK per produsert kWh. I tillegg er det beregnet at implementeringen av dette prosjektet vil redusere CO_2-utslippene med totalt 54,6 tonn årlig. Tilfelle 2 har en beregnet kostnad på 169 millioner NOK og vil levere totalt 17 555 MWh. Av de tre tilfellene ga det den laveste strømkostnaden, på 1,308 NOK/kWh. Det beregnede totale utslippet som blir spart av dette prosjektet årlig, er forventet til å være 5 450 tonn CO_2. Tilfelle 3, det største prosjektet, er forutsatt å ha en total kostnad på 169 millioner NOK , og vil årlig levere totalt 876 000 MWh med kraft. Den beregnede strømprisen for dette tilfellet er forutsatt å være 1,587 NOK/kWh og beregnet til å årlig spare 14 892 tonn CO_2.

Samlet sett presenterer denne oppgaven funn som støtter den tekniske og økonomiske levedyktigheten av å oppnå grønn selvforsyning av strøm i Norge. Likevel understreker den behovet for ytterligere forskning og utvikling innenfor modellering og konstruksjon av de foreslåtte tilfellene.

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Acronyms

UN	**U**nited **N**ations
EU	**E**uropean **U**nion
PEM	**P**olymer **E**lectrolyte **M**embrane electrolysis
PEMWE	**P**roton **E**xchange **M**embrane **W**ater **E**lectrolysis
PEMFC	**P**roton **E**xchange **M**embrane **F**uel **C**ell
HER	**H**ydrogen **E**volution **R**eaction
OER	**O**xygen **E**volution **R**eaction
BMS	**B**attery **M**anagment **S**ystem
$\mathbf{H_2O}$	Water
$\mathbf{O_2}$	**O**xygen gas
$\mathbf{H_2}$	**H**ydogen gas
$\mathbf{CO_2}$	**C**arbon di**o**xide
$\mathbf{NH_3}$	Ammonia
CRISP-DM	**C**ross-**I**ndustry **S**tandard **P**rocess for **D**ata **M**ining
API	**A**pplication **P**rogramming **I**nterface
CoSSMic	**Co**llaborating **S**mart **S**olar-powered **Mic**ro-grids
ENTSO-E	**E**uropean **N**etwork of **T**ransmission **S**ystem **O**perators for **E**lectricity
LCOE	**L**evelized **C**ost **o**f **E**nergy
CAPEX	**Cap**ital **Ex**enditure
OPEX	**Op**erating **Ex**penses
NPV	**N**et **P**resent **V**alue
NOK	**No**rwegian **K**rone

1. Introduction

The transition to a global net-zero is one of the most significant challenges that human kind has ever faced. It requires a complete transformation of our consumption habits, our production methods and how we move around. Currently, the energy sector accounts for approximately three-quarters of greenhouse gas emissions, and is therefore a crucial factor in mitigating the severe impacts of climate change. By substituting polluting coal, gas, and oil-fired power with renewable sources, like solar and wind energy, it is possible to drastically decrease the carbon emissions. [1]

To make this transition possible and meet the EU climate and energy targets, the renewable energy sector needs to increase its efficiency and improve flexibility. This refers to the energy system's capacity to adjust to changing needs and a variability and uncertainty of demand and supply across different time-frames.[2]

To achieve this flexibility, it is necessary to have a form of energy storage. Since the production of power generated from renewable sources is fluctuating, the use of energy storage would make it possible to deliver power even when the production is low. In addition, the use of energy storage could offer additional benefits, such as reducing price fluctuations and lowering electricity costs during peak periods.

Since 2020, the EU Commission has been publishing annual progress reports on the competitiveness of clean energy technologies. These reports provide an overview of the present and future outlook for various clean and low-carbon energy technologies and solutions. The 2022 report specifically highlights renewable hydrogen production through water electrolysis and batteries, recognizing their critical role in achieving success in the decarbonization of the energy sector.[2]

In Norway, the government submitted in 2022 an enhanced climate target. The new goal is to reduce emissions by at least 55 percent by 2030. [3] To make this happen, many new concepts and projects have been and must be tested in Norway. Some with success, others not.

In this thesis, some solutions will be investigated for implementing green power production, to enhance the knowledge and explore the possibilities that exists to reach the goal of 55 percent by 2030.The cases that will be investigated, will include the usage of power produced by wind, and the possibilities of using hydrogen and batteries as storage methods of power. This thesis will look into the technical and economic potentials of three cases of self-sufficiency only by green power. All cases will be located in Norway, two on an island called Utsira in the southern of Norway, and one up north at Berlevåg. The first case is a reconstruction of a previous test-project, the second is a solution to a current problem, and the third is based on a future project. This thesis will investigate different aspects and challenges, and has an ambition to increase the knowledge of possibilities within green powerization of the Norwegian Market.

1.1 Motivation

The motivation for this thesis builds upon my interest in renewable energy and what problems that needs to be solved to get a green and sustainable future. A great place for me was to look upon the 17 sustainable goals of the UN [4], and see where I could contribute my part. In this thesis, I see work towards goal 9 and 7, *build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*[5], and *Ensure access to affordable, reliable, sustainable and modern energy for all*[6]. To accomplish the goal of green energy, I see that the need for energy-storage is a merging problem. This is because of the fluctuation of green energy production. Therefore I wanted to look at what green possibilities there are within energy-storage.

One such green storage, is hydrogen production. Many development activities are being conducted within this field, but there is still much to be done before it is technologically and economically possible to upscale. With my background and knowledge, I therefore wanted to look into what the status are in this topic and what the possibilities are.

To get this insight, I looked into two cases of green hydrogen production in Norway. This mainly to get an insight into the experience already done, and a knowledge of what the key technological problems are. With these cases, I hope to find the main factors that drive the economical aspects and furthermore try to generalize my findings.

1.2 Scope of Work

The aim of this thesis is to investigate the alternatives to green self-sustainability in Norway. The base of the study is built upon research of the decommissioned green hydrogen plant in Utsira and possibilities and plans for the new plant in Berlevåg. Furthermore, the work considers factors that ensure a good economic and technical operation of green hydrogen. To accomplish this, a case-study is being implemented with the use of the newly released modeling program HyOpt. It is used to calculate the techno-economic optimization of the green power plant, as well as calculate the emissions. As an addition, the possibilities and limitations in the use of the HyOpt, version released 27 January 2023, is being explored.

1.3 Research Limitations

Aspects that have not been considered in this study, due to a limitation of time are:

- Transportation has been disregarded
- Laws and regulations have not been examined
- Only a few alternative model configurations and their potential opportunities have been explored
- A specific detailed examination of the components required for operating the facility has not been investigated
- A detailed analysis of the operational requirements for such a project is not included
- The area requirements for the various components have not been explored in detail

1.4 Outline of The Thesis

Chapter 1 is an introduction to the thesis and the study that has been done, highlighting the reasons for this subject and the choice of problem.

Chapter 2 includes some of the necessary knowledge needed for this thesis, ranging from the technical components and software, to economical calculations and market understanding.

In Chapter 3 the methods used for this thesis are described. Included in this, some of the selected data for the modeling is described and explained.

Chapter 4 goes through the calculated results of the different cases in this study, separated into technical, economical and environmental values.

Chapter 5 is the part where the results are compared and discussed. Included in this chapter, some of the limitations, factors and the errors encountered are explained.

In Chapter 6 the conclusion of the study is drawn, with an additional section of proposed further work.

2. Theory

This chapter will cover some of the main theory used to build the model and some of the knowledge necessary for the case analysis. The first part will explain the key technology of how the energy is produced. The second part will consider how hydrogen could be used as a storage of energy, followed up with a brief explanation of batteries. Fourth, the marked knowledge necessary is explained. Afterward, the key economical calculations are presented. Lastly, the optimization program and some important understanding of software, are explained.

2.1 The Wind Technology

There are many ways of producing green electricity, one of which is harnessing the energy from the natural wind to generate electricity using wind turbines. This is one of the power production methods in Norway that is predicted to have the greatest potential at some of the lowest costs [7]. In this study, the harnessing of power from the wind is set as a source of energy.

2.1.1 The Wind Turbine

Wind turbines mainly consist of four parts. The first part is the rotational blades. This is where the energy from the wind is harnessed and converted into mechanical rotational energy. The most common industrial wind turbines are vertical with three blades, where bigger blades make it possible to harness more wind. In addition, it is possible to rotate both the blades and the direction in which the blades are facing. This is done to optimize the power production at any given wind-speed. The second part is the housing of the generator, where the rotational energy is converted into electricity. This is achieved by either a direct driven or a geared generator, where the geared option has the benefits of a higher rotation-speed and with that a smaller generator. The third part is the power transmission, where the quality is checked and the low voltage electricity is transformed to high voltage, before it is passed into the grid. All of this is built in a housing and upon a foundation. This may vary, depending on the location and type of the turbine [8].

2.1.2 The Production Potential

The production potential of a wind turbine is dependent on various factors. One key factor is the wind speed. A modern wind turbine needs at least a wind speed of 3 to 4 m/s to generate power. From this, the wind turbine produces proportionally more power with increasing wind. This to the point where it reaches its «rated output speed»and the maximum power production. At this wind speed, the wind-blades start turning, to decrease the power that hits the blades. This is done to make sure the rotation speed is not exceeding the limits of what the turbine is designed to manage. The rated output power is held until the wind is too strong, and the turbine has to be stopped, the Cut-out speed. Typically this is at the wind-speed rate of 25 to 28 m/s[8]. This is again done for the safety of the wind turbine and the fear of overload. One example of the power curve of a wind turbine can be found in Raggovidda Vindpark, where the Siemens SVT-3.0-101 is used. This turbine can produce power up to 25 meters per second. In the figure below, the power curve of Siemens SVT-3.0-101 is illustrated, showing the power production at a given wind speed:

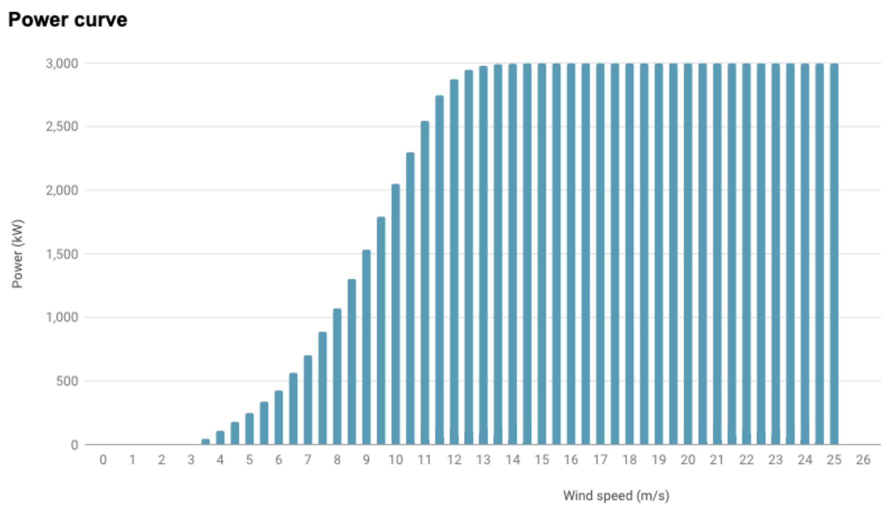

Figure 2.1: Power-curve of Siemens SWT-3.0-101 [9] .

Another factor is the efficiency of the turbine. A theoretical maximum of how much power a wind turbine can gather from the kinetic energy of the wind that passes through its area is defined. This limit, the Betz limit (C_p), is at 59,3 %, where the speed of the wind is 1/3 of the wind out. The reason for this is that an efficiency closer to 100% would make the wind stop, and no more wind could pass through [10].

How much power a turbine realistically can gather is lower than this. This is due to various losses throughout the turbine. In practical calculations, the estimation of the efficiency of a turbine is at around 40%. This percentage has greatly increased in the last years, due to innovations and an increased efficiency [11].

The total power output of a turbine, P_{el}, is given by the formula:

$$P_{el} = \frac{1}{2} C_p \rho A v^3 \tag{2.1}$$

Where C_p is the efficiency of the turbine at a given wind speed, ρ is the density of the air, A is the total circle area that three turbine-blades create, and v is the wind speed. With this formula, it is clear that the wind speed is the most crucial factor, but also that the area and efficiency greatly impact the power production.

2.1.3 The Norwegian Wind Power Production

Norway has a long history of producing power with wind turbines. The first wind turbine was installed in Andøya in 1916, and produced enough power for 16 households. Today, Norwegian wind farms have a total capacity to power about 10 percent of the Norwegian population. In 2022 it consisted of 64 wind farms, 1 383 wind turbines, with a total capacity of about 4 650 MW[11].

Some of what makes Norway a perfect location for wind power, is the long coastline and the possibility of using the phenomena of ocean breeze. This phenomenon occurs due to the mainland heating up more rapidly than the ocean in the early hours of the day. This causes the air onshore to rise, and generate winds where the cold air from the sea comes towards the coast to replace the rising hot air. In the evening, the wind shifts as the mainland cools down faster than the ocean, leading to the breeze moving away from the land. Overall, this results in the highest wind intensity and, consequently, the highest energy production from wind turbines during the morning and evening periods[12]. In addition, the coastline does not give any form of obstacles, in the form of terrain, giving wind with less turbulence.

2.2 The Hydrogen Technology

The industry of production of Hydrogen has seen some significant steps towards development in the last years. In Norway, the shift towards green energy alternatives, has given a boost to the Norwegian hydrogen industry. In 2022 there was a total of 815 jobs in Norway connected to this industry. But with the increased interest, the hydrogen industry is expected to increase to a total of 5800 within the year 2030, all over the country[13].

The chemical element hydrogen, is the lightest and the most abundant element in the known universe. Hydrogen or hydrogen gas, H_2, makes up a total of 90% of the atoms and 75 % of the matter in the universe. On Earth, Hydrogen mostly exists in the state of hydrogen gas. The production of hydrogen started as early as the sixteenth century. This was first produced from metals and acids. Two hundred years later, Henry Cavendish, discovered the existence of hydrogen gas. [14, p. 177]

Green Hydrogen has a lot of benefits. One of the benefits of producing green hydrogen, is firstly the environmental impact. The conventional production methods of hydrogen consist mainly of extracting hydrogen from fossil fuels. Using fossil fuels to extract hydrogen also produce CO_2, which escapes into the atmosphere. By changing to green hydrogen, the production of hydrogen could be done by splitting water down to hydrogen and oxygen. This electrolysis process is powered by renewable energy, where the only byproduct is oxygen. With the shift to green hydrogen production, is it possible to cut down on the worlds CO_2-emissions. One other benefit is the possibility to store hydrogen and use it as a fuel, either for the production of heat or electricity, or as a raw material directly to the industry[15].

2.2.1 Hydrogen Variants

Even though hydrogen is the most abundant element in the universe, on Earth it is not an energy vector. This means that it is necessary to process it to turn it into fuel. There exist a lot of ways of doing so, some sustainable, others not. To distinguish the different methods, the source is classified. With this, the most common types of hydrogen are grey, blue and green[16].

Grey

Grey hydrogen is the most common of them all, and also the cheapest. Even though greenhouse gases are generated when it is used, the process of producing it does. Grey Hydrogen is created from natural gas with the process of steam reforming, separating hydrogen from the gas. The technology does unfortunately not capture the carbon emissions created, which instead is released into the atmosphere.

Blue

Blue hydrogen is also created with the steam reforming process, but in contrast to grey hydrogen, the carbon emissions are captured and stored. In that way, the process limits its carbon footprint, but does not limit it. Blue hydrogen is also called «low carbon hydrogen», indicating that it does not avoid the creation of carbon emissions, just limiting them by storing it.

Green

Green hydrogen does not emit any greenhouse gasses throughout the whole production cycle. It uses renewable energies to power the production process, which also is carbon neutral. It is often done by electrolyzing water, using energy from wind or solar power. The process results in no negative greenhouse gases being released into the atmosphere. This method is therefore a great alternative to blue and grey, but still has some challenges to compete with the production costs. With the growing polarity of green energy, a lot of innovation is expected to be done in the coming years.

2.2.2 Hydrogen Production - PEMWE

With electrical power, it is possible to produce hydrogen. Multiple ways of producing hydrogen exist, but in the last years, the production technique of electrolysis with water has grown as one of the most favorable methods. This technique separates water into hydrogen and oxygen. One of the preferred components for doing so, is called Polymer Electrolyte Membrane (PEM).

Today the desire of green hydrogen has made the interest in PEM water electrolysis (PEMWE) grew. The development of PEM has made it cost-effective and competitive against the non-green hydrogen production possibilities. The preference of PEM - electrolyzer is also done in the real cases that are also seen in other studies[17].

The electrolyzer consists of one polymer electrolyte membrane, with a catalyst layer on both sides. The Anode side is either of the material Irriduim or Ruthenium, and the Cathode side is made of Platinum[18]. On the outside of these, the supply of water and electrical power are connected. H_2O is channeled into the Anode side (OER), where it is oxidized to oxygen, electrons and protons. With this, the protons go through the membrane, react with the electrons in the cathode (HER), and produces hydrogen gas. At the anode side, the oxygen stays and is released as a gas. A simplified buildup of the structure are showed in the figure 2.2.

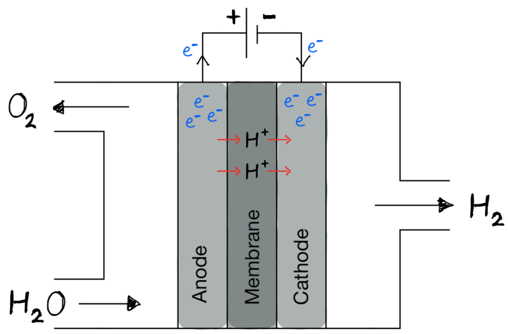

Figure 2.2: Simplified illustration of PEM

The basic and most important reactions that happens within the electrolyser:

$$\begin{aligned} Anode\,(OER) &: H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- \\ Cathode\,(HER) &: 2H^+ + 2e^- \rightarrow H_2 \\ \\ Total &: H_2O_{(l)} \rightarrow H_{2(g)} + \frac{1}{2}O_{2(g)} \end{aligned} \tag{2.2}$$

This PEM method has its advantages and its disadvantages. The key technical benefits of PEMWE compared to other methods producing hydrogen, is the fast heat-up and cool-off time, including the short response time. This makes it more compatible to fluctuating power, e.g. wind power. The key disadvantage is the high manufacturing cost, making it more expensive than competing technologies. The cost is mainly because of the expensive materials needed[19].

2.2.3 Hydrogen to Electricity - Fuel Cells

Hydrogen is often used in the industry as a chemical component, but it can also be used as a fuel to produce electrical power. The conversion of hydrogen to usable electricity is done with fuel cells. A fuel cell uses the chemical energy of hydrogen to produce electricity, often at a higher efficiency than traditional combustion engines. It involves a reverse water electrolysis reaction, in which the hydrogen extracts the electrons released when it reacts with oxygen to produce water[20].

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + energy \tag{2.3}$$

The fuel cell is quite similar to a PEM-cell, and consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around the electrolyte. Unlike the PEM-cell, it uses hydrogen and oxygen as fuel, and produces power and clean water. With this technology, the hydrogen can be turned back into electrical energy. One simplified illustration of the process within a fuel cell, is shown in the figure below.

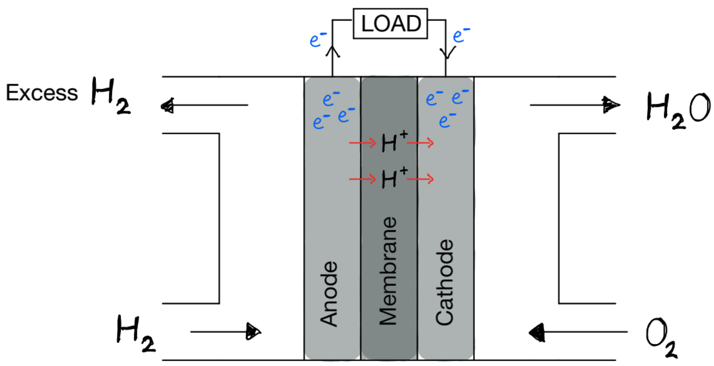

Figure 2.3: Simplified illustration of a Fuel Cell

Each fuel cell is often relatively small in scale, but by combining multiple fuel cells, it is possible to extract significant power at scale.

2.2.4 Hydrogen Storage

The storage of hydrogen is the key to hydrogen technologies and applications. A big part of the future of hydrogen lies within the storage of it, where the positive prospects of hydrogen is dependent on an effective way of storing it. Each method of hydrogen storage having different benefits and challenges.

Compressed hydrogen

One way to store hydrogen is by keeping it compressed in fuel-tanks. When considering using hydrogen for cars or other small engines, compressed is seen as the most convenient method. Compressing hydrogen requires energy, and is done by a series of compressors that stepwise increase the density to the desired level. The hydrogen is then stored in pressured tanks, typically in the range of 150 to 700 barm and a size of a few, up to thousands of liter.

In addition to this, the temperature is essential when storing and transferring. When transferring and storing hydrogen from a high-pressure state into an empty low-pressure tank, an expansion happens, that heats the gas. This temperature has to be controlled, and can be done using a heat exchanger or pre-cooling[21].

Liquid hydrogen

One other way of storing hydrogen is turning it into a liquid. By turning hydrogen into liquid, it is possible to increase the energy density of the hydrogen and it gives more possibilities, but also challenges. To turn hydrogen into liquid, it must be lowered to a temperature below 30 Kelvin (21,3K). To make this easier, it is possible to increase the pressure and use the Joule–Thomson Effect. By using expansion it is possible to cool down Hydrogen quite efficiently and controlled[14, p. 254]. The formula for the rate of change of temperature with respect to pressure, can be expressed as:

$$\mu = (\frac{\partial T}{\partial P})_H = \frac{V}{C_P}(T\alpha - 1) \tag{2.4}$$

Where T is the temperature, P is the pressure, V is the volume, C_P is the heat capacity at constant pressure, and a is the thermal expansion coefficient. To reduce the difference of temperature, liquid nitrogen is usually used.

After the liquidation of hydrogen, a specialized storage vessel is needed. A liquid hydrogen tank usually consists of an inner and outer vessel, with a vacuum insulation layer separating the two. This vacuum layer is a crucial part of preventing heat transfer into the tank, through conduction, convection, and radiation. In addition, aluminum spacers or aluminum-evaporated films, are often used to reduce the heat transfer from the high-temperature surface of the outer tank. But with this, there is always some inevitable leakage, due to some inward heat leakage [14, p. 254].

Ammonia

A third option of storing the energy of hydrogen, is turning it into a chemical binding. One such option is turning it into ammonia (NH_3). By combining hydrogen with nitrogen, the most common gas in the atmosphere, it is possible to produce ammonia. The process of ammonia needs energy, but this energy can later be extracted by the decomposition of ammonia back to hydrogen and nitrogen[14, p. 262].

$$NH_3 \longleftrightarrow \frac{1}{2}N_2 + \frac{3}{2}H_2 \;\; (\Delta H = \pm 92.4\, kJmol^{-1}) \tag{2.5}$$

The benefit of turning hydrogen into ammonia, is that it is a better carrier of hydrogen than pure hydrogen. One of the key reasons for this is its energy density and the simple way of storing it. Ammonia is a gas in it natural form, but can easily be changed to a liquid by condensation. Ammonia can be stored under the pressure of only 10 bars, not needing any form of cooling. In addition, ammonia also has a greater energy density than hydrogen, where 1 liter of ammonia contains more energy than than 1 liter of pure liquid hydrogen[22].

Ammonia could either be changed back into hydrogen or used directly. The usage of ammonia as a hydrogen carrier, enables hydrogen to be transformed into ammonia, transported, and then changed back into hydrogen locally. By using the ammonia directly, it is possible to use it or sell it to the industry, to production of example fertilizer. One other possibility is to use ammonia as a fuel, especially in the long-distance transport sector. When needing a fuel for long distances, energy density is key, ruling out batteries and compressed hydrogen. This has already been tested and used in the shipping industry, and is expected to increase in popularity in the years to come[22].

2.3 Batteries

In this case study, batteries are implemented to work as short-term power storage. Different types of batteries exist; chemical, mechanical and more. In this study, the main focus is on the usage of Lithium-ion batteries, which comes with its advantages and disadvantages.

2.3.1 Lithium-ion Batteries

Lithium-ion batteries are widely used in modern electronics today. This battery type has more or less replaced nickel-based battery types due to their advantages of higher capacity and lower weight.

A lithium-ion cell typically consists of a positive electrode (cathode) made of lithium cobalt oxide, a separator, and a negative electrode (anode) made of carbon. An organic electrolyte is used as an ion transporter[23].

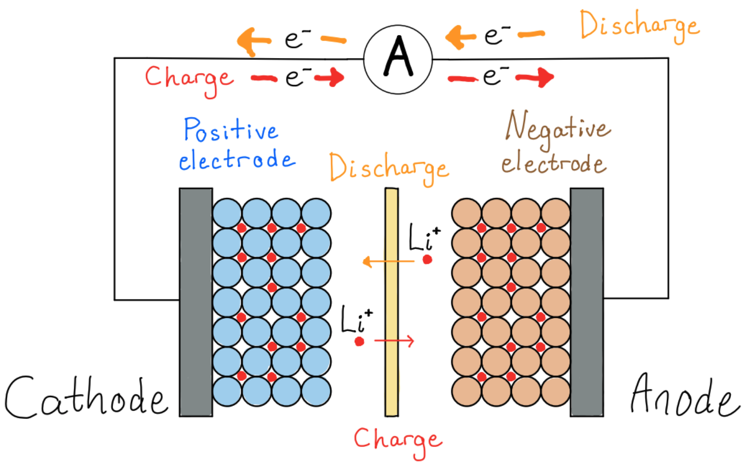

Figure 2.4: Simplified illustration of a typical Lithium-ion battery

Modern lithium-ion batteries tolerate intermittent charging well; ideally, they are used until they reach about 40 percent capacity and then recharged up to 80 percent of full capacity. Most battery types experience some voltage loss over time due to self-discharge. In this regard, lithium-ion batteries are very stable compared to other types [23].

Lithium-ion batteries for large-scale storage consist of several hundred individual cells connected to form a battery pack. Some advantages of lithium-ion batteries are the high specific energy and power, long calendar and cycle life, high round-trip efficiency, low self-discharge rate and a relatively good charging speed. Some of the disadvantages are the high capital cost, advanced BMS, weak recovery and complex to recycle[24]. Some of these advantages can be slightly compensated by changing the type of Lithium-Ion battery used, but this is not further investigated in this study.

2.4 The Marked

2.4.1 Price Areas in Norway

In Norway there are 5 different electricity price areas. Because of the topography, long distances within the country, weather differences and difference in power-production within the the country, the demand of electricity may vary substantially between the ares. The pricing areas are illustrated in Figure 2.5 , and are the areas Østlandet (NO1), Sørlandet (NO2), Midt-Norge (NO3), Nord-Norge (NO4) and Vestlandet (NO5). The most recent years the pricing between the areas has grown significantly. The biggest difference has been between Nord-Norge and Sørlandet. The high power-supply and low demand has given Nord-Norge low electricity prices. On the other part Sørlandet has had high electricity prices, due to their connection with powercabeles directly to the central of Europe and the lack of energy and high demand that has been there. And because of the lack of enough power-transfer possibilities between the areas, there have been a great price-difference between the areas[25].

Figure 2.5: Illustration of the different pricing-areas in Norway[25]

Because of this increased demand of power and a need of power, it is planned to increase the flow of electricity between the areas. The plan is to build more high-voltage cables, at an investment cost between 60-100 billion NOK. But this will come with a huge natural impact, with cables going far between points of interest. That is why the popularity of other possibilities has grown substantially the last years[25].

In figure 2.6, the historical prices of electricity in the different areas is illustrated. The data is gathered using the historical data of NORDPOOL[26].

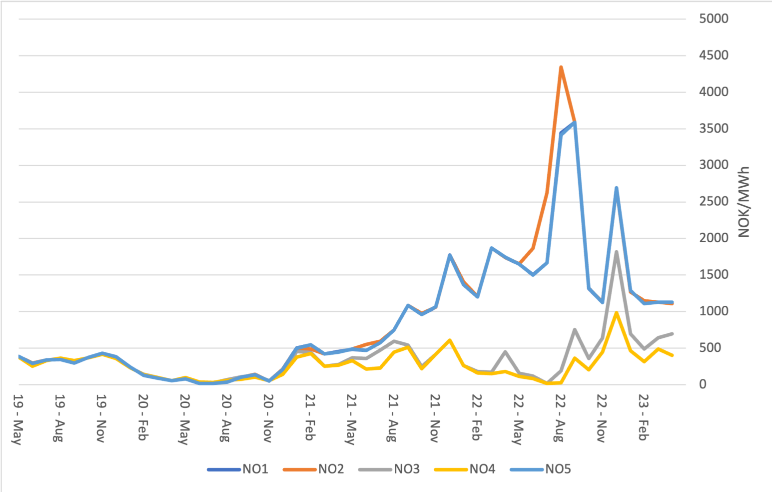

Figure 2.6: Historical prices of the different price areas in Norway[26]

2.4.2 Emission Taxses in Norway

To limit the demand for CO_2 - products, many countries have started implementing a carbon tax. As one of the first countries in the world, Norway introduced in 1991 its first carbon tax. This tax is linked to all forms of CO_2 emissions, where its levied to pay any form of combustion linked to oil, gas or diesel in petroleum operations. For the combustion of natural gas the tax rate in Norway was 705 NOK per tonne of CO_2 that are released into the atmosphere. With this tax, the profitability of the non-environmental friendly industries are reduced drastically. This creates an incentive for the industries to shift towards greener alternatives. In addition, the carbon tax for 2023 has been increased to 761 NOK per tonne of CO2, and are expected to increase into the years to come.[27]

2.4.3 Trade of Electrical Power

Norway holds a unique power production position, with the highest share of renewable electricity in Europe. Hydropower is the origin of the majority of the power production in Norway, supplemented by an increasing proportion of wind power. At the same time, Norway is closely interconnected with the Central European power system, enabling the importation or exportation of electricity from neighboring countries through cross-border cables. Consequently, a portion of the electricity in the Norwegian grid may originate from elsewhere and be generated using different production technologies[28]. This gives a mix of electrical power, with the possibility of multiple origins when purchasing the power.

2.5 The Economical Calculations

2.5.1 Levelized Cost of Energy - LCOE

A key calculation within the energy industry is the Levelized Cost of Energy. This is a calculation of the total costs of a power plant (both Capital Expenditure and Operating Expense) divided by all the power production throughout the lifespan of the power-plant. This gives an indicator of how much each kW power produced will cost. With this, it is possible to calculate the margins of the project, when the LCOE for 1kWh is compared to what the market gives for 1kWh [8].

The simplified formula of the Levelized Cost of Energy:

$$LCOE = \frac{NPV\ of\ Total\ Cost}{Total\ Electical\ Power\ Produced} \tag{2.6}$$

2.5.2 CAPEX - Capital Expenditure - Investment Cost

One of the key aspects of the optimization, is the calculation of capital expenditures. The reason for this is that the CAPEX can tell how much money that is needed to invest in new or existing assets. With this, it is possible to take into count the lifespan of the different assets, and what is profitable and what is not. The main reason is to see what amount of capital is required to run the given project.

The amount of capital expenditures a company is likely to have, depends on the industry. Some of the most capital-intensive industries have the highest levels of capital expenditures, including oil exploration and production, telecommunications, manufacturing, and utility industries[29].

2.5.3 OPEX - Operating Expense - Operating Cost

The Operating Expense is connected to the expenses that occur in the normal operations of a company or business. This includes the expenses that are needed day to day to generate revenue and operate the business, whether fixed or variable costs. Essentially the operating costs include payroll to workers, equipment, rent, inventory, research, development, etc. On the contrary, the non-operating costs include the costs that are not directly connected to the core operations of the company, typically interest costs and loss of disposed assets. One key notice is that what is viewed as an operating cost, may vary on the industry. This is important, due to the variation of the tax-deductibility.

2.5.4 Net Present Value - NPV

The Net present value (NPV) is the calculation of the present value of money, compared to the present value of money in the future. Because of factors such as inflation, the current value of money is not the same in the future. Net present value calculations are typically used for investment planning, to analyze whether an investment in a project will pay itself in future incomes.

The calculation formula of the net present value (NPV) is given:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{2.7}$$

Where R_t equals the net cash inflow/outflow for a given period t, i equals the discount rate or return that could be earned in alternative investments (often given a risk-free rate), and t equals the number of periods.

2.6 Software

Software is the keystone of the modern age. It is the binary files that make it possible to use all the modern electronics that surround us. The software is the core instruction of how and when a set of tasks should be done, where the possibilities of its use are many[30].

Even though the hardware has grown significantly more reliable at a low cost, the need of software has outpaced its need, where software is replacing many of the earlier use of hardware. With this, a vast number of techniques are developed to improve and measure the reliability of the software, both quantitatively and qualitatively. In addition to this, the techniques aim to improve the quality of software products as well as the quality of the process of the development of software. In total, all of these techniques contribute to improving software reliability[31].

2.6.1 Modeling and Optimization - HyOpt

As mentioned, this thesis relies on the use of software, and in this case the optimization program HyOpt. The HyOpt model is an optimization program to evaluate energy-systems, with a focus on Hydrogen-based technology. Based on the inputs of a planned energy-system, combined with energy demands and costs, it determines the optimal way to solve the objective given. This is typically the highest net value or the modeled system [32]. The program was created and published by SINTEF, one of the largest independent research organizations in Europe.

The structure and parameters

HyOpt is node-based. The model system bases all the elements as a node with given properties, where every pair of nodes allows a flow of elements between them. These elements could include liquid or compressed hydrogen, oxygen, natural gas, water, electricity, etc. Furthermore, the model allows requirements such as downtime and transportation time between two nodes to be set. The goal of HyOpt is to figure out which nodes that should be installed, at what size and at what time. The capacity could then be modeled as energy (volume) or power (flow). [33]

The optimization

The HyOpt model separates its decision-making into two, the strategic variables and the operational variables. The strategic variables are the decisions made at the beginning of the strategic periods. These decisions selects the adding,or removal, of capacity to the nodes in the network. The operational variables are the decisions made for the operational periods. This includes the nodes that represent production, loads delivered or obtained from the market, storage level and the flow between. With all this, the HyOpt model calculates the optimal values for each node, then returns the solution of the whole structure [33]

Possible extensions

In addition to calculate the optimal techno-economical solution, it is possible to set a requirement on the emission reduction. Currently, this only works for CO2-emissions related to the production of the purchased power. In this case study, the goal is to calculate a zero-emission solution. For HyOpt this means that the total purchased power equals zero, as it does not take into count the emissions of the plant built.[33]

2.6.2 Problems and Errors

Wherever there is software, there are errors. *Errors* are defined as human actions that result in software containing a fault[31], but are often used as a fault that the software is not running or giving the result as intended. An effective software reliability program will easily identify and correct errors and faults at or near the phase in which they occur. Unfortunately, this is often not the case. The errors that do occur, is some times hard to locate, where an error in one phase, often leads to a another error in a another phase. A simplified illustration of the key phases and where their effects are showed in the figure 2.7 below:

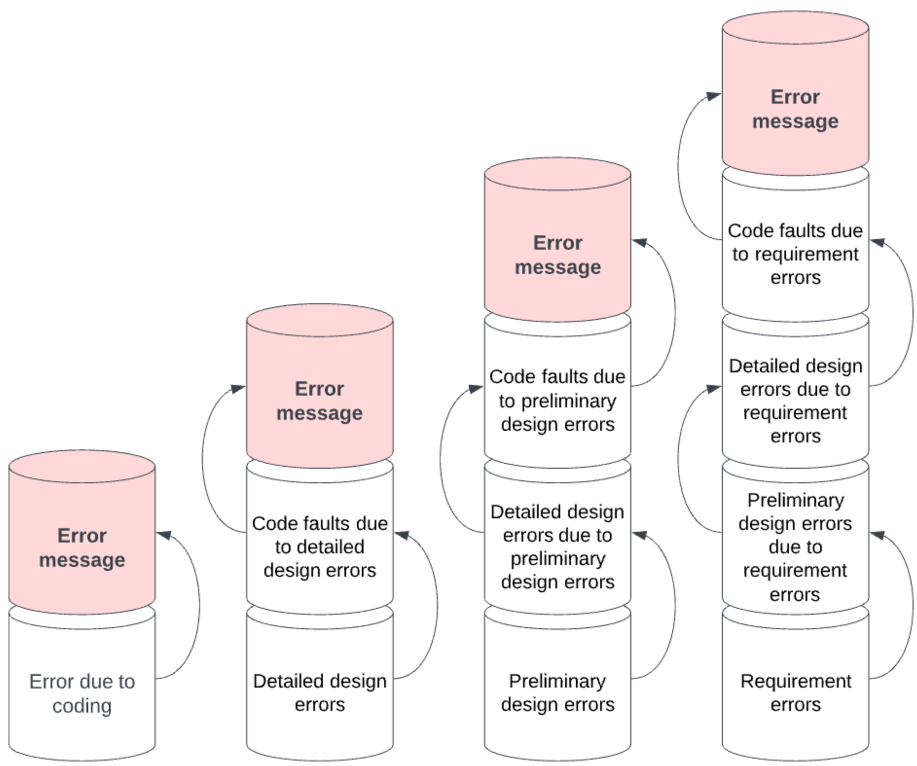

Figure 2.7: The cascading of errors through the development phases.

These errors often occur due to the absence of various quality factors, which can be divided into ten categories[31]:

1. Correctness: The degree to which software is free of design and coding defects

2. Efficiency: The degree to which software performs its intended functions, with minimal use of computing resources.

3. Flexibility: The ease with which software can accommodate enhancements or modifications.

4. Integrity: The extent to which software safeguards against unauthorized access or modification of data or code.

5. Interoperability: The capability of multiple products to exchange information seamlessly.

6. Maintainability: The degree of how easy the software can be maintained

7. Portability: The ease with which software can be transferred from one computer system to another.

8. Reusability: The extent to which a module can be utilized in multiple applications

9. Testability: How easy it is to test the software

10. Usability: The extent to which software incorporates human engineering capabilities and features

3. Method

In this chapter, the methods and workflow of this thesis are described. The first part shortly explains how the method CRISP-DM was used as a guide for how to build up, model and evaluate the HyOpt-optimization program. The next part describes how the necessary data was gathered and decided. This includes the explanation of the choices and assumptions that were taken to get to run the optimization program HyOpt. The third part describes the HyOpt model, and how the needed parameters are calculated. Lastly, the cases of this study are presented, and a flowchart illustrates the decisions that are made.

3.1 CRISP-DM

The first step of this study, was the determination of a plan of how the workflow should be. In this case study the method of Cross-industry standard process for data mining (CRISP-DM) is used to guide for how to use the HyOpt effectively and correctly. CRISP-DM is a six-step method and serves as a base for a scientific process in the use of data. These steps are; 1. Business understanding, 2. Data understanding, 3. Data preparation, 4. Modeling, 5. Evaluation and 6. Deployment. An illustration of the process is displayed in figure 3.1, with the inputs of how the data is processed[34].

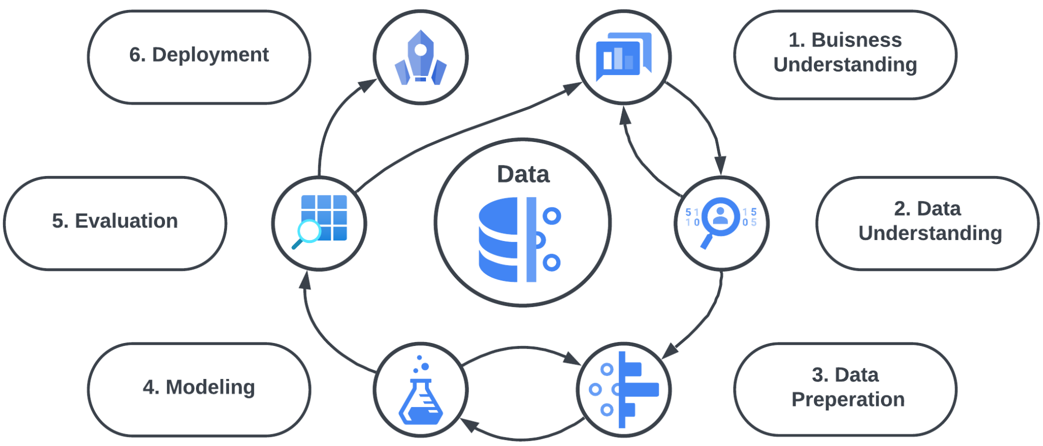

Figure 3.1: Illustration of CRISP-DM

The first steps are to understand the business and data. These parts pinpoint the importance of understanding what data that are necessary for the given case, and then make it easier to gather the data that is needed. With this, the next step is the data preparation, which includes to checking and organizing the data gathered. After this, the modeling phase starts. This model data is built, in this case HyOpt, and its optimization. Lastly, the data results undergo an evaluation to determine if it is ready for use, or if some adjustments are needed.

In this study, the first part was a clarification of the problem that wanted to be studied and the data that is needed. Secondly, the data was gathered and explored. Thirdly, the data was deeply explored and cleaned if needed. Then the different models were constructed and executed for the study, involving a process of trial and error with iterative iterations. After this, the data was evaluated, through the visualization program and directly in the database created. Lastly, the data was selected and presented in this study.

3.2 Data Understanding and Preparation

In this part, the data necessary to run the HyOpt model are described. Most of the data is gathered by third-party sources or programs. The rest of the data is either calculated based on this data, or gathered from other cited studies.

3.2.1 Wind Data - Renwable Ninja

The Wind power data needed for the selected area, is accessed through API, from the simulation website of Renewable Ninja. The website allows simulations of hourly power output from both wind and solar power plants, located anywhere in the world. It is built by Stefan Pfenninger, a professor of energy systems modelling at the Faculty of Technology, Policy and Management at TU Delft, and Iain Staffell, Senior Lecturer in Sustainable Energy. They made this simulation website to make scientific-quality weather and energy data available to everyone[35].

The Renewable Ninja simulation tool let you choose between a series of factors. The first choice is the location, where you can choose between a specific point or a whole country. By selecting a specific point, you either choose the name of the place or the exact latitude and longitude of the point of interest. By choosing a country, the average of the country will be presented. For this case study, the specific latitude and longitude were selected, to get the most exact data.

Furthermore, the selection lets you choose between solar data, wind data, or weather data. For this case, only the wind data was chosen. Renewable Ninja gives the option to select the data-set from which the data will be acquired, where MERRA-2 (global) was chosen. After this, multiple choices were made, the year of interest selected, the total capacity of the power-plant given, the hub-height given and the turbine model selected. In the selection of the model of the wind turbine, it allows the choice of multiple pre-selected wind turbines. The type of turbine selected affects how much power that is produced, the efficiency of the turbine. The selection includes the name of the manufacturer, the diameter of the blades in meters, and the rated capacity in kW or MW.

The selected turbines for this study were $Enercon\ E40\ 600$, for Utsira, and $SiemensSWT - 3.0 - 1.0.1$, for Raggovidda Wind park. In addition, the year 2022 and the total capacity of the wind-park was selected, where the hub height for Utsira was set to 60m, and 115m for Raggovidda.

From this, a file with a table of hourly output of the whole year was given, with the second column giving the electricity generated and the third providing the wind speed at the given hour. A representation of the data given is shown in table 3.1. The representation illustrates the data of some hours in January, where the data is acquired from the location of Raggovidda. As expected, the data varies throughout the day.

Table 3.1: Renewable Ninja output of Siemens SWT-3.0-1.0.1

utc_timestamp	electricity	wind_speed
01.01.2022 01:00	33479.006	10.583
01.01.2022 02:00	36734.680	11.403
01.01.2022 03:00	39089.940	12.179
01.01.2022 04:00	40454.583	12.736
01.01.2022 05:00	40977.652	12.987
01.01.2022 06:00	40708.051	12.862
01.01.2022 07:00	40027.377	12.554
01.01.2022 08:00	38900.280	12.110
01.01.2022 09:00	37403.504	11.599
01.01.2022 10:00	35549.047	11.078
01.01.2022 11:00	33787.796	10.655
01.01.2022 12:00	32515.645	10.373
01.01.2022 13:00	31962.209	10.265
01.01.2022 14:00	32533.864	10.384
01.01.2022 15:00	33802.480	10.664
01.01.2022 16:00	35213.327	11.001
01.01.2022 17:00	35636.582	11.105
01.01.2022 18:00	35635.786	11.107
01.01.2022 19:00	35637.954	11.101
01.01.2022 20:00	35205.577	10.990

In addition to this, it was necessary to render the data. This because the HyOpt model needs a variable, which gives the capacity factor for the given hour as a variable cap_factor. This capacity factor was calculated by dividing the produced electricity by the total capacity of the power-plant. The calculation for each hour was then inserted into column four and given the name cap_factor.

This should not be necessary, since the model does have a script that does this automatically. But since the script of get_wind_data did not work as it was constructed, it was needed to render it manually. For later use, it would be necessary to look into what is wrong in the file or if there is something else that created this mistake.

3.2.2 Powerload Data - ENTSO-E and Selected

The demand data of power to the cases, are either based on collected real data or given a value manually. The HyOpt test cases come with some pre-calculated demand data for six of eleven selected industrial and residential buildings in Germany. This data-set is from the project CoSSMic (Collaborating Smart Solar-powered Micro-grids), and are gathered using the site Open Power System Data. The data package collected contains measured time series data for household- or low-voltage-level power. The starting time for the data series, as well as data quality, varies with small and bigger differences. For the purpose of this study, the data were not used.

For this study, the demand data are changed to correspond to the local market in Norway, for the location of the powerplants. To get this data, *ENTSO-E* [36]is used, which is a program created by the European network of transmission system operators for electricity, to create a file of the historical demand of a given region.

To access the API, a token is required. This can be granted by sending an email-request to ENTSOE. This allows the enabling of connection and interaction between two computer programs, and allows to download the electricity data for a selected region. With *ENTSO-E*, it is possible to gather the hourly power data for a whole pricing area in Norway. In this case, the data are selected to correspond to the wind data of the year 2022. Since the data are the total of the whole pricing region, it is necessary to scale down this data.

For the cases of Utsira, this is scaled down to either correspond to an average demand of 10 households, or an average of 2 MW to correspond to the quoted demand of the whole island.

For the case Berlevåg Ammonia production, the demand data is manually set to 100 MW each hour. Within 2024, it is expected that the production of ammonia will begin, and will need a total of 100 MW[37]. Therefore, the total power demand is set to 100 MW at every hour of the day, giving a constant demand.

Table 3.2: Example of the demand data

utc_timestamp	resident1
2022-04-11 00:00:00+01:00	20.41114744
2022-04-11 01:00:00+01:00	20.66208361
2022-04-11 02:00:00+01:00	19.9694998
2022-04-11 03:00:00+01:00	20.70725212
2022-04-11 04:00:00+01:00	20.13511767
2022-04-11 05:00:00+01:00	21.20410572
2022-04-11 06:00:00+01:00	22.77496609
2022-04-11 07:00:00+01:00	23.87908521
2022-04-11 08:00:00+01:00	24.23541456
2022-04-11 09:00:00+01:00	23.40732522
2022-04-11 10:00:00+01:00	22.59429206
2022-04-11 11:00:00+01:00	23.0359397
2022-04-11 12:00:00+01:00	22.37346823

(a) Power input of Case 1

utc_timestamp	resident3
2022-04-11 00:00:00+01:00	100000
2022-04-11 01:00:00+01:00	100000
2022-04-11 02:00:00+01:00	100000
2022-04-11 03:00:00+01:00	100000
2022-04-11 04:00:00+01:00	100000
2022-04-11 05:00:00+01:00	100000
2022-04-11 06:00:00+01:00	100000
2022-04-11 07:00:00+01:00	100000
2022-04-11 08:00:00+01:00	100000
2022-04-11 09:00:00+01:00	100000
2022-04-11 10:00:00+01:00	100000
2022-04-11 11:00:00+01:00	100000
2022-04-11 12:00:00+01:00	100000

(b) Power input of Case 3

3.2.3 Techno-Economic Parameters

In addition to the previous data, the HyOpt model needs various sets of data to represent the costs and efficiency of the different modules. This input data is presented below. The prices and values for each key component are shortly explained, considered and given a selected value.

Wind Turbines

The specifications of the turbines significantly determine the final cost. Since the turbines have a high CAPEX, the size of it affects the result substantially.

Table 3.3: Input data for the Wind turbine

Wind Turbine	HyOpt - original	Selected Value
CAPEX [Euro/MW]	1 288 000	1 250 000
OPEX [Relative %]	4.75	4
Unit size [MW]	0.150	0.150 - 3

The value of CAPEX is calculated based on the total cost of the existing Raggovidda wind park. This had a total cost of about 60 000 000 Euros [38], which equals about 4 000 000 euros for each turbine. Because each turbine equals 3 MW, the total CAPEX of each MW, equals about 1 250 000 euros. This figure is used for all cases.

The relative OPEX is expected to be lower in a large turbine, which is why the percentage is lower. The calculation unit size is set to 3MW for Raggovidda, because each turbine is 3 MW, and 150 kW for Utsira, where the turbine of 600 kW was pitched down to 150 kW to better match the demand. Some of the newer turbines do have a lower OPEX, but due to the challenging weather conditions, it is estimated that the OPEX is higher than the lowest end.

Battery

In this case study, a Lithium-ion battery is chosen. The reason is to effectively work as a short term storage. The high efficiency and low effect loss, makes it perfect for short-term storage. But because of the high cost, compared to hydrogen, it is not as suitable for long-term storing of energy. In this study, the selected CAPEX is high, compensated by a low OPEX.

The input-values chosen is given in the table below:

Table 3.4: Input data for the Battery[39][40]

Battery	Similar Studies	HyOpt - original	Selected Value
CAPEX [Euro/kWh]	200 - 1000	955	900
OPEX [Rel. %]	2.4 - 4	1.0	1.0
Efficiency [kWh out/kWh in]	0.92 - 0.96	0.95	0.95
Liftetime [years]	10+	12	12

Electrolyzer

In this case, the PEM electrolyzer is being used in both of the real cases. As mentioned in Chapter 2.2.2, PEM as the selected electrolyzer, gives both flexibility and a short response time, compared to other electrolysis methods. The data input for this simulation is based on the values given in other similar studies. The input-values chosen are given in the table 3.5:

Table 3.5: Input data for the Electrolyser [41][42][18][43][44]

Electrolyser	Similar Studies	HyOpt - original	Selected Value
CAPEX [Euro/kWh]	800 - 2200	1200	1000
OPEX [Rel. %]	2.4 - 4	2.4	2.5
Efficiency [kWh/kg]	0.51 - 0.64	0.575	0.6
Liftetime [hours]	40 000 - 100 000	100 000	100 000

The $Efficiency$ calculation is based on the assumption that 1 kg of hydrogen has an energy equivalence of 33.33 kWh. In the electrolysis process, it takes 58 kWh of energy to produce this 1 kg of hydrogen. By dividing the energy content of hydrogen (33.33 kWh) by the energy consumed in its production (58 kWh), the efficiency is calculated to be 0.6, or 60%.

The values chosen, differ compared to the pre-selected values in the original HyOpt-casefile. The CAPEX chosen is set to 1000 Euros/kWh, which is a bit lower than original. Compared to similar studies, 1000 Euros/kWh is more appropriate.

Hydrogen Storage

The hydrogen storage method chosen for this study, is a gaseous hydrogen storage tank. This is done to cover long-term energy storage. The hydrogen storing of gaseous hydrogen is the most area-efficient method, and comes with a lower cost. The benefits are that the operating costs are quite low and the lifetime is long. The input-values chosen are given in the table 3.6:

Table 3.6: Input data for the Hydrogen Storage [42][43][44]

Hydrogen Storage	Similar Studies	HyOpt - original	Selected Value
CAPEX [Euro/kg]	600 - 1000	1000	600
OPEX [Rel. %]	0 - 4.0	1.0	1.0

Fuel Cell

To change the hydrogen back into electricity, a fuel cell is chosen. How efficient the fuel cell is, varies on the type, whereas newer models are generally more effective. Fuel cells do have a high CAPEX and OPEX that are set to 2 percent. The lifetime may vary, but for this case, it is probably selected a high value compared to the lowest end.

Table 3.7: Input data for the Fuel Cell [42][43][45][44]

Fuel cell	Similar Studies	HyOpt - original	Selected Value
CAPEX [Euro/kWh]	2 250 - 5 000	5 000	2 500
Efficiency [kWh/kg]	0.4 - 0.6	0.55	0.6
Liftetime [years]	4.5 - 10	10	10

Financial and currency assumptions

In addition to the CAPEX and OPEX, the HyOpt needs some given values to correspond to each case. In the table below, some of the chosen values of the parameters are presented. It is equal in all cases.

Table 3.8: Various values needed for the HyOpt model

Parameter	Given Value
Exchange rate 1 dollar	0.85 euros
Exchange rate 1 euro	10 NOK
Discount rate (Included 2% inflation)	6 %
Simulation Period	10 years
Relative OPEX if not given	2 %
Energy-density of 1 kg compressed H_2	33.33 kWh
CO_2-tax per kWh	0.07 euros/kg

Emission calculation

The calculation of the emissions is based on the power substituted. The average amount of carbon needed to produce 1 kWh, is used to calculate how much CO_2 is saved by replacing it with 1 carbon-neutral kWh. The amount of CO_2 in a purchased kWh, changes based on the area that the kWh is purchased. For Central Europe, this average is set to 311kgCO_2/kWh[46], and for Norway, set to 17kgCO_2/kWh[28]. Since the CO_2-emission of this study is set equal to zero, the total amount of carbon saved is given the formula:

$$\sum CO_2 - saved = Average\ kg\ CO_2\ in\ purchased\ kWh\ * \sum kWh\ produced \tag{3.1}$$

3.3 Modeling - HyOpt

HyOpt is a model that gives the possibility of simulating and calculating the optimal sizes of a given case. As mentioned in 2.6, it is made by SINTEF, and used to aid the decision-making of different energy systems, with a focus on hydrogen-based technology. The model will optimize which and at what size each of the *nodes* accomplish a given goal. In this study, the goal of the simulation is set to calculate the most cost-effective solution to the needed energy demand. In addition to this, the calculated LCOE of the project will be, and how much CO_2-emissions is saved by delivering green energy, instead of buying it from the grid.

The usage of the HyOpt model can be separated into four parts (3+1); data gathering, data modeling, optimization, plus the visualization of the results.

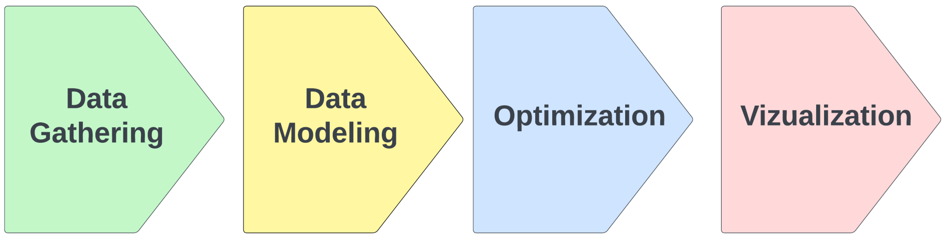

Figure 3.2: Workflow of HyOpt

The first part, data gathering, is typically gathering CSV files from web-based data or pre-selected data. This data are then either used in its initial form, or tuned to match the wanted criteria. In this case, the Windows ExCel is used, where the data easily can be viewed and changed.

The second face is modeling a SQL-database and building a case to fit the specifications. To make this database, a JSON-script is run. Here it is possible to use one of the three pre-made JSON-files, change these, or create one by scratch. The JSON-file determines the different nodes, including the different parameters. To change the values, the script can easily be changed manually, or given a file to represent multiple data. After the case values are constructed in the JSON-file, the file can simply be run with a python-script, and with that, a SQL-database is built.

The third part is the optimization, where $FICO^{TM} xpress$ [47] is used to run the HyOpt-model. This model is written in the language $FICO^{TM} Mosel$, which figures out which selection of data that gives the optimal data for the given cases. To make this possible, it is necessary to download the $FICO^{TM}xpress$ program, and obtain a license. In this study, a static academic license was used. Complimentary to this, multiple other files are run during this part, mainly python-scripts, but also some others, such as a Batch-file. This optimized data is then sent back into the SQL-database, and typically put in the selection of *res*-folders. This optimization sequence could use a long time, often multiple hours. The reason for this is the many possible solutions that are explored, where a case with many nodes and possibilities, uses a longer time. To shorten this time, it has the possibility to simplify the assumptions of data, which can influence the optimal solution. In this study, this was chosen as a preferred method, due to the limited amount of time. This was done by using the pre-made script that uses every hour of four separate weeks, to represent winter (01.11 to 01.18), spring (04.11 to 04.18), summer (07.11 to 07.18) and autumn (10.11 to 10.18). To get a more detailed optimization, running the script for every hour of the year should be considered.

The fourth and final part, is the visualization of the data. The visualization is done by running it through a database viewer. An example of this is *DB Browser for SQL* [48], or the *Bokeh Visualisation library* [49], which can be run with a Python script given. The pre-made Bokeh-script for the HyOpt-model is not much tested and comes with some errors, but makes it easier to compare the different values. In this study, both visualization methods were used. The Bokeh-script was used to get an overview, to check if the simulation ran as intended, and that the data were not far off what was expected (Some examples of the Bokeh-vizualisation, is added in the Appendix). After that, the SQL-lite DB Browser was used to go into depth and determine the results. By browsing the different calculations and results, it was possible to compare and understand the calculated values.

3.4 Cases

In this section, the cases will be presented. In this study, it was desired to understand the techno-optimal capacity of the already planned and installed projects of Utsira and Berlevåg. To do this, it was necessary to recreate the cases, and use some of the technology that did exist. With this comparison, it was also interesting to test if some of the already installed or planned projects will be economically feasible. Lastly, it is interesting to see if there are some general operating strategy that can be seen, and a conclusion of what a green self-sustainability do cost.

Figure 3.3: Locations of Utsira (U) and Berlevåg (B)

3.4.1 Case 1: Utsira - Supply 10 households

In this case, the pilot-project that was built in Utsira in 2004 to supply 10 houses with enough power was reconstructed. It was the worlds first combined windpower and hydrogen power plant, and was built with a combined partnership of Statoil ASA and Enercon GmbH. In its beginning, it consisted of two Enercon E40 wind turbines that each had a (peak) production capacity of 600kW. One produced electricity directly to the nearby grid, while the other was connected to a system that tried to better suit the demand.To stabilize the fluctuating energy coming from the renewable energy, a 5kWh flywheel was installed. Combined with this, a 100kVA master synchronous machine was installed to handle the voltage and frequency.[50]

The energy storage part of this power-plant was Hydrogen-based, where an electrolyzer with a peak load of 48 kW was installed. The Hydrogen produced was stored in a 2,400 Nm^3/ 200 bar vessel. To compress the Hydrogen, a 5 kW Hofer compressor was used. This stored energy was again extracted using a 55 kW MAN hydrogen internal combustion engine with a 10 kW IRD fuel cell. [50]

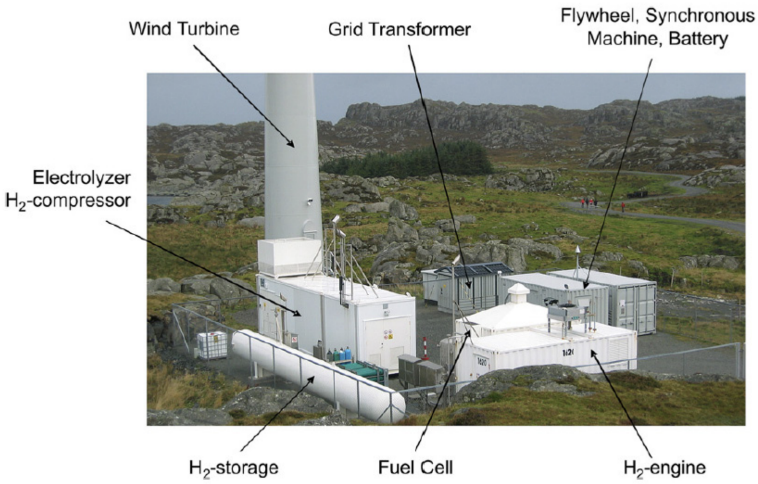

Figure 3.4: Overview of Utsira Hydrogen park [50].

This project was running continuously in 4 years. During its operational period, the project ran autonomously for more than 50% of the time. The project grew a large publicity, and won the Platts award, in New York, for *Renewable Project of the Year*. [50]

Despite a satisfied demonstration of what possibilities lies within this concept, a number of challenges were identified throughout the project. In total, the utilization-rate of the windpower revealed to be only 20%, demonstrating a need for improvement of the key technologies. The biggest improvement possibilities were thought to be in the development of a more efficient electrolyzer and an improved hydrogen-electricity conversion efficiency. Some other technical problems occurred at the fuel cell, which did include a leak of coolant fluid, damage to the voltage monitoring and error in frequent false grid failure alarms. The hydrogen engine ran effectively for three years, but had to be replaced after this, due to some technical problems. In addition to this, there was a rapid degradation of the fuel cell.[50]All this led to an uncertainty as to whether they could reliably deliver enough power to the connected houses, in times of no wind.

Therefore this case is built upon the Enercon E40 - 600kW wind-turbines, but in contrast to the real case, this built case is integrated with newer up-to-date technology. Like the real case, the model has the possibility to pitch down the turbine to a scale of 150 kW.

3.4.2 Case 2: Utsira - Supply an Island

In this case, a facility is constructed to deliver power to the whole island of Utsira. Since Utsira is located far from the mainland, several ideas are contemplated to make the island self-sufficient in energy.

The main lifeline of people and goods to be transported to and from Utsira is the ferry boat. It takes about 70 minutes to cross the sea to the mainland. An almost equally important lifeline for the island community is the 17-kilometer undersea cable that has ensured the island's power supply for decades. However, the cable is aging, has a low capacity, of about 1 MW, and with the announced plans to build a large smolt facility, the future power demand on the island is predicted to be upwards to 2 MW. To implement a new cable to meet this demand, the predicted cost is about 40 million NOK[51].

This self-sufficiency case is therefore conducted as a study if it could be a possible solution to the problem. The predictions of the future need for power at around 2 MW, to support the power of the 200 people living there, will be set as a baseline. To be more precise, the demand will fluctuate based on the demand of the season. The case will use the same turbines that is already installed on the island, Enercon E40 600kW, and use up-to-date technology of battery and hydrogen storage.

3.4.3 Case 3: Berlevåg - Ammonia Production Facility

The last case that is built, is a facility that makes the upcoming Berlevåg Ammonia production facility. It is expected that the facility will need a power of 100MW each hour, and is predicted to be built in Berlevåg by the end of 2024. The case constructed in this study is this time achieving self-sufficiency at the Ammonia Facility self-sufficient.

The location of the wind farm is modeled at the already existing wind farm of Raggovidda. The wind park consists of 15 Siemens turbines, class IEC IA. The current park has a total production capacity of 45 MW. [52] The wind park was built upon the Rakkocearro plateau, which is about 10 kilometers south of Berlevåg. It has an area of about 10 km^2 and its highest point is about 450 meter meters above sea level. The nature of the area is special in the way that it has low vegetation, consisting mainly of rocks. Despite this, the area is used by the reindeer in the summer, for grazing and as a calving ground. In the winter, the area is covered with snow and closed of to the public, due to dangerous icing on the blades of the turbines[53].

Figure 3.5: Raggovidda Wind Park [52].

The hydrogen part will be primarily based on the existing hydrogen power plant in Berlevåg. The leading company of the hydrogen power plant is Varanger Kraft. This company has a concession of a total of 95MW, split between Raggovidda (45MW) and Hamnefjell (50MW). In 2017 Varanger Kraft also won the possibility to collaborate with EU, and started the project Haelous. This project is a part of the FCH2 JU (fuel cell hydrogen joint undertaking), connected to the EU´s Horizon 2020-program. Research and development are conducted to show the potential of: energy storage of wind-power, remote energy location in rural places, small-grid potential and possibilities in use of electrolysis to balance the power-grid[54].

3.4.4 Flowchart of the Cases

As mentioned, the HyOpt model makes continuous decisions based on the given inputs. To enhance the understanding of the nodes and the connections that are evaluated, a flowchart was created. In Figure 3.6, it is possible to get an overview of the cases. Each case follows the same structure. The differences lay in the left and right ends, where the amount of wind energy available and the demand of power in each case. The decisions that are made, is fundamentally how big and how much power each component needs to be, and the amount of flow between them.

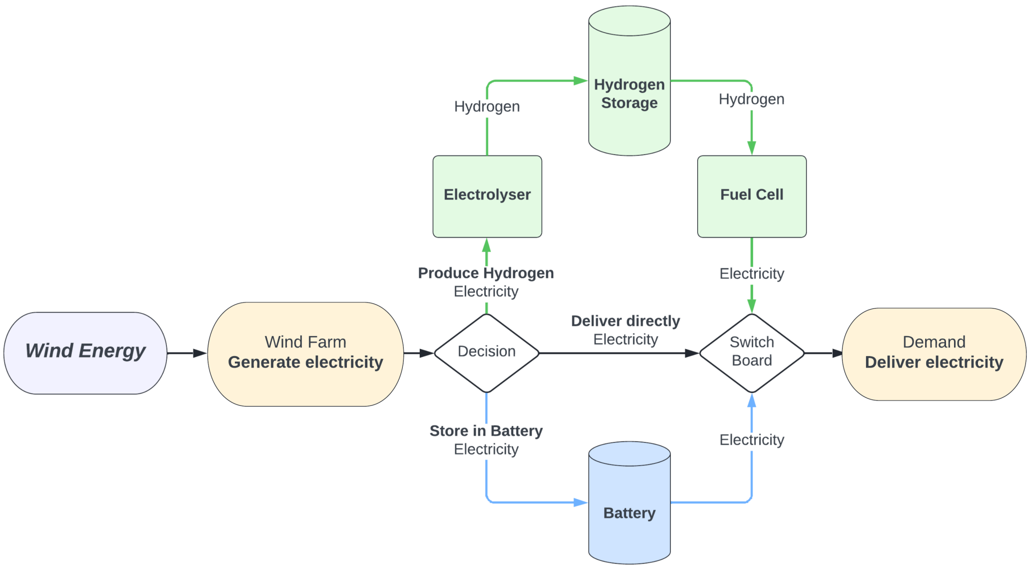

Figure 3.6: Flowchart of the cases

4. Results

This section provides a summary of the results and findings obtained from the case study. It will present the key findings from the simulations using the HyOpt model. The data are then analyzed and evaluated if they meet the criteria of the case and have been conducted in the intended way. The results of the cases are separated into three parts, presenting the Power-output and Dimensions, Costs and Powerprice, and lastly, the Emissions.

4.1 Case 1: Utsira - Supply 10 households

This section presents the results of the case study of 10 households. This case has been built as a replica of the real-life study project built and tested in 2004. The real case has been used to compare the accuracy of the values obtained through the HyOpt. Considering the technological advancements over the past 20 years, it is expected that the calculated result, with up-to-date technology values and prices, will be more efficient.

4.1.1 Power-output and Dimensions

In the table 4.1, the calculated specified dimensions necessary for the different modules are presented. As the table shows, the required capacity of the wind turbine is 150kW, which is the lowest possible value of the constraints given to the model. This means that it is only necessary with one turbine with a production of 150 kW. It is estimated to produce 185.68 MWh throughout the year, resulting in an average daily power-production of 509 kWh

A total of 61.65 MWh are directed to storage, with the majority sent to short-term storage. Approximately 49.66 MWh goes into battery-storage, while a total of almost 12 MWh goes to long-term storage, producing a total of 216 kilos of hydrogen over the year. The hydrogen is then converted back into 4.32 MWh of electricity, and used as power by the households.

Combining the capacity of the battery and the fuel cell, they have a possible total capacity of delivering 33,04 kW when there is no wind. This is almost 10 % above the peak power demand, which is 30.05 kW. Looking at the hydrogen storage, it has the possibility of storing 6.08 kilograms of hydrogen. At this capacity, the total flow is equal to 35.5 tanks. The total power capacity of one full tank is equal to 203 kWh, but gives only 122 kWh of electricity due to the losses in the fuel cell. Consequently, the 122 kWh provides a total of only 6.1 hours of average power demand. The battery storage has a total capacity of 14.91 kW, but with losses considered, a full battery gives 14.54 kWh or 45 minutes of power. Combining the two storage components, gives a total power backup of 7 hours of power.

Table 4.1: Dimensions and Yearly flow Utsira powerproduction (10 households)

Variable	Capacity	MWh_{in}	MWh_{out}	kg H_{in}	kg H_{out}
Wind Farm	150 kW	-	185.68	-	-
Batteries	14.91 kW	49.66	47.21	-	-
Electrolyzer	1.52 kW	11.99	-	-	216.01
Hydrogen Storage	6.08 kg	-	-	216.01	216.01
Fuel cell	18.13 kW	-	4.32	216.01	-

In addition to this, the chart 4.1 is built to illustrate the flow of power. In the chart, the values are presented as percentages of their corresponding capacities, to make it possible to fit all the values in the same chart. The blue line represents the battery level, while the green line represents the hydrogen level in the storage vessel. Furthermore, the black line represents the capacity factor of the wind farm, indicating how much power that has been generated. The red line shows how much power that is demanded, in relation to the wind-curve. This means, if the black line is above the red line, it is a surplus of power generated, and the energy goes to storing. Correspondingly, if the black line is below the red line, there is a power deficit, indicating that power has to be gathered from either the battery or the hydrogen. It is important to note that the lines are presented in different scales, with only the black and red lines sharing the same scale.

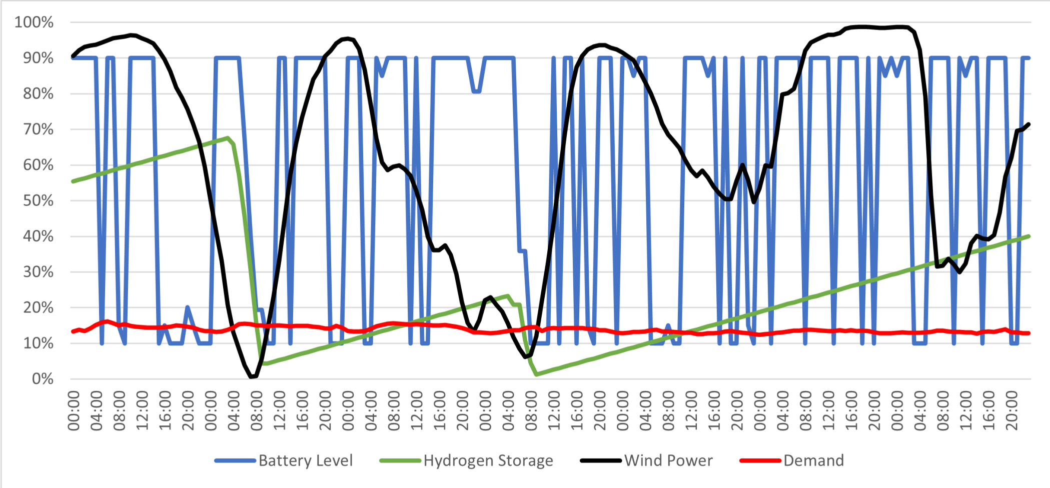

Figure 4.1: Flow of energy

The chart illustrates some of the different usages of short-term and long-term storage. The hydrogen storage serves as the primary storage medium, and are very stable. In addition, the difference between the upward and the downward slope, clearly shows the difference in the capacities of the electrolyzer and the fuel cell. Meanwhile, the battery level fluctuates greatly, where the battery is mainly used as a short-term energy leveler, in addition to a storage of power. In addition to illustrating the flow of the different components, the graph also show some of the complexity that the HyOpt has to take into consideration when making the choices. Each hourly choices affect subsequent hours, highlighting the interconnected nature of the system.

4.1.2 Costs

The table 4.2 provides a calculated cost breakdown of the Utsira power production, to provide power for 10 households over a period of 10 years. The total need of capital to initiate the project, total CAPEX, is estimated to be just above 2.5 million NOK. As mentioned previously, it is calculated to have only one turbine, which gives an investment cost of 1.875 million. This is believed to be a bit low, considering that the actual turbine has a capacity of 600 kW. This turbine does represent the largest part of the needed CAPEX, where the 1 875 000 NOK is approximately 75 % of the capital cost. The battery storage does cost a total of 134 215 NOK, equivalent to 5% of the capital cost. The hydrogen module, including electorlyzer, storage and fuel cell,is calculated to have a total cost of 504 849 NOK. This makes a total of approximately 20 % of the capital cost.

The total OPEX over the next ten years is calculated to have an NPV of 539,231 NOK. The majority of this cost, goes to the operation of the wind turbine, accounting for approximately 84% of the total OPEX. The battery has a total running cost of 10 172 NOK, and representing only 2 % of the total OPEX. The Hydrogen module, electrolyzer, storage and fuel cell, are calculated to cost a total of 74 335 NOK. This makes up the remaining 14% of the total OPEX. The overall cost of the entire project, the sum of CAPEX and OPEX, is calculated to have a net present cost just above 3 million NOK.

Table 4.2: Costs of Utsira power production (10 years - 10 households)

Variable	CAPEX	OPEX(10 years)	Total
Wind farm	1 875 000	454 725	2 329 725 NOK
Battery	134 215	10 172	144 387 NOK
electrolyzer	15 209	2 882	18 091 NOK
Hydrogen Storage	36 479	2 765	39 243 NOK
Fuel Cell	453 161	68 688	521 849 NOK
Total	2 514 064	539 231	3 053 294 NOK

In relation to the investment and running costs, the calculated needed price of the power is presented in the table below. The HyOpt model determines the price to be 2.363 NOK/kWh, to reach the economic objective of 6% discount rate. In addition to this, the utilization rate of the power produced is at 94.54 %, meaning that only 5.46% are lost during the power storing processes. In total, the power delivered to the ten houses is calculated to be 175 550 kWh annually.

Table 4.3: LCOE of Utsira powerproduction (10 households)

Total power produced yearly	175 550 kWh
Total power produced over 10 years	1 755 500 kWh
Discount rate	6 %
Utilization rate of produced power	94.54 %
Generated Powerprice (LCOE)	2.363 NOK/kWh

4.1.3 Emissions

In the table 4.4 below, an overview of the environmental aspect of the project is presented, considering both the Norwegian Average and the Central European average. The HyOpt-model estimates the total annually saved CO_2 emissions of the project to be 2 984 kilograms, with the use of the Norwegian average. Here are 2 108 kilos saved by producing green energy by the wind turbine, about 70 % of the total reduction. Another 876 kilograms are saved by storing the energy, instead of purchasing it from the grid. Using the European average, the total emissions saved annually are calculated to be 54 595 kilograms.

Table 4.4: Carbon emmisions of Utsira powerproduction (10 households)

	Norway	Europe
Saved CO_2-emmisions by Wind Park	2 108 kg	38 570 kg
Saved CO_2-emmisions by Energy storage	876 kg	16 025 kg
Total emissions saved Annualy	2 984 kilos	54 595 kilos

4.2 Case 2: Utsira - Supply an Island

The following section presents the power output and dimensions of the different modules in the Utsira power production project for the entire island. Additionally, the costs of the project are presented and lastly the total emissions. This case are similar to an up-scaled version of Case 1.

4.2.1 Power-output and Dimensions

The table 4.5 below shows the suggested capacities and yearly flow of the key modules. According to the HyOpt model, a wind farm with a capacity of 4.2 MW is recommended. This equals to a total of 7 turbines at the given capacity of 600kW each. The total annual power production from the wind farm is estimated to be nearly 22 MWh. A total of 721.4 MW of it will go towards short-term battery storing, and 6 787.3 MW of it will go towards long-term storing of Hydrogen.

Combining the capacity of the battery and the fuel cell, it is possible to see that the project has a total capacity of 2.722 MW, when there is no wind and no power generated from the wind turbines. This is below the peak value of power, needed throughout the year, but from the data it indicates that this does not correspond to times of no wind. In terms of hydrogen storage, a capacity of 2,787 kilograms of compressed hydrogen is required, with an annual flow of 122,217 kilograms. This equals to approximately 43.85 tanks of the size that is chosen. With the power potential of 1 kilo hydrogen, a full tank can give a total power of 92 890 kWh. Due to losses through the fuel cell, this results to only 55 734 kWh of electricity. Consequently, the power backup from the hydrogen storage is equal to 27.9 hours, in times where there are no power generated. The battery storage provides a relatively limited power backup of approximately 12 minutes. However, looking at the flow of the power, it seems that it is used frequently. The total flow throughout the battery, equal the capacity of 1785 battery packs of the same size.

Analyzing the combined power delivery and storage capacities raises the question of whether a larger storage capacity should be installed. Having a backup of only a little over one day of power, might be considered low, especially during periods of little or no wind. However, increasing the total capacity would also raise the overall project cost.

Table 4.5: Dimensions and Yearly flow Utsira powerproduction (Whole island)

Variable	Capasity	MWh_{in}	MWh_{out}	kg H_{in}	kg H_{out}
Wind Farm	4.2 MW	-	21 934	-	-
Batteries	0.404 MW	721.4	685.8	-	-
Electrolyzer	1.271 MW	6 787.4	-	-	122 217
Hydrogen Storage	2787 kg	-	-	122 217	122 217
Fuel cell	2.318 MW	-	2 443	122 217	-

In the Figure 4.2 below, the corresponding flow of one week in the spring is shown for this case. At this time, the line indicating the hydrogen storage, is much more rounded, indicating a smaller difference between the fuel cell and the electrolyzer. The battery level experiences less fluctuation but still alternates rapidly between full and empty. One thing to notice is that the battery is sometimes used, despite the fact that a power surplus is being generated. Furthermore, the demand is higher this time, compared to the capacity of the wind farm. One last thing to notice, is that the capacity of the wind farm only hits zero once during the 168 hours shown.

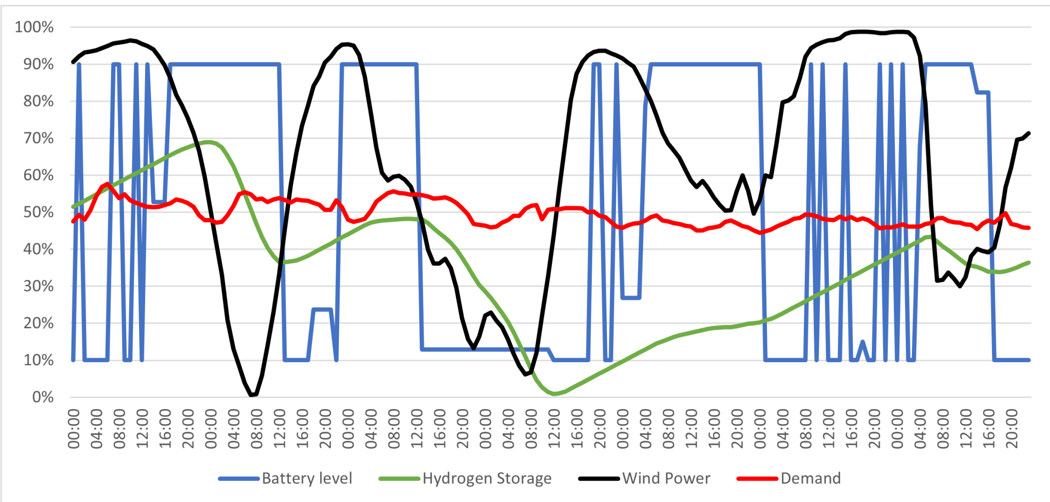

Figure 4.2: An example of one week of flow of energy.

4.2.2 Costs

In the table 4.6 below, is the calculation of CAPEX and OPEX for the given project. The total initial capital required to start the project is estimated to be 143.5 million NOK. As mentioned earlier, the HyOpt model suggests the construction of seven wind turbines, with an estimated investment cost of 52.5 million NOK. Despite this, this is not the largest part of the investment cost, which is the cost of the fuel cell. It has an estimated total investment cost of almost 58 million NOK. The part with the lowest cost, are the batteries, which may be due to the relatively small need for short-term storage.

The total capital needed throughout the 10-year period, is calculated to be a net present cost of 25 466 000 NOK. Among the operational expenditures, the wind turbines have the highest cost at 12.7 million NOK over the 10 years, averaging 1.27 million NOK per year. The lowest cost is again the batteries, with a total of 270 000 NOK. The total cost of the hydrogen system, including the electrolyzer, storage, and fuel cells, sums up to just below 12.5 million NOK. The main part of which is due to the cost of the fuel cell, making up about 70 % of the total running cost of the hydrogen storage.

The total cost of the whole project is calculated to be 168 982 000 NOK. This sums up the total CAPEX and 10 years OPEX of each of the different modules.

Table 4.6: Costs of Utsira powerproduction (10 years - Whole island)

Variable	CAPEX	OPEX(10 years)	Total
Wind farm	52 500 000	12 732 000	65 232 000 NOK
Battery	3 633 000	275 000	3 908 000 NOK
electrolyzer	12 708 000	2 407 000	15 115 000 NOK
Hydrogen Storage	16 722 000	1 267 000	17 989 000 NOK
Fuel Cell	57 951 000	8 784 000	66 735 000 NOK
Total	143 515 000	25 466 000	168 982 000 NOK

In relation to the calculation of the costs, the HyOpt model also calculates the needed price of the power. The model suggests a power price of 1.308 NOK/kWh to meet the given parameters. Furthermore, the utilization rate represents the proportion of power generated by the wind turbines that is delivered to the end user. In this case, it is at 80 % , meaning that 20 % is lost. This due to losses throughout the storage systems. In total, 17 554 903 kWh are delivered to power the island.

Table 4.7: LCOE of Utsira power-production (Whole island)

Total power produced yearly	17 554 903 kWh
Total power produced over 10 years	175 549 030 kWh
Discount rate	6 %
Utilization rate of produced power	80.06 %
Generated Powerprice (LCOE)	1.308 NOK/kWh

4.2.3 Emissions

In this part, the environmental aspect of the Hyopt calculations is presented. As mentioned, the HyOpt model allows to calculate a fully self-sustained power system. Furthermore, the model calculates the amount of CO_2 emissions that can be saved by not relying on the existing grid for power supply. The table below presents the calculated values. To this it is chosen to summarize and separate it into how much power comes from the wind park, and how much that is due to energy that is stored and then used. In this case 82 % is saved by power directly delivered by the windpark, and the rest is delivered through storage.

Table 4.8: Carbon emmisions of Utsira powerproduction

	Norway	Europe
Saved CO_2-emmisions by Wind Park	245.24 tons	4 486.37 tons
Saved CO_2-emmisions by Energy storage	53.20 tons	973.21 tons
Total emissions saved Annualy	298.43 tons	5 459.57 tons

4.3 Case 3: Berlevåg - Production Facility

In this section, the results of the case of Berlevåg Ammonia production facility, are presented. The total input power required for the facility is 100 MW per hour throughout the year. The calculated optimal dimensions for the different modules, as well as the total CAPEX, OPEX and emissions, are presented below.

4.3.1 Power-output and Dimensions

In the table 4.9, the calculated optimal dimensions are presented. The HyOpt-model calculates that it is necessary with a wind-park with a total capacity of 312 MW, meaning a total of 104 turbines of the type Siemens 3.0 MW. Throughout the year, this wind farm is calculated to produce a total of 1 210 561 MWh, a daily average of 3 316 MWh. This gives an average capacity rate of 44.28%.

A total of 524 540 MWh of the produced power goes to storage. The most of it, 99.6% is delivered to the long-term storage of hydrogen, and just 0.4 % through the battery storage. For the hydrogen part, a total of 9 410 163 kilos of hydrogen are produced throughout the year, which is again transformed into 188 184 MWh of electrical power, after losses in the process.

Combining the two storage methods, the battery and the fuel cell, can deliver a total of 100.02 MW if necessary in periods of no wind. This is just above the needed power of 100 MW. Looking into the sizes of the storage of hydrogen, it has a capacity of 190 857 kilos. At this size, it equals to 6 361 263 kWh, but due to losses through the fuel cell, only 3 816 758 kWh will be converted to electricity. The total flow of hydrogen is the size of 49.3 tanks at that given size. The battery has a storage capacity of 2.71 MWh, but delivers 2.64 MWh due to losses. Combining the two power storing methods, the total power backup of the project is 3 816 760 MWh. This equals 38.17 hours, or just above 1 and a half day.

Table 4.9: Dimensions and Yearly flow of Berlevåg powerproduction

Variable	Capasity	MWh_{in}	MWh_{out}	kg H_{in}	kg H_{out}
Wind Farm	312 MW	-	1 210 561	-	-
Batteries	2.71 MW	1 937.6	1 841.94	-	-
Electrolyzer	111.61 MW	522 602	-	-	9 410 163
Hydrogen Storage	190 857 kg	-	-	9 410 163	9 410 163
Fuel cell	97.31 MW	-	4.32	9 410 163	-

In the chart below, an example of a week in the spring is presented. This time the line of power is a bit lower, at around 33 % of the peak Wind-Farm. Additionally, the hydrogen storage is larger. This gives an effect in the graph of only small changes in percentage, despite hours of power-production-deficit. Like the other cases, the battery level is fluctuating rapidly. Looking at day 2, it seems that the battery also this time is used as a stabilizer to the small changes in the power-production during the day. This way, the total capacity of the electrolyzer can be maximized.

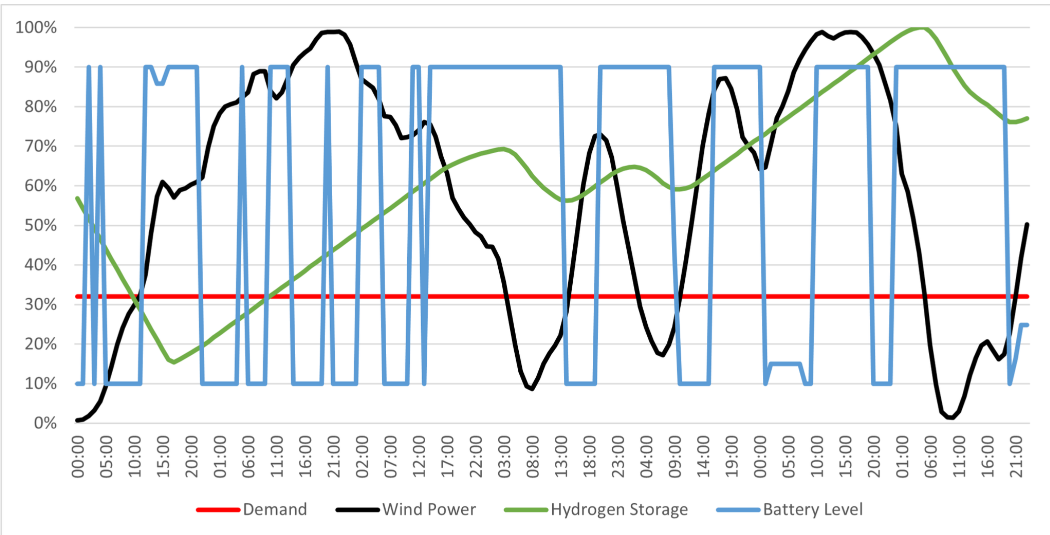

Figure 4.3: One week flow of energy

4.3.2 Costs

The table 4.10below, provides a calculated cost breakdown of the 10-year period to provide Berlevåg Ammonia with power. The need of capital to initiate the project, total CAPEX, is estimated to be 8.6 billion NOK. The Wind farm of 104 wind turbines has an estimated cost of 3.9 billion NOK, about 45 % of the total CAPEX. The short-term storage of power, the battery, has a total cost of 24.4 millions, only 0.3 % of the total. The hydrogen part, the electrolyzer, storage and fuel cell, has a total investment cost of 4.7 billions, 54.7 % of the total investment cost.

The total capital needed to run the project through the next ten years, is calculated to be at a total of 1 615 million NOK. The highest cost comes from running the wind turbines, which make up about 59 % of the total OPEX. The battery storage is the least expensive part, where it makes up only 0.1% of the total running costs. The hydrogen costs, have a total OPEX of 667 millions over the 10 years. This makes up about 41 % of the total running costs.

To build and run the project over the next ten years, is calculated a total cost of 10 233 million NOK.

Table 4.10: Costs of Berlevåg powerproduction (10 years)

Variable	CAPEX	OPEX(10 years)	Total
Wind farm	3 900 000 000	945 827 434	4 845.83 MNOK
Battery	24 385 000	1 848 110	26.23 MNOK
electrolyzer	1 116 125 951	211 470 862	1 327.59 MNOK
Hydrogen Storage	1 145 139 228	86 787 187	1 231.93 MNOK
Fuel Cell	2 432 863 494	368 761 063	2 801.62 MNOK
Total	8 618.51 MNOK	1 614.69 MNOK	10 233.21 MNOK

In combination to this, the calculated price of power (LCOE) is presented in the table 4.11below. The HyOpt-model determines that a price of 1.587 NOK/kWh will meet the given criteria. In addition to this, the utilization rate of the power produced by the the wind farm, is calculated to be 72.36 %. This gives a total of 27.64 % of losses due to storage. In total, the production project has an annually calculated power delivery of 876 000 MWh, 100 MW each hour throughout the year.

Table 4.11: LCOE of Berlevåg powerproduction

Total power delivered yearly	876 000 000 kWh
Total power delivered over 10 years	8 760 000 000 kWh
Discount rate	6 %
Utilization rate of produced power	72.36 %
Generated Powerprice (LCOE)	1.587 NOK/kWh

4.3.3 Emissions

In table 4.12, the environmental impact of the project is presented, considering both the Norwegian average and the Central European average. The HyOpt-model calculates that the total annually saved CO_2 emissions of this project is 14 892 000 tons, using the Norwegian average. In this, 11 662 364 tons are saved by delivering green energy directly from the wind turbines, about 78 % of the total. 3 229 636 tons are saved by storing the energy, instead of buying it from the grid. By the European average, the total saved annual CO_2 emissions saved, sums up to 272 436 000 tons of CO2 emissions annually.

Table 4.12: Carbon emissions of Berlevåg powerproduction

	Norway	Europe
Saved CO_2-emissions by Wind Park	11 662 tons	213 353 tons
Saved CO_2-emissions by Energy storage	3 230 tons	59 083 tons
Total emissions saved Annually	14 892 tons	272 436 tons

5. Discussion

In this chapter, the results of the study will be discussed. The different cases will be compared, evaluated both towards each other and toward the real-life cases. Secondly, the Limitations and some Influential Factors will be assessed and judged upon their impact on the study. It will also present some possible limitations and errors that have occurred, combined with thoughts about HyOpt. The purpose is to discuss some of the changes that can be done, so that future research can be improved.

5.1 Comparison

In this section, some of the key takeaways of each case will be explored, compared and discussed. Firstly some of the technical aspects, secondly the costs, and lastly the environmental impact.

5.1.1 The Powerdimensions and Costs

When comparing different cases, it is important to have comparable metrics that are possible to analyze against each other. One interesting comparison, is the level of power storage chosen in the different cases. In the table 5.1 the different values of storage are presented for each case. In addition, the distribution of the power stored is calculated as a percentage of the battery storage capacity in correlation to the hydrogen storage (BS/HS). Lastly, power-capasity of delivering power for the battery and hydrogen power, is compared with each other. The battery capacity of delivering power (BC_D) is shown as a percentage of the hydrogen capacity of delivering power(HC_D).

Table 5.1: Comparison of power backup and distribution

Case	Power Backup	BS/HS	BC_D/HC_D
CASE 1	7 hours	12.3%	82.2%
CASE 2	28 hours	0.72%	17,43%
CASE 3	38 hours	0.07%	2,78%

The table first indicates that a small-scale project requires less power storage compared to a large-scale project This is believed to be caused by three main reasons. The first is that the peak power of the wind farm, is much larger than the average demand. Looking at 4.1, it is clear that the peak power output is well above the demand line. The reason for this mainly lies in the commands given to the model. In Case 1, the wind farm has to be in a factor of 150 kW, but since the model chooses the lowest value possible, this indicates that the turbine installed is too big, and could potentially be smaller. Secondly, the selected locations for the cases experience consistent high wind speeds, reducing the need for extensive power storage. However, the case located in Raggovidda, has less wind compared to Utsira, giving a need for a larger wind farm and greater power backup. Third, the cost aspect of the cases, indicates that it is more cost-effective to invest in a larger wind farm rather than increased storage capacity.

When comparing the size of the battery and the hydrogen module, notable differences can be observed. Examining the cases, higher demand of power is linked to a smaller percentage of battery storage relative to hydrogen storage. In Case 1, supplying the 10 households, the size of the battery storage is 12.3% of the size of the hydrogen storage. This substantially changes as the demand increases, where Case 3, supplying the ammonia production, only has 0.07 % of the hydrogen storage. Correspondingly, the same trend is indicated in the capacity of delivering power, where the battery capacity is almost the size of the fuel cell in Case 1, but only 2.78 % in the large Case 3.

Furthermore, analyzing the different flow charts, reveal some correlations. In all cases, the batteries are used as a short-term power stabilizer, rather than a long-term storage of power. Looking at the chart, this is due to the need to maximize the electrolyzer's capacity, by operating at a high level over an extended period, resulting in surplus power being utilized for hydrogen production. But since the power generation fluctuates, the battery is used as a stabilizer to give more constant power. Additionally, it is more important to be able to extract the power from hydrogen in a short time, than storing power in hydrogen rapidly. Looking at all cases, the capacity of the fuel cell is greater than the capacity of the electrolyzer. This show that storing of power can happen over longer periods, but when the power is needed, it is needed quickly.

5.1.2 Levelized Cost of Energy and Economical Feasibility

When comparing the cases, the grade of economic feasibility is important. In order to determine if the cases could realistically be implemented, they need to generate income. The primary source of income for these cases would be the price of the power delivered (LCOE). The calculated LCOE values for each case are presented in Table 5.2.

Table 5.2: Levelized Cost of Energy

Case	LCOE
Case 1: Utsira - 10 households	2.363 NOK/kWh
Case 2: Utsira - Whole Island	1.308 NOK/kWh
Case 3: Berlevåg Ammonia production	1.587 NOK/kWh

To understand if these prices are realistic and possible, they must be compared to the market in which they would compete. Each case is developed based on a specific power demand. This means that if the suggested constructed power-plants of this study are not built, the consumer of the power need to look elsewhere for this power, such as the local grid. Therefore, the level of economic viability is determined by comparing the calculated prices to the historical prices of the given location. Since Case 1 and 2 are located within a different price area than Case 3, they are compared to a different market price.

Firstly, in the illustration 5.1, the LCOE of Case 1 and Case 2 is compared to the historical prices of NO2. Looking at the chart, it is clear that Case 1 would be economical in 3 of the 40 last months. All of which was in the year of 2022, a year with significant price fluctuations. Comparing it to the beginning of 2023, the LCOE of Case 1 is about 1NOK higher than the trend of 2023. This indicates that the price of power of Case 1 is too high, and would realistically be challenging to achieve in the given market. When comparing the LCOE of Case 2, the situation is somewhat different. Looking at the chart, the LCOE of this project is similar to or lower than the price for 17 of the last months. This indicates that the price needed is competitive with the existing market, although it has been a small margin higher than the trend of 2023.

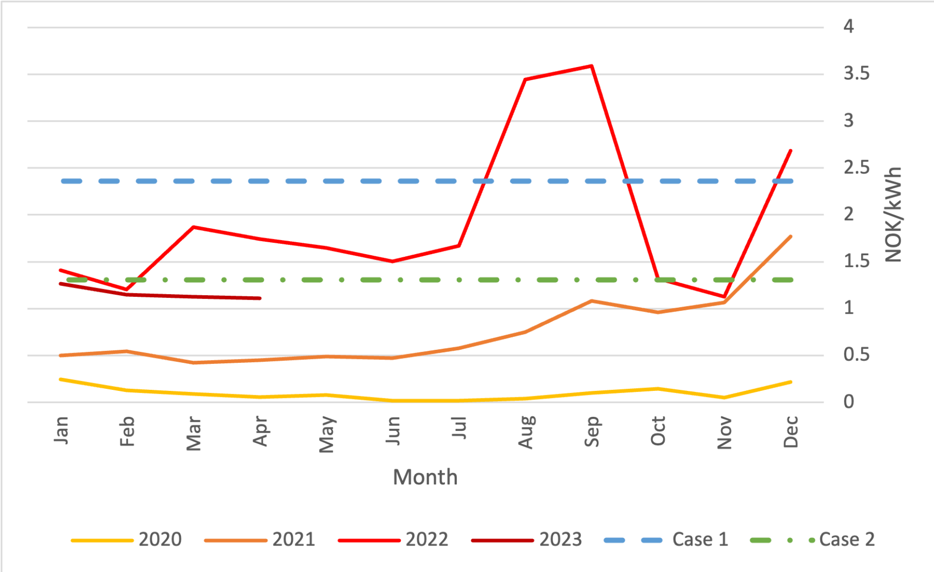

Figure 5.1: Historical prices of NO2 compared to the LCOE of Case 1 and Case 2

Something to notice when looking at the chart 5.1, is that the price of power has increased substantially over the past few years. The average price of 2022 is nearly 20 times higher, than what it was in 2020. However, the price seems to have stabilized slightly above 1 NOK/kWh.

In the Case of Berlevåg, the situation is significantly different. From the chart 5.2, it is quite clear that the LCOE of Case 3 is substantially higher than the historical market price. Even though the price of power has increased, the difference is still quite significant, where the LCOE of April 2023 was 4 times higher than the market price. This indicates that the price of power of this installation will not be able to compete. Currently, the price-trend is not the same as observed in NO4. Looking at the trend, the prices of 2023 are not far from what it was in 2020. This is probably due to the fact that the market of NO2 is not as well linked to other areas experiencing power deficits.

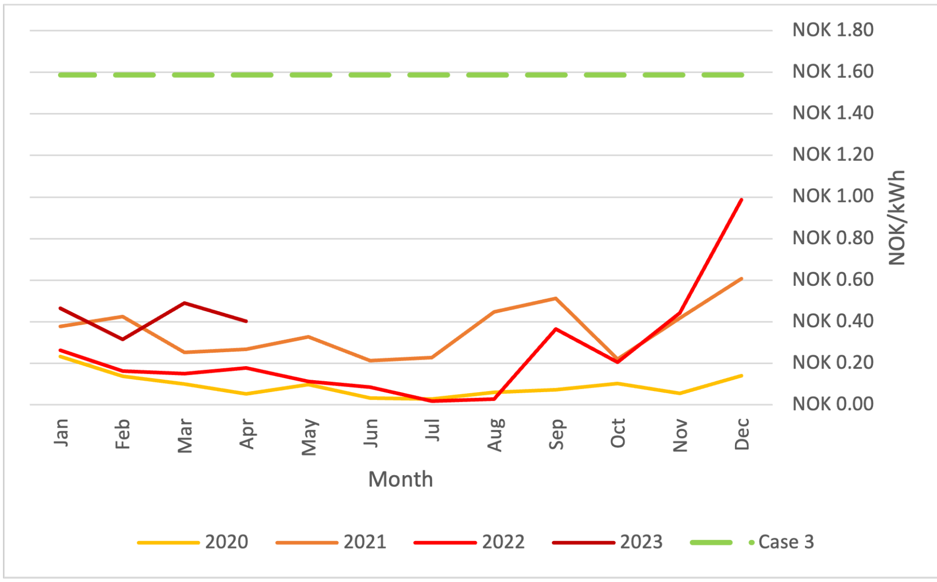

Figure 5.2: Historical prices of NO4 compared to the LCOE of Case 3

5.1.3 Environmental Impact

Since this is a study of self-sufficiency, all of the cases ends up with a total net positive carbon emissions saved. This is due to how the model calculates emissions, given the average level of carbon in the purchased power. Consequently, it is not surprising that all the cases show substantial carbon savings, where the plant producing the most energy, did save the most carbon emissions.

Table 5.3: Comparison of CO_2-emission saved annually

Case	**Norway**	**Europe**
CASE 1: Utsira - 10 households	2.984 tons	**54.595 tons**
CASE 2: Utsira - Whole island	298.43 tons	**5 459.57 tons**
CASE 3: Berlevåg Ammonia production	**14 892 tons**	272 436 tons

However, when considering the geographical locations of the power plants, the reality could be different. Case 1 and 2 are located within NO2, where their power-mix are directly linked to the Central Europe. Consequently, the European average calculation are considered to provide the most accurate values for these cases. On the other hand, looking at Case 3, it is located at a place with almost all its power coming from Norwegian energy producers. This means that in Case 3, the values of Norway are the most reliable and relevant. Considering this, Case 1 saves the least and Case 3 still does save the most CO_2-emissions, with almost 15 000 tons, and equals 0.03% of the annual total emissions in Norway [55]. Case 2 saves about one third of Case 3. However, the difference is quite surprising, considering that Case 3 generates approximately 50 times more power than Case 2. This implies that placing the green power-plant in the southern region of Norway, makes it possible to save substantially more CO_2-emissions for each kWh produced, compared to placing it in the northern region of Norway.

In addition, it is possible to give these emissions an economic value, based on the Norwegian tax on emissions. As mentioned, the emission of one ton of CO_2, costs 761 NOK. For the case 1, this results in an annual total of 41 547 NOK, for case 2, this equals 4 154 733 NOK, and for the Case 3, this results in 11 332 812 NOK. The results cannot be directly implemented in the economical calculations, but is interesting to acknowledge.

5.1.4 Comparison of the Calculated and the Real Values

As mentioned in chapter 3.4, two of these cases are a reconstruction of real cases, that has been or will be implemented. Therefore, it was interesting to compare the results of this study and investigate if the values correspond. This comparison was also done to check the reliability of the model and the results given.

Some of the key takeaways from the comparison of Case 1, Utsira - 10 households, and the pilot-project that was built in Utsira, were the dimensions of the wind turbine, battery and the fuel cell. The calculated necessary size of the wind turbine was 150 kw, which equals the capacity of the turbine used in the project built in 2004. This is a positive result. One could argue that this value could have been different, because of the increased efficiency of the components over the years. Due to the limitations set for the model, this was not possible and was not investigated further. Comparing the scale of the battery, the model decided to implement a capacity (14.91kW) that was three times the size of the real-life project (5kW). The reason for this could be that the batteries implemented in this study have a lower cost-to-kW ratio than the real-life case, making it more cost-effective to implement a greater battery. Despite this, the fuel cell also had a higher capacity, 18.13.kW compared to 10 kW. When combining the effect of the battery and the fuel cell, it could indicate that the demand of power is greater in this study, than what was in the real-life case. Despite this, the results of this study are notably similar to the selected capacities of the real-case.

The comparison regarding Case 3 - Berlevåg Ammonia facility, was how the facility is going to be supported by enough power. As of 2023, a substantial amount of the power generated to the nearby grid, comes from Raggovidda Wind Park and Hamnefjell. It has a total capacity of 95 MW, substantially lower than the calculated needed capacity of 312 MW. Regarding this, it is planned to increase the Raggovidda Wind Park. Firstly, implementing 12 new turbines, adding a capacity of 48 MW, and at a later stage adding an additional 103 MW. This gives a total of capacity of 200MW to the Raggovidda Wind Park. Despite this, the calculated need of capacity is still greater than this. With this in mind, the calculated demand of power for Berlevåg Ammonia facility, could be higher than the real-life values.

5.2 Assumptions and Influential Factors

Throughout this study there have been made assumptions regarding the values for the model. Some of these assumptions and choices are discussed in this section.

5.2.1 Technical Values and Choices

Many of the technical assumptions and choices are based on other studies. All of these values are critical and do make an impact on the final result. Therefore it will be necessary to discuss what could have been different. With this it is also critical to mention that a degradation of the different components is necessary to remember, where the capacity may change through out the 10 year period.

Wind turbines

The selection of wind turbines are based on the ones already installed. One advantage of this approach, is the possibility to use some of the already installed turbines, giving a reduced investment cost. However, due to degradation, the operating costs may be higher since they are already a few years old. One negative aspect of this, is that an another turbine would have been more suitable for these cases. One could argue that it should be possible to implement a choice of multiple wind turbines, and let HyOpt, or another optimization program, choose the best turbine for the given problem.

One other aspect regarding the turbines, is that the input capacity factor may be wrong. In the case of Raggovidda, the turbine efficiency might be higher in reality than what is proposed by Renewable Ninja. As a report stated, Raggovidda was a leading wind farm regarding efficiency and operating hours[56]. Taking this into consideration, it may not be necessary with that many turbines to generate the desired amount of power.

One third important aspect, is that the wind turbine sometimes consumes power. In this case study, the wind turbines are assumed to use no power, which is not the case in reality. When there is little to no wind, the turbines do not produce any power. But to start a turbine that is not rotating, takes power, and therefore it sometimes uses power to keep the turbine rotating slowly. This is done because it takes less power to keep it running slowly, than starting it from a standstill position. How much this power is, varies by the type of turbine. This should therefore be taken into consideration when making a more reliable model.

Batteries

The values assumed for the batteries, could be quite different in reality. When selecting the battery, it is necessary to know how long the power is going to be stored. A battery with a capacity of 8 hours, is cheaper per kWh than a battery with a capacity of 2 hours. However, to assure an 8 hour backup is more costly per hour, than a 2 hour backup. Furthermore, a battery that will be used with such high cycle use that is shown in the cases, may lead to a rapid degradation for some types of batteries. Therefore, it is crucial to incorporate these aspects when considering battery options in the calculations.

Additionally, the lithium-ion battery was chosen as the best fit, there could be other options that are more suitable for the cases. As mentioned, there are multiple ways of storing power in short-term. One possibility is to use something else than the conventional chemical batteries, such as a mechanical battery, for example, the flywheel that is used in the real case of Utsira.

Electolyzer

The PEM electrolyzers were selected as the best option when choosing an electrolyzer. This was due to the fact that this is the preferred method in the real case. However, other options should be taken into consideration. One of the reasons being that PEM typically has a higher capital cost. This is due to the expensive materials used, such as platinum and iridium. Therefore it would be interesting to explore what the outcome would be if it other methods of electrolysis was implemented.

Hydrogen Storage

Although hydrogen compression is the preferred method in this study, it would have been interesting to investigate other storage methods. The use of compressed hydrogen was chosen because it is already utilized in one of the real cases. Exploring alternative storage methods and their effect on the model, would be interesting, especially the use of liquid hydrogen. This could have been a better match if area is a limitation.

Fuel cells

Selecting the lifetime of fuel cells in this simulation is more complex. Like any other technical component, regular maintenance is essential. Looking at the reports from Utsira, the fuel cell was one of the components with the most problems. Some of which was mechanical and other was due to software. Surprisingly, rapid degradation was observed even when the fuel cells were idle.

5.2.2 Technical Limitations

In addition to the selected parts, some aspects are not taken into account in this study, but could have an impact.

Transport

One crucial part that is not included in this study, is the aspects of transportation. In this case, it was not included since it was unclear how big or long the cables should be. However, if these cases were to be implemented, transportation aspects should be thoroughly examined, including potential losses and costs. This is crucial, and could influence the other components as well.

Starting time

One aspect not implemented in the model, is the starting time of different components. Each component requires a certain amount of time to initiate its operations. While this does not need to be significant, it can still impact the outcome of the results to some degree.

Area

The study does not account for limitations in terms of available space. In real, this may be the case, affecting the choices made throughout the study. This could lead to a need of more area-efficient components.

Degradation and risk

In this study, the level of degradation is not directly implemented. Unlike reality, the components used in this study have not been given a level of degradation. Some components have been given some values to indicate their lifetime, but not a selected value that will influence their efficiency during the running time of the cases. This should be taken into consideration if possible. Additionally, the importance of risk involved in the usage of hydrogen is necessary to remember. High levels of safety and fail-safe mechanisms are crucial when selecting components or maintenance procedures, as hydrogen is a highly flammable gas that can lead to fires or, at worst, explosions.

Weather change

The weather and wind input, will change during the next years. The cases are based on the historical wind-speed of the given location during the whole year. With the history and the environmental change in mind, the result will vary somewhat year to year. Hence, to compensate for this, it is possible to use«Typical Meteorological Data »to create a baseline.

5.2.3 Economical Values and Choices

When selecting the different economical values for this study, there were set assumptions and selected limitations. In this part, some of them are discussed, due to their possible impact on the result.

Costs of components

Due to inflation, the prices of electronics may be higher than what was calculated in this study. In the last year, inflation has increased, increasing overall prices. This makes it possible that selected values are lower than reality. On the other hand, it is possible that technological improvements over the years have made it cheaper and more efficient to make some of the components. This makes it possible for some of the selected values to be higher than the reality over time.

Valuta calculations

Currency exchange rates play a significant role in determining the value of different components. If the Norwegian Krone weakens against the Euro, it implies that the purchasing power of the NOK has decreased compared to the Euro. Consequently, when converting the costs from Euros to NOK, the amounts in NOK could be higher than initially estimated.

Marginal cost

One aspect of HyOpt, is that it does not consider the marginal cost. For example, the cost of building ten turbines, is often less than ten times the cost of building just one. The cost of each turbine would decrease, as the cost of such planning is not that different. Therefore it is less appropriate to only implement a linear CAPEX to NOK/kW, when this typically is not the case in reality. Given that aspect, this could be quite a substantial amount when increasing the number and size of the project.

Change in energy consumption demand

One other factor that may change, is the required power. Historical data indicate a yearly increase in power demand. Relevant in the case of Utsira, where energy consumption has risen, and is expected to increase further in the next years. Therefore it is interesting to look at what can be done to meet the rising demand.

The possibility of selling power to the grid

In this project, it has not been possible to sell some of the surplus energy to the grid. Making this possible, would increase the value of power storage, as it opens up the possibility of selling the power and implementing the opportunity of economic arbitrage.

The possibility of selling the hydrogen

In addition to selling power, the potential for selling hydrogen should be considered. Although not implemented in this case, it is possible to implement this into the model. This aspect is particularly relevant in case 3, where power delivered is used to produce ammonia. Since the production of ammonia first involves producing hydrogen, it would be more efficient to sell the hydrogen directly.

Discount rate and change of WACC

The economic aspects rely on a realistic discount rate. In this study, it is chosen a yearly discount rate of 6 percent. This includes a 4 percent risk-free rate and a 2 percent expected inflation. However, considering the last few years, the discount rate could change. The inflation has risen, potentially making the 4 percent a relatively low value. As a result of this, the risk-free rate would increase as well, as the cost of capital would probably increase.

5.2.4 Environmental Values and Factors

This section discusses some of the values, factors and limitations connected to the environmental aspects. With the increasing importance of environmental impact in industries, the values in this calculation may change in the years to come.

Environmental impact

The calculations estimates the amount of emissions saved based on electricity usage, but they do not account for the emissions generated during the production of the components or operation. Additionally, the model does not take into consideration the impact on the local environment where the installation is being implemented. Further research is necessary to obtain a more realistic picture of these factors.

Cost of emissions

The present-day value was selected to calculate the cost of releasing emissions into the atmosphere. However, this could increase during the next years, when it is expected that the cost of emissions will increase, as a result to prevent a global environmental crisis.

The value of going green - Green Premiums

One aspect which is considered when examining the economic feasibility of the cases, is the possibility that the value of green power is greater than the regular power. With the increased popularity of going green, it has already been shown that some are willing to pay extra for a more environmentally friendly alternative. This option of extra cost is sometimes referred to as a «A Green Premium »[57]. This indicates that it could be possible to sell the power, despite the fact that the price of power from the grid is lower.

Governmental and private support

There are several factors that can inspire individuals and businesses to invest in green projects. One such motivating factor is the potential for support from the government or other institutions. It is possible to receive financial assistance or tax incentives to encourage investment in sustainable initiatives. These forms of support can significantly reduce the financial cost associated with implementing green projects and make them more attractive to investors.

Moreover, the growing interest in environmental sustainability has led to an increased attention from private investors. Many individuals and organizations are now actively seeking opportunities to invest in green projects. They recognize the long-term benefits of supporting environmentally friendly initiatives, both financial and good PR benefits. This interest from private investors further increases the potential for funding and collaboration in the green energy projects.

5.3 Errors and Software Limitations

Building upon the previously established limitations, encountered errors have significantly impacted the outcomes of this study. This section discusses some of these errors and their impact on the study, based on the section 2.6.

This case study relies heavily on the correctness of the HyOpt model and its calculations. Given the numerous files running for each simulation, there is a possibility that the model may not operate as intended. As mentioned in chapter 2.6, there could be different reasons for this.

The process of using this newly released optimization program, has given an insight of a broad spectrum of various possibilities, when it comes to calculating complex energy estimations. It provides a good oversight of the key components, where the possibilities are seemingly endless.

However, the usability of the HyOpt model has been more complex than initially anticipated. Throughout this study process, errors and setbacks have occurred, proving both time-consuming and somewhat frustrating. While some errors have been resolved and others worked around, certain issues remain unresolved. As mentioned in chapter 2.6 , there could be multiple reasons for these errors. Some of the easy ones, regarding interoperability, was that the data gathering file, gathering data from RenewbleNinja, did not work as intended. The calculations of the CAP_FACTOR did not work. This was easily worked around, by implementing the same calculation manually in Excel after the data gathering, and making a column containing the CAP_FACTOR. This was then uploaded and used alternatively.

One of the problems considering the portability, is that the first computer used was a Macintosh. While the model worked for a considerable period, errors were encountered when attempting to run a Batch-script. This is due to the fact that these files are made for the operating files of Windows only.

Furthermore, flexibility-related problems arose when programs or library files were not in the correct version. One source of problems encountered, was fixed by running older versions of the programs and libraries, aligning with the versions used by the author of the HyOpt-model. This solved initial errors, and allowed for the first successful optimization simulation. For example, a SQLite-version lower than 2.0 was required, although the exact reason behind this requirement remains unclear. Understandably the model still has room for improvement to enhance maintainability.

Some of the key problems came as the reusability of the example-files was not as good as first believed. An example of this is apparent in the visualization part of the model. When trying to run the Bokeh file, only a part of the files works as intended. The reason for this is not clear. The assumption is that the flexibility of the visualization module is not as good as anticipated, where the case-study is not close enough to the example file of HyOpt. This means that it tries to visualize numbers that do not exist in the database created for the cases of this study.

Lastly, it is important to note the influence of the operator. As an operator of a modeling program, it is important to understand whether something is wrong or not. As an result to this, every operator will influence the results in some way.

6. Conclusion

In this section, the conclusion of the findings of this study is presented. Additionally, there are given some suggestions of the next steps towards further research.

This thesis has explored the potential utilization of green hydrogen technology to achieve power self-sufficiency in a selected location in Norway. The study focuses on assessing the technical and economic feasibility of these environmentally friendly solutions. This was done by exploring three distinct cases, with varying locations, sizes and levels of demand.

The investigated cases involved the provision of electricity to 10 households, an entire island with a population of about 200 people, and a large industrial facility. Power generation in these cases relied on wind turbines, with green hydrogen and lithium-ion batteries serving as energy storage systems to supply power during periods of little or no wind. The best solution gave a Levelized Cost of Electricity (LCOE) of 1.308 NOK/kWh, and delivered enough power to an entire island, with an average hourly demand of 2 MW. This price is expected to be able to compete against the cost of electricity from the local grid. The techno-economical optimal solutions of the other cases, determined a LCOE of 2.363 NOK/kWh in the small case, and 1.587 NOK/kWh in the industry case. These prices are considered relatively high and may not be competitive with the current market of 2023 rates offered by the nearby grid.

Furthermore, an estimation of the environmental impact of these cases was conducted, indicating a total reduction in CO_2-emissions of a total of 54.6 tons in the smallest case, 5 460 tons in the case of the island, and 14 892 tons in the case of the industrial case. The exact value of these emissions savings are influenced by the market connection of the areas and the available energy mix, as well as the volume of power being substituted.

This techno-economical optimization is done by utilizing the HyOpt modeling program. This program is made to ease the decision-making process of large-scale energy production including hydrogen. The model provided valuable insights into potential operational strategies, revealing, for instance, that a large battery system is most efficient for the small-scale case, while a large hydrogen module is most effective for the largest cases.

The conclusion of the study suggests that it is technically possible to build economically feasible green power-plants in Norway, with the usage of green hydrogen as storage combined with a battery. It is important to note that the assumptions, limitations and changes of variables, may affect the outcome of this study.

6.1 Further Work

As mentioned in chapter 5.2, the values selected in this study, may differ from reality. The selected values are based on general historical data and may deviate from the true values. To establish reliability in the results of this study, it is essential to modify the input values to align with actual values. This includes the consideration of the efficiency, cost, emissions, or the implementation of other components. It is also interesting to investigate the effect of implementing every hour of the year, when running the optimization, not only four representing weeks.

Although the model provided valuable insight, it had its limitations. The utilization of the model proved to be more complex than initially anticipated, and did not give all the answers and possibilities desired, in the time-frame that was given to the project. This was due to various encountered errors and problems, varying from interface problems to minor coding errors. In further research, it is crucial to address and fix the persisting errors, while also improving the usability of the model.

Lastly, one way of improving the reliability of results in this research, is by implementing a form of sensitivity analysis. Evaluating the probability of the proposed solution's success is crucial for project managers and investors when deciding whether to adopt the suggested approach. If just a small change would alter and impact the result substantially, the reliability of the resulting numbers would drop significantly.

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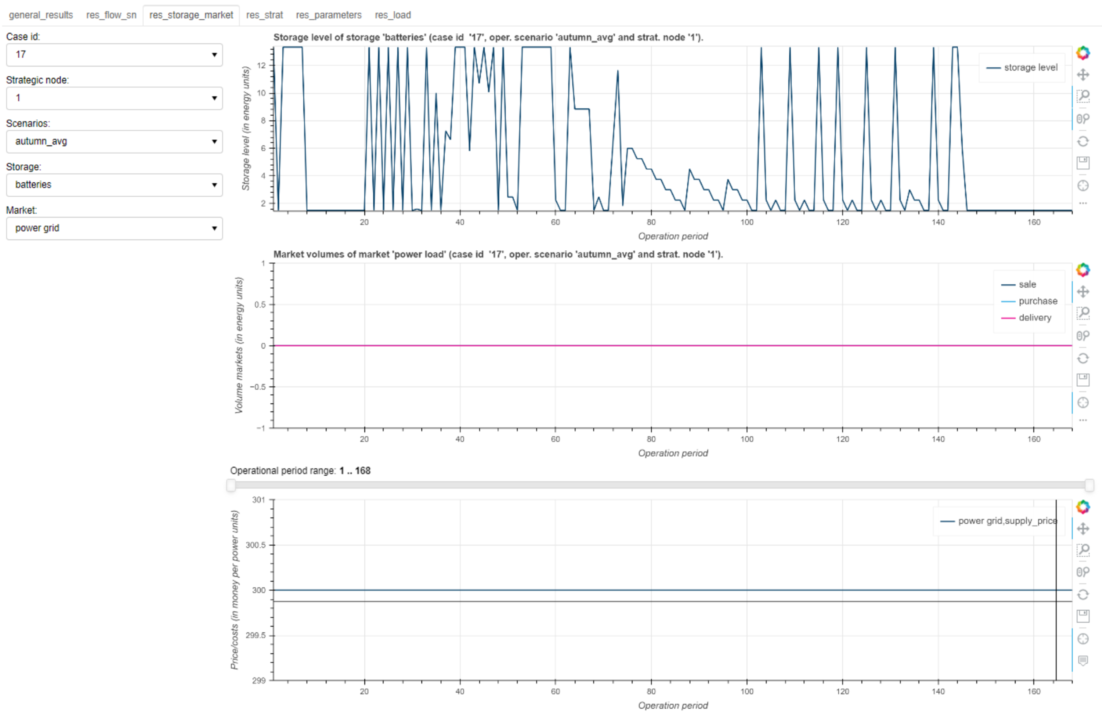
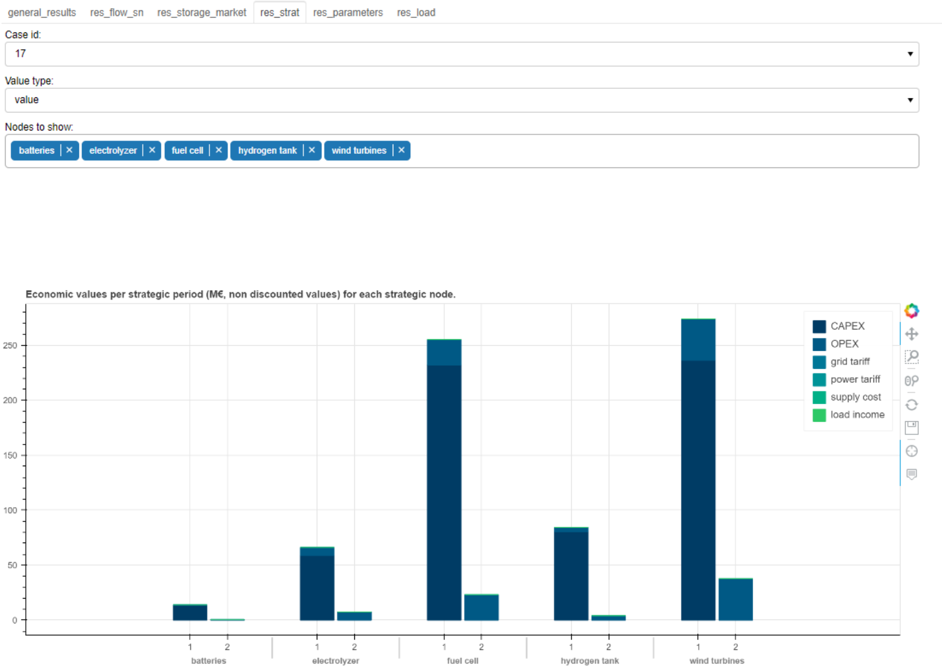
Appendices

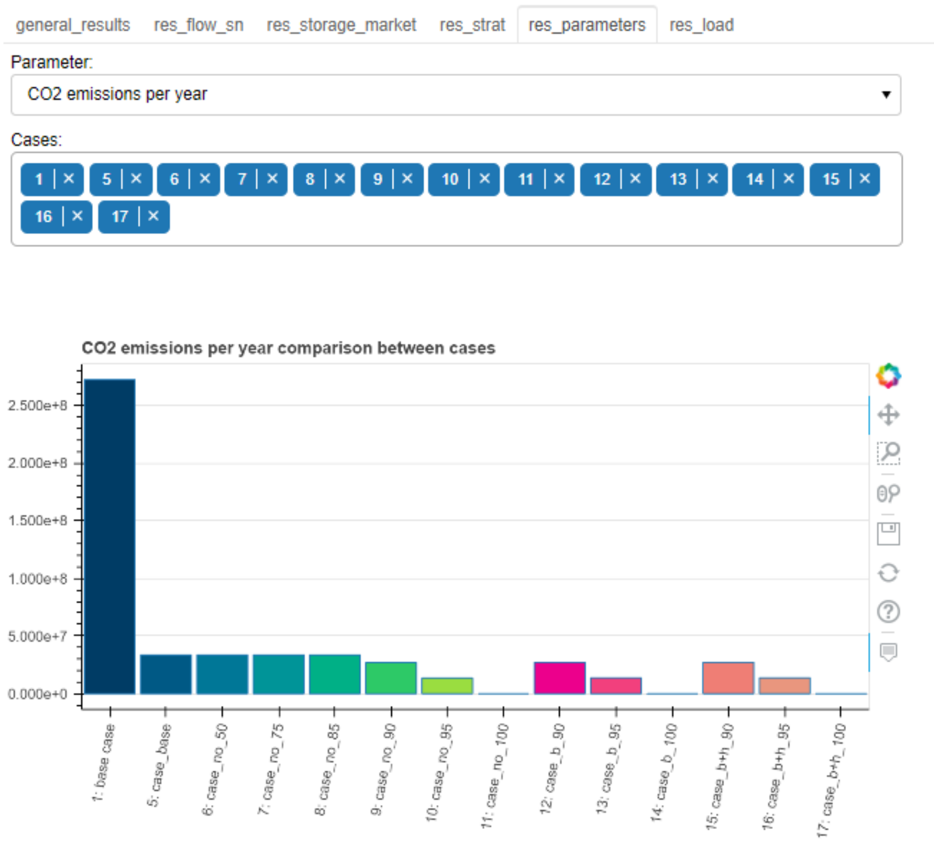
Screenshot of the Bokeh-visualisation

On top its possible to select between the six tabs that is created. The screenshot below, represent the *res_storage_market*. The left side gives the options of browsing between the cases, scenarios, storage methods and market. The graph on top show the values for the battery, the middle show the purchased power from the grid, and the last one show the price. The Visualisation is just a representation, where the values differ from the actual data used in the study.



The next page includes the screenshot of *res_strat* and *res_parameters*. The first one, the different costs is illustrated, and can be given in both discounted and not discounted values. The second one, gives the possibility of illustrating multiple cases at ones, and comparing them in different given parameters. The parameter selection of *CO2 emissions per year* and *Gen. power price*, was used most often.


general_results
res_flow_sn
res_storage_market
res_strat
res_parameters
res_load
Case id:
17
Value type:
value
Nodes to show:
batteries
electrolyzer
fuel cell
hydrogen tank
wind turbines
Economic values per strategic period (M€, non discounted values) for each strategic node.
CAPEX
OPEX
grid tariff
power tariff
supply cost
load income
250
200
150
100
50
0
batteries
electrolyzer
fuel cell
hydrogen tank
wind turbines


general_results
res_flow_sn
res_storage_market
res_strat
res_parameters
res_load
Parameter:
CO2 emissions per year
Cases:
1
5
6
7
8
9
10
11
12
13
14
15
16
17
CO2 emissions per year comparison between cases
2.500e+8
2.000e+8
1.500e+8
1.000e+8
5.000e+7
0.000e+0
1: base case
5: case_base
6: case_no_50
7: case_no_75
8: case_no_85
9: case_no_90
10: case_no_95
11: case_no_100
12: case_b_90
13: case_b_95
14: case_b_100
15: case_b+h_90
16: case_b+h_95
17: case_b+h_100

The Yaml file of Case 1

case_1_v − U.yaml:

```yaml
parameters:
  strat_per_dur:  # duration of strategic periods, in years
    - 5
    - 5
  time_unit_s: 3600  # internal time unit, in seconds
  discount_rate: 0.06  # standard interest rate in Norway
  #
  default_rel_opex: 0.02  # default OPEX, where not given; as capex/
     year

solver:
  name: cbc  # name of the solver - lower case, as used in the HyOpt
     model
  # TODO implement also the following:
  #solver_path
  #solver_options

node_data:
  power_grid:
    name: power grid
    co2_g_per_kwh: 311  # CO2 emissions, g/kWh; value for Germany for
       2020 (from EEA)

  wind_power:
    name: wind turbines
    unit_cap: 0.150      # MW  (150 kW) - rated capacity of each
       turbine [MW]
    capex_var: 1.250   # M  /MW  (1288   /kW)
    opex_var:  0.04  # M  /MW/y  (47.6   /kW/y)

  solar_pv:
    name: PV panels
    capex_var: 1.167   # M  /MWp - average between commercial (966)
       and residential (1368)
    opex_var:  0.0151  # M  /MW/y

  electrolyzer:
    name: electrolyzer
    capex_var:   1.000   # M  /MW - 1.328 - Endret etter rapport
    opex_var:    0.025 # M  /MW/y
    efficiency: 0.6
```

```
    lifetime_h: 100000 # with 0.25% degradation per 1000 h, we get 25% after 100000

  h2_tank:
    name: hydrogen tank
    capex_var: 0.0006  # M /kg (1000  /kg)
    opex_rel: 0.01

  fuel_cell:
    name: fuel cell
    capex_var: 2.5     # M /MW
    efficiency: 0.6 #
    lifetime_y: 10   #

  battery:
    name: batteries
    capex_var: 0.9       # M /MWh
    opex_rel: 0.01         # 1% of CAPEX per year
    loss_in: 0.025         # (orginalt 0.025)round-trip efficiency 95%
    loss_out: 0.025      # (orginalt 0.025)round-trip efficiency 95%
    min_charge_rel: 0.1    # minimal state of charge
    max_charge_rel: 0.9    # maximal state of charge
    lifetime_y: 12         #
    max_charge_c: 1        # estimate
    max_discharge_c: 1     # guess

oper_scenarios:
  sources:
    power_load: data/building_power_loads_utsira_10_10houses.csv  # created by data/process_household_power_data.py, changed to fit desired demands
    wind_power: data/ninja_wind_59.3132_4.9045_Utsira22.csv   # created by data/get_wind_data.py, changed to fit desired values
    solar_pv: data/solar_pv_cap-factor_0.csv     # created by data/process_household_power_data.py, not needed for this study
  scenarios:
  - name: winter_avg
    time_step: 1
    weight: 0.25
    power_load:
      start: '2022-01-11'
      end: '2022-01-18'
      incl_end: false
```

```
      time_col: utc_timestamp
    wind_power:
      column: cap_factor
      start: '2022-01-11'  # only 2019 data can be downloaded from Renewables.ninja API without an API key
      time_col: utc_timestamp
    solar_pv:
      column: cap_factor
      start: '2017-01-11'
      time_col: utc_timestamp
  - name: spring_avg
    time_step: 1
    weight: 0.25
    power_load:
      start: '2022-04-11'
      end: '2022-04-18'
      incl_end: false
      time_col: utc_timestamp
    wind_power:
      column: cap_factor
      start: '2022-04-11'  # only 2019 data can be downloaded from Renewables.ninja API without an API key
      time_col: utc_timestamp
    solar_pv:
      column: cap_factor
      start: '2017-04-11'
      time_col: utc_timestamp
  - name: summer_avg
    time_step: 1
    weight: 0.25
    power_load:
      start: '2022-07-11'
      end: '2022-07-18'
      incl_end: false
      time_col: utc_timestamp
    wind_power:
      column: cap_factor
      start: '2022-07-11'  # only 2019 data can be downloaded from Renewables.ninja API without an API key
      time_col: utc_timestamp
    solar_pv:
      column: cap_factor
      start: '2017-07-11'
      time_col: utc_timestamp
```

Andreas Lie Aarøe


```
  - name: autumn_avg
    time_step: 1
    weight: 0.25
    power_load:
      start: '2022-10-10'
      end: '2022-10-17'
      incl_end: false
      time_col: utc_timestamp
    wind_power:
      column: cap_factor
      start: '2022-10-10'  # only 2019 data can be downloaded from
          Renewables.ninja API without an API key
      time_col: utc_timestamp
    solar_pv:
      column: cap_factor
      start: '2017-10-10'
      time_col: utc_timestamp
output:
  db_file: case_1_v-U.sqlite  # The DB of the created case

cases:
  - name: case_base
    description: 25% reduction, no storage
    battery:
      use: false
    hydrogen:
      use: false
    co2_price_kg:
      - 0.07  #   /kg
      - 0.10  #   /kg
    co2_red_per_per:
      - 25%
      - 25%
  - name: case_no_50
    description: 50% reduction, no storage
    based_on: case_base
    co2_red_per_per:
      - 50%
      - 50%
  - name: case_no_75
    description: 75% reduction, no storage
    based_on: case_base
    co2_red_per_per:
      - 75%
```

```yaml
      - 75%
  - name: case_no_85
    description: 85% reduction, no storage
    based_on: case_base
    co2_red_per_per:
      - 85%
      - 85%
  - name: case_no_90
    description: 90% reduction, no storage
    based_on: case_base
    co2_red_per_per:
      - 90%
      - 90%
  - name: case_no_95
    description: 95% reduction, no storage
    based_on: case_base
    co2_red_per_per:
      - 95%
      - 95%
  - name: case_no_100
    description: 100% reduction, no storage
    based_on: case_base
    co2_red_per_per:
      - 100%
      - 100%
  - name: case_b_90
    description: 90% reduction, battery
    based_on: case_base
    battery:
      use: true
    co2_red_per_per:
      - 90%
      - 90%
  - name: case_b_95
    description: 95% reduction, battery
    based_on: case_b_90
    co2_red_per_per:
      - 95%
      - 95%
  - name: case_b_100
    description: 100% reduction, battery
    based_on: case_b_90
    co2_red_per_per:
      - 100%
```

```yaml
    - 100%
  - name: case_b+h_90
    description: 90% reduction, battery & hydrogen
    based_on: case_base
    battery:
      use: true
    hydrogen:
      use: true
    co2_red_per_per:
      - 90%
      - 90%
  - name: case_b+h_95
    description: 95% reduction, battery & hydrogen
    based_on: case_b+h_90
    co2_red_per_per:
      - 95%
      - 95%
  - name: case_b+h_100          # ONLY DATA FROM THIS PART IS USED IN
      THE STUDY
    description: 100% reduction, battery & hydrogen
    based_on: case_b+h_90
    co2_red_per_per:
      - 100%
      - 100%
```

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