Zero-Emission Fish Farm Powered by Wind Power and Hydrogen - A Feasibility Study

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Abstract

The fish farming industry is transitioning from fossil-fueled energy systems to grid-connected systems. However, not all of the existing fish farms have the possibility to do so. Therefore, other solutions are needed in order to reduce CO_2 emissions. The aim of this thesis is to design and size an energy system consisting of wind power and hydrogen with the goal of covering the power demand of a fish farm.

Wind speed data from the data set NORA3 and power demand data provided from SalMar Aker Ocean were used to carry out two case studies. The aim was to investigate the feasibility of an energy system consisting of wind power and hydrogen. The first case included just wind power and hydrogen, and the second case added a diesel generator to the energy system. Both cases had a gradually increasing power demand, where the number of fish farms connected to the energy system increased from one to six. Both cases had a duration of 20 years in the simulations that were created in the programming language Python.

In case 1, it was found that four 750 kW wind turbines alongside a 2.5 MW fuel cell, one PEM MC250 electrolyser, and 55 tonnes of hydrogen storage capacity were needed in order to cover the power demand during the 20 years. However, the economic part of this case showcased that hydrogen storage was the main cost driver and that this energy system was not feasible.

In case 2, it was found that two 750 kW wind turbines alongside a 2.5 MW fuel cell, one PEM MC250 electrolyser, and 5 tonnes of hydrogen storage were needed to cover the power demand during the 20 years when a diesel generator with the capacity of 4 MW was added. The changes made to the energy system made this system more feasible.

It was concluded that it is technically possible to cover the power demand from a fish farm with an energy system consisting of wind power and hydrogen. However, the needed capacity for hydrogen storage is so large that the energy system is not profitable when it consists of only wind power and hydrogen. Therefore, by adding a diesel generator to the energy system, it is possible to drastically decrease the needed hydrogen storage and wind power capacity, thus making the energy system more profitable.

Contents

Acknowledgements **i**

Abstract **iii**

1 Introduction **1**
1.1 Background . . . 1
1.2 Previous related work . . . 2
1.3 Aim and Objectives . . . 2
1.4 Thesis outline . . . 2
1.5 Literature review . . . 3

2 Theoretical Background **5**
2.1 Hydrogen . . . 5
2.1.1 Hydrogen Production . . . 6
2.1.2 Hydrogen Storage . . . 8
2.1.3 Hydrogen Utilisation . . . 9
2.1.4 Hydrogen in Norway . . . 10
2.2 Wind Power . . . 11
2.2.1 Wind Turbine . . . 12
2.2.2 Offshore vs Onshore . . . 13
2.2.3 Offshore foundations . . . 14
2.2.4 Wind Speed Interpolation . . . 15
2.2.5 Wind Power in Norway . . . 16
2.3 Energy Demand at Fish Farms . . . 16

3 Methods **19**
3.1 Introduction to the case studies . . . 20
3.2 Data . . . 20
3.2.1 Consumption data . . . 20
3.2.2 NORA3-WP data . . . 22
3.3 Python . . . 23
3.4 Designing and Sizing the Energy system . . . 24
3.4.1 Assumptions . . . 25
3.4.2 Power Demand . . . 25
3.4.3 Power Production . . . 26
3.4.4 Hydrogen System . . . 26

3.4.5 Energy System 28
3.4.6 Monte Carlo Simulation 29
3.4.7 Economics 29

4 Results **33**
4.1 Consumption 33
4.2 Wind Power 34
4.2.1 Interpolated Wind Speeds 35
4.2.2 Power Production 35
4.3 Case study 1 - Wind Power and Hydrogen 37
4.3.1 The Energy System 37
4.3.2 Monte Carlo Simulation 45
4.3.3 Economics 45
4.4 Case study 2 - Wind Power, Hydrogen and Diesel 48
4.4.1 The Energy System 48
4.4.2 Economics 51
4.5 Comparison of Case study 1 and 2 53

5 Discussion **55**

6 Conclusions and Future Work **61**

Bibliography **63**

Appendix **67**
.1 Python Packages used 67
.2 Calculating Power Coefficients for the 750 kW wind turbine 68
.3 NPV calculation case study 1 68
.4 NPV calculation case study 2 69

List of Figures

2.1 Principle of electrolysis [7]. 6
2.2 Principle of fuel cell [7]. 9
2.3 The wind turbines power curve displays the increase in power production, cut-in speed, rated speed, and cut-out speed. 13
2.4 An illustration of different offshore foundations for wind turbines at increasing water depths. 14

3.1 Overview of the methods in this thesis. 19
3.2 Ocean Farm 1 before immersion [40]. 21
3.3 Location of Ocean Farm 1 (63.94203N,9.133442E) [42]. 21
3.4 Yearly consumption modified. The blue line represents the hourly consumption and the orange line represents the hourly mean consumption each day. 22
3.5 The geographical domain covered by NORA3-WP (red rectangle) [44]. 23
3.6 (a) System schematic of wind/hydrogen system, (b) System schematic of wind/hydrogen/diesel system. 25
3.7 Operational range PEM MC250 electrolyser. It operates in the range of 10-100 % of the capacity. 28

4.1 Illustration of the energy system which consist of wind turbines, an energy hub which includes electrolysers, fuel cells, diesel generators (case study 2) and the six fish farms, as well as the hydrogen storage. 33
4.2 Consumption 2023-2028: The blue and orange line's displays the hourly consumption and the daily average. The red dots displays when a new farm is connected to the energy hub. 34
4.3 Comparison of wind speeds extrapolation methods at 55 m.a.s.l. 35
4.4 Occurrence of the different wind speeds (red) and corresponding production by a 750 kW wind turbine (blue) with NORA3 wind speed data from 2003-2008. 36
4.5 Power Production each month during the six year period. 37
4.6 Amount of hydrogen stored 2023-2028: The blue and orange line's displays actual and potential amount of hydrogen stored during the simulation. The orange line is limited to 35 tonnes of hydrogen stored. The red dots shows when each of the fish farms start operating and the wind turbine symbols shows when a new turbine start operating. The increasing power demand is displayed in shaded gray. 38

4.7 Distribution of surplus energy during the six year period. Yellow and Red line showcases when the electrolyser start and stops production. . . . 39
4.8 Required energy that the fuel cell has to provide. 40
4.9 Share of energy supply during the period 2023-2028. 41
4.10 Consumption and power production during two weeks in 2023. . . . 42
4.11 Consumption and power production during two weeks in 2028. . . . 43
4.12 Amount of hydrogen stored 2023-2042: The blue and orange line's displays actual and potential amount of hydrogen stored during the simulation. The orange line is limited to 55 tonnes of hydrogen stored. The red dots shows when each of the sh farms start operating and the wind turbine symbols shows when a new turbine start operating. The increasing power demand is displayed in shaded gray. 43
4.13 Monte Carlo Simulation: 1000 simulations of the energy system with varying wind speeds have been performed and the amount of hydrogen stored over time is plotted for each simulation. 45
4.14 Investments - different hydrogen storage prices. 46
4.15 OPEX and savings during the rst case study. 47
4.16 Net present value - different hydrogen storage prices. 47
4.17 Amount of Hydrogen Stored 2023-2043 (Case study 2). The orange line displays the amount of hydrogen stored during the simulation with a limit of 5 tonnes. The red dots shows when each of the sh farms start operating and the wind turbine symbols shows when a new turbine start operating. The increasing power demand is displayed in shaded grey. . . . 49
4.18 Amount of consumption that are covered by the diesel generator during the simulation shown in blue.The consumption is shown in red in the background. 49
4.19 Shares in energy distribution with a hydrogen storage capacity of 5000 kg. 50
4.20 Shares in energy distribution with a hydrogen storage capacity of 20000 kg. 50
4.21 Investment case study 2 - regarding different hydrogen storage prices. . 51
4.22 OPEX and savings during Case study 2. 52
4.23 Net Present Value - Case 1 vs Case 2. 52

Chapter 1

Introduction

1.1 Background

In 2015, the Paris agreement was signed, and stated that all parties in the United Nations pledged to ﬁght climate change [1]. The aim is to prevent the global temperature to rise to a level below 2 °C above pre-industrial levels. In addition, the International Maritime Organization set its own quite ambitious targets; to reduce CO_2 emissions in transport by 40 % in 2030 and 70 % in 2050. The Norwegian ﬁsh farm industry is responsible for around 650 000 tonnes of CO_2 yearly, including all activities connected to the facilities [2]. Approximately 60 000 tonnes of CO_2 emissions come from the energy consumption at the facilities. Today around 55 % of the facilities are connected to the electricity grid, and several more have the opportunity to do this. However, not all have this opportunity due to distance to shore or poor grid infrastructure in the nearby area. This leaves these facilities to look at other solutions to be able to reduce their emissions. A hybrid system consisting of wind power and hydrogen can be a sustainable solution to this problem

Wind power has seen a signiﬁcant expansion in recent years, and it is predicted to become an important energy source in the future energy mix. According to the Norwegian Water Resource and Energy Directorate (NVE), 11.8 TWh of electricity were produced in Norway in 2021, which is a doubling from 2019 [3]. All of this production comes from onshore turbines, but two areas outside Norway have been selected to be the ﬁrst areas for Norwegian offshore production. However, the electricity production from wind turbines is not constant over time, and the produced electricity can only be stored for short periods and in small amounts. To cope with this problem requires other storage options, like chemical storage such as hydrogen. Hydrogen production from electrolysis, which uses electricity to split water into hydrogen and oxygen, has no CO_2 emissions and can support decarbonization in industry, transport, and power generation when used as an energy carrier [4].

Both wind power and hydrogen are key alternatives that the Norwegian government is looking at when it comes to decarbonizing the Norwegian energy sector. This was stated in the national hydrogen strategy, which was released in 2020 and highlighted the importance of hydrogen in both industry and transport [5]. Furthermore, the recent

decision regarding a 1500 MW offshore wind park at "Sørlige Nordsjø II" states that offshore wind will supply power to the Norwegian grid [6]. There are several planned projects that concerns hydrogen production or utilization in Norway. NORLED, a Norwegian shipping company, leads the revolution with its hydrogen driven ferry [5]. Some other hydrogen related projects in Norway are presented in Chapter 2.

1.2 Previous related work

In 2020 my co-students and myself wrote our bachelor thesis "Assessing the Feasibility of Hydrogen Plants Powered by Floating Photovoltaics" [3]. We carried out three case studies in order to explore the feasibility of oating photovoltaic powered hydrogen plants and different locations. The rst case study was related to an off-grid facility at the coast of western Norway. We investigated the feasibility of covering a consumption with oating photovoltaic and wind power where the surplus energy was used to hydrogen production. The study showed that in order to cover a consumption of 361.2 MWh/yr, a 100kW wind turbine and 650 kW FPV array was needed. I learned a lot from working with the bachelor thesis, and the experience from this work is the reason behind the decision to investigate the feasibility of a wind/hydrogen energy system to cover the consumption of a sh farm .

1.3 Aim and Objectives

The main aim of this thesis is as followed:

- Design and size an energy system consisting of wind power and hydrogen with the goal of covering the power demand of a sh farm and assessing the feasibility of this.

Several objectives follow to meet the aim :

- Investigate the wind resources for the chosen location
- Carry out a case study where wind power and hydrogen aim to cover the power demand of a sh farm
- Carry out a similar study, where a diesel generator is added to the energy systems
- Create python scripts to access and process the different data in order to design and size the two energy system. It is a goal that the different data sets can be used for similar studies in the future

1.4 Thesis outline

Chapter 1 includes the introduction to the thesis and a literature review. Chapter 2 presents the theoretical background. Chapter 3 presents the methods used to address the aim and objectives set for this thesis. Chapter 4 presents the results of the study before they are discussed in Chapter 5. Finally, Chapter 6 includes the conclusion and proposals for further work.

1.5 Literature review

A literature review shows that the combinations of wind power and hydrogen to power a sh farm are not widely looked into. However, several studies of green hydrogen production from wind power have been conducted in the past. These studies have included the maturity of hydrogen technology and the cost of hydrogen/wind power systems compared to existing solutions, to name some examples. Some of the most relevant studies that previously have been conducted regarding the combination of wind power and hydrogen are presented below.

Greiner, Korpås, and Holden performed a case study regarding the possibility of replacing the fuel used on a ferry from diesel to hydrogen by running simulations in Matlab [8]. They looked at an energy system where hydrogen was produced from a wind turbine, both for an isolated system with a backup diesel generator and for a grid-connected system. They concluded that there were several issues regarding the isolated system and, therefore, the grid-connected system was preferred. The system experienced extensive power dumping during periods with high power production from the turbine, and during the summer with low wind speeds, most of the hydrogen was produced with power from the generator.

A techno-economic analysis regarding a stand-alone hybrid renewable energy system where power was produced from wind and solar power was performed by Kalinci, Hepbasli, and Dincer [9]. They investigated the possibility of supplying the electric energy demand of the island Bozcaada in Turkey. The energy system was created using the simulation software HOMER and consisted of 300 kW of solar panels and 2 x 300 kW wind turbines, and a 100 kW fuel cell. Their best simulation showed that 69 % of the load was covered by wind power, 21 % by solar power, and the remaining 10 % by the fuel cell that utilised hydrogen produced by excess energy. They concluded that a hybrid renewable energy system is technically convenient but it is an expensive solution.

In 2004, an autonomous wind/hydrogen energy demonstration system located at Utsira in Norway was of cially launched [10]. After four years of operation, operational data was collected and used to evaluate the operation of the Utsira plant by using a set of updated hydrogen energy system modeling tools. The system demonstrated that it is possible to cover the energy demand of remote area communities with wind power where hydrogen is used as energy storage. However, for this system to become competitive with existing commercial solutions, there is a need for further technical improvements and cost reductions. One of the recommendations from this study was to develop a hybrid system where a diesel engine could cover a small part of the annual load. This is something that will be further investigated in this thesis.

A master thesis from the University of Agder conducted a case study investigating the possibility of supplying a sh farm with energy from wind power [11]. One of the topics in this thesis was a comparison between different sized power consumption based on data from Reitan sh farm and the produced power from a 750kW and a 2.3MW wind turbine. The author concluded that wind power without energy storage or additional power sources was not feasible for any of the conducted scenarios. This conclusion showcases the importance of energy storage. Therefore, it is the aim of this

thesis to design and size an energy system that consists of wind power and hydrogen to cover the power demand of a sh farm.

Chapter 2

Theoretical Background

This chapter will present the essential theoretical aspects of hydrogen production, utilisation and storage. Some fundamentals about Wind Resources, how to harvest them and how a wind turbine operates and different offshore foundations for offshore wind follows. There is also a small section about the energy demands at a sh farm. The theoretical background will be limited to what is relevant for this thesis.

2.1 Hydrogen

Hydrogen has been highlighted as a crucial part of decarbonizing the world's energy sector. This is due to hydrogen's different properties as an energy carrier. An energy carrier is a substance used to store, move, and deliver energy from primary energy sources like wind and solar. In this thesis, hydrogen is seen as energy storage for the intermittent energy produced from wind power. Table 2.1 below showcases the difference in properties between hydrogen and diesel, which is the fuel mainly used to power a sh farm alongside the electricity grid and batteries [12].

Table 2.1: Hydrogen properties compared to diesel [13, 14, 15, 16].

Energy carrier	Hydrogen (350bar)	Diesel
Mass Density [kg/m^3]	23 [13]	820-845 [14]
Gravimetric Energy Density [kWh/kg]	33.33 [15]	11.8 [15]
Volumetric Energy Density [kWh/m^3]	767	9676-9971
Flashpoint [C]	-231 [16]	62 [16]
Flammability range [%]	4-75 [16]	0.6-5.5 [16]

In order for hydrogen to become this essential part of the energy sector, the hydrogen value chain must be established and built to meet the needed demands. The hydrogen value chain consists, in simplicity, of production, storage, and utilisation. The different steps in the value chain will be presented in the coming sections of this chapter.

2.1.1 Hydrogen Production

Hydrogen has several production methods available today. The most common ones are steam methane reforming, partial oxidation, and autothermal reforming, utilising fossil fuels. Another method is water electrolysis, which utilises electricity. In 2008, approximately 96 % of the hydrogen produced worldwide was produced by utilising fossil fuels, thus leaving a huge carbon footprint [16]. It is believed that the share of global hydrogen production has not seen a signi cant change since then. Therefore the production of hydrogen from electrolysis powered by renewable energy sources is the key for hydrogen to become a sustainable fuel. Due to the purpose of this thesis, only the concept of electrolysis is further explained.

Electrolysis is an electrochemical reaction where water is split into hydrogen and oxygen using electricity. The process consists of an electrical DC source and two electrodes separated by a conductive electrolyte. A simpli ed electrolysis illustration can be seen in Figure 2.1. The different electrolysis applications are named after their electrolyte, and both Alkaline-and Proton Exchange electrolysis will be presented below.

Figure 2.1: Principle of electrolysis [7].

Alkaline Water Electrolysis

Alkaline Water Electrolysis (AWE) has been used for several years and is one of the most popular options when it comes to electrolysers [17]. The electrolyte is an alkaline solution, often NaOH(aq) or KOH(aq), which prevents the usage of expensive acid-resistant materials. The electrodes consist of nickel-based materials and have porous structures to maximise their surface area. The reactions during AWE are shown in Equations 2.1, 2.2 and 2.3.

$$\text{Anode: } 2OH^- \rightarrow H_2O_{(g)} + \frac{1}{2}O_{2(g)} + 2e^- \tag{2.1}$$

$$\text{Cathode: } 2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^- \tag{2.2}$$

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

AWE is best suited to operate at constant power due to low operating pressures, limited current densities, and low energy ef ciency [18]. This is not suitable for renewable energy sources like wind power, which are intermittent. However, high-powered AWEs have responded fast enough to the changes in energy delivered to the electrolysers from a renewable power plant. In terms of expenditures connected to AWEs are the capital expenditures (CAPEX) ranging from 8000 - 15000 NOK/kW [19]. The operational expenditures (OPEX) are approximately 2-3 % of the investment cost per year.

Proton Exchange Membrane Water Electrolysis

Proton Exchange Membrane Water Electrolysis (PEM) consists of an electrolyte made of solid polysulfated membranes [17]. Water reacts at the anode, and protons travel through the membrane to the cathode, where electrons and protons re-combine and produce hydrogen. The reactions during PEM are shown in Equations 2.4, 2.5 and 2.6.

$$\text{Anode: } H_2O_{(l)} \rightarrow 2H^+ + \frac{1}{2}O_{2(g)} + 2e \tag{2.4}$$

$$\text{Cathode: } 2H^+ + 2e \rightarrow H_{2(g)} \tag{2.5}$$

$$H_2O_{(l)} \rightarrow H_{2(g)} + \frac{1}{2}O_{2(g)} \tag{2.6}$$

Compared to AWE, PEM operates at high pressures and current densities. With a fast response to load changes and compact design, PEM is one of the most favorable methods for green hydrogen production [18]. Noble metals like platinum and iridium are often used for the cathode and anode. This makes the PEM more expensive than the AWE, which uses basic metals. Today, the CAPEX of a PEM ranges from 14000-21000 NOK/kW, and the maintenance cost is estimated to be 3-5 % of the investment cost per year [19].

Comparison of different Electrolysers

Table 2.2 compares critical factors to consider when selecting an electrolyser. The table displays that the alkaline electrolysers have a higher capacity per stack, are cheaper and have slightly higher ef ciency. However, the PEM electrolysers have a faster response time and have a longer lifetime.

Table 2.2: Comparison of different electrolysers [19].

Electrolyser	AWE [19]	PEM [19]
Maximum Capacity per stack [MW]	6	2
Ef ciency [%]	63-71	60-68
Cold start-up time [min]	60-120	5-10
Warm start-up time [min]	1-5	< 1
Price per kW [NOK/kW]	8000-15000	14000-21000
Opex per year [% of capex]	2-5	3-5
lifetime [h]	55000-90000	60000-100000

2.1.2 Hydrogen Storage

One of the main difficulties regarding the hydrogen value chain is storage. Due to hydrogen's properties, it is a challenging substance to contain. With its high diffusibility and low mass density, special materials are required for the storage modules under standard conditions. There are three main hydrogen storage methods: Compressed Hydrogen (CH_2), Liquefied Hydrogen (LH_2), and solid-state [20].

Compressed Hydrogen

Compression of various gasses is a widely used process to achieve lower volumes in storage, and hydrogen is no exception. For example, CH_2 is often stored at 350 or 700 bar, corresponding to a mass density of 23 and 38 kg/m^3 [13]. Selecting suitable materials for storage vessels is essential with higher storage pressures. The vessels can be categorised into four categories ranging from type I to type IV. Type I is made of regular carbon steel, and the rest uses composite to some degree alongside other materials. The cost of type II to IV increases for each type due to material selection. The expenses related to hydrogen storage vary depending on the application and the storage pressure. The price ranges from 3500 NOK/kg for low-pressure storage to 7000 NOK/kg for higher pressures.

Liquefied Hydrogen

If hydrogen is cooled to a temperature below -253 °C, it will turn into liquid form and have a mass density of 71 kg/m^3 [21]. This process is energy demanding, and it is reported that almost 30 % of the energy contained in the hydrogen is lost due to this process. In addition to the energy loss during cooling, around 2-3 % of the hydrogen evaporate each day due to boil-off. Therefore, several components and more robust storage vessels are required to prevent boil-off and hold hydrogen in its liquid form than for storing CH_2.

Liquid Organic Hydrogen Carrier

Liquid Organic Hydrogen Carriers (LOHC) is a storage method that prevents boil-off and other hydrogen losses under long-term storage [22]. The concept of LOHC is constructed around two processes, hydrogenation and de-hydrogenation. Hydrogenation is the process when hydrogen reacts with unloaded LOHC molecules ($LOHC_0$). The loaded LOHC (H_nLOHC) has similar properties as conventional fuels and is easier to handle than CH_2. When the loaded LOHC is de-hydrogenated, the hydrogen is used through a fuel cell, and the remaining unloaded LOHC can be re-used to store more hydrogen. Unfortunately, there are some losses during these cycles, and the LOHC needs to be replaced after a specific time.

Other Storage Methods

In addition to CH_2 and LH_2, there are several other storage options for hydrogen. Material-based storage is the collective concept for storage where hydrogen atoms or molecules are bound with other elements [21]. Absorption and adsorption are the

two basic bonding mechanisms for material-based storage. In the absorption process, metal hydrides form when hydrogen reacts with a given type of metal. Therefore, large amounts of hydrogen can be stored with this method.

The adsorption process is when hydrogen atoms or molecules get attached to the surface of a material. This method has its advantages with its low operating pressures and simple design. However, there is a signi cant problem with the availability of light materials that have suf cient bonding sites.

Subsea Storage

Recently, several ongoing projects regarding hydrogen storage have looked at the possibility of placing tanks or containers with CH_2 on the seabed. One of these projects is Technip FMCs Deep Purple. Technip FMC is also involved in the Hardanger Hydrogen Hub project, which plans to use the same storage technology. Unfortunately, there is not much public information or scienti c reports on the technical solution regarding these concepts.

2.1.3 Hydrogen Utilisation

Hydrogen can be utilised through several different methods. One method is inserting hydrogen through a fuel cell, which converts chemical energy into electricity. There are many varieties of fuel cells, but they are all built up in the same way. A fuel cell consists of two electrodes, an anode and cathode, and an electrolyte. Figure 2.2 illustrates the principles of a fuel cell in a simpli ed manner. The following subsections will detail how the Alkaline Fuel Cell (AFC) and Polymer Electrolyte Membrane Fuel Cell (PEMFC) is built up and what separates the two. A comparison of the two can be seen in Table 2.3.

Figure 2.2: Principle of fuel cell [7].

Alkaline Fuel Cell

The AFC has traditionally consisted of an aqueous solution of potassium hydroxide as the electrolyte [23]. However, polymer anionic exchange membranes as electrolytes seem to be the future for the AFC. The electrodes consist of low-cost base metals, such as Platinum or Palladium. However, industry and academia are heavily working on

developing non-Platinum Group Metals catalyst that surpasses the performance of the traditional ones. Equations 2.7 and 2.8 display the chemical reactions at the electrodes.

$$\text{Anode: } 2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \tag{2.7}$$

$$\text{Cathode: } O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{2.8}$$

Polymer Electrolyte Membrane Fuel Cell

The PEMFC often consists of platinum-based electrodes and a polymer membrane electrolyte [24]. The membrane is usually made of Na on, and the protons (H^+) are led through it. The electrodes consist of a metal-based catalyst, often platinum, making it expensive to construct. The reactions at the electrodes are shown in Equations 2.9 and 2.10. Hydrogen ows into the Anode side, where it reacts, and the protons are led through the membrane, as mentioned above. These protons react with oxygen at the cathode and combine into water.

$$\text{Anode: } H_2 \rightarrow 2H^+ + 2e^- \tag{2.9}$$

$$\text{Cathode: } \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2.10}$$

PEMFC is known for its low operating temperature and high power density, and it is easy to scale up due to how its constructed. However, the main challenge for PEMFCs is to decrease the cost by developing cost-ef cient alternative materials for both membrane and electrodes.

Table 2.3: Comparison of different fuel cells [23, 25, 26].

Fuel cell	AFC	PEMFC
Electrical capacity [kW]	1-100 [25]	10-1000 [25]
Ef ciency [%]	45-60 [25]	40-60 [25]
Price per kW [NOK/kW]	1000-1700 [23]	10000-13200 [26]

2.1.4 Hydrogen in Norway

The Norwegian government released a Norwegian hydrogen strategy in May 2020 [27]. This strategy presented the different sectors where hydrogen could be implemented. Some of the ongoing hydrogen projects in Norway were also mentioned in this report. For example, the shipping company, Norled, has built a ferry in which 50 % of the consumption shall be covered by hydrogen. ASKO, Norways largest grocery wholesaler, already has a truck that uses hydrogen produced locally from electricity produced from solar panels at their facility in Trondheim. In the industry sector, Tizir Titanium & irons is working on a project where hydrogen shall replace coal in the prereduction process in the production of iron and titanium. The Haeoulus project in Berlevåg is another

exciting project. This project looks at a hydrogen factory powered by surplus energy from the wind farm at Raggovidda.

2.2 Wind Power

The earths wind energy systems result from pressure differences on the earths surface due to uneven heating from the sun, the Coriolis force, frictional forces, and inertial forces [27]. The wind speeds created by these forces vary in both time and space and are an essential aspect when utilising the kinetic energy the wind speed holds. The variation in time is divided into four categories: inter-annual, annual, diurnal, and short-term variations.

Variations in wind speeds that occur over a time scale more extensive than a year are called *inter-annual* variations. It is essential to estimate these variations due to their effect on a large-term wind turbine production. Meteorologists have concluded that it takes at least five years to calculate a reliable annual wind speed at a location. However, it is recommended to have a sample size of nearly 30 years to get it more accurate.

Annual variations are the most common type of variation when it comes to wind speed, and it is the most challenging variation when it comes to the aim of this thesis. In Norway, it is normal with stormy winters and more calm summers with varying wind conditions. This means that a wind turbine produces much power during winter and less in the summer, further indicating the need for additional power from an external source.

The two other variations are *diurnal* and *short-term*. These two include variations during a daily time scale mainly because of temperature differences during the day, and a time scale of minutes or seconds because of turbulence and gusts. These variations are significant when it comes to the design of a turbine.

Energy content in the wind

It is easy to be confused by the different equations regarding the energy contained in the wind and how much a wind turbine actually produces. The potential energy in the wind is showed in Equation 2.11 by combining the continuity equations of fluid mechanics (mass transport per unite time) and kinetic energy per unite time [27].

$$\frac{P}{A} = \frac{1}{2}\rho v^3 \qquad [W/m^2] \tag{2.11}$$

The equation above showcases how vital the wind velocity, v, is for the wind power density. The rapid increase in power density with increasing wind speeds is shown in Table 2.4. The table showcases that only a slight increase in wind speed makes a big difference when it comes to how much power is available when passing through a wind turbine. This is because the energy delivered from the turbine is the amount of power generated during a time period. For example, if the average wind speed through a wind turbine is 5 m/s during one hour, the potential energy generated is 76.6 Wh/m^2 during that time.

Table 2.4: Power contained in the wind per unite area under standard conditions.

Wind speed [m/s]	Power/area [W/m ^{2}]
0	0
5	76.6
10	612.5
15	2067.2

Unfortunately, it is impossible to utilise all of the potential energy in the wind, and the theoretical maximum ef ciency of a wind turbine is limited to 59.3 %. This is known as the Betz limit and shows that only 59.3 % of the kinetic energy from wind can theoretically be utilised through a wind turbine [28]. In reality, only around 45-50 % of the potential energy can be harvested from the best modern wind turbines. The equation for the average ef ciency, or power coef cient, of a wind turbine, can be seen in Equation 2.12.

$$\text{Ef ciency} = \frac{\text{Energy produced per year}}{\text{Energy in the wind per year}} \tag{2.12}$$

The average ef ciency of a turbine tells how much of the energy in the wind can be harvested, but it does not tell how well the turbine operates from time to time [27]. This can be showcased by the capacity factor of the turbine. The capacity factor is the ratio of how much energy a turbine produces, compared to the energy that could have been produced, given that the turbine ran at rated power over a given time. This can be measured over a year for the whole turbine, as Equation 2.13 shows, but it can also be used to investigate which wind speeds the turbine operates most ef ciently [26].

$$\text{Capacity Factor} = \frac{\text{Energy produced per year}}{\text{Energy at full power per year}} \tag{2.13}$$

2.2.1 Wind Turbine

Wind turbines convert the kinetic energy in the wind into mechanical and then electrical energy by the rotor and the generator [27]. A wind turbine differs from other generators because it can only produce electricity with suf cient wind resources. In contrast to water at a hydropower facility, the wind cannot be stored and must be converted into electricity when the wind blows.

The produced electricity can be transported to the end-user through the electricity grid or stored, for example, as hydrogen, as explained previously in this chapter. A power performance curve can predict the produced power from a wind turbine. Such a curve can be seen in Figure 2.3. The curve displays cut-in, rated, and cut-out wind speed and the estimated power production for different wind speeds. The cut-in wind speed showcases when the turbine starts producing power, and the cut-out showcases when it stops producing.

As seen in Figure 2.3, there is a gradual decline in power production after cut-out. This is because the turbine cannot shut down immediately. How a turbine shut-down varies

from turbine to turbine. Some have a brake function installed that kicks in when the wind speed reaches cut-out, while others can rotate the turbine sideways to prevent the lift from the wind.

The gure shows that the power output increases until it reaches the rated wind speed, and from that point, the turbine will produce constant power until cut out. This is called rated power and is the maximum power output from a wind turbine. The manufacturers deploy these power performance curves after eld tests and standardised wind turbine testing methods.

Figure 2.3: The wind turbines power curve displays the increase in power production, cut-in speed, rated speed, and cut-out speed.

2.2.2 Offshore vs Onshore

Historically, single turbines and wind farms have been installed onshore close to the end-users and the electricity grid. However, in 1991, the rst offshore wind farm was set into production in Denmark with an installed capacity of 5 MW [29]. The fundamentals of how the wind turbines are built are similar for both onshore and offshore turbines, but several other differences separate the two. Table 2.5 shows some advantages and disadvantages of onshore and offshore wind farms. Onshore turbines require a less expensive infrastructure than offshore ones, thus making it a cheaper solution [30]. However, more signi cant wind resources are at sea, which results in greater power generation from fewer turbines offshore than onshore. The importance of wind speed was previously shown in Table 2.4.

Table 2.5: Comparison of onshore and offshore wind harvesting locations [30]

Location	Advantages	Disadvantages
Onshore	• Quick installation • Shorter cables • Cheaper	• Large variations in wind speed • Potential wind blockages • Visual and sound effects
Offshore	• Capacity factor • Larger systems • Less visual impact	• Maintenance • Higher cost • Possible impact on marine life

2.2.3 Offshore foundations

The foundation selected for an offshore wind turbine varies from project to project. It depends on the water depth where the turbine operates and is classi ed as grounded or oating systems [31]. Foundation cost covers 25-34 % of the total cost in an offshore wind turbine project and it is the most important design consideration in a project. A simple illustration of the different foundations described in the following paragraphs can be seen in Figure 2.4.

Figure 2.4: An illustration of different offshore foundations for wind turbines at increasing water depths.

Monopile and Gravity type

Monopile-and gravity type foundations are mainly used in shallow waters down to 30 m [32]. Gravity-type foundations consist of a circular pile with a concrete plate structure

resting on the seabed. This solution is not used on wind turbines with a capacity of over 3 MW due to heavyweight and high construction costs. Monopile is the most commonly used foundation for European offshore wind farms due to the shallow depths and the soils, consisting of sand and gravel, at the wind farm locations. The monopile is often a hollow steel cylinder, and it is often driven 10-20 m into the seabed, and there is rarely needed any seabed preparation [27].

Tripod and Jacked

For depths deeper than 30 m, substructures are required at a lower construction cost to keep the total investment down [33]. Space frame structures provide suf cient strength and stiffness and come in variants such as a tripod or jacked. Both are based on foundations used in the oil and gas industry and require minimal seabed preparations. Like the monopile, the turbine is placed upon a steel pile for the tripod foundation. The pile is attached to a steel frame with three steel piles driven into the seabed, and the loads are distributed evenly through these. The jacked foundation consists of several sections of structural tubing or pipes that are welded together, and the turbine is mounted on top of this construction. The weight of a jacked foundation is much lower compared to a monopile of the same size. Therefore, transportation and installation cost is much lower as well.

Floating Foundations

Bottom xed foundations are constrained to water depths down to 50-60 m. In order to harvest power from areas with signi cant wind resources at deeper depths, oating foundations are needed [32]. Ballast stabilised foundations, or spar buoys, is a foundation developed and tested at the Hywind Demo project back in 2009. The foundation consists of a cylinder with ballast to keep the center of gravity below the center of buoyancy. In order to keep the foundation at its position, mooring lines and anchors are used. Other options for oating foundations are Tension leg platforms and Semi-submersible foundations [34].

2.2.4 Wind Speed Interpolation

Wind Speeds are commonly measured at a given height at a location due to the infrastructure at the site. It can be at the top of a building or on the top of a stationary buoy at sea, to name some examples. In order to use these measurements to calculate the wind speeds at the height of a wind turbine, wind speed interpolation is necessary [35]. Two commonly used methods are the Logarithmic Wind Pro le Law and the Power Law. These two are further explained in the following subsections.

Logarithmic Wind Pro le Law

The logarithmic wind pro le law, or the log law, is a widely used formula when calculating wind speeds at different heights. The formula is shown in Equation 2.14.

$$\frac{v}{v_0} = \frac{\ln(\frac{H}{z_0})}{\ln(\frac{H_0}{z_0})} \tag{2.14}$$

Where v_0 and H_0 are reference wind speed and height and z_0 is called the roughness coef cient length. This coef cient represents the land type surrounding the area, and it ranges from 0.0002m for calm open sea to 1.6m or more for city areas with high buildings.

Power Law

Another commonly used method when it comes to interpolation of wind speeds is the Power Law. The formula is shown in Equation 2.15.

$$\frac{v(z)}{v(z_r)} = (\frac{z}{z_r})^a \tag{2.15}$$

Here $v(z_r)$ and z_r are the reference wind speed and height, $v(z)$ is the wind speed at height z. In addition there is the power law exponent a, which varies depending on certain conditions. Parameters like temperature, elevation, time of day, season, surrounding terrain and various thermal and mechanical mixing parameters like the stability of the atmosphere impacts the a value. However, in many cases with stable conditions are a set to 1/7.

2.2.5 Wind Power in Norway

In 2021, wind power was responsible for 7.5 % of the energy production in Norway, with a production of 11.8 TWh distributed between 1304 turbines [3]. These turbines are spread across the whole country. From the previously mentioned Raggovidda Wind Farm in the north with 45 MW installed capacity to Tonstad Wind Farm in the south with 208 MW installed [36, 37]. Most of the produced energy from wind comes from onshore installations, and in contrast to other European countries, there are no offshore wind farms in Norway. However, the government has allocated licences for two different offshore wind farm production areas, "Utsira" and "Sørlige Nordsjø II" [6]. In addition to this is Equinor working on their Hywind Tampen project [38].

This is a project where a wind farm, including 11 units with a combined installed capacity of 88 MW, would be located 140 km off the Norwegian coast between Bergen and Florø . The water depth at this site ranges from 260 to 300 m, and the planned foundation is a spar structure, which can be seen in Figure 2.4. This project aims to partially power the two offshore oil and gas elds in the area, Snorre and Gullfaks .

2.3 Energy Demand at Fish Farms

The energy demand at a sh farm varies from the different facilities due to size, amount of sh in the barge, and other energy use [12]. The primary energy drainer is the feeding

process, which stands for 70 % of the total energy consumption at the average facility and the energy system has to be dimensioned after this. There is also a considerable variation in the consumption from day to day, ranging from 400 kWh to 1300 kWh a day. The large variations result from periods where there are feeding several times a day to periods where only the baseload has to be covered due to no sh in the barges.

Chapter 3

Methods

The following chapter introduces the data sets that contains wind speeds and power consumption and the software used during this thesis to design and size an energy system consisting of wind power and hydrogen to cover the consumption of a sh farm. A case study will be conducted, and it is introduced before a more detailed description of the work is included to make it reproducible. A schematic overview of the methods used is found in Figure 3.1 and shows input data, calculated data, and various output data.

Figure 3.1: Overview of the methods in this thesis.

3.1 Introduction to the case studies

The consumption data used during this thesis, which is presented later in this chapter, was provided from SalMar Aker Ocean. Therefore, it was natural to carry out a case study where the energy demand of a sh farm should be covered by wind power and hydrogen. After discussions with the Jørgen Mjønes in SalMar Aker Ocean, it was decided to perform a case study where the number of sh farms would increase from one to six over ve years[39]. The case study will investigate the feasibility of an isolated energy system consisting of wind power and hydrogen as energy storage. It was decided to perform two case studies in the end, one where the energy system consisted of only wind power and hydrogen. And another study where a diesel generator was added to the energy system as well, both studies are presented below.

The rst case study aims to design an energy system consisting of wind power and hydrogen to cover the demand of the increasing number of sh farms. First is the rst six years of operation presented with a more in-depth look at the development throughout the period. Following this, the same system is investigated over 20 years to see if any changes have to be made to meet the sh farms' power demand. Both technical aspects, such as the sizes of the different components included in the energy system and the economic aspects regarding the net present value and Levelized cost of energy, are calculated during this study.

The second case study aims to design an energy system consisting of wind power, hydrogen, and a diesel generator. This study will only investigate the system over a 20-year period. This case follows the same structure as the rst case study. It is conducted to see how the implementation of a diesel generator affects both the energetic, technical and economic aspects found in case study 1.

3.2 Data

This section will describe the different data sets that have been used in this thesis. SalMar Aker Ocean provided power consumption data from the Ocean Farm 1 sh farm, and the hindcast data set NORA 3 was used when obtaining wind speed data. Information regarding the two data sets and how they were received follows below.

3.2.1 Consumption data

The energy consumption was obtained by contacting sh farms directly or industry clusters with connections to the sh farming industry. Firstly, consumption data from E.Karstensen's sh farm at Langeråa, located outside of Florø, was obtained. However, this sh farm was already connected to the electricity grid, and due to its location close to land, it was discarded. Instead, contact was made with SalMar Aker Ocean, and power consumption from their test facility Ocean Farm 1, the world's rst offshore sh farm, was received. A picture of the facility before immersion can be seen in Figure 3.2.

Figure 3.2: Ocean Farm 1 before immersion [40].

Ocean Farm 1 is located around 20 km from the mainland of Norway, with Trondheim as the nearest large city, isolated from the electricity grid. See Figure 3.3 for the location of the sh farm. The water depths at the location of the sh farm is approximately 150 m. The facility is 69 m high and has a diameter of 110 m. And with a barge volume of 250000 m^3, it has the capacity to hold over 1 million salmon simultaneously. It started operating in late 2017 [41].

Figure 3.3: Location of Ocean Farm 1 (63.94203N,9.133442E) [42].

Data for power consumption for the sh farm, with a resolution of both 10 minutes and 1 hour, was provided from 2019 and 2020 in excel format [39]. The NORA3 dataset has a resolution of 1 hour, and therefor it was decided to use this resolution regarding consumption. The total consumption from 2019 and 2020 was 696.8 MWh and 767.3 MWh, respectively. Three diesel generators with a capacity of 184 kW each, 552 kW total, have powered Ocean Farm 1 during these years [43]. The most energy-demanding process at a sh farm is feeding the sh. During the two years of power consumption data that was given, there was sh at the barge from 22 October 2019 to 15 September

2020 [39]. Because of this, it was decided to create a yearly power demand that would be as representative as possible, see Figure 3.4. This power demand is created by using the first and last five months of power consumption data where there was fish in the barge. The remaining two months used data from where there were no fish in the barge. The yearly power demand for this created consumption is 771.4 MWh, slightly more than the total of the received raw data.

Figure 3.4: Yearly consumption modified. The blue line represents the hourly consumption and the orange line represents the hourly mean consumption each day.

3.2.2 NORA3-WP data

The NORwegian hindcast Archives Wind Power data set, or NORA3-WP, is created using variables from the original NORA3 data set. NORA3 is created upon the state-of-the-art reanalysis of ERA-5 by the Norwegian Meteorological Institute. NORA3-WP uses air temperature and pressure in several near-surface model levels alongside estimated wind resource and wind power-related variables from the original NORA3 dataset. NORA3-WP covers a significant area in Northern Europe, as shown in Figure 3.5, and has a grid resolution of 3 x 3 km. Wind power variables calculated for three different turbines at 101, 119, and 159 meters above sea level (m.a.s.l) is available as hourly wind speed and hourly generated wind power for the turbines [44].

Figure 3.5: The geographical domain covered by NORA3-WP (red rectangle) [44]

3.3 Python

Python was chosen as the preferred software for the computations in this thesis. Other software like Excel or Matlab would also do the work. However, the user-friendliness of python, alongside several valuable functions and the possibility to work with several large data sets, made python stand out. Python has been used to extract the wind speed at the desired location from the original database and all the main calculations during this thesis. A short description of the python script created to extract wind speed data and the script created for the main calculations follows below:

Script for wind speed collection

Since the NORA3 datasets cover a signi cant area, there is a substantial amount of wind speed data for each dataset. Therefore, to only access the relevant data for this thesis, a python script was created to only download the wind speed data for the nearest grid point to the location of Ocean Farm 1. This python script makes it possible to download wind speed data for any location, as long as it is inside the area in Figure 3.5, with a margin of under 3 km from the actual location. Therefore, this script could become helpful for others who are using the NORA3 datasets since the user does not have to download several gigabytes of data when they are only looking at one speci c location.

Script for designing the energy system

The main script created for this thesis is created for the purpose of being a valuable tool when designing an energy system. This thesis uses wind speed data from the NORA3 dataset and consumption data from Ocean Farm 1. However, it is believed that any wind speed data set and consumption data can be used to give a rough estimate of the design of a wind/hydrogen energy system. The script uses wind speed- and consumption data as input and runs a simulation based on these inputs alongside other xed variables, which will be presented later in this chapter. As stated earlier, the input data has a resolution of 1 hour and therefore, each time step in the simulation is representing one hour. The simulation outputs give a rough estimate of the sizes of the different components in the energy system. However, some manual changes in the script are necessary to get the best results.

Several library modules have been used during the work, and a short description of the most used modules can be seen in Appendix 1. Finally, the usefulness of the two presented python scripts in the future will be discussed in Chapter 5.

3.4 Designing and Sizing the Energy system

The majority of this thesis is based on computations and simulations using data and information presented above. Two case studies are carried out to investigate the feasibility of an isolated energy system consisting of wind power and hydrogen to cover the power demand of a sh farm. Figure 3.6 displays the system schematic of the two studies. The wind/hydrogen system will be referred to as the WH2-system, and the wind/hydrogen/diesel system will be referred to as the hybrid system. The system schematic regarding the two systems is similar except for the diesel generator in the hybrid system. However, the sizing of the different components in the system is different. The two studies have already brie y been introduced at the start of this chapter. However, a more detailed description regarding power production from the wind turbines, the power demand at the sh farms, and the hydrogen system are provided below.

Figure 3.6: (a) System schematic of wind/hydrogen system, (b) System schematic of wind/hydrogen/diesel system.

3.4.1 Assumptions

A few assumptions were made before starting analysing and using the data to dimension the different components of the energy system. The assumption and explanations for each of them are listed below:

- The sh farms consumption always has to be covered - The effect of this is that if the amount of hydrogen stored ends up negative during one of the time steps in the simulation, the simulation stops, and changes have to be made.
- Start/Ramp-up times regarding the electrolyser, fuel cell, and wind turbine are neglected due to the resolution of one hour.

3.4.2 Power Demand

There is a gradual increase in the number of sh farms in the case studies, from one to eventually six facilities, over a time period of ve years. Thus, the total power demand increases during the case studies. This is done by using the created power consumption shown in Figure 3.4. Each time a new sh farm is connected to the isolated-grid, it uses the created demand, thus increasing the total power demand during the simulations. With this, the sh farms operate in different cycles, depending on what time of the year they are added to the isolated-grid.

3.4.3 Power Production

Since the wind speeds used from the NORA3 database were measured at 101 m.a.s.l, it is essential to calculate the corresponding wind speed at the height of the turbine rotor. This is emphasised in Section 2.2, where the importance of wind speed is showcased when it comes to the power density contained in the wind. There are several methods to interpolate wind speed, and both the logarithmic wind pro le law and the power-law have previously been presented. Both laws have been tested and compared before deciding which methods are more suitable for this thesis.

The power-law Equation 2.15 can be rearranged, and then the alpha values for each time step can be obtained. The rearranged power-law equation can be seen in equation 3.1.

$$a = \frac{\ln(\frac{v(z_2)}{v(z_1)})}{\ln(\frac{z_2}{z_1})} \tag{3.1}$$

The new wind speed for each time step can then be calculated using Equation 2.15 and the calculated alpha value. The other method is the logarithmic wind pro le law, previously shown in Equation 2.14. The roughness coef cient length used is 0.0002 m.

Power Production

The power production at the site is calculated by interpolation between power curves from different wind turbines and the wind speed at the turbine's hub height. This is performed for each time step with the "Interp1d" function in python. Information regarding the different wind turbines that have been compared in this work can be seen in Table 3.1.

Table 3.1: Wind turbine information [45, 46, 47].

Turbine Capacity	500 kW [45]	750 kW [46]	2300 kW [47]
Cut-in wind speed [m/s]	4	3-4	3.5
Rated Wind Speed [m/s]	15	15	15
Cut-out Wind Speed [m/s]	25	25	25
Tower height [m]	40.5/53	55	58.5-100

3.4.4 Hydrogen System

The ef ciencies used during the calculations regarding the hydrogen components in this thesis are obtained from the literature and datasheets available online. The different components used and their ef ciencies are shown in Table 3.2.

Table 3.2: Ef ciencies used for fuel cell, converter, compressor and desalination [25, 48, 49, 50].

Component	Ef ciency	Reference
Fuel cell	50 %	[25]
DC-AC Converter	98 %	[48]
Compressor	90 %	[49]
Desalination	99 %	[50]

Table3.2 shows that it is assumed that the fuel cell operates at a constant 50 % and that the losses regarding DC-AC conversion are 2 %. Ef ciencies regarding the compression of the hydrogen gas and desalination of seawater to be used during the electrolysis are 90 % and 99 %. When calculating the amount of hydrogen produced in kilos, the lower heating value of hydrogen used with its 33.33 kWh/kg [15]. Instead of using a constant ef ciency when it comes to electrolysis, data from the datasheet of NEL Hydrogens PEM MC250 electrolyser was used to create a simplistic electrolyser model [51]. Information regarding the electrolyser can be seen in Table 3.3.

Table 3.3: Information regarding the PEM MC250 electrolyser [51].

	Value
Net Production Rate: Nm^3/h @0 C, 1bar	246 Nm^3/h
Net Production Rate: kg/24 h	531 kg/24 h
Average Power Consumption at stack	4.5 kWh/Nm^3
Production Capacity Dynamic Range	10-100 %

The information stated above has been used to create a very simplistic electrolyser model. By multiplying the average power consumption at the stack and the net production rate of 246 Nm^3/h, the capacity of the electrolyser is stated to be 1107 kW. Since the daily net production rate is 531 kg/24h, the maximum amount of hydrogen produced each hour is 22.125 kg. Furthermore, from the dynamic range, it is stated that the electrolyser starts producing at 10 % of maximum capacity. The operational range of the created model is shown in Figure 3.7. In reality, is not the production rate linear, but for simplicity and lack of information, is it assumed for this thesis.

Figure 3.7: Operational range PEM MC250 electrolyser. It operates in the range of 10-100 % of the capacity.

3.4.5 Energy System

The energy systems, shown in Figure 3.6, are created by several steps during a simulation. The difference between produced power from the wind turbine(s) and the power demand from the sh farms is calculated rst for both systems. If the demand per hour is greater than the amount of energy produced from the wind turbine(s), there is a need for additional power. The additional power is provided by utilising hydrogen through a fuel cell for the WH2-system. For the hybrid system, is the remaining required demand covered by hydrogen if enough hydrogen is stored at that time step. If not, the power demand is covered by the diesel generators. For the time steps where power production from the wind turbine(s) is larger than the power demand, surplus power can be used to produce hydrogen.

Whenever there is surplus energy available for hydrogen production, there are a few options. If the amount of available power is between the production range set for the electrolyser, is interpolation used to calculate the amount of hydrogen produced given the available power. If the amount of power is larger than the capacity of the electrolyser, the production is set to max, which is 22.125 kg of hydrogen. Furthermore, there is no production if the amount of power is less than the minimum limit, which is 10 % of the maximum capacity.

During underproduction from the wind turbine(s), there is a need for additional power in the form of hydrogen. Equation 3.2 shows how the amount of hydrogen needed each hour in kilos is calculated.

$$\text{Amount of Hydrogen [h]} = \frac{\text{Amount of power needed [h]}}{\text{Hydrogen}_{LHV} \quad h_{\text{FuelCell}} \quad h_{\text{Inverter}}} \tag{3.2}$$

Where,

- Amount of Hydrogen [h]: Amount of hydrogen required during that time step in order to cover the power demand.
- Amount of power needed [h]: Power demand during that time step
- Hydrogen_{LHV}: Gravimetric Energy Density of Hydrogen (33.33 kWh/kg)
- h_{FuelCell}: Fuel cell ef ciency
- h_{Inverter}: Inverter ef ciency

The values for the different parts of the equation can be seen in Section 3.4. For each time step is the difference between hydrogen utilised and produced calculated and put into a cumulative list to get an overview of the amount of hydrogen stored over time. This overview is a critical aspect of the WH2-system since one of the assumptions is that there always has to be available power to cover the consumption. Therefore, if the hydrogen storage at some point is completely emptied, the simulation is stopped. Changes to either wind turbine capacity or hydrogen storage capacity have to be made before a new simulation can start. However, hydrogen storage is not that important for the hybrid system since the diesel generator kicks in whenever the hydrogen storage is empty.

3.4.6 Monte Carlo Simulation

In order to get a deeper understanding on how the variability in wind speeds could affect the energy production from the wind turbines was a sensitivity analysis in form of a monte carlo simulation performed. The code is built up similar to whats described above, but in stead of using wind speed data from 2003 to 2008 is a pile of random years ranging from 1996 to 2019 used. The simulation is run 1000 times where each simulation picks 20 random years of wind speed data from pile. The pile is divided into normal years and leap years in order to get the simulation to run smoothly. The program picks 15 normal years and ve leap years, and when a year is picked is it unable to be picked again for a given simulation. After the monte carlo similation is performed, is it possible to see how many outcomes of negative hydrogen storage there is during 1000 different simulations.

3.4.7 Economics

This economical section was added to estimate the two case studies potential investments, cash ows, and pro tability. This is done by calculating the net present value of the project, see Equation 3.3.

$$NPV = \sum_{t=1}^{n} \frac{A_t}{(1+i)^t} \quad I_0 \tag{3.3}$$

- A_t = Net cash ow during period t
- t = Number of years

- i = Discount rate
- I_0 = Investment the first year

Net cash flow includes the operational costs for each year, the future investments after the first year, and the savings in diesel usage and CO_2 taxes. The calculated net present values in Chapter 4 use a discount rate of 7 %, which is slightly higher than rates that are used in other publications. The Levelized Cost of energy is also calculated with the formula shown in Equation 3.4. LCOE is used to compare different methods of energy production and shows the average cost of the building and operating the system per unit of produced energy [52].

$$LCOE = \frac{\sum_{t=1}^{n} \frac{A_t}{(1+i)^t} + I_0}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{3.4}$$

- E_t = Energy consumption during period t

The NPV of the total cost is calculated as presented above. However, the potential savings regarding fuel and taxes are removed during the calculation of LCOE. Usually, the LCOE is calculated by using the total amount of produced power. However, in this thesis, it is calculated by using the total power demand. The reason behind this is that not all of the energy produced is utilised during the simulations, so it was decided to perform it like this. The different prices for each of the components used during the investment calculations can be seen in Table 3.4 below. Table 3.5 shows the values used when calculating the running expenses for each year.

Table 3.4: Investment cost used for each of the components [53, 26, 19, 13, 54, 55].

Component	Cost	Reference
Wind Turbine	57 MNOK/MW	[53]
Fuel Cell	10 MNOK/MW	[26]
Electrolyser	15 MNOK/MW	[19]
Hydrogen Storage Tanks	0.35 - 10 MNOK/tonnes	[13]
Diesel Generator	4 MNOK	[54]
Stack Replacement	60 % of CAPEX	[55]

Table 3.5: Operation and Maintenance costs [53, 56, 54, 57].

Component	Cost	Reference
Wind Turbine	0.65 MNOK/MW	[53]
Fuel Cell	4 % of CAPEX	[56]
Electrolyser	4 % of CAPEX	[56]
Diesel Generator	4 % of CAPEX	[56]
Diesel (fuel)	15 NOK/l	[54]
CO_2-tax	2000 NOK/kg	[57]

The different capital cost for the different components varies from source to source, and many are expected to decrease in the future. Therefore, the different prices stated

above are a rough estimation and include prices that likely are outdated and prices that are yet to be reached. The investment cost regarding wind turbines includes the floating foundation cost [53]. The operational cost is estimated to be 4 % of the investments costs each year for the fuel cell, electrolyser and diesel generator after reviewing several scientific articles [19, 56]. The net present value and LCOE are calculated with a low, medium, and high-cost scenario because of the uncertainty in hydrogen storage cost at the seabed. The reflection behind the estimated hydrogen storage price is further elaborated in Chapter 5. The cost of diesel is hard to predict because of various events like covid and the war in Ukraine, and it is therefore assumed to be 15 NOK/l. The CO_2 tax is estimated to reach 2000 NOK/kg in 2030 [53], and for simplicity, reasons assumed to be constant [57].