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.

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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" [7]. We carried out three case studies in order to explore the feasibility of floating photovoltaic powered hydrogen plants and different locations. The first case study was related to an off-grid facility at the coast of western Norway. We investigated the feasibility of covering a consumption with floating 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 fish 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 fish 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 fish 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 fish 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 officially 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 fish 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 fish 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 fish 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 fish 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 fish 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 significant 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 simplified 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.

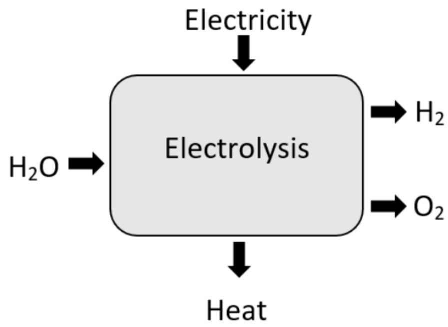


Figure 2.1: Principle of electrolysis [7].

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.

$$\text{Anode: } 2OH^- \rightarrow \mathrm{H_2O}_{(g)} + \frac{1}{2}\mathrm{O}_{2(g)} + 2e^- \tag{2.1}$$

$$\text{Cathode: } 2\mathrm{H_2O}_{(l)} + 2e^- \rightarrow \mathrm{H}_{2(g)} + 2OH^- \tag{2.2}$$

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

AWE is best suited to operate at constant power due to low operating pressures, limited current densities, and low energy efficiency [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.

$$\text{Anode: } \mathrm{H_2O}_{(l)} \rightarrow 2H^+ + \frac{1}{2}\mathrm{O}_{2(g)} + 2e^- \tag{2.4}$$

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

$$\mathrm{H_2O}_{(l)} \rightarrow \mathrm{H}_{2(g)} + \frac{1}{2}\mathrm{O}_{2(g)} \tag{2.6}$$

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 efficiency. 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
Efficiency [%]	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/m3 [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 (H_0LOHC). 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 significant problem with the availability of light materials that have sufficient 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 scientific 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 simplified 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.

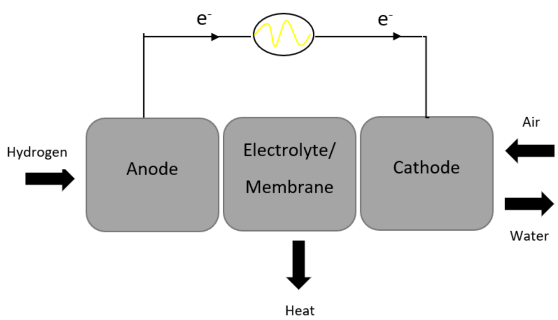


Figure 2.2: Principle of fuel cell [7].

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.

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

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

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 Nafion, 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 flows 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.

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

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

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-efficient 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]
Efficiency [%]	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 [5]. 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 efficiency 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 efficiency, or power coefficient, of a wind turbine, can be seen in Equation 2.12.

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

The average efficiency 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 efficiently [28].

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

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 sufficient 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 figure 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 field tests and standardised wind turbine testing methods.

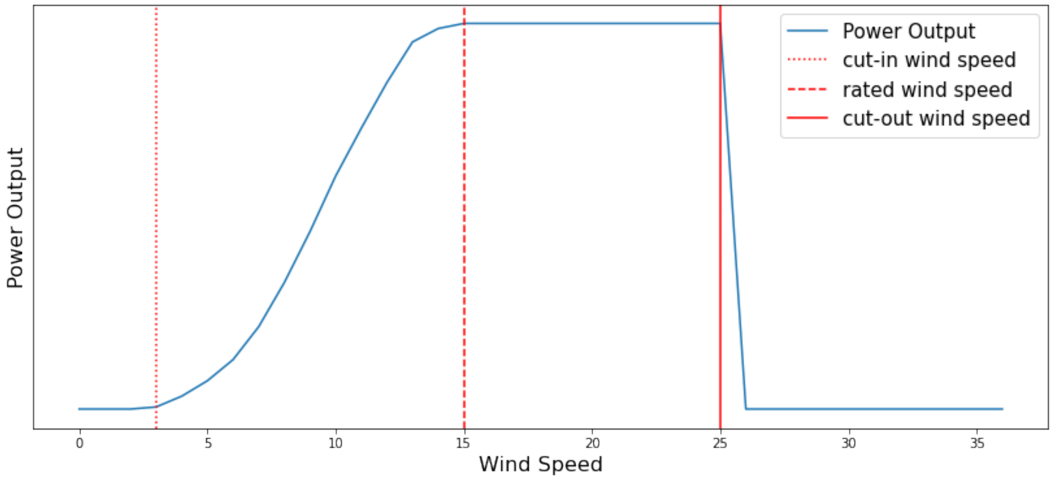


Figure 2.3: The wind turbines power curve displays the increase in power production, cut-in speed, rated speed, and cut-out speed.

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 first 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 option [30]. However, more significant 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 classified as grounded or floating 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.

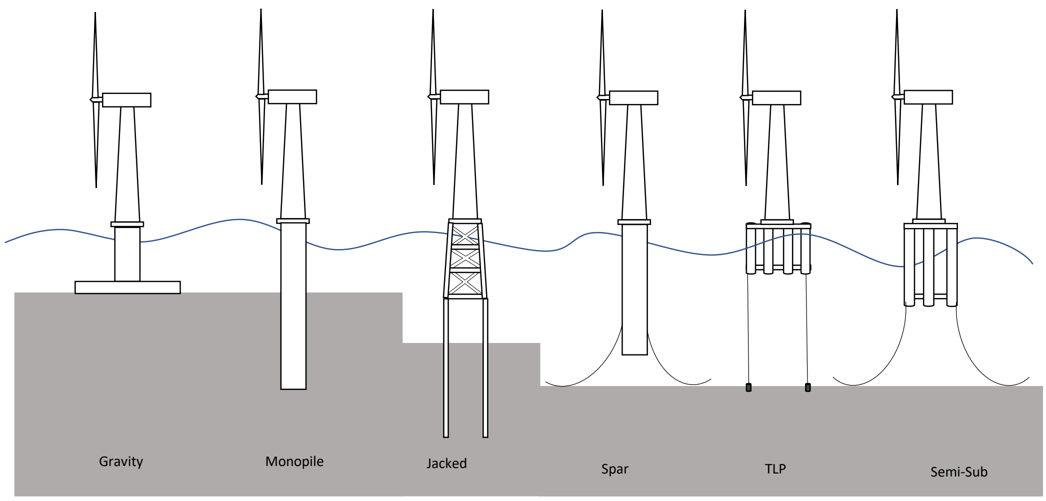


Figure 2.4: An illustration of different offshore foundations for wind turbines at increasing water depths.

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 sufficient 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 fixed foundations are constrained to water depths down to 50-60 m. In order to harvest power from areas with significant wind resources at deeper depths, floating 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 floating 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 Profile Law and the Power Law. These two are further explained in the following subsections.

Logarithmic Wind Profile Law

The logarithmic wind profile 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 coefficient length. This coefficient 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.

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

Here $v(z_r)$ and z_r are the reference wind speed and height, and $v(z)$ is the wind speed at height z. In addition there is the power law exponent α, 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 α value. However, in many cases with stable conditions are α 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 fields in the area, Snorre and Gullfaks .

2.3 Energy Demand at Fish Farms

The energy demand at a fish farm varies from the different facilities due to size, amount of fish 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 fish 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 fish 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.

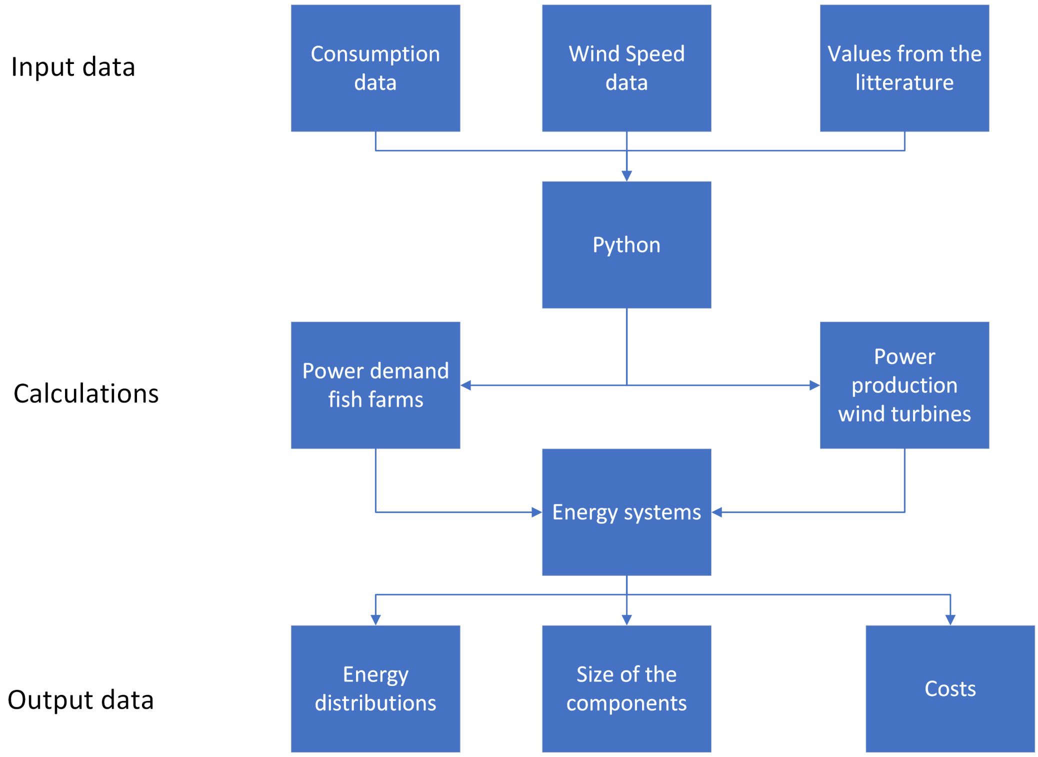


Figure 3.1: Overview of the methods in this thesis.

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 fish 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 fish farms would increase from one to six over five 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 first case study aims to design an energy system consisting of wind power and hydrogen to cover the demand of the increasing number of fish farms. First is the first 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 fish 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 first 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 fish 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 fish farms directly or industry clusters with connections to the fish farming industry. Firstly, consumption data from E.Karstensen's fish farm at Langeråa, located outside of Florø, was obtained. However, this fish 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 first offshore fish 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 fish farm. The water depths at the location of the fish 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 fish 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 fish farm is feeding the fish. During the two years of power consumption data that was given, there was fish 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.

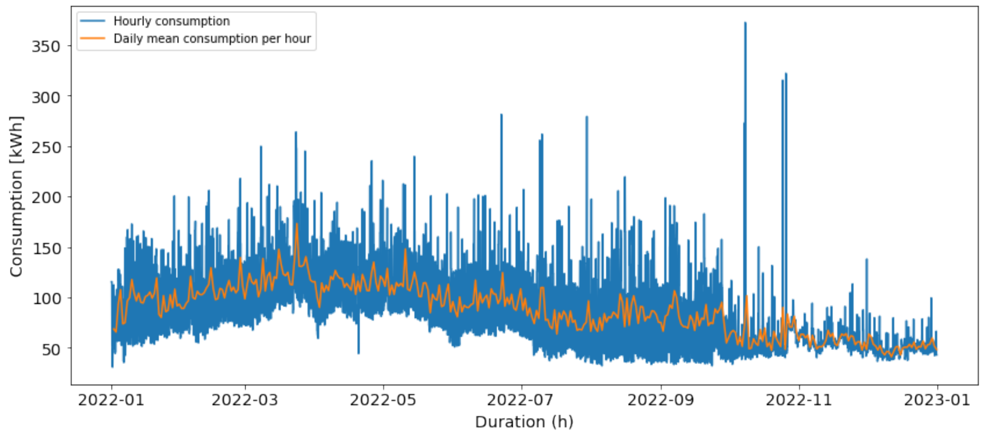


Figure 3.4: Yearly consumption modified. The blue line represents the hourly consumption and the orange line represents the hourly mean consumption each day.

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].

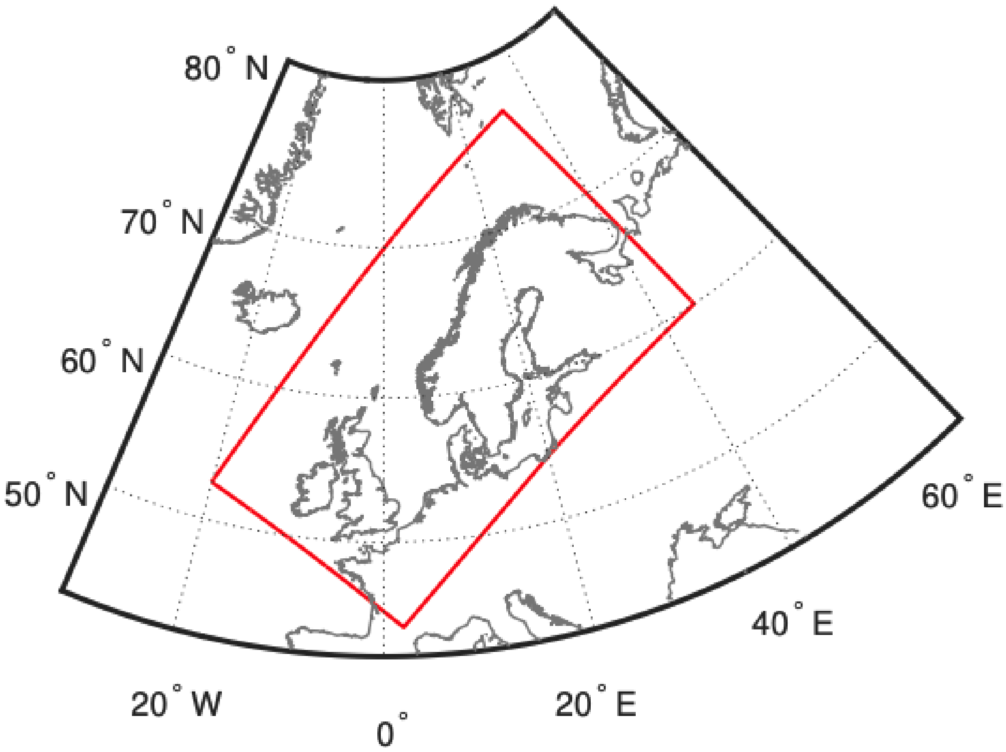


Figure 3.5: The geographical domain covered by NORA3-WP (red rectangle) [44].

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 significant 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 specific 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 fixed 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 fish 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 briefly 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 fish farms, and the hydrogen system are provided below.

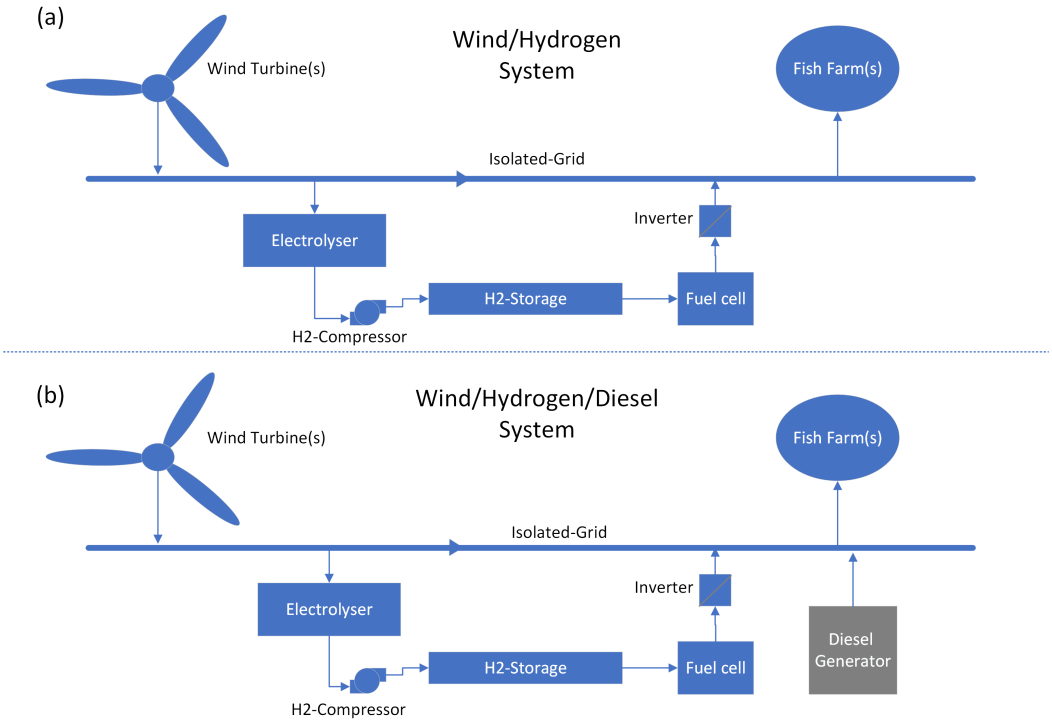


Figure 3.6: (a) System schematic of wind/hydrogen system, (b) System schematic of wind/hydrogen/diesel system.

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 fish 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 fish farms in the case studies, from one to eventually six facilities, over a time period of five 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 fish farm is connected to the isolated-grid, it uses the created demand, thus increasing the total power demand during the simulations. With this, the fish 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 profile 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.

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

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 profile law, previously shown in Equation 2.14. The roughness coefficient 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 efficiencies 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 efficiencies are shown in Table 3.2.

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

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

Table 3.2 shows that it is assumed that the fuel cell operates at a constant 50 % and that the losses regarding DC-AC conversion are 2 %. Efficiencies 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 efficiency 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.

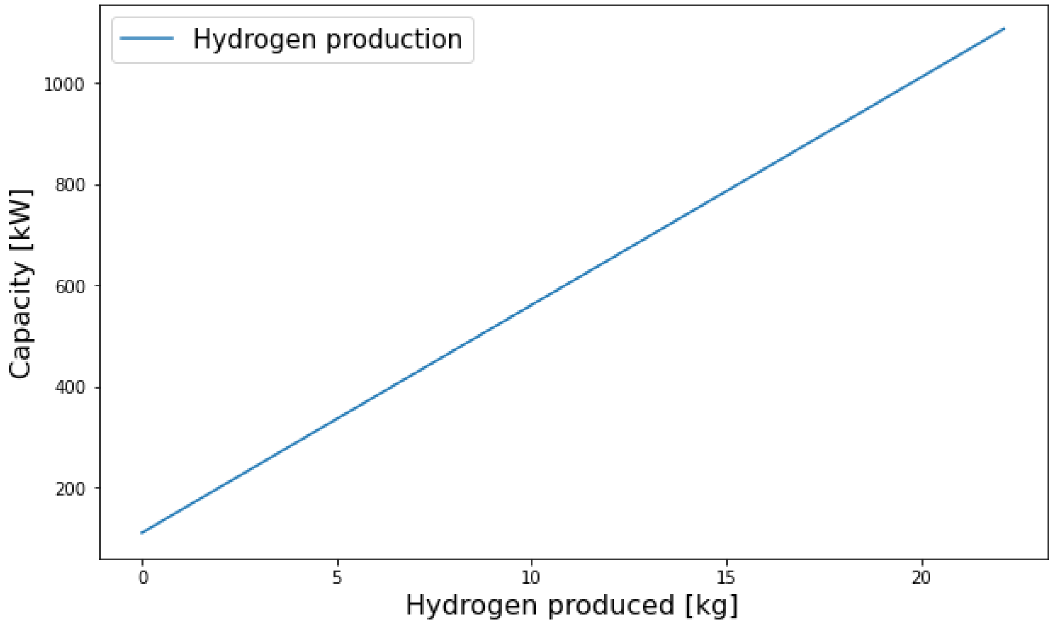


Figure 3.7: Operational range PEM MC250 electrolyser. It operates in the range of 10-100 % of the capacity.

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 fish farms is calculated first 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.

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

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)
- $\eta_{FuelCell}$: Fuel cell efficiency
- $\eta_{Inverter}$: Inverter efficiency

The values for the different parts of the equation can be seen in Section 3.4.4. 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 five 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 flows, and profitability. This is done by calculating the net present value of the project, see Equation 3.3.

$$\text{NPV} = \sum_{t=1}^{n} \frac{\text{A}_t}{(1+i)^t} - \text{I}_0 \tag{3.3}$$

- A_t = Net cash flow 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].

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{\mathrm{A}_t}{(1+i)^t} + \mathrm{I}_0}{\sum_{t=1}^{n} \frac{\mathrm{E}_t}{(1+i)^t}} \tag{3.4}$$

- 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].

Chapter 4

Results

This chapter presents the results of the work done for this thesis and is built up with a similar structure as in Chapter 3. A visualisation of the energy system can be seen in Figure 4.1. In this chapter, all of the different aspects of this figure will be accounted for. First is the increasing power demand from the fish farms presented before the wind turbines power production follows. Then, the results of the two case studies will be presented, including sizing of the different components related to hydrogen production, storage, and utilisation, the number of wind turbines necessary to power the fish farms, and the economics.

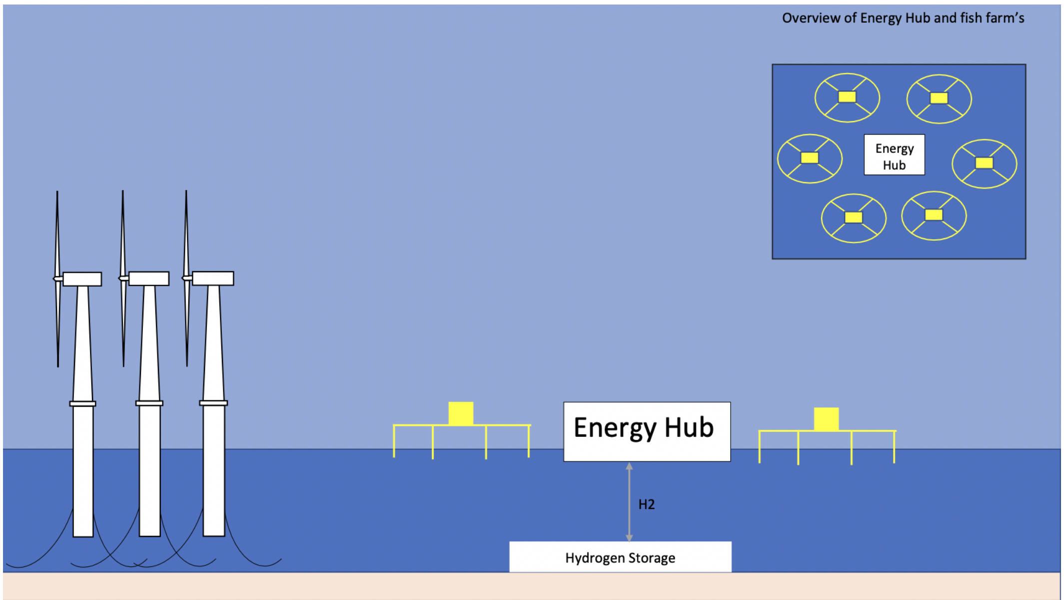


Figure 4.1: Illustration of the energy system which consist of wind turbines, an energy hub which includes electrolysers, fuel cells, diesel generators (case study 2) and the six fish farms, as well as the hydrogen storage.

4.1 Consumption

As mentioned in Section 3.4.2, it was decided to carry out two case studies where the number of fish farms connected to the energy hub would increase over time. This decision was made since it is more realistic than a study where six fish farms the size of Ocean Farm 1 would start operating simultaneously. The corresponding increase in power consumption for this period can be seen in Figure 4.2. The red dots in the figure show when a new fish farms gets connected to the energy hub. The blue and orange lines show hourly and daily mean consumption. The maximum hourly consumption over this period is 1188 kW, and from the first to the last year, the total yearly consumption increased from 648 MWh to 4640 MWh.

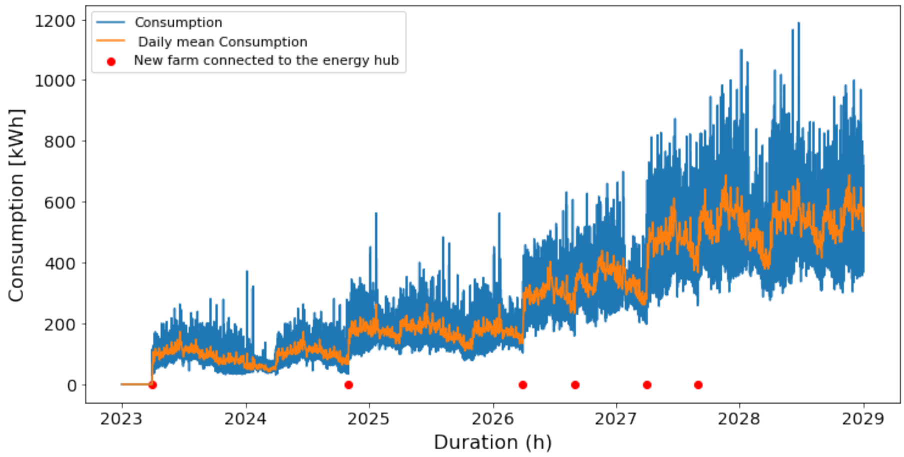


Figure 4.2: Consumption 2023-2028: The blue and orange line's displays the hourly consumption and the daily average. The red dots displays when a new farm is connected to the energy hub.

The suggested schedule that SalMar Aker Ocean provided stated that the first facility was set to operate from the 1st of April 2023 [39]. It was decided that the period for the case studies was set to start from the 1st of January 2023. The complete schedule for when each of the fish farms would be set to operate is as follows:

- Farm 1: April 2023
- Farm 2: November 2024
- Farm 3: April 2026
- Farm 4: September 2026
- Farm 5: April 2027
- Farm 6: September 2027

4.2 Wind Power

This section compares the two methods of wind speed extrapolation presented earlier in this thesis before a method is decided. Then, the extrapolated wind speeds are used to calculate the power production for the selected wind turbine. The wind speed data used during this section is from 2003-2008.

4.2.1 Interpolated Wind Speeds

The NORA3 wind speed is at 101 m, and these had to be interpolated to the hub height of the selected wind turbine. Both power- and log law have been tested and compared before selecting the preferred method for wind speed interpolation in this thesis. Both laws were used to interpolate the wind speeds from the height of 101 m.a.s.l to 55 m.a.s.l, which is the height of the selected wind turbine. The alpha values for each time step were obtained using Equation 3.1 for the power-law, and the roughness length used for the log-law was constant at 0.0002 m for each time step.

The mean wind speed over the six years was 9.4 m/s when using the power law and 9.5 m/s when the log law was used. However, a visual comparison of the two methods also showcased several outliers regarding the power law usage, as shown in Figure 4.3. Because of these outliers, sometimes with wind speeds over 100 m/s, and the power law had a lower mean wind speed, it was decided to use the interpolated values obtained with the log law during the remainder of the calculations.

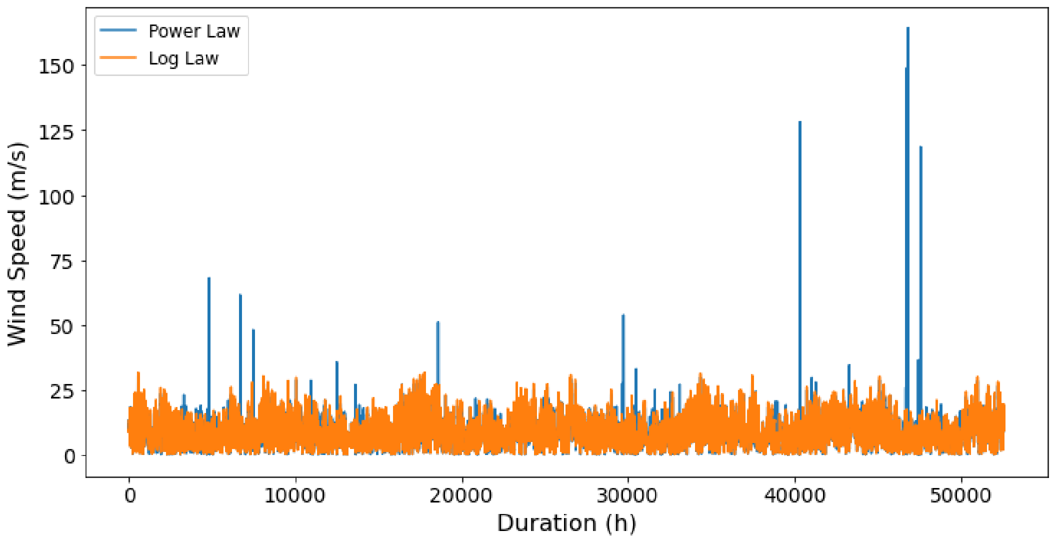


Figure 4.3: Comparison of wind speeds extrapolation methods at 55 m.a.s.l.

4.2.2 Power Production

Three different theoretical wind turbines, with a capacity ranging from 500 kW to 2.3 MW, were compared before it was decided to use the wind turbine with a capacity of 750 kW. The selection of the desired wind turbine was not only due to power production. The 2.3 MW wind turbine was not used since it would produce massive amounts of waste power during the early stages of the case studies, and the 500 kW one was not used since it would mean that the number of turbines needed would have increased. Information regarding the turbines can be seen in Table 3.1.

The turbine tower height is 55 m, so the wind speed had to be interpolated to this height, as explained earlier in this chapter. During the six years, with the selected wind data, is 19.28 GWh of energy produced from one wind turbine of this size with a capacity factor of 48.8 %. A capacity factor of almost 50 % is a good indication of great wind resources, and it is backed by how rarely there is no production at all from the turbine, with only 9.4 % of the time. In addition to this, the wind turbine produces maximum power nearly 15 % of the time. Figure 4.4 shows how often during the period each wind speed occurs and the power production by the turbine at that speed.

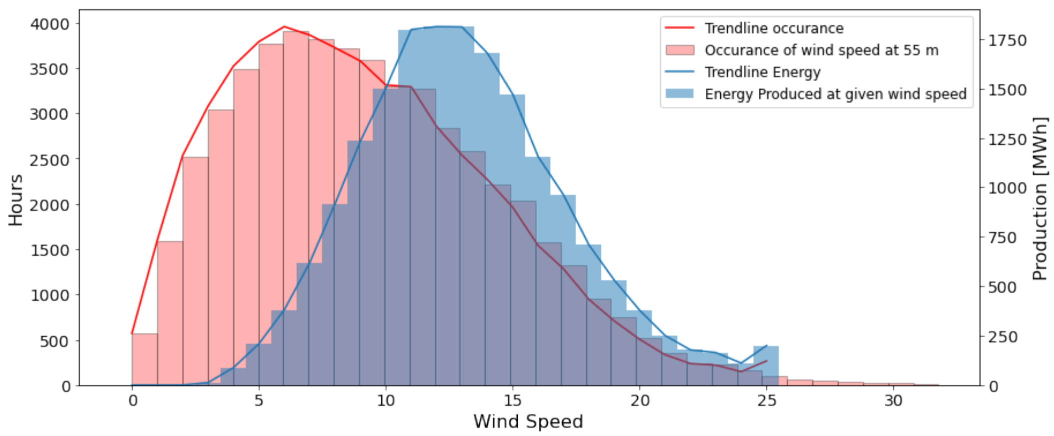


Figure 4.4: Occurrence of the different wind speeds (red) and corresponding production by a 750 kW wind turbine (blue) with NORA3 wind speed data from 2003-2008.

The figure shows that the highest energy production is when the wind speed is 12 m/s with a production of 1.81 GWh. However, the red part of the figure, which shows each wind speed occurrence, shows that the most common wind speed is 6 m/s. The wind speed with the highest power coefficient of 45.2 % is 8 m/s, which means that the turbine utilises the energy contained in the wind best at this wind speed. The calculated power coefficient for each wind speed can be seen in Appendix .2.

The produced power each month during the six years for the 750 kW wind turbine is displayed in Figure 4.5. The annual variations regarding wind speeds, presented in Chapter 2, are visible in the figure. The power production is high during the winter months and low during the summer months. This variation showcases why hydrogen could provide synergies well alongside wind power. When the power production is high during the winter months, surplus energy can be used for hydrogen production. Furthermore, during the summer, when the output is scarce, as shown in the figure, can the produced hydrogen again be used to cover the remaining potential consumption.

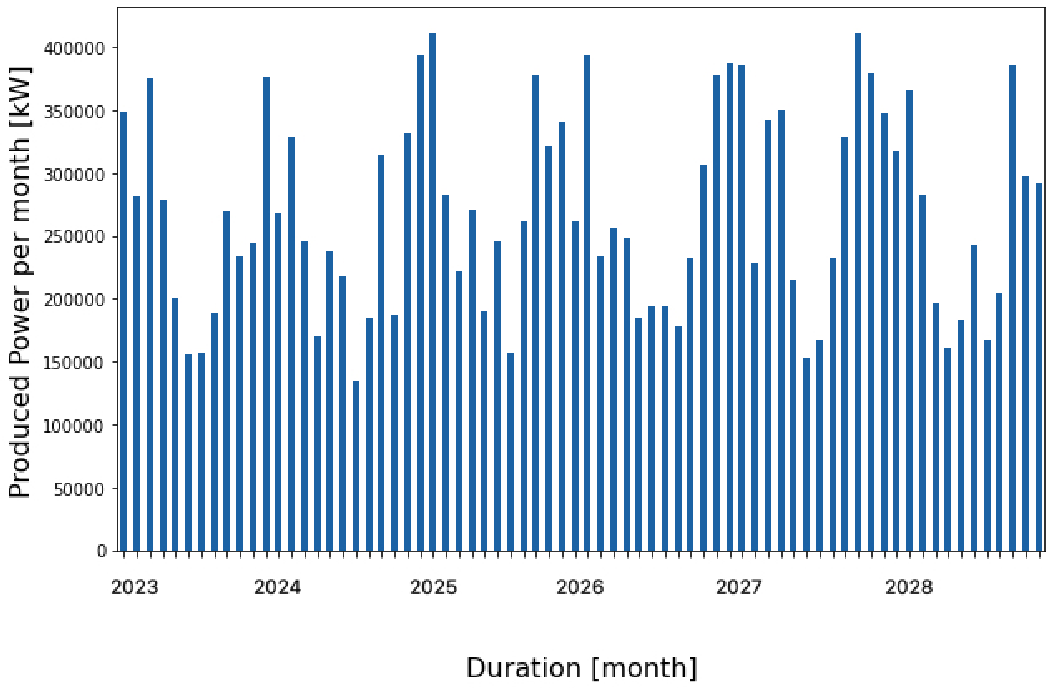


Figure 4.5: Power Production each month during the six year period.

4.3 Case study 1 - Wind Power and Hydrogen

This section will present the results of the simulations conducted when designing the WH2-system in Figure 3.6. First, the first six years of operation will be presented to show how the energy system develops during increasing power demand. Then, the same system will be presented over 20 years to see if any changes have to be made to cover the fish farms' demand. Lastly, the net present value and the Levelized cost of energy for the study are presented using values from Tables 3.4 and 3.5. This first case study aims to design and size an energy system that can cover the required consumption of the fish farms with energy from only wind power and hydrogen.

During the six years, power consumption and estimated power production are compared hourly. As explained in the previous chapter, this was performed during several simulations, assuming that the consumption always had to be covered by either wind power or hydrogen from the storage. The simulations showed that it was necessary to have three of the 750 kW wind turbines connected to the energy system to cover the consumption.

4.3.1 The Energy System

Since the consumption is gradually increasing depending on how many fish farms are connected to the energy hub, the number of turbines also needs to increase to cover the rising energy demand. When in time, each fish farm and the wind turbines start operating is illustrated in Figure 4.6, alongside the consumption, actual stored hydrogen, and the hydrogen that could have been stored without limitations in the storage capacity. The first turbine starts production from the first time step, the second starts when fish farm number four starts operating, and the last starts when the final fish farm is set to operate. The selection of when turbines two and three start to operate is due to the rapid decrease in hydrogen storage due to the lack of power from the wind turbines. The decrease in hydrogen storage occurs after fish farms three and five are set in operation and results from higher consumption, insufficient installed wind power capacity, and less wind during the summer months. The decision to install new turbines when needed is an individual decision for this thesis. In reality, it could be better to install all turbines simultaneously. This will be discussed further in Chapter 5.

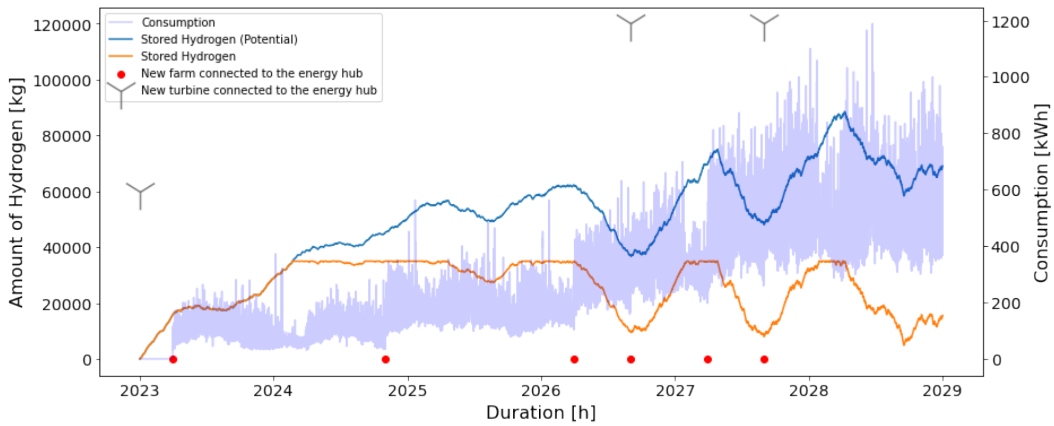


Figure 4.6: Amount of hydrogen stored 2023-2028: The blue and orange line's displays actual and potential amount of hydrogen stored during the simulation. The orange line is limited to 35 tonnes of hydrogen stored. The red dots shows when each of the fish farms start operating and the wind turbine symbols shows when a new turbine start operating. The increasing power demand is displayed in shaded gray.

Sizing of hydrogen storage

The blue and orange lines in the figure show the amount of stored hydrogen in the storage during each time step of the simulated period. The blue line indicates that, without any storage limitations, approximately 90 tonnes of storage capacity would be required. This would be very expensive, even if there is considerable uncertainty regarding the storage cost. Therefore, the hydrogen storage limit was set to 35 tonnes. This is the lowest storage capacity needed to constantly supply the fish farms with energy when hydrogen is required, and it is shown with the orange line in Figure 4.6.

Figure 4.6 shows that the hydrogen storage increases from the first time step due to the first fish farm not operating before the 1st of April in the simulation. This decision gives the possibility of creating a buffer of hydrogen stored before the first fish farm starts to operate. The storage is filled up during the first year and is stable through the first three years of operation. However, as mentioned above, the amount of hydrogen stored variates after the third fish farm is connected to the energy hub. The variation results from low wind speeds during the summer months and the installed wind turbine capacity being too low while the power demand increases. Thus, is new wind turbines added to increase the capacity and thus produce more hydrogen. At the end of the simulation, approximately 1/3 of the storage volume filled up. Details regarding hydrogen production and utilisation will be presented in the following sections.

Power available to hydrogen production

During each time step of the simulation, the difference in power demand and produced power from the turbines are calculated. If the production is higher than the demand, surplus energy could be used to produce hydrogen. Figure 4.7 displays the distribution of surplus energy after the wind turbines have covered the power demand from the fish farms. During the simulation, there was surplus energy, which could be used for hydrogen production, 65.5 % of the time. However, from the figure, it can be seen that a substantial amount of this energy lies outside the range of the hydrogen production due to the selection of a single PEM MC250 electrolyser. Therefore, all of the energy from 0 kW to the yellow line in the figure is going to waste since it is too low to start hydrogen production.

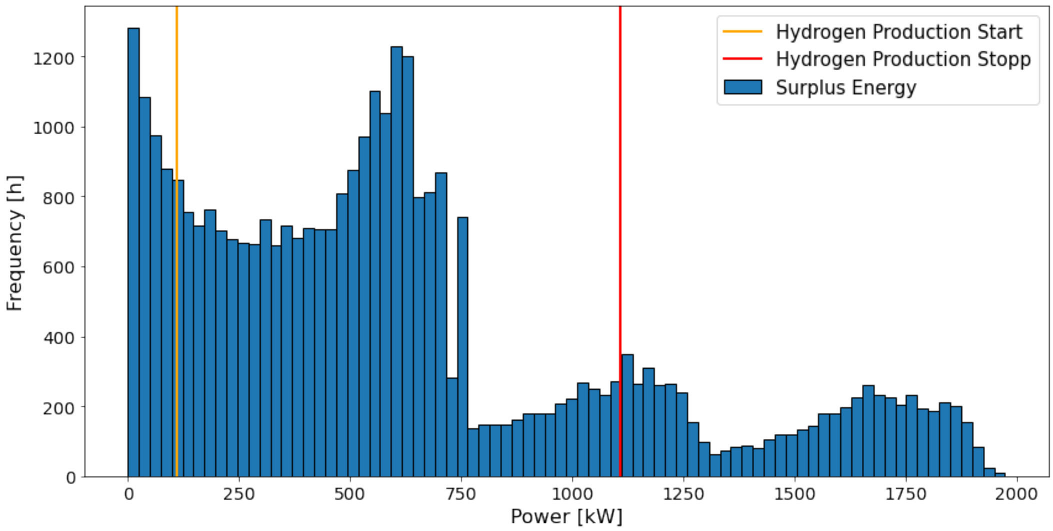


Figure 4.7: Distribution of surplus energy during the six year period. Yellow and Red line showcases when the electrolyser start and stops production.

Furthermore, for surplus energy higher than the electrolyser capacity of 1107 kW, all of the remaining energy after hydrogen production goes to waste. More on waste power will be further elaborated on later in this chapter. The electrolyser produced a total of 251.2 tonnes of hydrogen during the simulation period from the amount of energy that lies within the range of production, and most of it was used during periods where it was required.

Power demand is higher than power production from wind turbines

The simulation showed that the power demand from the fish farms was higher than the wind turbines could provide, 34.5 % of the time. Therefore, the remainder of the demand is covered by utilising hydrogen through a fuel cell. Figure 4.8 shows the load distribution that the fuel cell has to cover. The fuel cell had to cover a load in the range of 0.1 - 200 kW most of the time. However, the fuel cell is sized after the highest consumption during this period, 1188 kW. During the simulated period, it was only 644 hours, or 1.2 % of the time, when the fuel cell had to cover a demand above 600 kW. However, with a maximum required load of 1188 kW, a fuel cell efficiency of 50 %, and some other losses, the fuel cell capacity needed to be 2500 kW. In order to cover the remaining energy demand, 235.7 tonnes of hydrogen was utilised through this simulation.

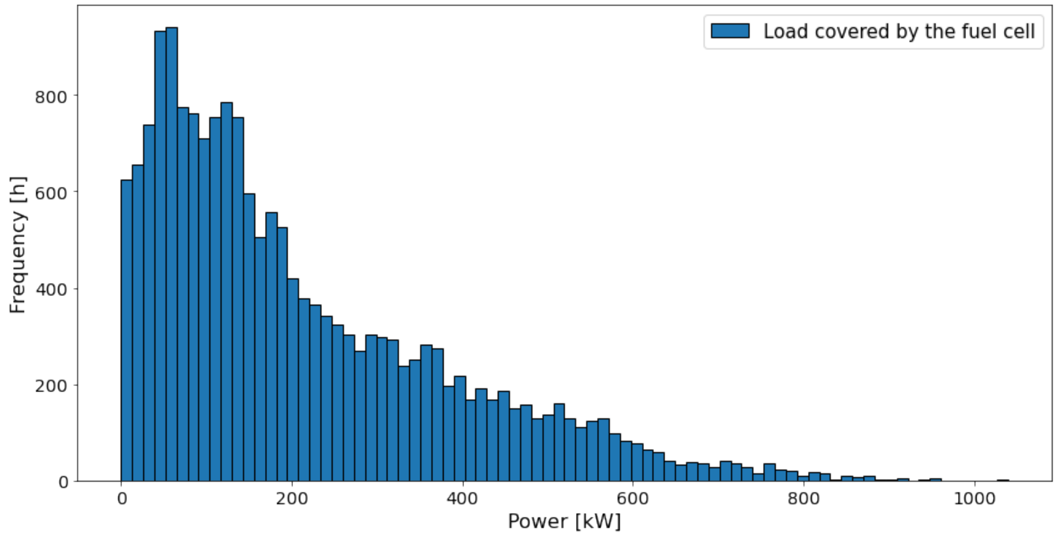


Figure 4.8: Required energy that the fuel cell has to provide.

Wasted Power

All of the produced energy goes to the grid for grid-connected wind turbines, and all of the produced energy is utilised. However, for an isolated energy system this is difficult. As mentioned above, some surplus energy is not utilised. During the simulation, a considerable amount of surplus energy goes to waste. 6.3 GWh, which is 21 % of all the energy produced during the period, is not utilised for several reasons. Most of the waste energy is lost due to the limitation in hydrogen storage capacity, where 3.7 GWh is lost due to no hydrogen production because the storage is filled. This corresponds to 54 tonnes of hydrogen that could have been used for other purposes. The remaining waste power came from the limitations of the created electrolyser model in Chapter 3, shown in Figure 4.7. If surplus energy after the covered consumption is lower than the 10 % of maximum capacity, it will count as waste. Furthermore, if the amount is larger than the maximum capacity for the electrolyser, is the remaining surplus energy after hydrogen production also wasted. A more detailed description of the limitations regarding the electrolyser was explained above and showcased in Figure 4.7. The limitation to this electrolyser model and the losses regarding storage limitation will be further discussed in Chapter 5.

Energy supply

So far has, the processes regarding hydrogen production and utilisation been presented. Furthermore, although hydrogen is needed 34.5 % of the time to cover the demand, wind turbines will be the primary energy provider for the fish farms. Figure 4.9 illustrates this by displaying the shares of the energy supply. It shows that 73.1 % of the fish farm's consumption is covered by wind power, and the remainder is covered by the fuel cell. The turbines powers the fish farms by themselves 65.5 % of the time, and the fuel cell covers the consumption alone for 9.4 % of the time. The turbines and the fuel cell operate together for the remaining time to cover the demand. Finally, in Table 4.1, some of the presented results above are summarised.

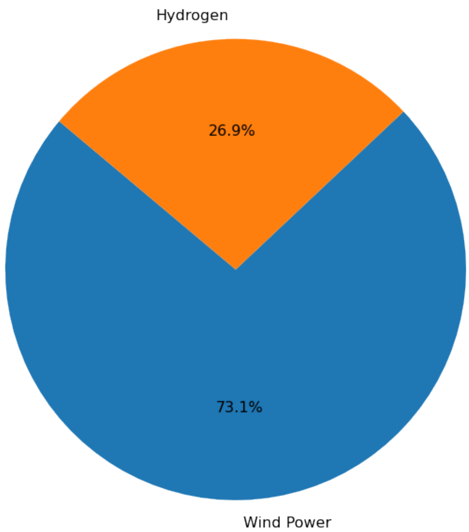


Figure 4.9: Share of energy supply during the period 2023-2028.

Table 4.1: Key information from the energy system during six years.

Results of the simulation		
Total production by wind turbines	31.8	GWh
Total Consumption fish farms	14.3	GWh
Wind power to cover demand	10.4	GWh
Power to hydrogen production	15.1	GWh
Total of waste power	6.3	GWh
Amount of hydrogen produced	251.2	Tonnes
Amount of hydrogen utilised	235.7	Tonnes
How often additional power is needed	34.5	%

Annual development of the energy system

Until now, the results have been presented for the whole period. To better understand the evolution of the energy system and how it works, the following sections will provide a more in-depth look at the results. Table 4.2 presents almost the same information as Table 4.1, but for each year, and shows how the system develops over time.

Table 4.2: Key information from the energy system (yearly).

Findings/Year	1	2	3	4	5	6	Total
Production wind turbines [GWh]	3.11	3.02	3.34	4.49	8.54	9.29	31.8
Consumption fish farm [GWh]	0.65	0.92	1.54	2.51	4.06	4.64	14.3
Covered by wind [%]	73.1	79.07	75.01	69.65	75.18	71.43	71.1
How often additional power	34.5	29.63	35.17	42.04	35.56	39.19	34.5
Hydrogen utilised [Tonnes]	10.78	11.80	23.60	46.70	61.63	81.16	235.69

The table shows that produced power is three times as high during the last year as during the first year, which is reasonable since the installed wind capacity has increased with the same amount. The same shows for the consumption, which is a bit more than six times as high during the last versus the first year. However, the amount of hydrogen used each year increased to almost eight times during the last year. Figures 4.10 and 4.11 partly show this by displaying the consumption and power production for two weeks during the first and last year.

Figure 4.10 displays the hourly power demand and power production from the wind turbines for two weeks during the first year of the simulation. The figure shows that most of the time, the power production is higher than the demand. However, when the demand is higher, the fuel cell only has to deliver power ranging from a bit under 100 kWh to almost 200 kWh, which is the difference in power demand and production. The fuel cell must consume approximately 12 kg of hydrogen to produce 200 kWh. The figure also shows that there is enough surplus energy when the consumption is covered that the amount of hydrogen used from the storage tank can quickly be replaced. The electrolyser uses approximately 600 kWh to replace the 12 kg of hydrogen.

Figure 4.11, on the other hand, shows that when the demand is higher than the produced power, the fuel cell has to cover up to almost 1000 kWh at some points and thus draining the storage faster. It also shows that the occurrence of surplus energy is much lower. Nevertheless, when there is surplus energy, it is rarely enough to replace what has been used. Hence, the hydrogen storage will be drained over time.

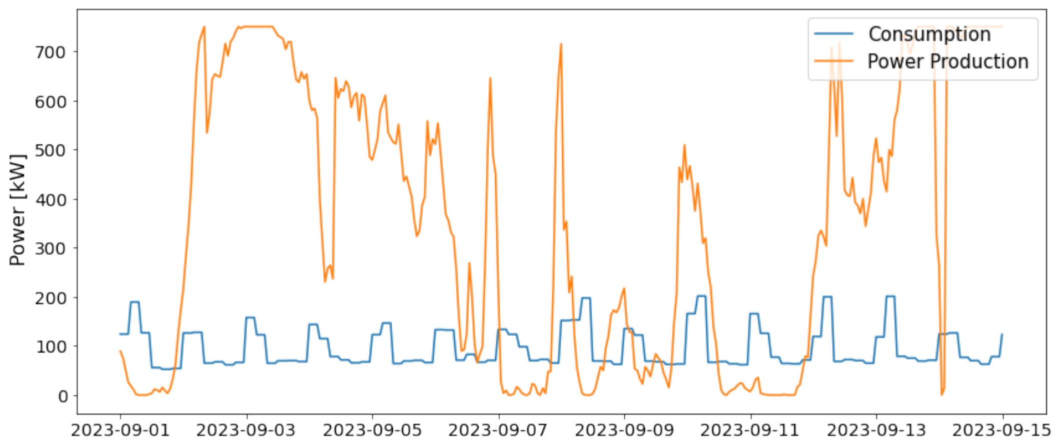


Figure 4.10: Consumption and power production during two weeks in 2023.

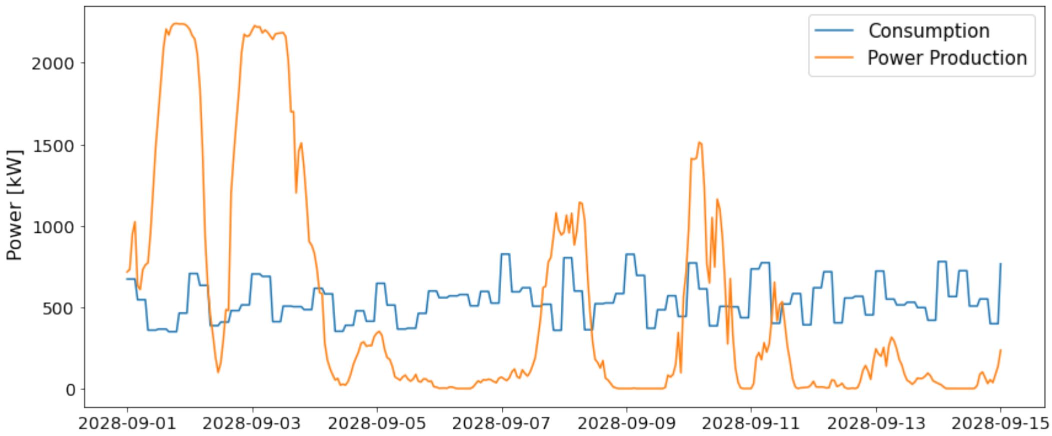


Figure 4.11: Consumption and power production during two weeks in 2028.

Extension of the time period

The results above show that the designed energy system, which consisted of three wind turbines, the electrolyser, 2.5 MW fuel cells, and 35 tonnes of hydrogen storage capacity, covered the power demand of the fish farms during the six years. However, the lifetime of a project like this is several years longer, and the number of time steps in the simulation is increased to 20 years since wind speed data is available for this long. Therefore, historical wind speed data from 2000 to 2019 have been used to calculate the produced power during the simulation.

This simulation showed that with no changes to the number of wind turbines or the storage capacity for hydrogen, it would not be possible to cover the power demand during this extended period. Therefore, there were necessary to either increase the storage capacity substantially or add another wind turbine and increase the storage capacity. As shown in Figure 4.12, it was decided to add one turbine and increase the hydrogen storage capacity from 35 to 55 tonnes to cover the power demand.

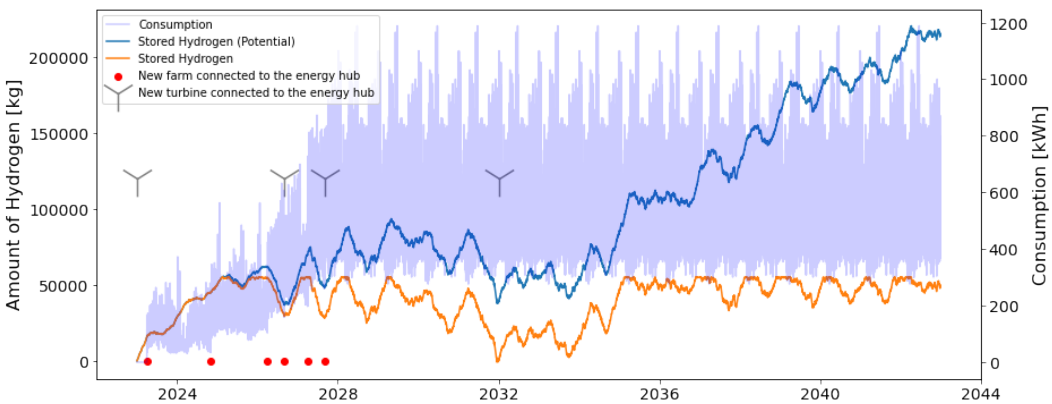


Figure 4.12: Amount of hydrogen stored 2023-2042: The blue and orange line's displays actual and potential amount of hydrogen stored during the simulation. The orange line is limited to 55 tonnes of hydrogen stored. The red dots shows when each of the fish farms start operating and the wind turbine symbols shows when a new turbine start operating. The increasing power demand is displayed in shaded gray.

Earlier in this chapter, it was necessary to increase the wind power capacity to cope with the variations in the hydrogen storage and prevent it from reaching zero. However, in Figure 4.12, the natural variations in hydrogen storage can clearly be seen after the fourth wind turbine is added. The orange line, which displays the stored hydrogen with a storage capacity limited to 55 tonnes, decreases during the summer and increases when there is surplus energy. From the blue line, showcasing how much hydrogen there could have been stored if there was no limitation to the hydrogen storage capacity, it can be seen that the wind turbine capacity is slightly over-dimensioned. However, this is necessary to keep the amount of stored hydrogen stable and thus have enough backup power to cover the energy demand when the wind speeds are low. Why a gradual increase in wind power capacity has been included in the simulations instead of installing all wind turbines simultaneously will be discussed in Chapter 5.

The share in energy supply had a slight change with the changes made to the system with the simulation extension, where 73.9 % were covered by wind, and 26.1 % were covered by hydrogen. There was an increase to 36.2 %, where additional power was required. On the other hand, wasted power increased substantially with the changes. A total of 62.6 GWh was not utilised, whereas 16.4 GWh was lost due to the limitation in storage capacity. The rest were lost because of the operational power range of the electrolyser. A summary of the key variables is displayed in Table 4.3.

Table 4.3: Key information from the energy system 20 years.

Results of the simulation		
Total production by wind turbines	191	GWh
Total Consumption fish farms	79.2	GWh
Wind power to cover demand	58.5	GWh
Power to hydrogen production	69.9	GWh
Total of Waste power	62.6	GWh
Amount of hydrogen produced	1315	Tonnes
Amount of hydrogen utilised	1265.2	Tonnes
How often additional power is needed	36.2	%

Comparing Tables 4.1 and 4.3 makes it possible to see how the changes made have affected the energy system. For example, in the six-year simulation, the total energy production from wind power was approximately two times higher than the consumption. However, when the simulation was extended, it produced almost 2.5 times more energy than the demand. The ratio between power used for hydrogen production and waste power also increased from 2.4 times more to 1.1, which shows that a significant amount of power is not utilised.

Placement of the hydrogen storage modules and selection of wind turbine foundation

The hydrogen storage modules in this thesis are placed on the seabed. It can be seen in Figure 4.1 at the start of this chapter. Today, it is a technology that is not commercially available, but as stated in Chapter 2, some projects are looking into this solution. Hydrogen storage is placed beneath the ocean's surface because of safety reasons and space savings. The calculation performed regarding hydrogen compression before storage, in the simulation, compresses the hydrogen to 350 bar. The storage capacity of 55 tonnes corresponds to a volume of 2619 m^3, which would have meant that a separate platform would probably be necessary to place the storage tanks.

The current Ocean Farm is located around 20 km from the mainland of Norway, where the water depth is approximately 150 m, as mentioned in the previous chapter. Therefore, it is necessary to use floating foundations for wind turbines. Figure 2.4 shows that there are several different floating foundations to choose from. Figure 4.1 shows how it would look when a spar foundation is used for this project. The cost of the spar foundation is included in the turbine cost used in this thesis, and this impacted the selected foundation. Floating foundations will be further discussed in Chapter 5.

4.3.2 Monte Carlo Simulation

The result of the sensitivity analysis regarding the variability in wind speeds are illustrated in Figure 4.13. The outcomes where the amount of hydrogen stored never became negative is displayed with blue lines. Whereas the outcomes where it does become negative, is displayed with red lines. A negative amount of hydrogen indicates that the energy system does not supply the required amount of power to the fish farms. The analysis showed that the stored amount of hydrogen became negative for 34 % of the outcomes. The difference in the amount of hydrogen stored is almost 120 tonnes between some of the outcomes during analysis, showcasing the importance of stable and great wind resources.

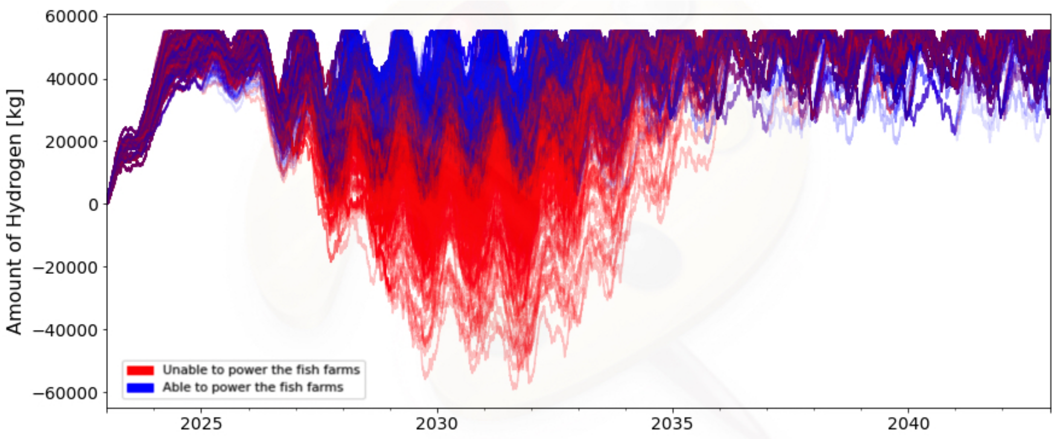


Figure 4.13: Monte Carlo Simulation: 1000 simulations of the energy system with varying wind speeds have been performed and the amount of hydrogen stored over time is plotted for each simulation.

4.3.3 Economics

This section presents the profitability and Levelized cost of energy from the energy system in the first case study. The cost analysis is based on the system from the extended period in this case. During the period, there were several investments since new turbines were added to the system along the way. In addition, there are two stack replacements regarding fuel cell and electrolyser during the period due to the lifetime of the components. Therefore, the stack replacement is also added to the investments. Furthermore, since hydrogen storage at the seabed is yet to be commercialised, is the analysis performed with three different storage prices, ranging from 0.35-10 MNOK/-tonnes. This is due to the considerable uncertainty in the storage cost, as mentioned in the previous chapter. The three different investments in the analyses are displayed in Figure 4.14. The figure shows that wind turbines and hydrogen storage are the main cost drivers. A table including all of the values regarding CAPEX, OPEX, and savings used in this analysis can be found in Appendix .3.

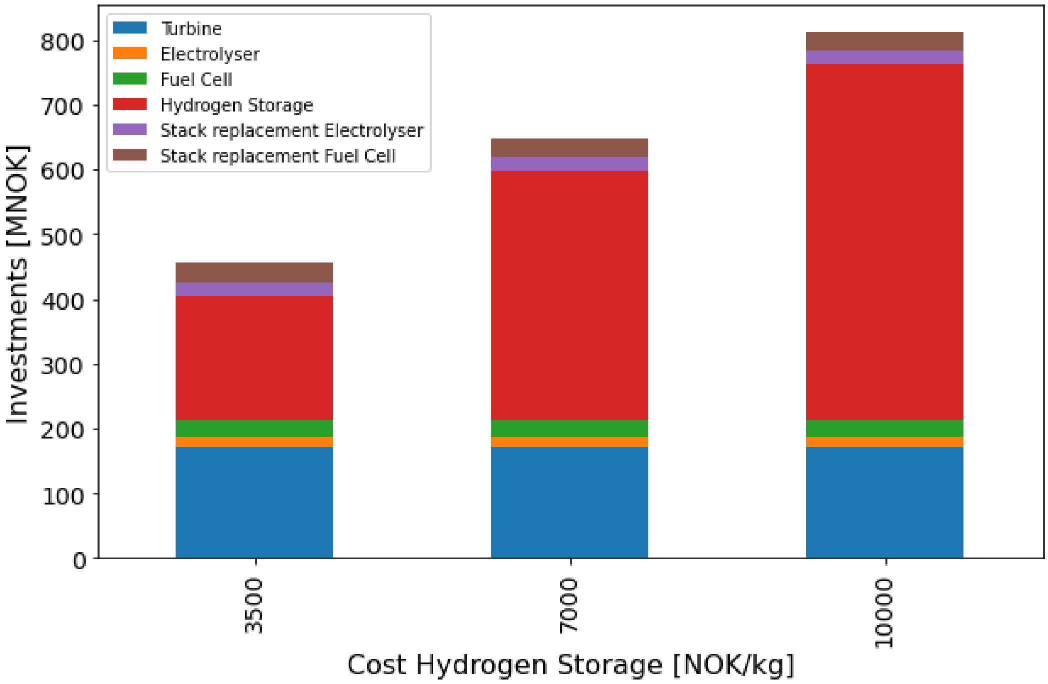


Figure 4.14: Investments - different hydrogen storage prices.

The cash flow during the period consists of operational costs, future investments, and the potential saved costs regarding diesel consumption and CO_2 taxes. This was explained in Chapter 3. The amount of savings, which is money saved by not utilising diesel to power the fish farms, is gradually increasing alongside the increasing consumption before flatting out when all of the fish farms are operational. This is shown in Figure 4.15. The figure also shows that the operational cost regarding the components used in the project is much lower than the savings from not using diesel to cover the consumption.

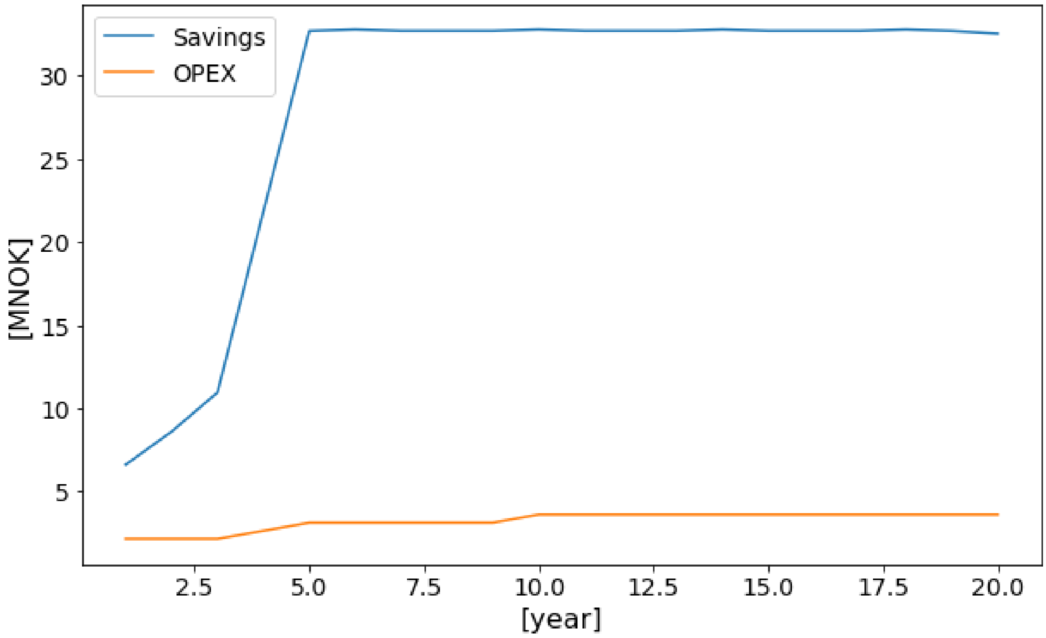


Figure 4.15: OPEX and savings during the first case study.

The net present value is calculated using the presented cash flow and investment with a discount rate of 7 %. The different values regarding the hydrogen storage prices can be seen in Figure 4.16. The figure shows that the project is not profitable for any of the three hydrogen storage prices. The Levelized cost of energy for the project has been calculated as well and is as follows: 10.52 NOK/kWh, 15.31 NOK/kWh, and 19.42 NOK/kWh for the different storage prices.

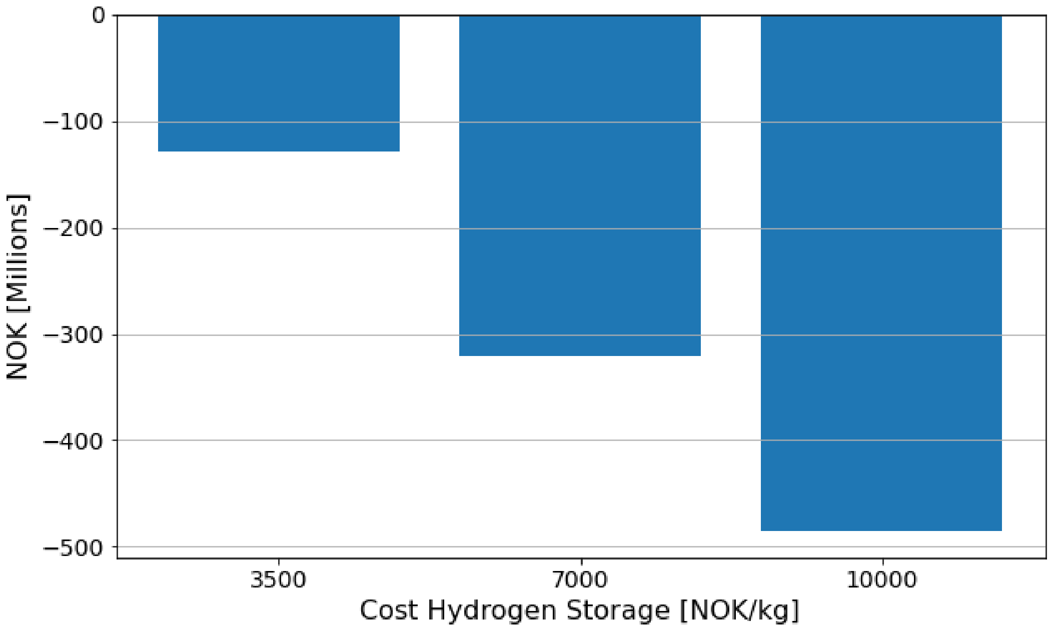


Figure 4.16: Net present value - different hydrogen storage prices.

Summary case study 1

So far in this chapter, the results from the simulations for the first case study have been presented. The results showed that it is possible to cover the consumption of the fish farms with wind power and the usage of hydrogen. However, the system is not flawless. Almost 1/3 of the produced power from the wind turbines is not utilised, and the needed hydrogen storage capacity of 55 tonnes makes the system not profitable. The monte carlo simulation showcased that 34 % of the outcomes from the simulation was not capable of providing the fish farms with enough energy. This simulation shows that additional back up power is needed when there is low production from the wind turbines. Therefore, in order to further optimise the energy system, will a second case study be presented in the following section. This case will introduce a diesel generator to the energy system to investigate how it will affect the overall system.

4.4 Case study 2 - Wind Power, Hydrogen and Diesel

In this case study, a diesel generator is added to the energy system, see Figure 3.6 (b). With the implementation of the generator, it was possible to make changes to the overall design of the energy system. The previous case was designed never to reach an empty hydrogen storage because that would mean that the consumption was not covered. However, in this study the energy system is designed so that the diesel generator would cover all of the remaining consumption each time the hydrogen storage is empty. This case study aims to investigate how much the implementation of the diesel generator affects both the energy system and the economic part. The changes made to the energy system over 20 years are presented below.

4.4.1 The Energy System

With the addition of the diesel generator, it was decided to decrease the number of wind turbines from four to two because this would better show the generator's impact on the system both economically and on the system's energy distribution. The decrease in turbine capacity made no changes to the fuel cell capacity, which still has to be 2.5 MW since the highest consumption during time steps with no production from the turbines is 1188 kW. In order to cover a demand of 1188 kW during an hour, the needed diesel generator capacity was 4 MW when the efficiency of the generator is 30 %. The calculations regarding generator capacity can be seen in Equation 4.1.

$$\text{Required Generator Capacity} = \frac{\text{Highest required load}}{\eta_{\text{Diesel generator}}} = \frac{1188 \text{ kW}}{30\%} \approx 4000 \text{ kW} \quad (4.1)$$

The hydrogen storage capacity has been lowered from 55000 kg, in the previous case, to 5000 kg to see the diesel generator's impact and how this impacts the economic part of this case. It is possible to lower the storage capacity by this much since it is no longer a problem with the energy provision of the fish farms when the hydrogen storage is empty. The change in stored hydrogen can be seen in Figure 4.17, which displays the same as Figure 4.6 apart from potential hydrogen stored. The figure shows that the storage quickly decreases when the consumption starts ramping up. However, it is not clearly visible from the figure when the diesel generator operates. How much power the diesel generator has to provide during the simulation is illustrated in Figure 4.18. It shows that there are several periods where most of the consumption is mainly covered by diesel.

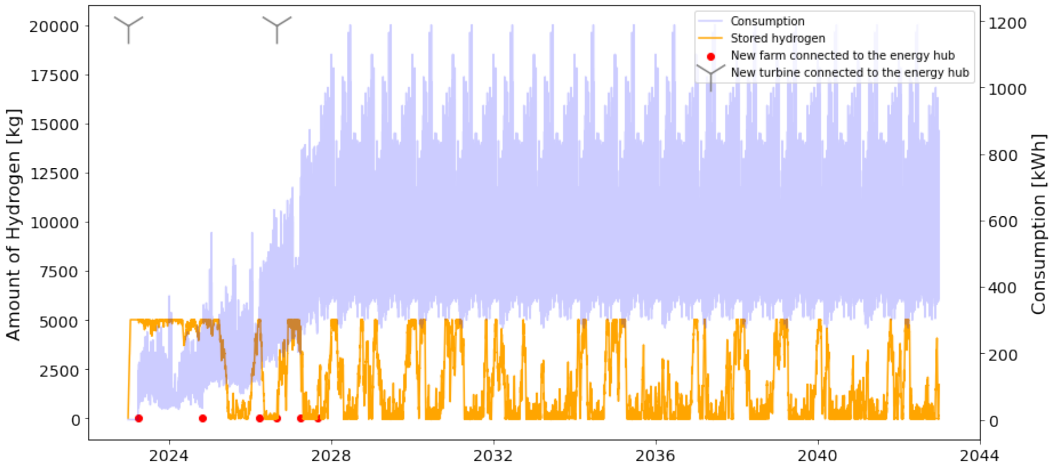


Figure 4.17: Amount of Hydrogen Stored 2023-2043 (Case study 2). The orange line displays the amount of hydrogen stored during the simulation with a limit of 5 tonnes. The red dots shows when each of the fish farms start operating and the wind turbine symbols shows when a new turbine start operating. The increasing power demand is displayed in shaded grey.

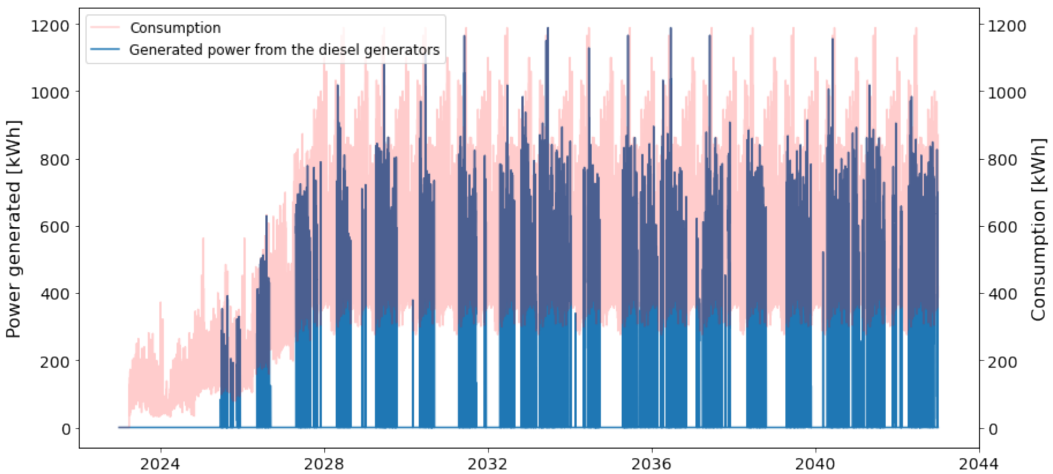


Figure 4.18: Amount of consumption that are covered by the diesel generator during the simulation shown in blue.The consumption is shown in red in the background.

Changes to the energy supply by increasing the hydrogen storage capacity

The implementation of the diesel generator alongside decreasing the number of wind turbines impacts the shares in energy distribution to the fish farms. Figure 4.19 illustrates this and shows that wind turbines cover 66.9 % of the consumption, 16.3 % is covered by the fuel cell, and the generator covers the remaining 16.8 %. With the decrease in turbine capacity, is required time of additional power in this case is 44.6 %, approximately 10 % more than in the previous case.

Figure 4.20 shows the shares in energy distribution when the hydrogen storage capacity is increased to 20 tonnes. The figure shows that the share of hydrogen usage only increases to 18.8 % when the storage capacity is four times larger. However, as earlier mentioned, hydrogen storage quickly drains when there is insufficient energy production from the turbines, which is also part of why the share of hydrogen usage does not have a more significant increase.

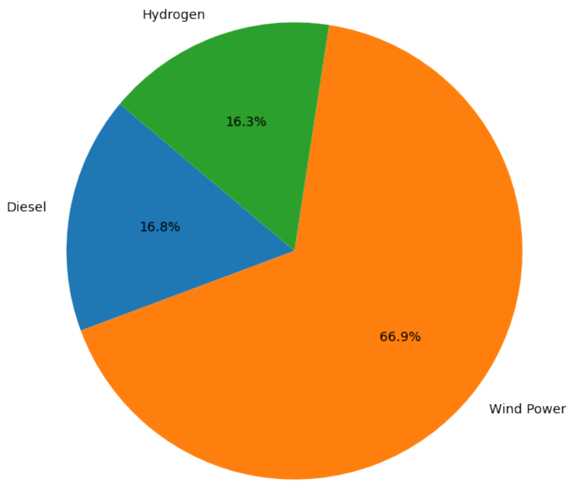


Figure 4.19: Shares in energy distribution with a hydrogen storage capacity of 5000 kg.

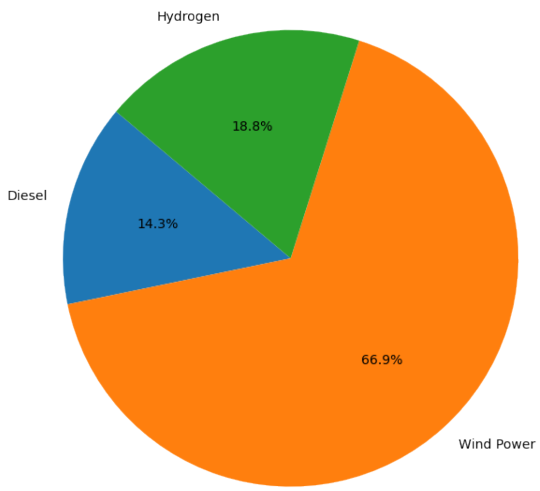


Figure 4.20: Shares in energy distribution with a hydrogen storage capacity of 20000 kg.

Waste Power

The amount of wasted power is significantly lower in this case study than in the previous one. This can be seen in the summary of the key variables in Table 4.4. Less than 10 % of the produced power goes to waste, with only 10.13 GWh during the 20 years.

The majority of this waste results from the low hydrogen storage capacity of 5000 kg, which is responsible for 9.38 GWh of lost energy, which could have been used for hydrogen production. The remaining comes from the previously mentioned limitation of the electrolyser.

Table 4.4: Key information from the energy system 20 years.

Results of the simulation		
Total production	111.8	GWh
Consumption	79.2	GWh
Power to hydrogen production	48.7	GWh
Waste power	10.13	GWh
Amount of hydrogen produced	792.5	Tonnes
Amount of hydrogen utilised	790.8	Tonnes
Amount of Diesel utilised	3818	Tonnes
How often additional power is needed	44.6	%

4.4.2 Economics

The net present value and LCOE in this case study are calculated with the changes made to the system when the diesel generator was added. There were several changes in the investments in this case in contrast to the first one. The number of wind turbines was decreased from four to two, the storage capacity was decreased from 55 tonnes to 5 tonnes, and a diesel generator with a capacity of 4 MW in total was added. The total investment during the whole period regarding the different hydrogen storage prices is displayed in Figure 4.21. In contrast to the investments in case study 1, which can be seen in Figure 4.14, the hydrogen storage costs do not dominate the overall investment in the same way. The wind turbine and hydrogen storage are still the main cost drivers, but their influence on the total investment is more evenly shared in contrast to case study 1. A table including all of the values regarding CAPEX,OPEX, and savings used in this analysis can be found in Appendix .4.

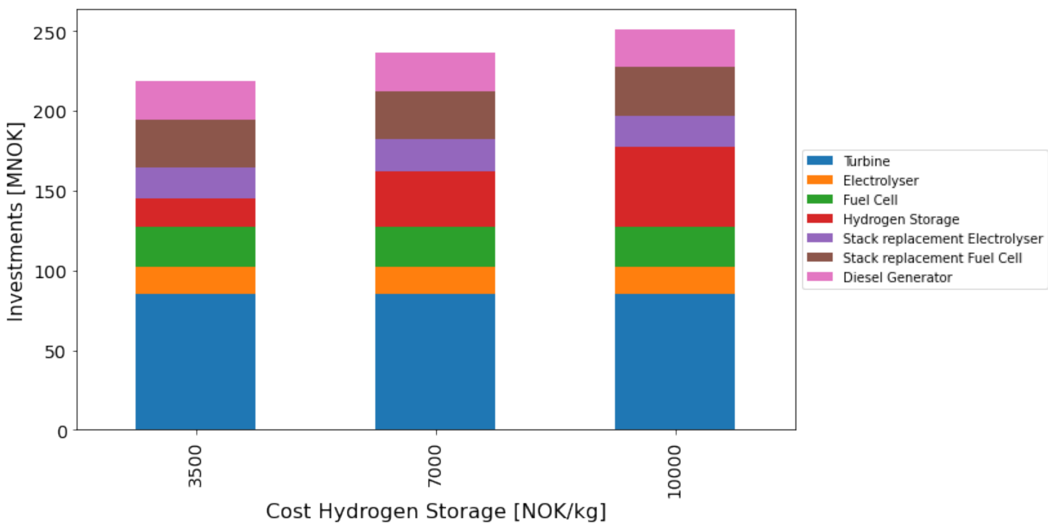


Figure 4.21: Investment case study 2 - regarding different hydrogen storage prices.

For the operational costs were the fuel cost and the following CO_2 tax for the utilised diesel during each year added to the cash flow as well as maintenance of the diesel generator. The running operational costs and savings can be seen in Figure 4.22. It shows that the increasing diesel usage during the period increases the OPEX and the savings decrease since the hydrogen storage is more often empty.

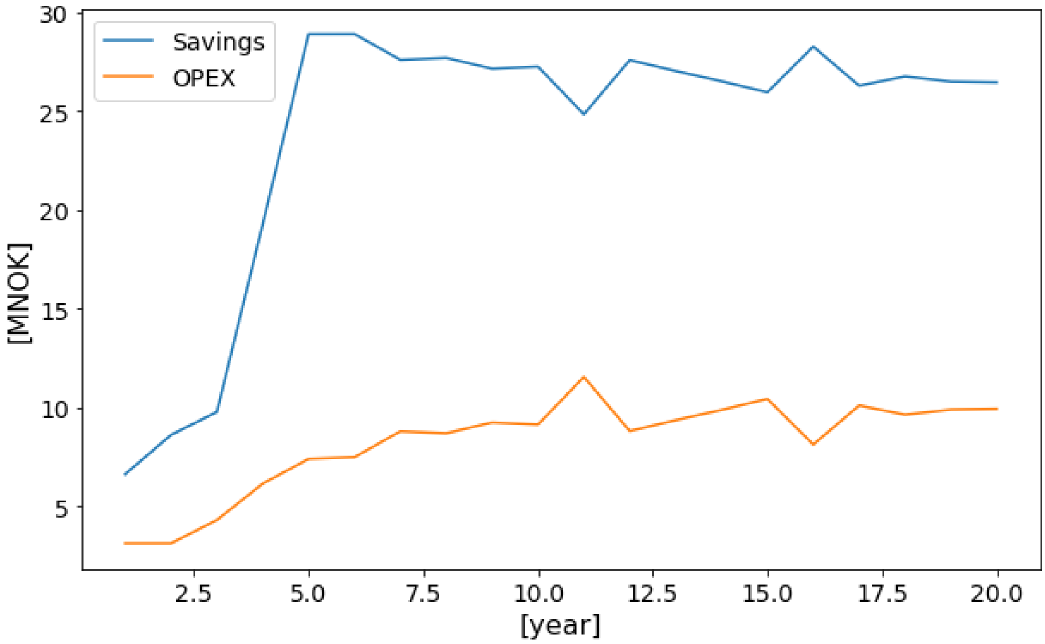
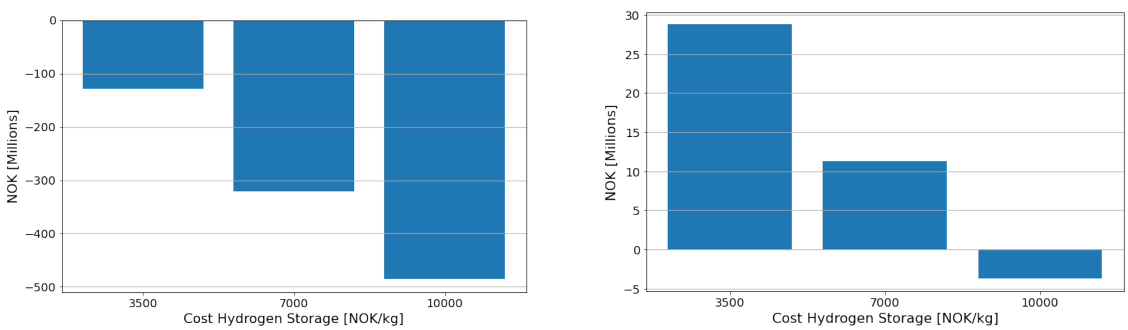


Figure 4.22: OPEX and savings during Case study 2.

Figure 4.23 shows the calculated net present value with the discount rate of 7 % for both case study 1 and 2 to quickly compare the two. It shows that the energy system in case study 2 is profitable for two of the three storage prices, in contrast to case study 1, where non of the calculated net present values were profitable. The LOEC in this case was lower for all three storage prices than the lowest in case study 1, with 6.62 NOK/kWh, 7.06 NOK/kWh, and 7.43 NOK/kWh.



(a) NPV - Case study 1

(b) NPV - Case study 2.

Figure 4.23: Net Present Value - Case 1 vs Case 2.

The economic analysis has not considered the opportunity to sell the excess hydrogen that could have been produced in either of the two case studies. The reason behind this will be explained in the discussion.

4.5 Comparison of Case study 1 and 2

Table 4.5 summarises and compares the results regarding the two case studies that have been presented in this chapter. The decrease in the number of wind turbines from four to two has, naturally, affected the total wind power production, which decreases from 191 to 111.8 GWh in the studies. It also affects how often additional power is needed to cover the demand from the fish farms, where it increases from 36.2 % in case study 1 to 44.6 % in case study 2. This additional power was in case study 1 only provided by hydrogen, and 1310.5 tonnes were utilised. However, in case study 2, both hydrogen and diesel were utilised to cover the power demand that the wind turbines could not. As a result, 792.5 tonnes of hydrogen and 3818 tonnes of diesel were utilised in this case. With diesel usage, the CO_2 reduction was reduced to 83.2 %, compared to 100 % in case study 1.

The amount of waste power is heavily decreased from 63.9 GWh in case 1 to 10.1 GWh in case 2. In the WH2-system, most of the waste power is a result of the electrolyser capacity, but for the hybrid system is the limitation in hydrogen storage the reason behind most of the waste power. The calculations regarding the net present value of the two energy systems showcase that the WH2-system never is profitable and that the hybrid system always is. This is mainly due to the hydrogen storage capacity, the main cost driver in case study 1. The differences between the two energy systems will be further discussed in the following chapter.

Table 4.5: Comparison of the results in Case study 1 and 2.

	Case study 1	Case study 2	Unit
Total production	191	111.8	GWh
Consumption	79.2	79.2	GWh
Power to hydrogen production	68.9	48.7	GWh
Waste power	63.9	10.13	GWh
Amount of hydrogen produced	1310.5	792.5	Tonnes
Amount of hydrogen utilised	1265.5	790.8	Tonnes
Amount of Diesel utilised	0	3818	Tonnes
How often additional power is needed	36.2	44.6	%
CO_2 Reduction	100	83.2	%
NPV (Best case)	-128.2	28.8	MNOK
NPV (Worst case)	-485.7	-3.7	MNOK
LCOE (Best case)	10.52	6.62	MNOK
LCOE (Worst case)	19.42	7.43	MNOK

Chapter 5

Discussion

The previous chapter showcased the results regarding the design and sizing of an energy system consisting of wind power and hydrogen to cover the power demand of an increasing number of fish farm facilities. Raw consumption data from SalMar Aker Ocean's Ocean Farm 1 were used to create a representative power demand for the two case studies. The energy system in the first case consisted of several wind turbines, and hydrogen was produced with excess power. The second case included a diesel generator in the energy system to investigate how it would influence the energy system. The NORA3 wind power data set was used to calculate the power production from the wind turbines during both case studies.

Power demand

Since the raw consumption data provided by SalMar Aker Ocean was declared non-representative, it was decided to create a yearly power demand that better would represent the consumption at a similar fish farm. After discussions with Jørgen Mjønes at SalMar Aker Ocean , it was decided to use the data from the first and last five months of the provided consumption data where there was fish in the barges. The remaining two months were data from where the barges were empty, and the consumption was relatively constant. Of course, if there were actual consumption data available, that would have been preferred, but for this thesis, the artificially created power demand is expected to be as good as possible.

This power demand was then used for each of the increasing numbers of fish farms that started operating at different times throughout the simulation. Having the farms on different operating cycles regarding when there was fish in the barges or not was seen to be the most effective way of smoothing the consumption during the simulation. If the fish farms were to have the same cycles, there would be a significant difference in the power demand during a year. It would have required that the energy system had to be designed differently.

Wind resources and power production

The wind speed data used were recorded at 101 m.a.s.l. Wind speed interpolation was used to get the wind speeds at the height of the turbine, which was 55 m for the used

750 kW wind turbine. The log law was chosen after comparing it with the power law. Both laws used simplistic approaches regarding how the different alpha values were obtained for the power law, and for the log law, a constant roughness length of 0.0002 m was used. More robust approaches could have been used to get even more accurate values for these variables. However, for the purpose of this thesis, it was decided that the simplistic approach was sufficient.

Case study 1 - Wind power and hydrogen

The first case study was divided into two intervals. First, the energy system designed for the first six years of operation was presented to show how the energy system developed while the number of fish farms increased. This resulted in an energy system consisting of three wind turbines, a 2.5 MW fuel cell, the PEM MC250 electrolyser, and hydrogen storage with the capacity to hold 35 tonnes of hydrogen. When the time period was increased to 20 years, the simulations showed that one extra wind turbine had to be added to the energy system and that the hydrogen storage capacity had to increase to 55 tonnes. The economic part of this study showed that the system is not profitable with any of the estimated hydrogen storage prices.

The number of wind turbines increased during the simulated period in this case. This was a decision to prevent an over-dimensioned wind power system from the start and thus prevent the amount of waste power. However, this is not a feasible solution since installing one large wind turbine at once is cheaper than installing four different wind turbines along the way. It also made it difficult to see how the variability in the wind speeds affected parts of the simulation since a new turbine was added to the energy system when the hydrogen storage was rapidly decreasing.

During the simulations, the created model of the PEM MC250 electrolyser was used. The PEM MC250 was used since the specification sheet for this electrolyser was available online. This model was used instead of a constant electrolyser efficiency. If a constant efficiency of, for example, 65 % had been used for all of the available surplus energy, more hydrogen had been produced during the simulation. However, it would have been unrealistic that the electrolyser could produce hydrogen from this surplus energy since it ranges from 1-2000 kW.

However, the usage of the PEM MC250 significantly increased the amount of surplus power wasted. The wasted power was a result of the operational range of the electrolyser. This range was between 10-100 % of the capacity of the electrolyser, and all surplus energy below 10 % of maximum capacity was wasted. The surplus energy greater than the electrolyser capacity was used to produce hydrogen, and the remaining energy after production went to waste.

The results of the performed Monte Carlo simulations, in figure 4.13, gave valuable information regarding the consistency in energy supply from the energy system. It showed that the energy system could not supply the fish farms with energy for 34 % of the outcomes. This showcases that the usage of historical wind speed data to design an energy system does not guarantee that it will be able to deliver energy to a consumer. However, by implementing a diesel generator as backup power, as in case study 2, this uncertainty is removed since the generator can provide the consumer with energy when the hydrogen storage is empty.

Case study 2 - Wind Power, hydrogen and diesel

A diesel generator was added to the energy system in the second case study. The addition of the diesel generator made it possible to decrease the number of turbines from four to two and the hydrogen storage capacity from 55 tonnes to 5 tonnes. This was possible since the diesel generator would provided the fish farms with power when the hydrogen storage was empty. The electrolyser and fuel cell capacity were unchanged, and the needed diesel generator capacity was 4 MW. The economic part of this case showcased that this system was more feasible than the system in the first case study.

The changes made in the second case study regarding the number of turbines and the hydrogen storage capacity can not be concluded to be the optimal solution. However, these changes were made to showcase how a significant decrease in the wind turbine- and storage capacity would influence the energy supply and the economic part. Other aspects of this case study will be further discussed in the next section, where the comparison of the two case studies is discussed.

Comparison of the two case studies

The simulations performed showed that 63.9 GWh and 10.1 GWh of power were wasted in case studies 1 and 2. Some of it is a result of the electrolyser model, which has been discussed above. However, a large amount of this power is a result of the hydrogen storage capacity, and that the electrolyser is shut down when the storage is full. Figure 4.12 shows the potential hydrogen production in case study 1. The figure shows that a large amount of hydrogen could have been produced and used for other purposes. It was considered to investigate the possibility of providing passing ships or workboats with hydrogen weekly or monthly to utilise more of the wasted power. However, this was left out of the thesis due to difficulties implementing this to the python scripts and to limit the scope of this thesis.

The share in energy supplied to the fish farms from the wind turbines did not change significantly, even if the number of turbines was halved from case study 1 to case 2. In the first case study, 73.9 % of the power demand were covered by wind power, and in case study 2 was this 66.9 %. From the simulations performed, there are a few reasons behind this that stand out: There was no production from the wind turbine 9.4 % of the time, as presented in section 4.2.2. Therefore, the number of turbines will not change this. The other reason is that the wind power capacity is over-dimensioned to produce enough hydrogen with surplus energy to cover the demand when the wind resources are scarce.

Since the hydrogen storage at the seabed is yet to be commercialised, it was hard to find any reasonable estimates regarding the cost of this technology. Therefore, it was decided to calculate the net present value and Levelized cost of energy by using three different hydrogen storage prices. The low and medium-cost of 3500 and 7000 NOK/kg of stored hydrogen are the cost of compressed hydrogen storage found in the literature. On the other hand, the high cost of 10000 NOK/kg of stored hydrogen is a rough estimate, and it is believed that the actual cost of hydrogen storage lies between the medium and high cost used in this thesis.

In the cost analysis performed in this thesis, the profitability of the energy systems is calculated depending on three different hydrogen storage prices. Firstly, the different prices stated in Tables 3.4 and 3.5 results from a review of several scientific articles and reports. However, it is challenging to say how accurate the different prices are since most manufacturers of the different components do not share their prices, and therefore estimates must be made. Because of this, it is impossible to state that the profitability of the two systems is what is presented in chapter 4. However, for comparison of the two energy systems, is it acceptable, since the same prices are used for both systems.

The changes made to the energy system from case studies 1 to 2 showcase that a hybrid system is far more profitable than an energy system consisting of only wind power and hydrogen. The main reason behind this is the reduction in hydrogen storage capacity needed. There is big uncertainty regarding hydrogen storage at the seabed, but even for a low cost of 3500 NOK/kg, hydrogen storage were the main cost driver for case study 1, as figure 4.14 shows. This is a clear indication that hydrogen storage cost has to decrease if hydrogen shall contribute to decarbonizing the fish farm sector.

Other subjects of this thesis that requires discussion and clarification

This thesis has primarily focused on designing and sizing the different components in an energy system to be able to cover the power demand of a fish farm. However, several other subjects need further investigation to realize a project like this. In figure 4.1 is a spar foundation selected for the wind turbines. Several other floating foundations are available for selection, and a spar foundation can not be concluded to be the best option.

Most of the included prices used during this thesis have been converted from euros or dollars into NOK. However, the exchange rates for both euro and dollar have changed massively during the duration of this work. Therefore, it was decided to set a constant exchange rate for both currencies, which is 10 NOK/(Euro and Dollar). This exchange rate is approximately ± 0.2 NOK for both as of May 2022. Therefore, the constant exchange rate is decided acceptable for this thesis, but the different prices should not be used in future works since the exchange rates probably have changed then.

Batteries have not been included in the energy systems that have been designed in this thesis. The main reason for this is that it was found difficult to create a representative model of a battery in python. The primary issue with the battery model was found to be the charging part and to implement when the battery would operate. However, if a battery had been included in the energy systems, that would have benefited this thesis. Some of the surplus energy could have been used to charge the battery, thus decreasing the amount of waste power. In Figure 4.8, the distribution of load that the fuel cell had to cover is displayed. The fuel cell capacity was sized after the highest required load, which was 1188 kW. The battery would then have been used for peak shaving, which could have lowered the capacity needed for the fuel cell.

This thesis has focused on wind power as the primary energy source to cover the power demand of a fish farm. However, other energy sources like solar power and wave power are believed to be complementary energy sources to wind power. During the summer months, when the power production from a wind turbine is lower than during the winter, solar power could result in a more even energy production throughout these months. In addition, waves are created when the wind is blowing, and therefore this is also a possibility to increase power production. Future studies should consider investigating both solar and wave power since this could result in a lower need for wind power capacity.

The created python scripts used during the work of this thesis have been valuable for the purpose of this thesis. The goal when creating them was that they could be used by others in the future when conducting similar studies. However, for future usage, only the script regarding wind speed collection is seen as useful for others. For similar studies, the wind speeds can for all locations inside the area NORA3 covers, see Figure 3.5, be downloaded using this script. The script created in order to design the energy system is most likely only valuable use in the specific case of this thesis, but it can be used as a template for other similar studies.

Finally, the results of the two case studies show that it is possible to cover the energy demand of a fish farm with wind power and hydrogen as energy storage. However, the cost of an energy system consisting of just wind power and hydrogen is less profitable than a hybrid system where a diesel generator is included mainly due to the hydrogen storage capacity.

Chapter 6

Conclusions and Future Work

Two case studies were conducted in order to investigate the feasibility of covering the power demand of several fish farms with power produced by wind turbines with hydrogen as energy storage. The two case studies given energy systems consisted of: a wind/hydrogen energy system and a wind/hydrogen/diesel energy system.

The first case study showed that three wind turbines with a capacity of 750 kW each were needed in order to cover the demand over six years. The total energy system consisted of these turbines, alongside one PEM MC250 electrolyser, a 2.5 MW fuel cell, and hydrogen storage with the capacity to hold 35 tonnes of compressed hydrogen. When the duration of the case was increased to 20 years, it was necessary to increase the number of turbines to four and the hydrogen storage capacity to 55 tonnes. The economic calculations showed that this system would not be profitable given the cost of the different components used in this thesis.

The second case study showed that the power demand could be covered by two wind turbines, one PEM MC250 electrolyser, a 2.5 MW fuel cell, and 5 tonnes of hydrogen storage capacity when implementing a 4 MW diesel generator into the energy system. This energy system was far more profitable than the first, and it is recommended to investigate this solution further.

Lastly, it can be concluded that it is technically possible to cover the power demand from a fish farm with wind power and hydrogen. However, the needed capacity for hydrogen storage is so large that a wind/hydrogen system is not profitable for any of the storage prices used in this thesis. However, by using a diesel generator as backup power when the hydrogen storage was empty made it possible to make a drastic decrease in the storage capacity and still reduce over 80 % of the CO2 that would have been released for a fish farm that only uses diesel.

For future work it is recommended to further investigate the possibility of powering a fish farm with an hybrid system. Some aspects to investigate is:

- Adding batteries to the system
- Utilise more of the wasted power
- Adding solar power

Bibliography

[1] ABS, "Offshore production of green hydrogen," ABS, Tech. Rep., Feb. 2022.

[2] ENOVA, "Potensialet for reduserte klimagassutslipp og omstilling til lavutslippssamfunnet for norsk oppdrettsnaering," ENOVA, Tech. Rep., 2021.

[3] Norges Vassdrags- og Energidirektorat. "Tall og fakta." https://www.nve.no/energi/energisystem/vindkraft/tall-og-fakta/[Accessed: 2022-05-05]. ().

[4] J. Aarnes, M. Eijgelaar, and E. Hektor, "An evaluation of emerging hydrogen value chains," DNV GL, Tech. Rep., 2018.

[5] Olje- og energidepartementet and Klima- og Miljødepartementet, *Regjeringens hydrogenstrategi*, 2020.

[6] G. Stangeland, "Slik vil departementet dele opp utsira nord og sørlige nordsjø 2," *Energi24.no*, Feb. 2022. [Online]. Available: https://energi24.no/nyheter/slik-vil-departementet-dele-opp-utsira-nord-og-sorlige-nordsjo-2 (visited on 04/12/2022).

[7] J. Grov, S. Sandøy, and H. Torsvik, "Assessing the feasibility of hydrogen plants powered by floating photovoltaics open version," Bachelor Thesis, Western Norway University of Applied Sciences, 2020.

[8] C. J. Greiner, M. KorpÅs, and A. T. Holen, "A norwegian case study on the production of hydrogen from wind power," *International Journal of Hydrogen Energy*, vol. 32, no. 10-11, pp. 1500–1507, 2007.

[9] Y. Kalinci, A. Hepbasli, and I. Dincer, "Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options," *International Journal of Hydrogen Energy*, vol. 40, no. 24, pp. 7652–7664, 2015.

[10] Ø. Ulleberg, T. Nakken, and A. Eté, "The wind/hydrogen demonstration system at utsira in norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools," *International Journal of Hydrogen Energy*, vol. 35, no. 5, pp. 1841–1852, 2010.

[11] Andrea A. Justad, "Wind turbines for the power supply for offshore fish farms," M.S. thesis, University of Agder, 2017.

[12] RENERGY, *Energi i havbruk: Optimal energibruk på oppdrettsanlegg*, 2021.

[13] A. M. Elberry, J. Thakur, A. Santasalo-Aarnio, and M. Larmi, “Large-scale compressed hydrogen storage as part of renewable electricity storage systems,” *International Journal of Hydrogen Energy*, vol. 46, no. 29, pp. 15 671–15 690, 2021.

[14] Engineering ToolBox, *Fuels - densities and specific volumes*, https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html[Accessed: 2022-05-03].

[15] V. Kumar, D. Gupta, and N. Kumar, “Hydrogen use in internal combustion engine: A review,” *The International Journal of Advanced Culture Technology*, vol. 3, no. 2, pp. 87–99, 2015.

[16] B. C. Tashie-Lewis and S. G. Nnabuife, “Hydrogen production, distribution, storage and power conversion in a hydrogen economy - a technology review,” *Chemical Engineering Journal Advances*, vol. 8, p. 100 172, 2021.

[17] K. Sasaki, H.-W. Li, A. Hayashi, J. Yamabe, and T. Ogura, Eds., *Hydrogen Energy Engineering - A Japanese Perspective*. Fukuoka: Springer, 2016.

[18] L. Vidas and R. Castro, “Recent developments on hydrogen production technologies: State-of-the-art review with a focus on green-electrolysis,” *Applied Sciences (Switzerland)*, vol. 11, no. 23, 2021.

[19] A. Buttler and H. Spliethoff, “Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2440–2454, 2018.

[20] C. Tarhan and M. A. Çil, “A study on hydrogen, the clean energy of the future: Hydrogen storage methods,” *Journal of Energy Storage*, vol. 40, p. 102 676, 2021.

[21] F. Zhang, P. Zhao, M. Niu, and J. Maddy, “The survey of key technologies in hydrogen energy storage,” *International Journal of Hydrogen Energy*, vol. 41, no. 33, pp. 14 535–14 552, 2016.

[22] M. Niermann, S. Drünert, M. Kaltschmitt, and K. Bonhoff, “Liquid organic hydrogen carriers (lohcs) techno-economic analysis of lohcs in a defined process chain,” *Energy & Environmental Science*, vol. 12, no. 1, pp. 290–307, 2019.

[23] T. B. Ferriday and P. H. Middleton, “Alkaline fuel cell technology - a review,” *International Journal of Hydrogen Energy*, vol. 46, no. 35, pp. 18 489–18 510, 2021.

[24] Y. Wang, D. F. R. Diaz, K. S. Chen, Z. Wang, and X. C. Adroher, “Materials, technological status, and fundamentals of pem fuel cells a review,” *Materials Today*, vol. 32, pp. 178–203, 2020.

[25] X. Liu, G. Liu, J. Xue, X. Wang, and Q. Li, “Hydrogen as a carrier of renewable energies toward carbon neutrality: State-of-the-art and challenging issues,” *International Journal of Minerals, Metallurgy and Materials*, vol. 29, no. 5, pp. 1073–1089, 2022.

[26] K. Mongird, V. Viswanathan, J. Alam, C. Vartanian, V. Sprenkle, and R. Baxter, “2020 grid energy storage technology cost and performance assessment,” Pacific Northwest National Laboratory, Tech. Rep., 2020.

[27] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind Energy Explained: Theory, Design and Application*, 2nd ed. John Wiley & Sons Ltd., 2009.

[28] G. M. Masters, *Renewable and Efficient Electric Power Systems*. John Wiley & Sons, Inc., Jul. 2004.

[29] Ørsted A/S, "Making green energy affordable how the offshore wind energy industry matured-and what we can learn from it," Ørsted A/S, Tech. Rep., 2019.

[30] Brunel. "The pros and cons of onshore & offshore wind." (2021), [Online]. Available: https://www.brunel.net/en/blog/renewable-energy/onshore-offshore-wind (visited on 04/15/2023).

[31] S. Bhattacharya, *Design of Foundations for Offshore Wind Turbines*. John Wiley & Sons, Incorporated, 2019.

[32] K.-Y. Oh, W. Nam, M. S. Ryu, J.-Y. Kim, and B. I. Epureanu, "A review of foundations of offshore wind energy convertors: Current status and future perspectives," *Renewable and Sustainable Energy Reviews*, vol. 88, pp. 16–36, 2018.

[33] S. Lloyd. "Review of options for offshore foundation substructures. prepared by the center for wind energy at james madison university." (2018), [Online]. Available: https://docplayer.net/56327349-Review-of-options-for-offshore-foundation-substructures-prepared-by-the-center-for-wind-energy-at-james-madison-university.html (visited on 04/15/2022).

[34] International Renewable Energy Agency, "Floating foundations: A game changer for offshore wind power," International Renewable Energy Agency, Tech. Rep., 2016.

[35] F. Bañuelos-Ruedas, C. Angeles-Camacho, and S. Rios-Marcuello, "Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 8, pp. 2383–2391, 2010.

[36] Varanger kraft, *Raggovidda vindkraftverk*, https://www.varanger-kraft.no/lokal-kraft/vindkraft/raggovidda-vindkraftverk/[Accessed: 2022-05-05].

[37] Tonstad Vindpark, *Tonstad vindpark er i full kommersiell drift*, https://tonstadvindpark.no/tonstad-vindpark-er-i-full-kommersiell-drift/[Accessed: 2022-05-05].

[38] Equinor ASA, *Hywind tampen*, https://www.equinor.com/energy/hywind-tampen[Accessed: 2022-04-27], 2019.

[39] J. Mjønes, *Salmar aker ocean*, Private communication, Feb. 1, 2022.

[40] Salmar. "Teknologi og innovasjon er bærekraft." (2020), [Online]. Available: https://www.salmar.no/baerekraft/teknologi-og-innovasjon/ (visited on 05/28/2022).

[41] Ocean Farming - A Salmar Company, *Sluttrapport prosjekt ocean farm 1*, https://www.salmar.no/wp-content/uploads/2016/06/OF_SR_16122019.pdf[Accessed: 2022-05-07].

[42] Google. "Location of ocean farm 1." (2022), [Online]. Available: https://www.google.com/maps (visited on 05/28/2022).

[43] O. Foseide, *Salmar aker ocean*, Private communication, Apr. 5, 2022.

[44] I. M. Solbrekke and A. Sorteberg, "Norwegian hindcast archive's offshore wind power data set-nora3-wp," University of Bergen, Tech. Rep., 2021.

[45] Wind-Turbine-Models, *Vestas v39*, https://en.wind-turbine-models.com/turbines/383-vestas-v39[Accessed: 2022-01-19], 2017.

[46] Global Wind Power, *Gwp47 - 750kw*, http://www.gwpl.co.in/wind_turbines/pdf/GWP47-750kW.pdf[Accessed: 2022-01-19], 2013.

[47] The Wind Power, *Siemens swt-2.3-82 vs*, https://www.thewindpower.net/turbine_en_21_siemens_swt-2.3-82-vs.php[Accessed: 2022-01-19], 2018.

[48] K. Edelmoser and F. Himmelstoss, "High efficiency dc-to-ac power inverter with special dc interface," *AUTOMATIKA: Journal for Control, Measurement, Electronics, Computing and Communications (korema@fer.hr); Vol.46 No.3-4*, 2005.

[49] DNV GL, "Produksjon og bruk av hydrogen i norge," DNV GL, Tech. Rep., 2019.

[50] Y. J. Lim, K. Goh, M. Kurihara, and R. Wang, "Seawater desalination by reverse osmosis: Current development and future challenges in membrane fabrication a review," *Journal of Membrane Science*, vol. 629, p. 119 292, 2021.

[51] NEL, *Containerized pem electrolyser*, https://nelhydrogen.com/product/m-series-containerized/[Accessed: 2022-02-15], 2022.

[52] C. KOST *et al.*, "Levelized cost of electricity renewable energy technologies," *Fraunhofer Institute for Solar Energy Systems ISE*, vol. 144, 2013.

[53] Multiconsult, "Hywind tampen - samfunnsmessige ringvirkninger," Multiconsult, Tech. Rep., 2019.

[54] L. Andersen, *Abb*, Private communication, Apr. 4, 2022.

[55] Department for Business, Energy & Industrial Strategy, "Hydrogen production costs 2021," Aug. 2021.

[56] Ø. Ulleberg and R. Hancke, "Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in norway," *International Journal of Hydrogen Energy*, vol. 45, no. 2, pp. 1201–1211, 2020.

[57] M. E. Rustad, "Regjeringen vil øke co2-avgiften kraftig," *E24*, Oct. 2021. [Online]. Available: https://e24.no/det-groenne-skiftet/i/dnkVyJ/regjeringen-vil-oeke-co2-avgiften-kraftig (visited on 04/12/2022).

[58] w3schools. "Numpy introduction." (2022), [Online]. Available: https://www.w3schools.com/python/numpy/numpy_intro.asp (visited on 05/31/2022).

[59] ——, "Pandas introduction." (2022), [Online]. Available: https://www.w3schools.com/python/pandas/pandas_intro.asp (visited on 05/31/2022).

[60] ——, "Scipy introduction." (2022), [Online]. Available: https://www.w3schools.com/python/scipy/scipy_intro.php (visited on 05/31/2022).

Appendix

.1 Python Packages used

NumPy

The NumPy library is a useful tool when working with arrays in python [58]. A array is a grid of values and its recommended when working with a large amount of data. NumPy has many useful commands that:

- np.append()
- np.max()
- np.min()

The command "np.append()" is useful when adding arrays with each other and "np.max/min" quickly gives the maximum or minimum value in a array.

Pandas

The pandas library is used when working with data sets [59]. In this thesis is is used to load files into the python script and to create various data frames in order to store the data in a clear manner. Some of the commands used are:

- import pandas as pd
- data = pd.read_excel("Filename.xlsx")
- pd.DataFrame({"Name":data["Name"]})

Scipy.io

The scipy.io library stands for Scientific Python and is built upon NumPy [60]. Functions from NumPy has been optimized in scipy and additional function has been added. One of these functions is "Interp1d" who makes it easy to find a value between two points with interpolation. Interpolation is used both when calculating power output from a wind turbine and when calculating hydrogen production in this thesis. Equation 1 shows how values are interpolated during each time step, i.

$$\mathrm{y(i)} = \mathrm{y_1} + (x(i) - \mathrm{x_1})\frac{(\mathrm{y_2} - \mathrm{y_1})}{(\mathrm{x_2} - \mathrm{x_1})} \tag{1}$$

matplotlib.pyplot

Plotting different data to display the results is a very useful function in python. Matplotlib.pyplot is a module that makes it possible to plot and visualize data in arrays or data frames. This is handy when working with large time series to get a visualization and better understanding on how the data looks.

.2 Calculating Power Coefficients for the 750 kW wind turbine

This figure showcases the amount of power in the wind with the swept area of 1734.94 m^2 of the 750 kW wind turbine. The power coefficients is then calculated for all wind speeds. In addition is the occurrence of each wind speed and the total production at each wind speed during six years included.

Wind Speed [m/s]	Power turbin [kW]	Power in wind [kW]	Cp	Hours wind speed occurs [h]	Total Production at speed [MWh]
0	0	0	0	570	0
1	0	1,06265075	0	1599	0
2	0	8,501206	0	2534	0
3	4	28,69157025	0,139413771	3079	12,316
4	25	68,009648	0,367594904	3520	88
5	55	132,8313438	0,414058899	3789	208,395
6	96	229,532562	0,418241313	3955	379,68
7	160	364,4892073	0,438970474	3862	617,92
8	246	544,077184	0,452141731	3722	915,612
9	345	774,6723968	0,445349546	3575	1233,375
10	453	1062,65075	0,426292458	3310	1499,43
11	546	1414,388148	0,386032646	3292	1797,432
12	635	1836,260496	0,345811502	2854	1812,29
13	714	2334,643698	0,305828252	2536	1810,704
14	740	2915,913658	0,253779805	2268	1678,32
15	750	3586,446281	0,209120656	1961	1470,75
16	750	4352,617472	0,172310111	1540	1155
17	750	5220,803135	0,143656058	1282	961,5
18	750	6197,379174	0,121018898	945	708,75
19	750	7288,721494	0,102898705	707	530,25
20	750	8501,206	0,088222777	504	378
21	750	9841,208596	0,076210152	334	250,5
22	750	11315,10519	0,066283078	237	177,75
23	750	12929,27168	0,058007908	219	164,25
24	750	14690,08397	0,051054848	148	111
25	750	16603,91797	0,045170062	266	199,5

.3 NPV calculation case study 1

This figure shows the different investments, operation & Maintenance and saved cost used when calculating the profitability of the created energy system.

Year	Investment [MNOK]	O & M [MNOK]	Savings [MNOK]	
1	276,855	2,1517	6,616247192	H2 Storage cost = 3500 NOK/kg
2	0	2,1517	8,603030584	
3	0	2,1517	10,95387761	
4	42,75	2,6392	21,82175075	
5	42,75	3,1267	32,69529763	
6	0	3,1267	32,78602878	
7	0	3,1267	32,70131741	
8	0	3,1267	32,70131741	
9	0	3,1267	32,70131741	
10	67,713	3,6142	32,78644468	
11	0	3,6142	32,70162283	
12	0	3,6142	32,70162283	
13	0	3,6142	32,70162283	
14	0	3,6142	32,78549275	
15	0	3,6142	32,70193048	
16	0	3,6142	32,70193048	
17	0	3,6142	32,70193048	
18	0	3,6142	32,78497523	
19	0	3,6142	32,7001111	
20	24,963	3,6142	32,53630302	
1	469,355	H2 Storage cost = 7000 NOK/kg		
1	634,355	H2 Storage cost = 10000 NOK/kg		

.4 NPV calculation case study 2

This figure shows the different investments, operation & Maintenance and saved cost used when calculating the profitability of the created energy system.

Year	Investment [MNOK]	O & M [MNOK]	Savings [MNOK]	
1	125,855	3,1117	6,616247192	H2 storage cost = 3500 NOK/kg
2	0	3,1117	8,603030584	
3	0	4,29682742	9,768750195	
4	42,75	6,139880825	19,28106993	
5	0	7,391225297	28,90327233	
6	0	7,480466219	28,90476256	
7	0	8,787725616	27,59750316	
8	0	8,685859264	27,69936951	
9	0	9,237010587	27,14821819	
10	24,963	9,131593457	27,25363532	
11	0	11,5430465	24,84218227	
12	0	8,798541768	27,58668701	
13	0	9,350958396	27,03427038	
14	0	9,872914356	26,51231442	
15	0	10,42979272	25,95543606	
16	0	8,11518958	28,2700392	
17	0	10,09732568	26,28790309	
18	0	9,629012785	26,75621599	
19	0	9,891109765	26,49411901	
20	24,963	9,926481987	26,45874679	
1	144,36	H2 storage cost = 7000 NOK/kg		
1	158,36	H2 storage cost = 10000 NOK/kg		