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# Large-Scale Solar Plants and Offshore Wind farms

## – An Economic Comparison Including the Potential for Hydrogen Production and $CO_2$-Emission Effects

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Industrial Economics

# Preface

This thesis marks the conclusion of five wonderful years as a student at the Norwegian University of Life Sciences (NMBU). During the time working on this project I have developed academically in terms of writing, doing research and working independently, but I have also matured as a person. Through the work on this thesis I have learned how to structure my workday and follow a set progress plan while working towards a goal.

I have realized that the topic of my thesis is extremely relevant and well timed. Last month the government released their plans for investments in offshore wind; there has been summits with European politicians and debates on TV - about sustainability, hydrogen and offshore wind. It has been fun for me to try to follow some of this amid being busy writing my thesis ...

This thesis would not have been possible without the excellent support network around me. First off I would like to thank my fantastic supervisor Jesper Frausig, who has been supporting me tirelessly throughout this project. His feedback and leading questions have been of immense value when trying to piece this thesis together. I would also like to extend a big thanks to Anders Ødegård, my supervisor and contact at SINTEF, for setting the course of the project, and coming up with the basic topic for the thesis. The concept for this thesis materialized in the summer of 2021, while I was working as a summer intern in SINTEF and discussed potential subjects for the upcoming master thesis with Anders. A case comparison researching the potential of offshore wind farming with hydrogen storage, comparing it to a solar powered hydrogen plant was drawn up, and the rest is, as they say... history. I would also like to thank SINTEF as a whole, for supplying me with the necessary models and tools to go through with this project. I would especially like to thank Michal Kaut and Miguel Muñoz Ortiz for excellent technical support and explanations when I was struggling to understand the HyOpt-model.

Lastly I would like to thank my parents Randi Holmestad and Frode Rømo. Their vast knowledge of academic writing and scientific input, as well as their unconditional love and support have been incredibly valuable throughout this project, and I could not have done it without them.

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Jonas Holmestad Rømo

# Abstract

Fossil fuels are becoming increasingly undesirable and humanity is searching for green, sustainable, and reliable energy sources to satisfy the worlds energy consumption and preserve the earth for the future generations. Global research communities are working intensively to develop and implement the best technologies and solutions, and solar- and wind power are the most promising green energy solutions for the transition to a more sustainable energy future. This thesis investigates the economic feasibility and environmental impact of hydrogen storage used in tandem with a wind farm off the coast of Norway and a solar plant located in Algeria. An optimization model developed by SINTEF called HyOpt, determined an optimal investment strategy based on production data and market prices.

Five cases are analyzed using price- and production data from 2019: (i) a wind farm delivering electricity to the market, (ii) a solar plant delivering electricity to the market, (iii) a wind farm with a hydrogen production unit selling hydrogen to the market, (iv) a wind farm which delivers electricity to the Ekofisk oil field, and hydrogen to the market, and (v) a solar farm delivering electricity to a local processing plant and hydrogen to the market.

The HyOpt model uncovered that case (i), the wind farm solely selling electricity to the German market based on hourly spot-prices in 2019 would operate with a negative net present value of -16.9 bn NOK while cutting $CO_2$ emissions by 1,3Mtons annually. Case (ii), the solar plant only selling electricity to the French market had a similar net present value of -16.4 bn NOK while also cutting the annual $CO_2$ emissions by 1,4Mtons per year. It is important to notice, that both projects turned positive if the price level from 2021 is assumed to be representative for the future. The last three cases represent net profitable investments, based on the assumptions made. The wind farm selling hydrogen to the market (case (iii)) achieved a positive net present value of 1.3 bn NOK, meaning that the project is expected to be profitable while also having a positive impact on the environment by substituting approximately 1,2Mtons of $CO_2$. However, the biggest setbacks of these energy solutions are their production reliability. This thesis introduces the solution of hydrogen storage, whereby electricity produced is used to produce hydrogen from electrolysis which is compressed and stored, before being converted back to electricity using a fuel cell.

In case (iv), the project where the wind farm hourly delivered 110 MW electricity through the use of hydrogen storage to the Ekofisk oil field and sold the surplus hydrogen in the market, a positive net present value of 4.7 bn NOK was achieved, while simultaneously cutting the $CO_2$ emissions by 1,5Mtons annually. The solar counterpart with electricity supply to a local processing plant as well as selling the surplus hydrogen in the market, case (v), achieved a net present value of 3.4 bn NOK while substituting approximately 0,7Mtons of $CO_2$ in addition to the emissions that the local processing plant might reduce switching to green energy.

The findings indicate that hydrogen has a positive effect on both the economic feasibility and the environmental impact in the studied energy projects. All cases and conclusions are indicative. Large-scale solar and offshore wind farms installations in the GW range hardly exist yet, making all the cost estimates quite uncertain. However, common for all cases, are the potential to reduce $CO_2$ emissions significantly, and contribute to zero emission energy for our common future, thereby being economically sustainable.

# Sammendrag

Grunnet farene knyttet til den globale oppvarmingen er det nødvendig å redusere bruk av fossile energikilder til et minimum. Menneskeheten er derfor avhengig av å utvikle og implementere grønne, bærekraftige og pålitelige energikilder for å tilfredsstille verdens energiforbruk og bevare jordkloden for fremtidige generasjoner. Internasjonale forskningsmiljøer jobber intensivt med å utvikle og implementere de beste teknologiene og løsningene, og sol- og vindkraft er av de mest lovende grønne energiløsningene for overgangen til en mer bærekraftig energiframtid.

Denne oppgaven sammenlikner økonomiske og teknologiske aspekter ved storskala offshore vind i Nordsjøen, med tilsvarende storskala solenergianlegg i Nord-Afrika. I arbeidet er en optimaliseringsmodell utviklet av SINTEF kalt HyOpt, brukt til å bestemme en optimal investerings- og dimensjoneringsstrategi basert på produksjonsdata, teknologimuligheter og markedspriser.

Fem forskjellige prosjekter er analysert med pris- og produksjonsdata fra 2019: (i) en 1,4 GW vindparksom leverer strøm til markedet, (ii) et solcelleanlegg som leverer strøm til markedet, (iii) en vindpark med en produksjonsenhet for hydrogen som selger hydrogen til markedet, (iv) en vindpark som har en kontrakt på levering av elektrisitet (110 MW) til Ekofiskfeltet for å oppnå nullutslipp i forbindelse med produksjon, mens resten av kapasiteten selges som hydrogen til markedet, og (v) en solpark som har en forpliktelse til å levere 100 MW kontinuerlig lokalt, hvor resten brukes til hydrogenproduksjon for salg i markedet.

HyOpt-modellen beregner at prosjekt (i), vindparken som utelukkende selger elektrisitet til det tyske markedet basert på time-spotpriser i 2019 vil gi en negativ netto nåverdi på -16,9 milliarder NOK samtidig som $CO_2$-utslippene kuttes med 1,3 millioner tonn. årlig. Prosjekt (ii), solcelleanlegget som kun selger elektrisitet til det franske markedet, har en liknende netto nåverdi på -16,4 milliarder NOK, samtidig som det kuttet de årlige $CO_2$-utslippene med 1,4 millioner tonn per år. Det er viktig å merke seg at begge prosjektene får en positiv nåverdi, dersom prisnivået fra 2021 antas å være representativt for fremtiden. De tre siste prosjektene indikerer lønnsomhet, basert på de forutsetningene som er gjort. Vindparken som selger hydrogen til markedet (prosjekt (iii)) gir en positiv netto nåverdi på 1,3 milliarder NOK, noe som betyr at prosjektet forventes å være lønnsomt og samtidig ha en positiv innvirkning på miljøet ved å bidra til en reduksjon på ca. 1,2 millioner tonn $CO_2$.

En betydelig utfordringene ved disse energiløsningene er den naturgitte variabiliteten i produksjonen. Lagring av energi er derfor viktige teknologier for å øke verdi og fleksibilitet rundt slike anlegg. I denne oppgaven har vi derfor analysert hvordan grønt hydrogen som produseres via elektrolyse, og som deretter komprimeres og lagres, før den konverteres tilbake til elektrisitet ved hjelp av en brenselcelle, påvirker lønnsomheten. I prosjekt (iv), har vindparken et kontinuerlig leveransekrav på 110 MW

elektrisitet. Dette blir enten levert direkte fra vindparken eller via brenselsceller når det blåser for lite ved bruk av hydrogenlager, og selger restkapasiteten som hydrogen i markedet, Dette prosjektet har en positiv netto nåverdi på 4,7 milliarder NOK, og vil samtidig kutte $CO_2$-utslippene med 1,5 millioner tonn årlig. 0,5 millioner tonn av dette er fra installasjonen på Ekofisk. Solcelleprosjektet med samme struktur (v), med elektrisitetsforsyning til et lokalt prosessanlegg samt salg av overskuddshydrogen i markedet, oppnådde en netto nåverdi på 3,4 milliarder NOK. Reduksjonen av $CO_2$–utslipp ble her lavere enn i det tenkte Ekofisk-prosjektet (iv).

Funnene indikerer at hydrogen har en positiv effekt på både økonomi og miljøpåvirkning gjennom reduserte utslipp. Alle konklusjoner er rimeligvis beheftet med usikkerhet siden det per i dag finnes svært få storskala sol- og offshore vindparkinstallasjoner i GW-størrelse. Kostnadsestimatene som ligger til grunn, er derfor usikre. Felles for alle analysene er imidlertid potensialet for å redusere $CO_2$-utslippene betydelig, og vil kunne gi viktige bidrag for vår felles fremtid.

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# Contents

# List of Abbreviations

**API** application programming interface. 20
**ATR** autothermal reforming. 12

**CAPEX** capital expenditure. 17, 18, 20, 24, 25, 39, 49
**CCS** carbon capture and storage. 12
**CCU** carbon capture and utilisation. 12
**$CO_2$** carbon-dioxide gas. 12

**GUI** graphic user interface. 26

**$H_2$** hydrogen gas. 12, 13, 29, 30, 31, 32
**$H_2O$** water. 13
**HAWT** horizontal axis wind turbine. 5, 6

**IPCC** International Panel of Climate Change. 1

**LCOE** levelized cost of energy. 17, 33, 38, 49
**LCOH** levelized cost of hydrogen. 17, 33, 49

**MWp** mega watt peak. 29

**NPV** net present value. 25, 33, 35, 37, 39, 40, 44

**$O_2$** oxygen gas. 13
**OPEX** operational expenses. 17, 20, 39

**PEM** polymer electrolyte membrane. 13
**PV** photo voltaic (solar powered). 10, 11, 12

**Si** silicon. 8
**SMR** steam methane reforming. 12
**STC** standard test conditions. 10

**UNCLOS** United Nations convention on law of the sea. 3

# 1 Introduction

In August of 2021, the UN´s Intergovernmental Panel of Climate Change (IPCC) reported that the global climate changes are occurring at a much faster rate than initially assumed, observing the global average temperatures reaching irreversible levels if humanity does not alter the energy usage [1]. In a time where fossil fuels are becoming increasingly impermissible, humanity is searching for a green, sustainable, and reliable source of energy to satisfy the worlds energy consumption and preserve the earth for the future generations.

The international commercial and research communities are working intensively to develop and implement the best technologies and solutions. Solar and wind power are the most promising sources for the transition, while hydrogen production by water electrolysis is very promising for energy sourcing to the transporting sector. Furthermore, hydrogen can be used as input in high temperature industrial processes instead of fossil fuels.

This thesis will investigate the technological and economic viability of electricity produced by offshore wind turbines in the North Sea, and compare this to investing in a similar sized solar power plant in North Africa. Both power plants are in a position to serve the European energy market. After this, an assessment of how such large-scale plants may utilize $H_2$ in their value chains, is investigated.

Figure 1: *Map illustrating the approximate geographical location of the two energy projects.*

First, to set a baseline for the wind power aspect, there will be a review of a modern-day floating wind farm with a max capacity of 1400 MW, off the coast of Norway in an area called Sørlige Nordsjø II, looking at the energy outputs, as well as the investment and operational costs. In this case it is assumed that the landfall of the electricity is the German electricity market. The focus then shifts to a modern day solar-powered production facility in Northern Africa connected to the European market via France, noting the economical, logistical, and technological challenges connected to running such a plant. These two base-cases will then be compared with a hybrid of the two, where the energy plants are utilized to produce hydrogen which can be stored in storage containers and transported to the market or transported in hydrogen pipelines to the end-user markets. The thesis investigates whether this is a viable option, both economically and technologically.

This work has the ambition to increase the insight in level of profitability for different technologies important in the transition to a zero emission energy system. Is solar power and offshore wind comparable in economic terms? Can these systems expect to be combined with green hydrogen production in a good way, and how can this influence the investment decisions? Can green hydrogen from an offshore wind farm in Nordsjøen compete with green hydrogen from a solar farm in the Sahara desert? Finally, it is also important to estimate the global $CO_2$-emission impact large scale systems as these can have on the environment.

Finally, the thesis also seeks to evaluate if it is possible to supply the Ekofisk Oil Field with clean energy from a nearby wind farm utilizing hydrogen storage. This final case is based solely on assumptions from the author of this thesis and is not coordinated with any plans ConocoPhillips might have related to decarbonizing the operations at the Ekofisk field in the future.

## 1.1 Motivation

My motivation for writing this thesis and analyzing these green energy projects stems from the climate crisis our generation is currently facing. Our continued consumption of energy from fossil fuels is not sustainable, and forecasts say that if we do not make the switch to zero emission energy sources, our planet will suffer devastating consequences. Fortunately, it seems like the energy industry has taken these forecasts seriously. For instance, Equinor has released an industrial plan called "Norway Energy Hub", aiming to give Norway a key role in accelerating the energy transition in the coming years by investing more than 100 bn NOK into large scale zero-emission energy projects [2]. Moreover, about a month ago the government released a large scale plan for offshore wind [3].

The energy transition is a major societal challenge, and requires cooperation between states, industries and the scientific communities, and the motivation for this thesis has been to find out how the economic and technical potential for large scale zero emission power plants compares. The main focus in this report is the offshore wind, due to its significant natural and industrial potential in Norway. However, it is interesting to gain more insight in how the offshore wind farms compares to the development of large-scale solar energy plants.

## 1.2 Research Limitations

This work is mainly focusing on large scale systems and how they perform and is intentionally not diving deep into the technological details. Nonetheless, the main technologies are addressed at a relevant level to show how the main building blocks in the systems are integrated. These systems are linked to energy market properties but is not dealing in detail with regulatory and political aspects of energy supply. This is highly relevant in 2022 due to the ongoing war in Ukraine, in addition to the high energy prices in 2021-2022. The main assumption is that Europe is a relevant market for a future increase in zero-emission based energy sources, and that Norway and several countries in Northern Africa will play a crucial role in this energy transition.

## 1.3 Regulatory Aspects

In the thesis we do not consider regulatory and juridical aspects in any depth, but the work should be relevant anyway, since building large scale energy plants can be decided by nations like Norway. The most relevant elements to be considered and to adapt to are mentioned in this section.

Building large wind farms offshore, requires a solid juridical foundation in addition to financial muscles and offshore technology experience. The offshore activity and jurisdiction at the Norwegian continental shelf are regulated by United Nations Convention on Law of the Sea, UNCLOS [4].

UNCLOS is a convention under international law that was ratified by Norway in 1996. The treaty defines sea zones where the sovereign states have different rights and obligations. The division applies for the sea areas and the airspace above, but also for the seabed and its subsoil. The Norwegian Marine Energy Act [5] manages how Norway regulates the development of energy production and infrastructure within the nation's territorial waters and economical zones. In territorial waters, the coastal state has full sovereignty and can apply its legislation towards citizens and foreigners and has exclusive power. The territorial waters go 12 nautical miles out to the economic zone. In the economic zone, the coastal state does not have full sovereignty, but has the right to exploit natural deposits in the water masses, on the seabed and in the subsoil below the seabed. In addition, the coastal state has exclusive rights to economic activity, including electricity production based on wind power.The economic zone and the continental shelf go 200 nautical miles beyond this. This gives Norway the right to build offshore wind farms, like the main example in this master thesis.

The purpose of the reference plant for large scale solar production is primarily to investigate the economic scales compared to offshore wind. A discussion related to legal matters concerning the reference case for a large-scale Photovoltaic plant in Algeria with energy export to France is therefore not included. The solar case in Algeria is therefore not linked to any known or concrete plans or aligned with any preferences and regulations that the Algerian government or French authorities might have. Even though these calculations are relevant to gain insight, they are not related to any specific existing plans at the time of writing. However, Algeria and EU have strengthen their cooperation related to energy in the later years, and some concrete industrial cooperation is ongoing [6].

# 2 Theory

This chapter will provide the theoretical background required to perform the analyses that is conducted in this thesis. First the technical aspects and assumptions related to the analysis of the solar case and the wind case respectively, will be presented, going into detail regarding the state-of-the art technology as it is today, as well as the expected technological development in the near future. The chapter then goes in to detail on the technology used to produce and store hydrogen. Lastly, the theory section takes a look at the most important economic parameters, such as the market and the costs utilized by the HyOpt-model.

## 2.1 Wind power

### 2.1.1 Wind resources

Wind is like many other green energy sources a natural occurring phenomenon and is a result of air moving from an area of high atmospheric pressure to an area with low atmospheric pressure. Around the equator, the higher temperatures will heat up the air, making it rise high into the atmosphere, resulting in areas of low atmospheric pressure. This atmospheric process of continually rising air, will push the air towards the poles. At the poles, the ascended warm air will cool off due to the colder climate, which will result in it descending down to cause areas of high atmospheric pressure. The higher the difference in pressure, the stronger the wind will be [7].

The moving air will have kinetic energy which can be harvested as electricity by utilizing a wind turbine. The most common turbine type is the *horizontal axis wind turbines* (HAWT) and consists of a horizontally mounted axis with three blades at one end, while the other end is connected to a generator, enabling the axis to generate electricity upon rotation [8]. The three blades will rotate when wind blows perpendicular onto the structure, using the same principles as an airplane-wing. The angle and shape of the cross-section of the blades are shaped in such a way that the forces exerted by the wind will resolve into two components: the drag force and lift force, as seen in figure 2. The lift force is what generates the rotational motion of the three blades. The word lift does not necessarily mean that the force is exerted upwards, but it derives from the similarity between the rotor blade and an airplane wing.

### 2.1.2 Wind technology

Wind technology has become more and more efficient in recent years, and the investment cost has decreased at a similar rate. The *Hywind Scotland* project, a joint venture between Equinor and Masdar off the coast of Peterhead, Scotland, can be considered state-of-the art technology. This wind park is the worlds first commercial wind farm operating with floating wind turbines, consisting of five 6 MW turbines accumulating to a total capacity of 30 MW [9]. The Hywind Scotland project has proven that the floating wind park idea is worth developing further. A report from March 2021 named the Hywind Scotland wind park as *"the best performing offshore wind farm in the UK for 3 years in a row"* [10]. It achieved an average capacity factor of 57.1%

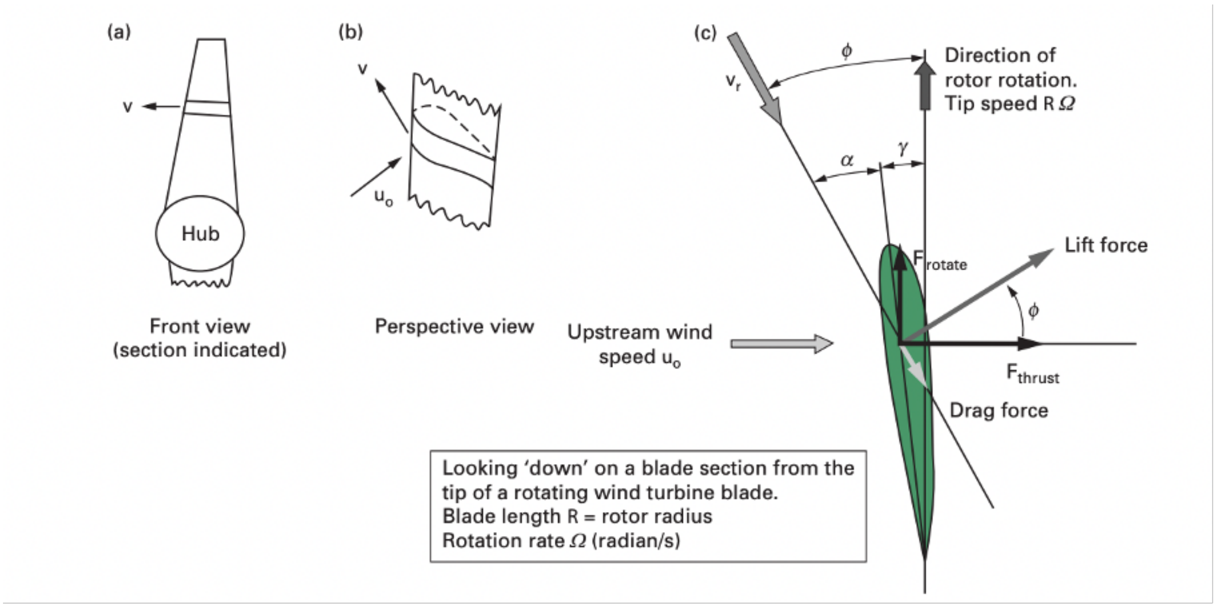

Figure 2: *Explanatory sketch of forces exerted from the wind, onto the cross section of the blades on a wind turbine. Figure from [8]*

between March 2020 and March 2021, compared to the UK's offshore wind farm average of around 40 % [10]. The capacity factor of a wind turbine is defined as the average power output divided by the maximum power capability, illustrated by equation 1. The capacity factor is a measure of how much of the wind parks capacity it is realistically possible to utilize, and is therefore an important measurement when analyzing the return of an investment in terms of energy output.

$$\eta = \frac{Power_{average}}{Power_{max}} \cdot 100\%. \tag{1}$$

### 2.1.3 Electrical systems

There are several different types of HAWTs, which in turn requires different electrical systems to function properly. Fixed-speed wind turbines are turbines that are optimized to operate within a certain wind speed, effectively giving them an upper limit for power generation. When the wind speed exceeds a certain limit, the rotor will lock down, and stop rotating, hindering the energy generation. This stoppage is carried out to prevent damage and breakage. The fixed-speed wind turbine has a simple and proven low-cost electrical system, but the simplicity comes at the cost of decreased efficiency [11].

A new development in technology saw the variable-speed wind turbines enter the market. The variable-speed wind turbine has grown to become one of the more dominant turbine technologies on the market. A variable-speed wind turbine is designed to achieve maximum aerodynamic efficiency across a wide range of wind speeds. This technology is opposed to the fixed-speed wind turbine which only achieves maximum aerodynamic efficiency on one specific wind speed. The variable-speed enables the turbines to adapt the rotational speed of the wind turbine $\omega$ to that of the wind speed $v$. Consequently, this will keep the turbine-speed constantly optimized.

The variable-speed wind turbines offers a wind turbine less prone to mechanical stress damage, improved power quality and a greater energy capture rate. The downsides of this technology are the increased complexity and cost of the electrical system, the losses in power electronics and a dramatic increase in circuit components [11].

### 2.1.4 Betz' criteria

The energy production of a horizontal axis wind turbine is limited by Betz' law, which states that it is only possible to utilize $\frac{16}{27}$, or around 59.3 % of the kinetic energy in the wind [8]. If all the kinetic energy from the wind was to be utilized for energy production, the turbines would not be able to rotate, since the previous gust of wind that gave all of its kinetic energy to the turbine will be stranded in front of the turbine, not progressing further due to the lack of kinetic energy. Betz calculated that the wind would need to retain $\frac{11}{27}$ or around 41 % of its kinetic energy in order to allow the wind to continue moving once it has cleared the rotating turbine. The electrical power output, $P_el$, can be given as a function of the air density, $\rho$, the wind speed, $v$, the rotor area, $A$ and the power coefficient, $C_p$:

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

Betz' criteria enforces an upper limit on the power coefficient, $C_p$, ultimately scaling the whole production, as seen in equation 2. This gives an upper limit for the efficiency of wind turbines [8].

## 2.2 Solar power

### 2.2.1 Silicon and the solar spectrum

Photovoltaic technology converts energy from the photons in the sun light into electricity. This conversion of energy, called the photovoltaic effect, describes how the electric potential in a conductor changes when photons dislodges electrons in the material [12].

Silicon is a semiconductor often utilized in solar panels. It is located in group 14 in the periodic table of elements, classifying it as a semi-metal, giving it certain conductive properties. In addition to this, silicon is the second most abundant element on earth after oxygen, which enables large scale production of silicon-solar panels [13]. The advantage with using silicon for solar panels is the high degree of energy conversion of incoming photons compared to other semiconductors combined with its relatively low manufacturing cost. This means that silicon absorbs a wide variety of photons with a range of different wavelengths [14]. Figure 3 illustrates the spectrum of wavelengths silicon is able to absorb. The allowed electromagnetic waves have a wavelength between 400 nm and 1200 nm, which overlaps the majority of the wavelengths of the sunlight containing the most energy.

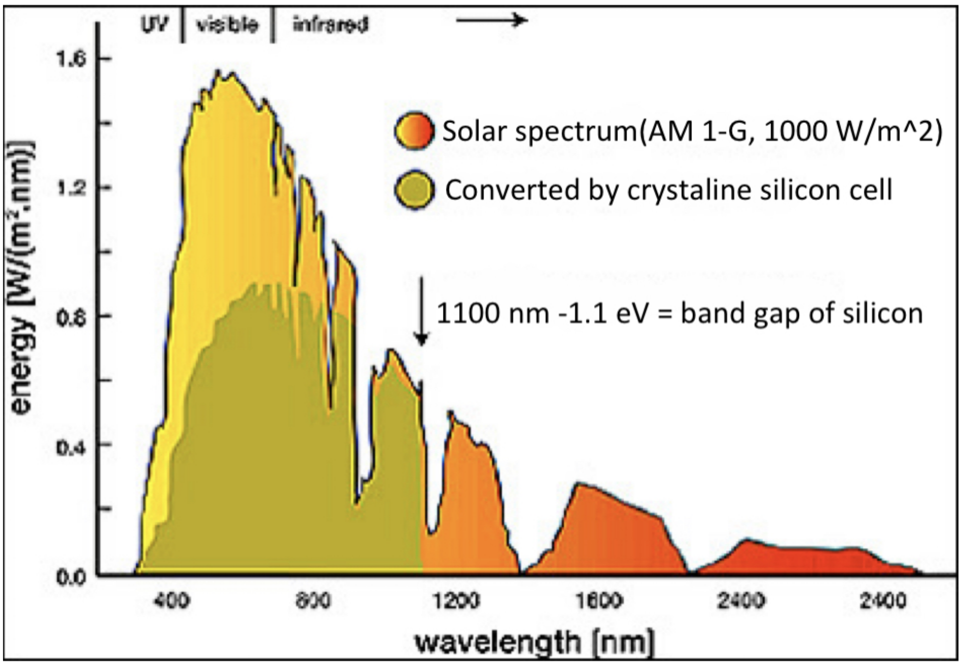

Figure 3: *The electromagnetic spectrum emitted from the sun with energy-unit* $W/m^2 \cdot nm$ *on the y-axis and the wavelength in nm on the x-axis. The wavelengths silicon operates with is illustrated with a dark yellow color* [15].

### 2.2.2 Energy levels and band gap of Silicon

A silicon (Si) PV-module is divided into two components. One side consists of P-type silicon, a silicon component doped to become positive. This means that the P-type silicon has a deficiency of electrons, and therefore an abundance of "electron holes". The other side consists of N-type silicon that has been doped to achieve a surplus of unbound electrons.

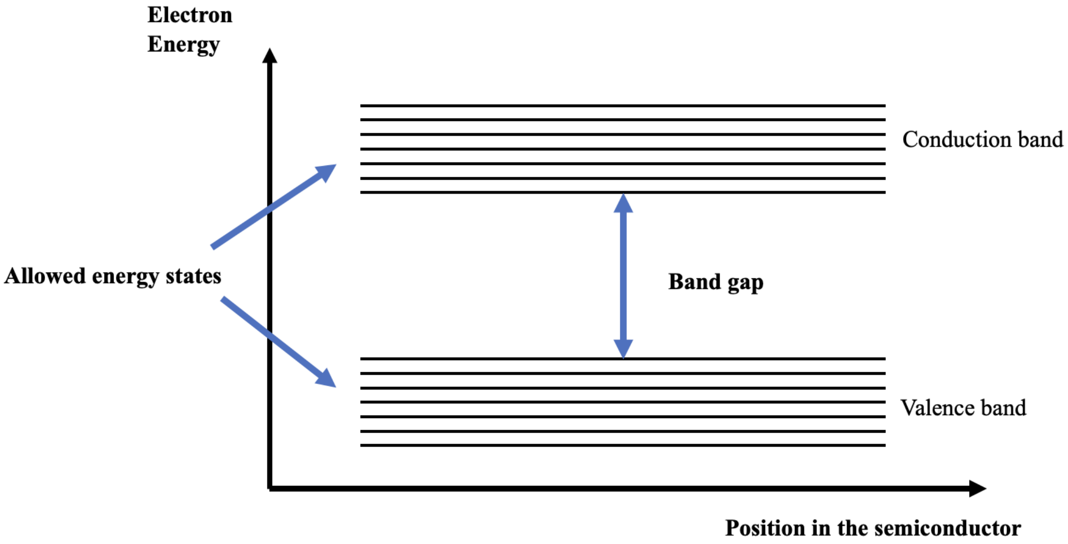

Figure 4: *The band gap and the allowed energy states in a semiconductor. When electrons absorb the quantified energy from an incoming photon, it will move from the valence band to the conduction band, given that the absorbed energy is greater than that of the band gap for that particular semiconductor. Adapted from:* [16].

To move the electrons from the N-type side of the solar panel to the P-type side, the energy of the incoming photons needs to equate or exceed that of a certain energy level. This energy level equates to the band gap illustrated in figure 4. The band gap seperates the valence band and the conduction band. Inside of these bands the electrons exist in their allowed energy states. Electrons in the valence band is bound to the atom (i.e. Silicon), but an electron can move over to the conduction band if it is hit by a photon possessing an energy level equal or above that of the band gap. The electron has now achieved an excited state. This means that it will have a higher energy state. In this energy state, the electrons will be unbound, and freely move around [14].

### 2.2.3 P-N junction

When P-type and N-type silicon are combined, it creates a P-N junction, as shown in figure 5. The P-N junction serves as a divider for the photo-generated electrons on the N-side, and the free holes on the P-side. This separation is caused by an electric field blocking the free electrons and holes from recombining with each other. This causes the N-side to have a surplus of free negative electrons, while the P-side has a surplus of positively charged holes with spaces for electrons to revert back to their more stable bound state [14].

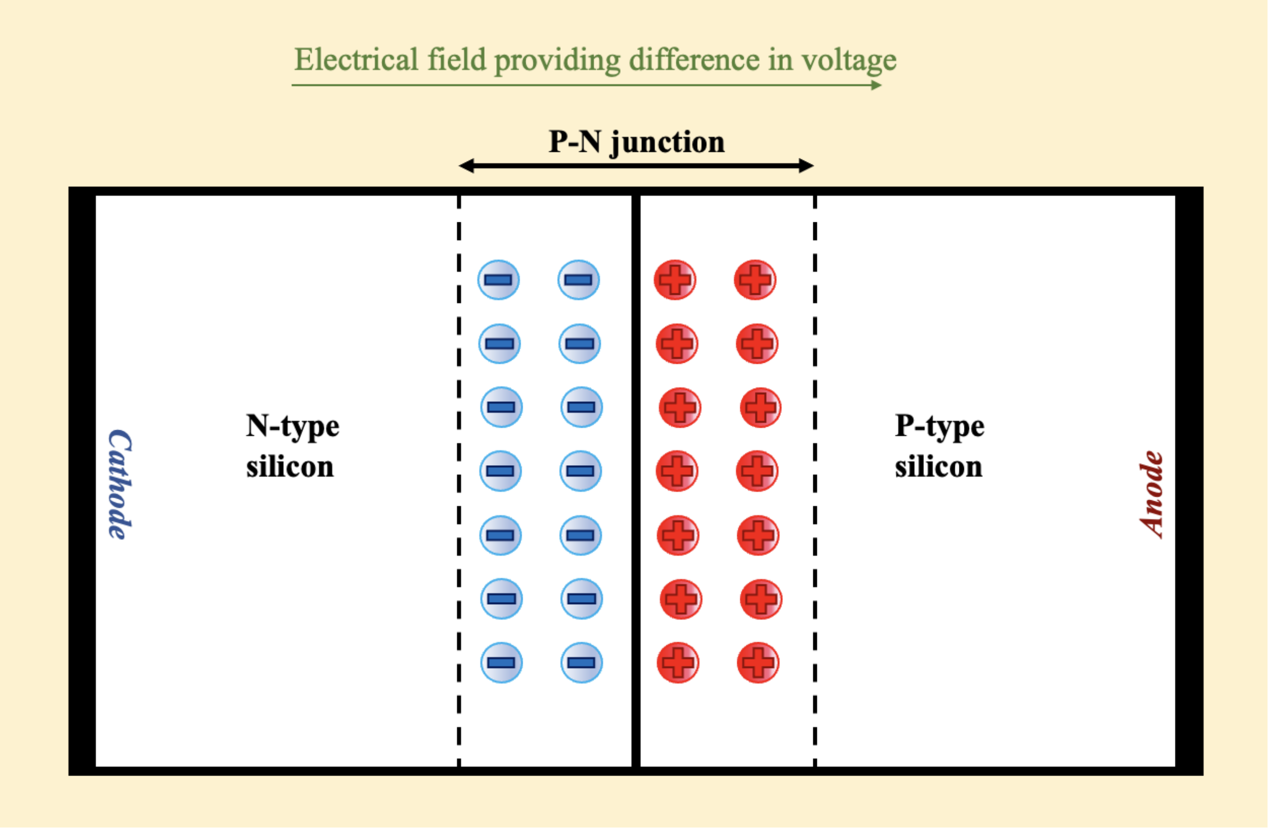

Figure 5: *A simple sketch of a "P-N junction". On the p-doped side, there is a surplus of holes, meaning there is a lot of free space in the electron shells. This makes the P-side positively charged. On the other side, there is a surplus of unbound electrons. The abundance of free unbound electrons on the N-side gives it a negative charge. The figure is adapted from: [8]* [17].

The excited electrons seek to recombine with the holes, seeing as the electrons pursue a more stable state and go into a lower energy level, but due to the P-N junction, the electrons cannot reconnect with the holes. If an external circuit is attached between the P-side and the N-side of the P-N junction, the electrons would be able to reconnect with the holes, putting them in a stable and bound state. When new sunlight hits the solar panel, new electrons will be energized, producing new electron-hole pairings on either side of the P-N junction. Electrons seeking to recombine with one of the free holes have to travel through the external circuit or a load, to get to the P-side. This generates current - and electricity [14].

### 2.2.4 Standard test conditions (STC)

The efficiency of a PV-module decreases as the internal cell temperature increases. STC (standard test conditions) are applied when measuring the efficiency of a PV-module. They follow four conditions: an irradiance of 1000 W/m$^2$, an internal cell temperature of 25°C, a wind speed of 1 m/s and 1.5 air mass (AM). The air mass represents the thickness of the atmosphere, i.e. how much of the atmosphere the solar radiation has to pass through before it hits the PV-module, and is given by the formula:

$$AM = \frac{1}{\cos\Theta}, \tag{3}$$

where $\Theta$ is the zenith angle, defined as the angle between the solar radiation and "the zenith", a thought line that is perpendicular to the earth. A higher AM would give the irradiated sunlight a longer way through the atmosphere, causing a larger portion of the sunlight to be scattered by the atmospheric particles and become reflected back where it came from, decreasing the efficiency [18].

### 2.2.5 Efficiency

When a solar panel is produced and ready for use, there are a lot of variables and key factors impacting its effectiveness. Today, around 99% of all solar panels are comprised of silicon [19]. Even though silicon has favourable characteristics in terms of absorbing a wide array of wavelengths, it is not able to absorb all possible wavelengths in the electromagnetic spectrum. Because of this, PV-panels manufactured from silicon has a theoretical upper efficiency limit of 33.16% which it cannot exceed called the Shockley-Queisser limit [20]. The efficiency measures how much of the solar irradiance, $P_{sun}$, that is converted into electrical energy. The electrical energy delivered by a PV-module is determined by the electrical current $I$ through the module, multiplied by the voltage $E$ applied to the module. This is shown by the equation:

$$P_{out} = EI, \tag{4}$$

where $E$ is given in V and $I$ is given in A. The efficiency is given by the following formula:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\%. \tag{5}$$

In equation 5, $\eta$ is the efficiency given as a percentage, and $P_{out}$ and $P_{in}$ are given in W. Even though the theoretical upper efficiency limit is 33.16%, most commercial PV-installations are operating with an efficiency under 20%. This is because the added production cost of making an "optimal" PV-cell is in most cases not worth the tradeoff.

### 2.2.6 Bypass-diodes

If multiple PV-cells are connected in series, the electricity in the circuit will be determined by the lowest performing cell. This renders a string of PV-cells only as strong as its weakest link. Under normal operating conditions with equal irradiance onto each cell, this is unproblematic. However, the problem arises as soon as one of the cells experiences a drop in irradiance, causing all the other cells to start underperforming. This can occur in the event of shade blocking one or more of the cells on the module, and the irradiated energy that no longer gets transformed by the module will then dissipate as heat in the blocked cells [21].

The solution to this problem is to connect a bypass-diode in parallel to each one of the cells, such that the electricity cannot go through, and is limited to the blocked off cell. Under normal operating conditions this bypass-diode is not going to conduct any electricity, but it will kick in if there is a significant difference in the generating capabilities between the cells in the module [22]. In a perfect world, every PV-cell should be connected to an own bypass-diode across the whole module, but due to this driving up the production cost, it is common practice to use one bypass-diode for every 15-20 cells [22].

### 2.2.7 Kirchoffs laws

In a PV-module with bypass-diodes, the electric current can take two different pathways through a circuit. The electric current will be able to go through the string of PV-modules, but also through the bypass-diode, avoiding potential shading. If one knows the electric current out of the module, and the electric current through the diode, it is possible to calculate the electrical current in the circuit through *Kirchoff´s current law*:

$$\sum_{k=1}^{n} I_k = 0. \tag{6}$$

This law states that the sum of all currents entering a junction point must be zero. This means that the current entering a junction point equals the current exiting the junction. Moreover, it tells that the current going through the PV-module circuit will equate to the difference between the module-current and the current running through the bypass-diode.

Next, it is possible to calculate the voltage by using *Kirchoff´s voltage law*:

$$\sum_{k=1}^{n} V_k = 0. \tag{7}$$

This law states that the sum of all voltages across components in a closed circuit equals zero, and indicates that the voltage drop across the bypass-diode also occurs in the loop with PV-cells.

## 2.3 Hydrogen technologies

In spite of being the most abundant element in the universe, hydrogen cannot be found in its pure form naturally. Hydrogen has several properties that makes it a great and natural energy carrier in the quest for a net-zero-emission future. Its role as an energy carrier means that it requires energy to be extracted from substances with natural occurring hydrogen. Comparisons as an energy carrier can easily be drawn to electricity, seeing as electricity is also utilized as a solution to transport energy [23]. Hydrogen gas is usually assigned a color code in addition to their name, given to it as an indicator as to whether or not the energy the hydrogen gas is created with is renewable or not. This is illustrated in figure 6 Usually the different types of hydrogen can be classified into *grey*, *blue*, *turquoise* and *green*. Grey hydrogen is hydrogen produced from fossil fuels like oil and gas either through a process called steam methane reforming (SMR) or autothermal reforming (ATR). The waste product from these processes are $CO_2$, and from every 1 kg of $H_2$ produced, the process also emits 10 kg of $CO_2$ [24]. In the long run this will have a negative impact on the environment, and in terms of sustainability it is not a viable option. Blue hydrogen is also produced through SMR or ATR, just like grey hydrogen. The only difference between grey and blue hydrogen production is how the two methods handle the waste product. Where the waste from grey hydrogen (mainly $CO_2$) is freely released into the atmosphere, producing hydrogen in a blue way, requires the emitted $CO_2$ is captured through either carbon capture and storage (CCS) or utilized in chemical production through a process called carbon capture and utilisation (CCU). Producing turquoise hydrogen is achieved through the pyrolysis of natural gas. Pyrolysis is the process of using thermal decomposition to alter the chemical composition of a compound. The waste from turquoise hydrogen comes in the form of solid $CO_2$ which can either be utilized in other chemical processes, or captured and stored underground. Utilizing a renewable energy source for the electricity applied in the production of turquoise hydrogen, can make it a sustainable and environmental friendly option despite the CCS required. The production of green hydrogen is usually achieved through electrolysis of water using electricity from renewable energy sources, such as wind power or PV-technology. Green hydrogen is the main focus of this thesis, and the rest of this chapter will deal with green hydrogen.

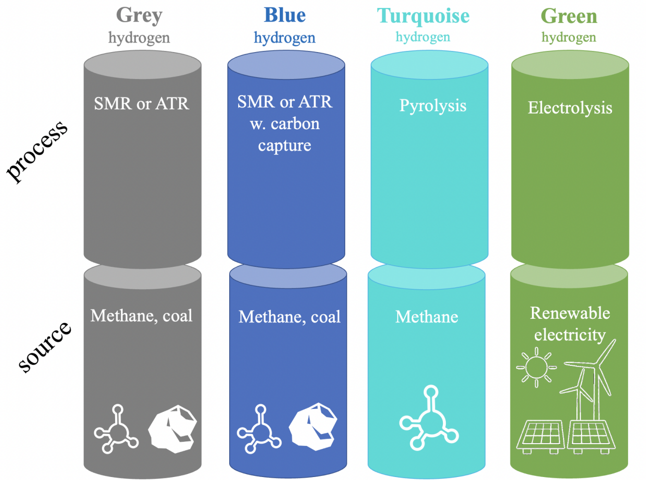

Figure 6: *Overview of hydrogen colors, the process and the energy source used in the different types of hydrogen production.*

### 2.3.1 Electrolysis of water

Electricity produced by wind turbines can be converted into hydrogen, and stored in sub-sea hydrogen tanks. The conversion of electricity to hydrogen is commonly done through a process called electrolysis, where a solution containing some sort of hydrogenic compound is subjected to an electrical current causing the hydrogen particles to separate from the other elements in the solution [25]. This process occurs in a compartment called an electrolyzer, and is illustrated in Figure 7. This thesis assumes the use of Polymer Electrolyte Membrane-electrolyzers (PEM) over Alkaline-electrolyzers, because of its smaller size. This is an important factor when building offshore installations. In a PEM-electrolysis in the offshore wind farm case, the hydrogenic compound utilized in the electrolyzer is seawater. Usually when performing chemical processes, the waste material might be poisonous or hazardous for the environment. However, in this case the seawater ($H_2O$) is split into hydrogen gas ($H_2$) and oxygen gas ($O_2$), meaning that as long as the electricity involved in the process of electrolysis is green, hydrogen production can be 100 % sustainable in terms of climate emissions.

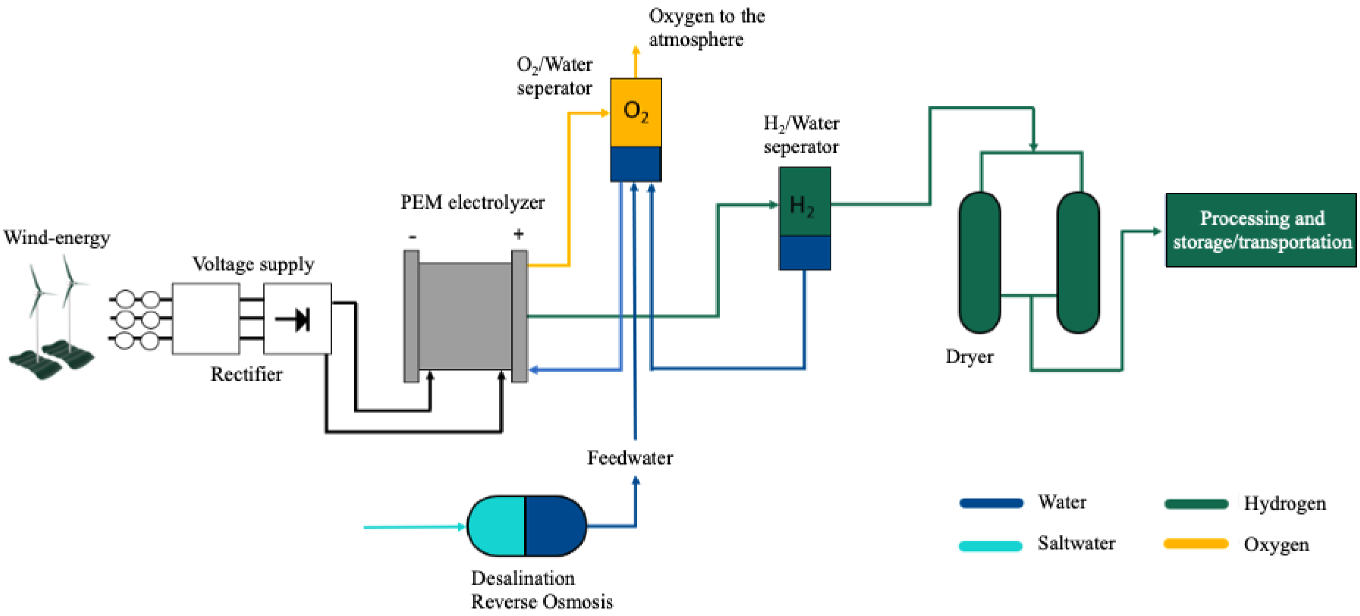

Figure 7: *Sketch illustrating the system flow when producing Hydrogen with an electrolyzer offshore.*

### 2.3.2 Fuel cells

Hydrogen is commonly imported directly into industrial processes, replacing fossil energy sources in high energy industrial process requiring high temperatures. However, in our case, we look at hydrogen as a storage technology, where the hydrogen can be converted back into electricity by utilizing fuel cell technology. This is the same technology used in hydrogen powered vehicles, and is in our case used to convert stored hydrogen back to electricity if other electricity sources are unavailable or not sufficient in periods of operations. Figure 8 below, shows a sketch of a fuel cell:

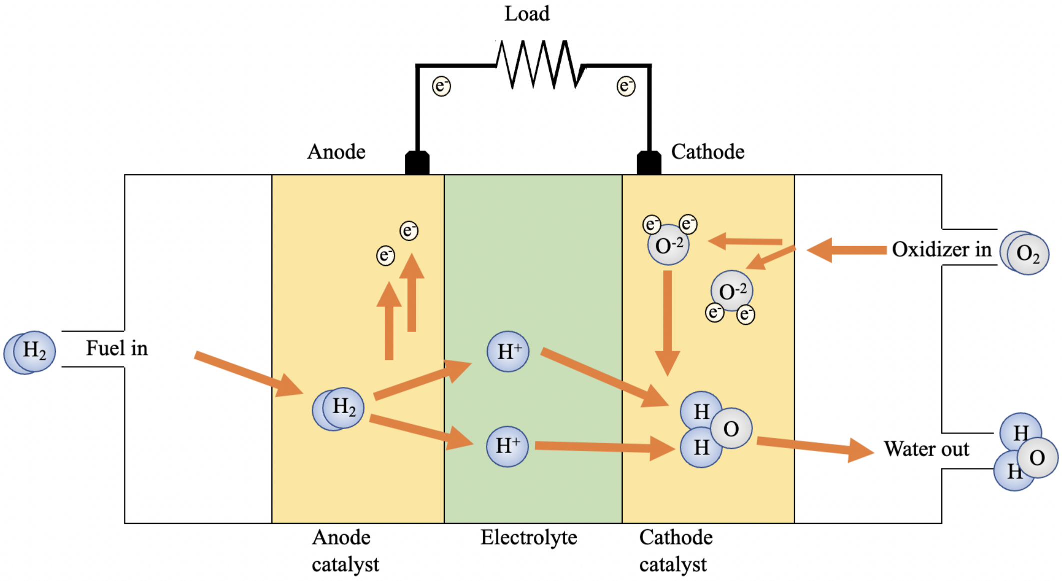

Figure 8: *An explanatory sketch of a fuel cell using Hydrogen to operate an external load*

To give a brief overview, the components in a fuel cell consists of an anode and a cathode electrode. In addition to this, there is an electrolyte and a catalyst material (i.e. platinum), which forms a membrane, where there is a chemical reaction, releasing electric energy (which can power a load, as illustrated in Figure 8) and produce water as waste. The chemical reaction happening inside the fuel cell is shown in equation 8 below:

$$2H_2(g) + 2O_2(g) <=> 2H_2O(l) + \text{Energy}, \tag{8}$$

### 2.3.3 Hydrogen storage

The produced hydrogen is compressed and can be stored in storage tanks. Offshore, technology exists where these tanks can be stored sub-sea under high pressure. Hydrogen storage works in principle as a battery [26]. The produced energy is stored under the sea on site and is withdrawn when needed. The need might occur if there is a period with no wind, driving the electricity prices up. The system will then rechannel the hydrogen into the fuel cell and revert it back to electricity which can be sold on the market. Another option is also to sell the produced hydrogen on the market without converting it back to electricity. Which market the system sells to is determined by whether or not it is more economically advantageous to sell the hydrogen or convert it back to electricity.

### 2.3.4 Hydrogen production and application in Norway and Europe

The role of hydrogen related to the green shift, is regarded as crucial to be able to obtain a trustworthy and reliable zero emission-based energy system. Today, according to DnvGL, about 3% of the world's energy consumption is used to produce hydrogen [27]. This production is mainly based on fossil energy sources and has a high carbon footprint. This footprint can be significantly reduced by using CCS which currently is still a very expensive technology, or by replacing hydrogen from fossil-based processes with hydrogen from water electrolysis based on renewable energy like hydro power, wind or solar energy.

In this way, hydrogen can help decarbonize sectors that do not utilize the potential related to H2 as energy carrier. In Norway, this primarily applies to the transport sector, where hydrogen can replace fossil fuels, for example in heavy transport by road and in the maritime sector. This assumes that the hydrogen is produced with a low carbon footprint. Europe have developed a very active strategy to include hydrogen's role into the future energy supply solution for the continent [28].

### 2.3.5 Loss of energy – but increasing value or reaching important environmental targets

Utilizing green electricity to produce hydrogen and then converting it back to electricity through a fuel cell will of course involve loss of energy. It requires energy to produce hydrogen, and there is a efficiency loss in the fuel cell when the hydrogen is transformed back to electricity. There is however, three arguments that can be used to justify this "waste of energy". Initially it is the economic argument that the ability to store energy leads to an opportunity to utilize the energy at times and in sectors where the energy cost is significantly higher than using the energy in the moment it is produced – referring to the value in the electricity spot markets. The second one, is the possibility to utilise stranded energy sources with no connection to the electricity grid. An example of this is the ambitions to develop large scale H2-production in Finnmark in the northern part of Norway [29]. The third argument and maybe the most important element is that hydrogen is one of the few ways of replacing fossil fuel in heavy duty transport with zero emission energy [30].

## 2.4 Markets

When looking at the economic aspect of the cases, understanding the different energy markets is important. From a micro-economic point of view, the market fluctuations in both the electricity- and the hydrogen market can be explained by the dynamic shifts in the supply and demand of the energy market. During certain timeframes, the demand for electricity will be higher than others. This can typically be during the day, when people are making food, watching TV, charging their electronic devices or merely keeping the lights on in their home or workplace. This increased demand for electricity will push the price up, seeing as there is a finite amount of available electricity on the market. This finite amount is referred to as supply, and is defined as the rate of which one is able to deliver electricity to the market. A high supply paired with a low demand yields an inexpensive market price, while a high demand paired with a low supply will inflate the prices. For any suppliers, the goal is obviously to sell when the demand is high and the supply is low, but that is of course challenging.

The generation of energy is also a stochastically fluctuating process, meaning that the fluctuations seem to be happening at random. For instance, it is impossible to control when and where the wind is going to blow. Usually the wind changes throughout the day, generating electricity at a seemingly random rate. Some parts of the day, there will be a relatively large amount of energy-production, while at other times, there might not be enough wind to rotate the wind turbines. If these periods of low production coincide with a time of day where there is a high demand for electricity, the price of electricity will increase. Similarly, if a period of very high production coincides with a time of day where the demand for electricity is low, the market price of the produced electricity will decrease. If an energy system can store the energy it produces, the supplier can use this storage-option to sell the energy when the market is high, and hold the energy when the market is low. This is for instance a common practice in a hydro power facility inside a dam, where the water that is allowed in from the water reservoir is regulated to meet the current market. In other cases it is more difficult to start and stop the energy generating process. It is possible to start and stop the wind farm, but it would be considered a waste, considering the wind can change or even dissipate at any time, hindering optimized operation and decreasing the total amount of energy the facility generates. A wind farm or a solar park without any storage capacity is forced to sell their produced energy to the market at the time it was produced. This storage-challenge is also very prominent when it comes to nuclear reactors, due to their complicated and expensive start and stop procedures.

### 2.4.1 Electricity market

The electricity market prices are constantly changing with the supply to the market, and the demand of the consumers. In 2019, the electricity market was relatively low compared to the prices in 2021. If we compare the average price in Germany in 2019 with the average price in 2021, the price increased from around 356 NOK/MWh to 803 NOK/MWh [31]. That is a 125 % increase in just two years. The outlook for energy prices will naturally influence the value of the investment projects evaluated in this thesis.

There are several indicators that the energy prices will be high in the coming years. This includes the increased $CO_2$-tax that will increase the value of zero emission energy. Germany´s decision to remove nuclear power from their energy mix and the ongoing war between Russia and Ukraine has made it urgent for the EU to limit their dependency on Russian natural gas. On the other side, the constant building of renewable energy projects, as well as further advancements in renewable energy technology making these project more efficient, will likely replace the expected loss for some of the anticipated limitations in the supply.

### 2.4.2 Hydrogen market

The hydrogen market is a growing market. This can be an incentive for potential investors to capitalize on this predicted market growth early, and achieve large market shares. The hydrogen market is in a growth period fuelled by the global shift in focus towards clean energy sources and the rapid industrialization and growth of hydrogen-producing infrastructure. This is especially prominent in the transport and shipping industry where a high number of heavy cargo ships run on hydrogen.

## 2.5 Costs

### 2.5.1 Investment cost (CAPEX)

An important concept to clarify when talking about the economics of an investment project is CAPEX. CAPEX is an abbreviation for "capital expenditure", and is related to the capital necessary in the acquisitions and upgrading assets related to a project[32]. This can be the investment cost of wind turbines and solar panels, or a pipeline for the purpose of transporting hydrogen. CAPEX are usually long term investments, and it is usually what project managers deem to be the most important when planning a project.

### 2.5.2 Operational cost (OPEX)

Another economic aspect that is taken into account for investment assessment, is OPEX. OPEX stands for "operational expenses", and is a term that is referred to when describing expenses occurring through normal business operations. OPEX covers the day-to-day operating expenses a project might have, such as rent, inventory cost, man hours, maintenance and insurance [33].

### 2.5.3 Levelized cost of energy and levelized cost of hydrogen

There are many different ways in which to measure and compare costs. One practical model to utilize when evaluating energy systems with different means of energy-production is the levelized cost of energy (LCOE). This model compares the annual cost with the annual energy output, eliminating the need to adjust the model when analyzing the different technology types. The mathematical formula for LCOE can be written as:

$$LCOE = a_r, Y \frac{\sum_m TC_m}{E}, \tag{9}$$

where $a_r, Y = \frac{r}{1-(1+r)^{-n}}$ is the annuity factor for discount rate r and Y years, $TC_m$ is the discount present value of the total cost for component $m$ and $E$ is the annual electricity generated [34]. Translated over to capital expenditure (CAPEX) and operational expenses (OPEX) terms, which is the form incorporated in the HyOpt model utilized in this thesis, the formula can be changed to:

$$LCOE = \frac{\sum_m a_r, Y * CAPEX_m + OPEX_m}{E}, \tag{10}$$

where $_m$ expresses one of the components in the system. By modifying the calculations from equation 11, it is simple to express the levelized cost of Hydrogen (LCOH) too. The LCOH can be expressed as:

$$LCOH = \frac{\sum_m a_r, Y * CAPEX_m + OPEX_m}{V_H}, \tag{11}$$

the difference being that the denominator is changed from annually generated electricity (E), to the number of annually produced kg of $H_2$ given as $V_H$. This simplifies the comparison when comparing different production technologies despite their different energy outputs.

### 2.5.4 Offshore case investments

One of the largest cost contributors in the offshore case is the wind technology itself. First off, there will be a relatively large investment in turbines. These should be state-of-the art, high producing wind turbines to provide the best possible conversion rate and power output.

Another relatively big cost-contributor is the energy transportation and distribution. There are many ways to transport electricity and hydrogen, however in this thesis the chosen solution is a sub-sea power cable between "Sørlige Nordsjø II" and Germany.

### 2.5.5 Solar case investments

Regarding the solar-power case, the largest capital expenditure (CAPEX), are the solar panels themselves. To construct a solar powered harvesting plant with a similar production scale to that of the wind farm, it is necessary to invest heavily into PV-technology. State-of-the art, high-efficiency solar panels, preferably with integrated bypass diodes are favoured, to provide a good energy conversion rate as well as a fail-safe to combat shading.

## 2.6 Optimization

The work in this thesis benefits a lot from the HyOpt model developed by SINTEF [35]. The model facilitates the coordination of technology data, market data and infrastructure investment decisions.

Operations research and optimization – is a powerful method to perform complex assessments for complex systems. The methodology was developed throughout the 20th century, with the development of the Simplex algorithm by George Danzig in 1947 [36]. His aim was to apply the methodology for real world problems, and that has proven to be a success story with a steadily growing use of advanced modelling and solving techniques. The algorithm's success led to a vast array of specializations and generalizations that have dominated practical operations research for decades. What has really helped the progress, is the development of high-capacity computers and database technologies. We benefit from his pioneering work when we are trying to evaluate different options for zero emission technologies in a system perspective in this thesis.

### 2.6.1 The basics of the model structure

In our case, the model is built up by nodes with some specified properties, and with upstream or downstream links to represent the interconnection of a physical and economic value chain. For each pair of nodes, we can have the flow of some products, which can be sporadic or continuous depending on the mode of transportation, the value of the output and the cost of any input.

The main purpose using this model is to find which nodes should be built, at what time, and with what capacity. Nodes can represent a variation of technologies, in our case a wind farm, a PV plant, transport infrastructure (cables, pipelines, ships), storages, electrolysers, fuel cells and different energy markets. To all these nodes, both investment costs and operational costs can apply.

Note that the capacity can be modelled in either power (flow), which is typical for production nodes, or in energy (volume) for storage nodes.

### 2.6.2 The decision variables in an optimization model

The purpose of using an optimization approach is to make decisions. There are two types of decision variables in the HyOpt-model: strategic variables for decisions done at the beginning of the strategic periods, and operational variables for all decisions in the operational periods. The strategic decision variables are about making investments in infrastructure and equipment to be able to produce electricity or hydrogen. These decisions are made initially and are a prerequisite for operating the model to potentially generate profit.

The income is a result of operational decisions, and is integrated in the model. That assures that the model can include hourly variations in both market signals and solar or wind properties for specific locations. This gives a much more realistic assessment of the potential in the investment. The alternative way is to use average assumptions, that will surpress the real dynamics of any production system.

### 2.6.3 The Objective function

As mentioned above, the model decides the optimal decisions in order to optimize a given objective. The objective is in our case maximizing the net present value of the whole modelled system (reflecting both the costs and incomes for the system). The net present value is calculated by discounting costs and income for a specified time horizon and discount rate.

If the investment is not profitable –which means that it has a negative net present value, the objective value will normally be zero, with no investments being made. However, it is possible to introduce restrictions that will force investments to be made.

# 3 Method

This chapter describes the data and methods used during the project, as well as the general work flow of the HyOpt-model. The first part of the chapter describes how the data is acquired and how it was modified to fit the correct format. The chapter then goes on to describe the HyOpt-model and the most important parameters that were modified during the analysis. Next, the differences between the wind-energy case and the PV-case and how the setup of the two projects would work in practice are described. Lastly, the method chapter describes the general flow of energy throughout the energy generation process to illustrate how low-quality energy such as wind or solar radiation is transformed into green, high-quality energy electricity or hydrogen.

## 3.1 Data

In this section, the different datasets used in the analysis are described. A model can have good structure and advanced solution methods, but the results and value of the assessment and the insight it should provide, are solely and strongly linked to the data used by the model. In this thesis, the basic data is related to the potential in the energy sources for the wind and the sun, and then linking these to technologies that can transform the energy to electricity. In addition, the value of energy needs to be handled correctly, to take care of realistic operations and priorities. These datasets are of a highly stochastic nature, so empirical data is required as a starting point here.

The third class of data is harder to get, and that is the investment cost (CAPEX) and operational cost (OPEX). These are needed to assess the profitability of building and operating these systems, but also to identify if there is any need for public support schemes to build these crucial energy parks. This is a highly relevant question on the way to achieve the goal of implementing sustainable low or zero emission energy systems in a foreseeable future.

### 3.1.1 Data acquisition - market data

The electricity price data for 2019 is downloaded from the ENTSOE-Transparancy platform, a collaborative platform between European countries, tracking electricity prices, electricity generation and transportation. A token was required to access their API, obtained by sending ENTSOE an email-request. An API is an interface enabling the connection and interaction between two computers or computer programs. This API key granted access to run a python script from [37] which downloaded the electricity price data based on region. In this case the most relevant markets are deemed to be Germany, France and Norway based on where the two energy projects are located and where the generated power ultimately will be sold. The offshore wind farm will either store the generated electricity in sub-sea tanks, or sell it off to continental Europe through the German market. The solar powered hydrogen-production facility in Northern Sahara will likely sell their product to central Europe through the French market. The Norwegian market is there to maintain a baseline when we are crafting the restraints for the model.

The downloaded electricity price data consists of 365 days with an hourly resolution. Originally the prices were given in $EUR/MWh$, but due to convenience this was changed to $NOK/MWh$. This scaling of the currency was performed using data from Norges Bank [38]. The currency exchange rate for $NOK$ from Norske Bank is only tracked on days when the currency markets are open, with a daily resolution. This means that there is a significant number of missing values for weekends and banking holidays. To work around this, the values from the days preceding the days with missing values have been extrapolated. This is a fair assumption, seeing as the Euro has an exchange rate that is relatively stable.

### 3.1.2 Data acquisition - wind energy data

The energy data was extracted from a website called "Renewables Ninja" [39]. This tool was created by Iain Staffell and Stefan Pfenninger through their work with implementing renewable wind- [40] and PV-technologies [41] into the existing energy systems. On the "Renewables Ninja" interface one could input coordinates or drop a pin on a map, before selecting the desired energy generation method.

When acquiring the wind data, it is possible to choose between different turbine types, and edit the height of the turbine tower, as well as the capacity of the wind farm in kWh. In addition it is also possible to choose which data source to generate the output data from. The downloaded data is generated by using weather data from satellite observations and global reanalysis models. Renewables Ninja currently has two different data sources; the "NASA MERRA" [42] and the "CM-SAF´s SARAH" data set [43]. Due to the global availability of the NASA data, it was chosen as the main data source of this thesis over the "SARAH" data set. Even though the "SARAH" data set supposedly has higher data quality, it is geographically limited to Europe.

Seeing as the solar case is located in Algeria, and to achieve a comparable data stream, it was decided to use the "NASA MERRA" data set for both the generation methods. In terms of other parameters, the year that was examined was 2019, the same as the price data, while the capacity and hub height was set to 1 MW, and 80 meters respectively.

The selected turbine type was a "Vestas V164 Wind turbine", a state of the art wind turbine with a wing span of 164 meters commonly deployed in offshore wind projects. It is nonetheless worth noting that at the time of writing, there are several turbines with a higher capacity than 10 MW under development [44].

Table 1 shows an example of how the raw data are presented – where the numbers are representative for the wind conditions the first 24 hour of 2019. The first hour between midnight an 01:00 had an average wind speed of 19,276 m/s, and a mill with 10 MW production capacity would produce 9,693 MW in the period. As expected, the data in table 1 illustrates a pattern in the data that says that a wind farm produces energy relatively independently of the time of day, unlike a solar plant, which will only produce energy in the daytime when the sun is out.

Table 1: *The wind speed and electricity generated at a given time of day on January 1. 2019. This is the exact same data format as the database used to operate the HyOpt-model.*

| **Time** | **Electricity** | **Wind speed [m/s]** |
|---|---|---|
| 2019-01-01 00:00 | 9.693 | 19.276 |
| 2019-01-01 01:00 | 9.751 | 18.929 |
| 2019-01-01 02:00 | 9.797 | 18.517 |
| 2019-01-01 03:00 | 9.828 | 17.724 |
| 2019-01-01 04:00 | 9.806 | 17.092 |
| 2019-01-01 05:00 | 9.786 | 16.839 |
| 2019-01-01 06:00 | 9.802 | 17.043 |
| 2019-01-01 07:00 | 9.820 | 17.347 |
| 2019-01-01 08:00 | 9.825 | 17.524 |
| 2019-01-01 09:00 | 9.828 | 17.753 |
| 2019-01-01 10:00 | 9.824 | 18.033 |
| 2019-01-01 11:00 | 9.814 | 18.274 |
| 2019-01-01 12:00 | 9.808 | 18.372 |
| 2019-01-01 13:00 | 9.812 | 18.307 |
| 2019-01-01 14:00 | 9.824 | 18.049 |
| 2019-01-01 15:00 | 9.827 | 17.585 |
| 2019-01-01 16:00 | 9.801 | 17.013 |
| 2019-01-01 17:00 | 9.750 | 16.502 |
| 2019-01-01 18:00 | 9.685 | 16.053 |
| 2019-01-01 19:00 | 9.596 | 15.591 |
| 2019-01-01 20:00 | 9.514 | 15.238 |
| 2019-01-01 21:00 | 9.422 | 14.912 |
| 2019-01-01 22:00 | 9.293 | 14.516 |
| 2019-01-01 23:00 | 9.098 | 14.010 |

### 3.1.3 Data acquisition - solar energy data

Acquiring the solar data unfolded as a similar process. After once again selecting the "NASA MERRA" data set for the year 2019 and the same capacity of 1 MW, it was time to set some of the parameters. The first parameter was the system loss, which would dictate how much energy the system would loose in terms of heat emissions and energy loss in the cell itself. Next it had to be determined whether or not the PV-rig were to engage in solar tracking. Solar tracking can be done utilizing a single-axis system or a two-axis system. A single-axis tracking system is a tracking system that rotates around one axis, usually in the east-west/ west-east direction, to follow the movement of the sun, to try and maximize the amount of solar radiation hitting the solar panels. A two-axis tracking system is a system that rotates around two axes. In addition to tracking the sun in the east-west direction (azimuth), a two-axis system also tracks the tilt of the solar panels. This way, the area absorbing the solar radiation is always maximized. To maximize the system efficiency, a two-axis system was selected. In terms of the tracking system, the azimuth and the tilt had to be determined. The tilt is the angle the PV-panels are inclined from the horizontal, while the azimuth is the angle between an upright panel and the northern compass direction. Both the azimuth angle and the tilt angle were set to their default values of 180° and 35° respectively. Seeing as a two axis tracking system would continuously update these values to reflect the positioning of the sun, these parameters would not have an effect on the amount of energy being generated.

Table 2: *The irradiance from the sun and the electricity generated by the PV-farm at a given time of day on January 1. 2019. This is the exact same data format as the database used to operate the HyOpt-model.*

| **Time** | **Local time** | **Electricity** | **Direct irradiance** | **Diffuse irradiance** | **Temperature** |
|---|---|---|---|---|---|
| 01.01.2019 00:00 | 01.01.2019 01:00 | 0 | 0 | 0 | 6.250 |
| 01.01.2019 01:00 | 01.01.2019 02:00 | 0 | 0 | 0 | 5.893 |
| 01.01.2019 02:00 | 01.01.2019 03:00 | 0 | 0 | 0 | 5.600 |
| 01.01.2019 03:00 | 01.01.2019 04:00 | 0 | 0 | 0 | 5.346 |
| 01.01.2019 04:00 | 01.01.2019 05:00 | 0 | 0 | 0 | 5.405 |
| 01.01.2019 05:00 | 01.01.2019 06:00 | 0 | 0 | 0 | 5.588 |
| 01.01.2019 06:00 | 01.01.2019 07:00 | 0 | 0.001 | 0.001 | 5.568 |
| 01.01.2019 07:00 | 01.01.2019 08:00 | 71.865 | 0.043 | 0.048 | 6.322 |
| 01.01.2019 08:00 | 01.01.2019 09:00 | 453.035 | 0.437 | 0.072 | 8.341 |
| 01.01.2019 09:00 | 01.01.2019 10:00 | 631.306 | 0.668 | 0.074 | 11.207 |
| 01.01.2019 10:00 | 01.01.2019 11:00 | 723.967 | 0.803 | 0.079 | 13.671 |
| 01.01.2019 11:00 | 01.01.2019 12:00 | 757.653 | 0.858 | 0.081 | 15.038 |
| 01.01.2019 12:00 | 01.01.2019 13:00 | 732.279 | 0.825 | 0.081 | 15.914 |
| 01.01.2019 13:00 | 01.01.2019 14:00 | 651.739 | 0.715 | 0.077 | 16.357 |
| 01.01.2019 14:00 | 01.01.2019 15:00 | 505.608 | 0.526 | 0.071 | 16.311 |
| 01.01.2019 15:00 | 01.01.2019 16:00 | 279.545 | 0.266 | 0.057 | 15.098 |
| 01.01.2019 16:00 | 01.01.2019 17:00 | 21.677 | 0.025 | 0.011 | 11.177 |
| 01.01.2019 17:00 | 01.01.2019 18:00 | 0 | 0 | 0 | 9.976 |
| 01.01.2019 18:00 | 01.01.2019 19:00 | 0 | 0 | 0 | 9.581 |
| 01.01.2019 19:00 | 01.01.2019 20:00 | 0 | 0 | 0 | 9.161 |
| 01.01.2019 20:00 | 01.01.2019 21:00 | 0 | 0 | 0 | 8.564 |
| 01.01.2019 21:00 | 01.01.2019 22:00 | 0 | 0 | 0 | 7.919 |
| 01.01.2019 22:00 | 01.01.2019 23:00 | 0 | 0 | 0 | 7.313 |
| 01.01.2019 23:00 | 02.01.2019 00:00 | 0 | 0 | 0 | 6.791 |

### 3.1.4 Estimation of cost for investing and operating large scale offshore wind farms

The cost input used for the offshore wind farm, is heavily influenced by the work done by Greenstat, addressing the potential to develop offshore wind on the Norwegian sectors offshore [45]. They also estimate the order of magnitude related to the investment cost for an offshore installation utilizing hydrogen production. The size of the wind farm is therefore defined by the export capacity of the electricity cables recently opened in the area, connecting the Norwegian electrical grid to the grid in Germany [46]. The capacity of this cable is 1,4 GW.

Since a very limited number of installed wind farms exists, these datasets are of a highly uncertain nature. Using an optimization model with a system perspective, gives the opportunity to evaluate the sensitivity to these costs to make the projects economically viable for nations and investors alike.

As for all emerging zero emission technologies, it is expected that the unit cost for offshore wind farms, relevant storage and hydrogen technologies will decline in the future, due to more mass production and technology development. On the other hand, the industry has seen delays and cost increases related to technical components due to a shortage of critical raw materials during the Corona pandemic in 2020. This is a significant risk factor and can be an obstacle when trying to implement further cost reductions.

Table 3: *Initial costs and capacities used when optimizing the wind cases.*

| **Node** | **Node Type** | **Unit** | **Max capacity** | **CAPEX [MNOK]** | **Variable CAPEX** | **Relative OPEX** |
|---|---|---|---|---|---|---|
| Converter | Transport | MW | - | - | 3.46 MNOK/MW | - |
| Electrolyzer | Electrolyzer | MW | - | 300 | 22 MNOK/MW | 3 % |
| Fuel Cell | Fuel Cell | MW | - | - | 2.5 MNOK/MW | 3 % |
| Hydrogen Storage | Storage | kg | - | 200 | 0.006 MNOK/kg | - |
| Power Cable to Market | Transport | MW | - | 5175 | - | - |
| Wind Farm | Wind Farm | MW | 1400 | - | 19.7 MNOK/MW | 2.4% |
| Power Cable to Ekofisk | Transport | MW | 120 | 290 | - | - |

The major investment cost is related to building a offshore wind fam, and operating it. There are interesting development going on, and Rystad Energy has estimated that going from a 10 MW Wind mill to a 14 MW (soon to be launched by Siemens Gamesa (SG 14-222DD) , will reduce the number of mills from 100 to 72 for å 1GW wind farm, and reduce the CAPEX with 100M USD [47]. Our main case is based on 10 MW mills in a 1,4 GW wind-park, and that will reduce the CAPEX with approximately 800*1,4 = 1 120 MNOK. This will give a Variable CAPEX of 18,9 MNOK/MW – compared to 19,7 MNOK/MW in our reference case. It is also safe to assume that the maintenance costs/OPEX will be smaller, due to 40 less windmills to inspect and refurbish. We assume that the OPEX related to CAPEX is reduced with 40/140 = 28,6%, to 1,7% of the initial CAPEX annually. (In the reference case (10 MW mils), the OPEX is estimated to 2,4% of initial CAPEX)

### 3.1.5 Estimation of cost for investing and operating large scale solar power plants

The data available for use in this work is currently limited. The number of large-scale solar plants are limited, but there are a few plants that are in the process of being built both in the U.S., Australia and India. All these three plants are in a GW scale, and the plant developed in the United States has also revealed the cost of developing this project.

The Mammoth solar park is currently under construction in northern Indiana, and is expected to be fully operational by 2024. The solar plant is going to be the largest plant in the United States, costing \$1.5 billion. Once completed, it will have a total capacity of 1650 MW [48]. Assuming that this cost includes both the solar panels as well as the converter, it is possible to use this information to come up with an estimation of the CAPEX for the solar farm. It can be estimated that the investment cost for the solar farm is between 6 an 10 MNOK/MW.$1.5 billion is valued at around 13 bn NOK as of April 2022. This yields a numeric value of 7.88 MNOK/MW, which is used as the CAPEX for the PV plant in this thesis, as seen in table 4.

In general, the numeric values used in this thesis is of a highly uncertain nature. However, in general we can say that the costs of producing the PV-cells and the systems is expected to decrease due to entering a phase of mass production. The efficiency per installed panel is also expected to increase due to research and innovation in the coming years. Today the state-of-the art is approximately 20 %, with some promising technologies reaching up to 24-25 % as mentioned in Chapter 2.2.5

Table 4: *Initial costs and capacities used when optimizing the solar cases.*

| **Node** | **Node Type** | **Unit** | **Max capacity** | **CAPEX [MNOK]** | **Variable CAPEX** | **Relative OPEX** |
|---|---|---|---|---|---|---|
| Converter | Transport | MW | - | - | 0.5 MNOK/MW | - |
| Electrolyzer | Electrolyser | MW | - | - | 11 MNOK/MW | 3% |
| Fuel Cell | Fuel Cell | MW | - | - | 2.5 MNOK/MW | 3% |
| Hydrogen Storage | Storage | kg | - | - | 0.006 MNOK/kg | - |
| PV Plant | Wind Farm | MW | 3577 | - | 7.88 MNOK/MW | 0.92% |
| Power Cable to Market | Transport | MW | - | 16560 | - | - |

Comparing table 4 and 3, it is evident that the CAPEX is significantly lower for land based production technology than for their offshore counterpart. This is because it is more expensive to install equipment offshore than on land. It is also worth noting that the export-cable has a much larger CAPEX than the wind farm. This is because the distance between Algeria and France is approximately double to that of Norway and Germany. Additionally the export cable requires a larger capacity due to a higher peak production than the wind farm.

## 3.2 The HyOpt model

The HyOpt Model is used to simulate the different scenarios and compare the calculations of the different investments in this thesis. The HyOpt Model is an optimization model developed by SINTEF, meant to aid in high-level decision-making when analyzing and evaluating different energy systems with a special focus on hydrogen-based technology[35]. Given the node structure of an energy system as well as the expected energy costs and the expected demands, the model will decide what nodes to invest into, as well as in what capacity in order to optimize a given object-function. When assessing whether or not an energy system is profitable, the object-function that is optimized is typically in regards to maximizing the net present value (NPV) of the system.

Utilizing the HyOpt model can be divided into three phases, as shown in Figure 9. The workflow typically starts with the initial ExCel phase. This is a phase where the collected datasets containing the market prices and the demands for electricity and hydrogen, as well as the investment costs for both the PV- and wind farming technology are processed and formatted. During this step it is very important to ensure that the resolution of time series line up, and that the units used are compatible. The next step is to generate a SQLite database. This can easily be achieved by constructing a JSON-file and running a python script. This automatically generates a database structure in the SQLite file format. This will include the node structure, the flow between nodes and all the price- and cost data. Lastly it is time to run the actual model itself. The HyOpt model is written in the FICO$^{\text{TM}}$ Mosel programming language, a programming language that is specially tailored for optimization. When the model is run through the FICO$^{\text{TM}}$ Xpress solver, it utilizes the data and network structure from the previously generated SQLite file, to generate new results under the "res" tab in the database. After this, the results can be reviewed in the SQLite file. This process is further illustrated in Figure 10.

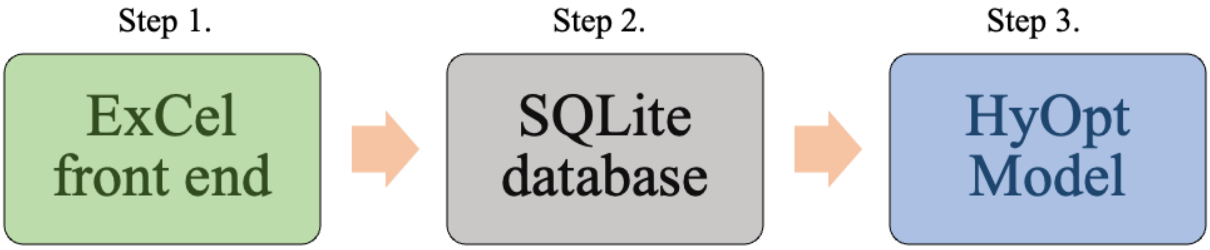

Figure 9: *Using the HyOpt model can be divided into three distinct steps. These are the ExCel front end, the SQLite database phase, and finally running the HyOpt-model itself.*

## 3.3 HyOpt parameters

To build the model, it is necessary to sort all the parameters that is required to build the different cases into a database. This is usually done by structuring the layout of the database in a JSON-file format. HyOpt does have a graphic user interface (GUI), but this is only a piece of software in the early development stage, used to assist the creation of the aforementioned JSON-file. When the basic node-network is set up with the correct links and capacities, the next step is to integrate the data acquired from Chapter 3.1. This data is typically price data, like the price of electricity, or the price of hydrogen.

Since the model is utilizing a database-structure, it is simple to edit the input parameters. The price of hydrogen can for instance easily be changed to "force" the model into investing in Hydrogen. This makes HyOpt an effective tool when analyzing the results, as long as the operator of the tool has some domain knowledge on how to operate the tool. Due to this easy-to-change database characteristic, the HyOpt model is incredibly helpful when performing a sensitivity analysis to analyze how different changes in the base-criteria will impact the costs and earnings of a project. This iteration-based workflow is illustrated in Figure 10. However it can also be very tedious to run the model for many iterations, performing a pincer maneuver, trying to find the break-even point.

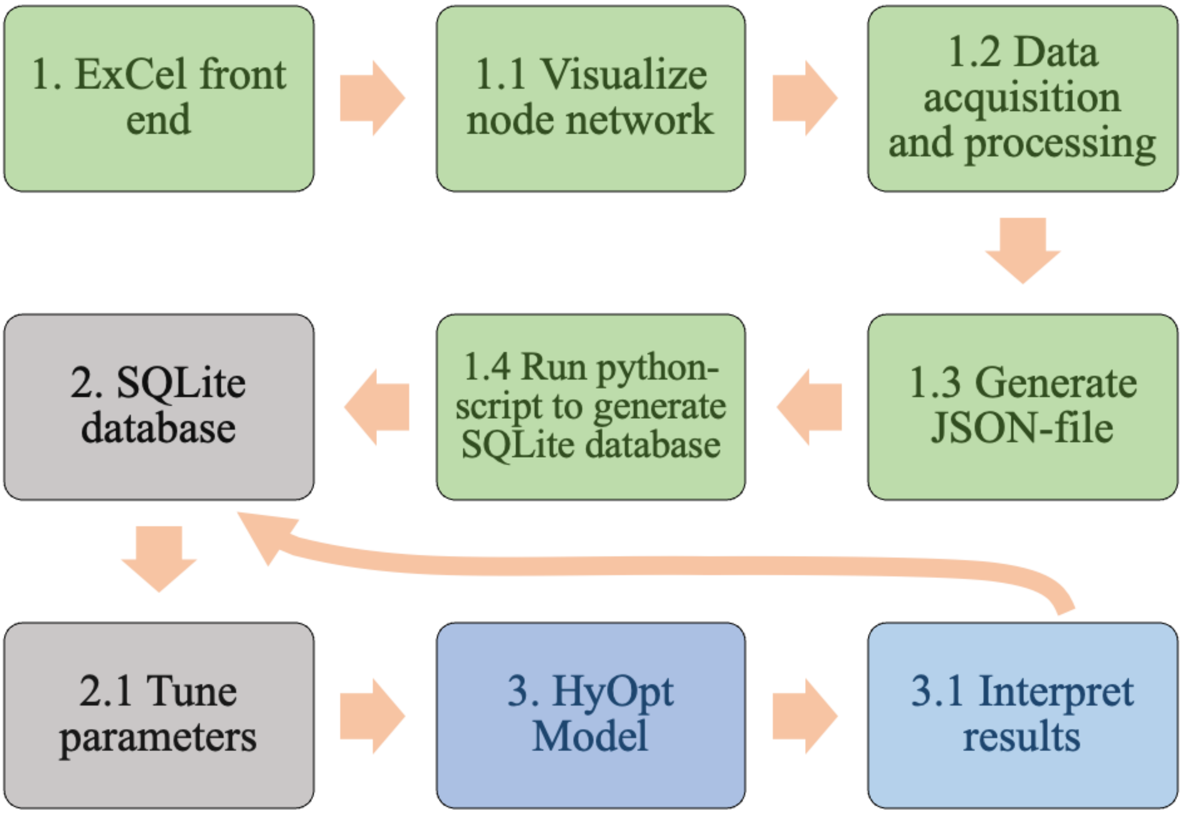

Figure 10: *Detailed view of the different phases in the work-process when utilizing the HyOpt model.*

### 3.3.1 Energy input

One of the primary parameters in the model is the energy input. This parameter dictates the energy production, meaning it will directly impact the decision as to whether the project is viable or not. This input is similar for both the wind cases and the solar cases. It contains a timeseries with an hourly resolution and the corresponding production-statistics for the whole year of 2019, from a previously determined piece of harvesting-technology in the appropriate location. The location of both the wind farm as well as the solar power plant will have a big impact on the energy input, since the conditions determine the production rates, but because this is predetermined, the locations can be considered as a "constant". Another parameter that would have a big impact on the production rates is the technology used to harvest the energy. An improved wind turbine or PV-cell would increase the production rate of the energy systems, but to limit the cases within reason, the efficiency of the harvesting technology can be regarded as another constant for the purpose of the analysis.

### 3.3.2 Market prices and the market price-level coefficient

The market prices of the finished product is another significant parameter. Producing clean energy is one thing, but if there is no market to sell it to, it will be impossible to get a return on any of the investments. This input is also similar for both the wind cases and the solar cases. There are 3 market nodes in each case; the electrical market(spot), the electrical market (contract) and the hydrogen market. The market prices(spot) parameter for electricity and hydrogen is given as a time-series with an hourly resolution and the corresponding market prices, for the year of 2019. The next price-parameter is the electrical market (contract). This is a price parameter where the project owner and the power supply company has negotiated a fixed price for which to sell the electricity. This is a great option if the power prices are down, but will have negative consequences when the price in the spot market is higher than the negotiated price.

The market price parameter for electricity is likely to be changed around a lot, seeing as one of the research questions asked in section 1 seeks to investigate when the model chooses to invest in hydrogen production in stead of solely focusing on electricity. This is done by changing a parameter called "levelFactorSpotPriceEl"(sometimes referred to as a *Market price-level coefficient*). The value of this variable corresponds to a simulated percentage-based increase or decrease in the market, hence the other term; *Market price-level coefficient.* For instance, changing this market price-level coefficient from its original value of 1.00 into 1.10, would allow the model to simulate the case using market prices that were 10% higher than the prices logged from 2019.

Practically, the prices will fluctuate to a great extent, causing periods with both low and high electricity prices. When the electricity is inexpensive, and the profit margin of selling hydrogen is higher than that of selling electricity, the model will invest in hydrogen production. By increasing or decreasing the market prices, it is possible to locate a threshold as to what the electricity price has to be for the project to start investing in hydrogen technology and become profitable.

### 3.3.3 Capacity

The capacity of a node signifies how much can flow through it. An example of this can be a power cable or a pipeline. No matter how much hydrogen or electricity is produced, the pipeline is only able to transport a fixed quantity. In these cases, there are two types of capacity nodes; production capacity (which was briefly discussed in Chapter 3.3.1) and transportation capacity. These capacity nodes should be as equal as possible to prevent energy loss. Investing in an increased capacity is usually very expensive, if it even is an extendable node, meaning that the cost of the increased capacity is essential when planning a project. The capacity parameter is therefore closely linked to the market prices as well as the profitability of the project.

### 3.3.4 Cost of capital and time horizon

The cost of capital is another important parameter when assessing an energy project. This is a measure of how much of a return is required for the investment to be made. This return on the investment will vary whether the project is privately funded of backed by a non-profit organization or a governmental organ. Usually a private company has a higher demand in regards to the return on their investment, as opposed the government or a non-profit organization, seeing as the companies in the private sector has to take into account the dividend payouts to stakeholders and the board of directors. A government-backed organization can make due with a cost of capital of around 4 %, while private firms usually seeks higher return on their investment.

Another thing to consider is the time horizon of the project. A wind farm project, usually has an operating lifetime of around 15 years, while a solar farm usually has a warrantied lifetime of around 20 years. These parameters are included in the HyOpt model, and will obviously impact the amount of energy created in the projects lifetime, which in turn will affect the return on the project.

## 3.4 Cases

This case study compares two different energy-technologies against each other. Seeing as it is a comparison, it is very important that the cases are comparable. To ensure this, both the wind farm and the solar facility will have the same dimension of capacity measured in *mega watt peak*. A relevant dimension of capacity, especially for the wind farm, could be related to the energy requirements of an oil field in the surrounding area called Ekofisk. According to an emission report from 2018 [49], the Ekofisk oilfield consumed 256.7 $MSm^3$ of natural gas. With a calorific value of 40.1 $MJ/Sm^3$ [50], this yields an annual energy consumption of 10295351 $GJ$ or 2859 $GWh$. This means that the gas turbines currently powering the Ekofisk oil platform consume around 326 MWh from natural gas every hour. By assuming that the efficiency of a gas turbine is around 33 % it is possible to calculate that the hourly energy demand from the Ekofisk platform is around 110 $MWh$. This is the demand-estimate used when running the model.

### 3.4.1 Wind case

The wind case consists of a state-of-the-art offshore wind farm enhanced with a hydrogen production and storage component, located in *Sørlige Nordsjø II* off the coast of south-western Norway. A sketch of the wind case can be seen in Figure 11.

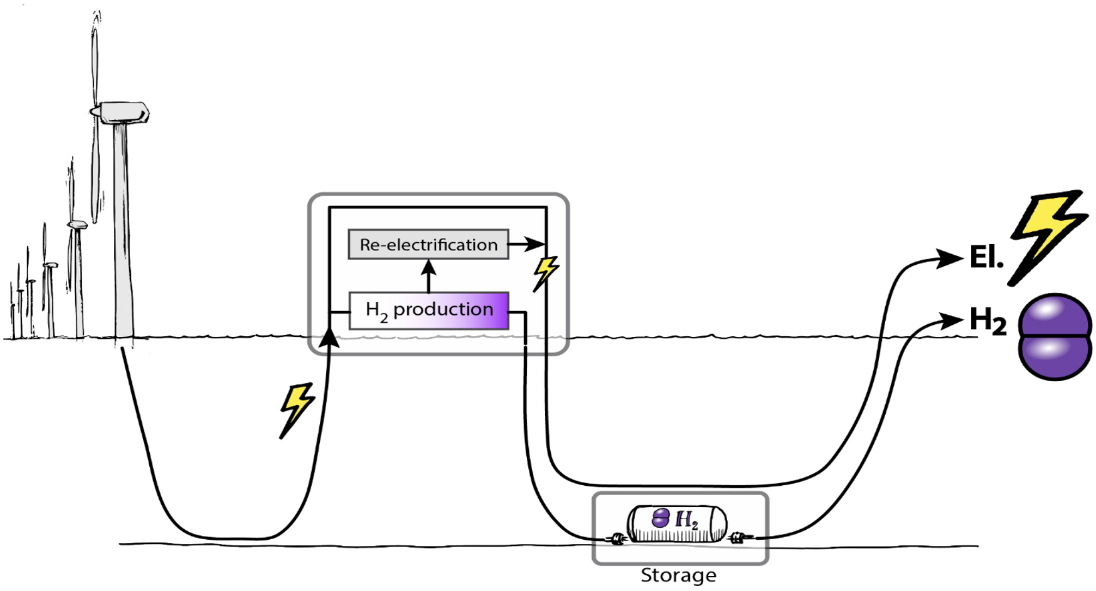

Figure 11: *The wind case consists of a wind farm, producing electricity and storing some of the excess electricity as hydrogen gas. Adapted from: TechnipFMC presentation.*

### 3.4.2 Solar-powered Hydrogen production

The solar case is comprised of a number of PV-cells clustered into PV-modules connected to a hydrogen production facility. The produced energy can be stored as $H_2$ in a large storage tank, and sold when the price of hydrogen is high. The rest of the generated electricity is sold to the market. A simplified sketch of such a facility can be viewed in Figure 12. Utilizing solar power to produce Hydrogen gas is estimated to be significantly less expensive than producing Hydrogen offshore.

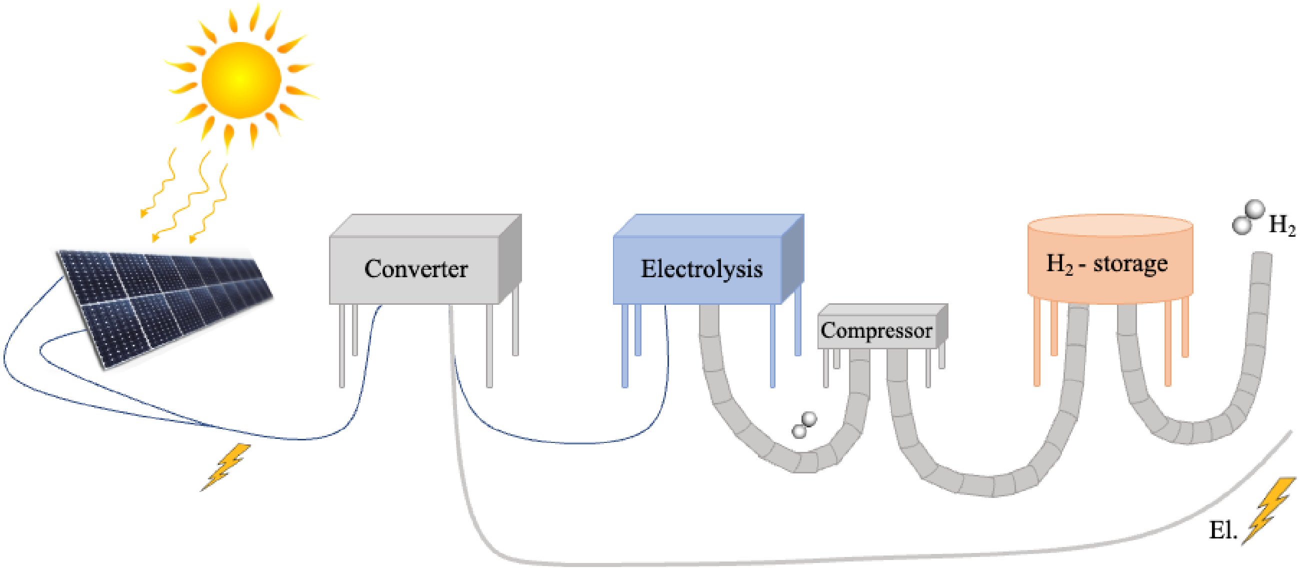

Figure 12: *The solar case consists of PV-modules, producing electricity and storing some of the electricity as hydrogen gas while the rest is sold to the market.*

### 3.4.3 Supplying Ekofisk

The last case is built around supplying a nearby oil- and gas field called Ekofisk. By utilizing hydrogen storage and transforming the chemical energy in the hydrogen through the use of a fuel cell, or by simply delivering electricity, the wind farm can supply Ekofisk with power to meet their operational power demand. If this system is implemented, Ekofisk should be able to phase out their current natural-gas based electrical system, and become emission free. The hydrogen storage builds up over time, so that even when there is an extended period without wind, the platform can keep operating with energy from the hydrogen storage. The relevancy of this case is emphasized by the ongoing Hywind Tampen project, an 88 MW offshore wind farm intended to supply the *Gullfaks* and *Snorre* oil fields in the North Sea with electricity [51]. This is a reassurance that the scale and dimensions of the Ekofisk-case discussed in this thesis is actually a real possibility rather than a thought experiment. This case is illustrated in Figure 13.

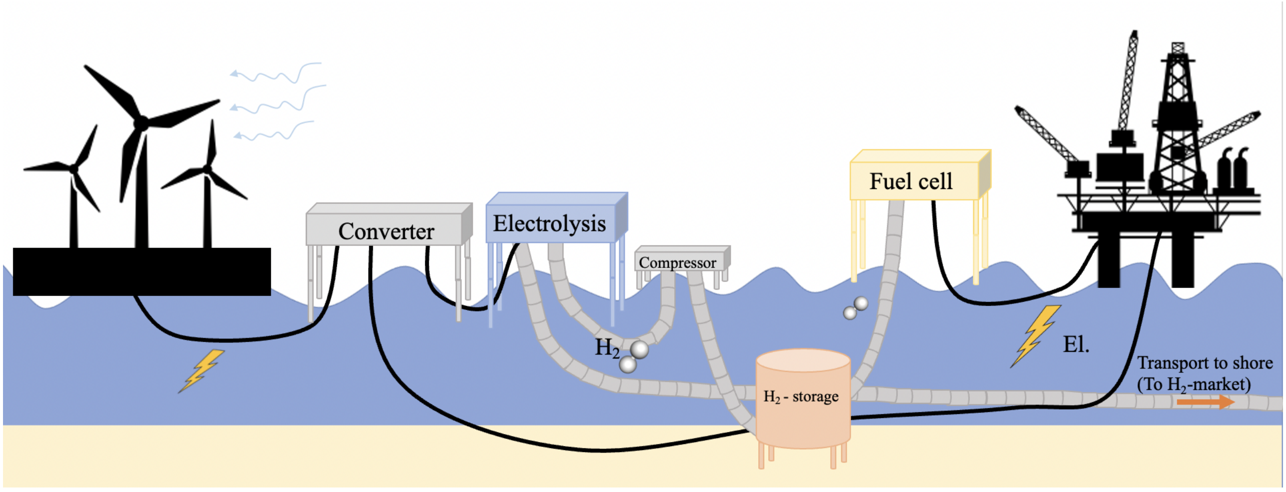

Figure 13: *The case where the wind farm will supply the Ekofisk platform has the same setup as the wind case, but this set up also includes a fuel cell component, so the hydrogen storage can deliver electricity to the Ekofisk-platform*

## 3.5 Financial support policies - Greenhouse gas avoidance

In spite of the UN and EU calling for a global change in the consumption patterns of fossil fuels, the European energy mix is not very clean in terms of emissions. As of 2020, it was comprised of only 40.8 % renewable energy, 30.5 % nuclear heat, 14.6 % solid fossil fuels, 7.2 % natural gas, 3.7 % oil and petroleum and 2.4 % non-renewable waste [52]. This equated to a carbon intensity of 231 grams of $CO_2$ pr. kWh in the European energy mix [53].

## 3.6 Flow diagram

As mentioned in section 3.2 and 3.3, the HyOpt-model is continuously evaluating the parameters, and constantly making decisions regarding what to produce, when to produce and when to store, etc. The most basic of these choices have been illustrated in Figure 14 and Figure 15 for the wind-case and the PV-case respectively. This illustrates some decisions the model has to make in the process of transforming a raw natural energy resource into a refined product ready for the market.

### 3.6.1 Wind project

Figure 14 follows the refinement process of wind power. The first choice the model has to make is wheter or not to produce $H_2$. The fraction of electricity that the model decides to use in $H_2$-production, $\alpha$, is decided by factors such as the price and market demand of electricity and hydrogen. This is a continuous process and the model constantly regulates the amount of power and hydrogen that is produced, to secure optimal and logical operating decisions. For instance, if the electricity prices are very low, while the $H_2$-prices are very high, the model would rather produce and sell a lot of Hydrogen than sell the electricity for cheap. After deciding how much of the generated electricity that should be used for $H_2$-production, the excess power (1-$\alpha$) is sold on the electricity-market, while the electricity used for hydrogen-production ($\alpha$) is funneled into an electrolyzer before the produced hydrogen is stored in large sub-sea tanks (see Figure 11).

From the storage tanks the $H_2$ can either be pumped into a pipeline and sold on the market, or it can be pumped into a fuel cell used to create electricity marked for local use. This outlet could be used to supply a nearby oil field called *Ekofisk* with power. With some refinements, this case could be tailored to supply the whole Ekofisk oil field with electricity, which controversially would make it a fossil-fuel extraction powered only by clean energy. Either way, the project would sell clean energy to the market, which was the goal of the refinement process.

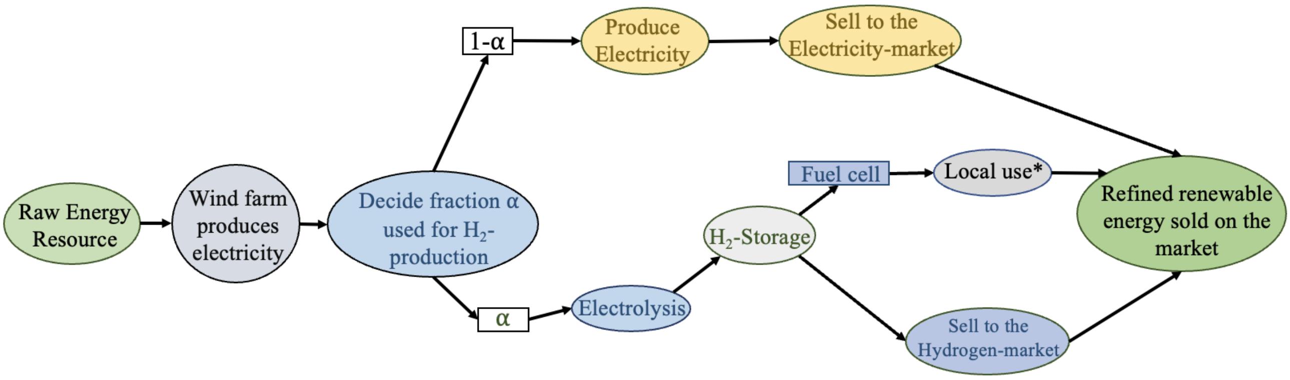

Figure 14: *The wind powered energy system depicted as a flow diagram following the process from raw energy resource until it is sold on the market as refined renewable energy. The color of the nodes are loosely related to what type of energy is used in that particular node. Blue is related to hydrogen, yellow is related to electricity. *Local use describes sending the produced hydrogen to Ekofisk, and is only relevant in the Ekofisk-case*

### 3.6.2 Solar project

Figure 15 follows the similar energy-refinement process as in the solar project. This process also includes the decision regarding how much of the generated electricity should be converted into $H_2$. Similarly to section 3.6.1, parts of the generated electricity ($\alpha$) is used for hydrogen production and storage, while the rest (1-$\alpha$) is sold to the electricity market. In the solar case there is no need for local use, as the facility is to be located in a remote and hostile dessert, and thus all the stored hydrogen is sold on the energy market.

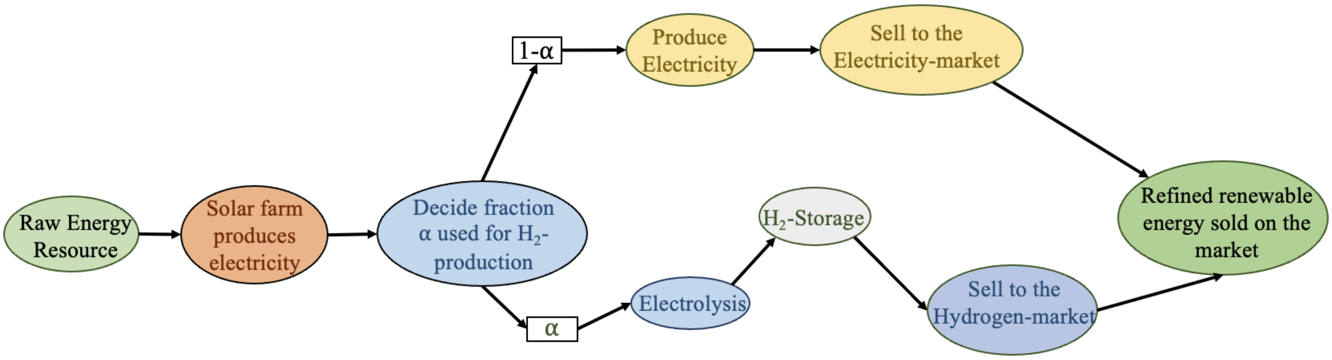

Figure 15: *The solar powered energy system depicted as a flow diagram following the process from raw energy resource until it is sold on the market as refined renewable energy.*

# 4 Results and discussions

This chapter systematically presents the results obtained from running the HyOpt-model with different input based on the various cases described in chapter 3.4. Every result from each case is then analyzed, first looking at selected technical aspects and solutions, before being evaluated on their economic viability and their environmental impact. In the last section of the chapter all the aspects of each case will be compared against each other.

When assessing the economic viability of a project, there are several economic parameters to interpret and analyze. This thesis implements a sensitivity analysis of the NPV and its dependence on two parameters, as well as the levelized cost of energy and the levelized cost of hydrogen. A sensitivity analysis is a data-analyzing process that explores how small changes in one of the parameters mentioned in chapter 3.3, can have a significant effect on the final outcome of the modelling process. First off, the sensitivity analysis will factor in the market price of electricity, before shifting focus over to how a shift in the required rate of return will impact the economic feasibility of the project.

The economic aspect is not the only measurement used to determine whether or not a project is considered a success, especially when evaluating energy projects. In a time where the current generation is facing the consequences of human-induced climate changes, new energy projects are often measured in how they impact the environment and how their emissions impact the greenhouse gas balance in the atmosphere.

One way to measure the environmental impact of an energy project is to measure how much $CO_2$-equivalents the new green energy generated from the project potentially could remove from the current energy mix, as touched upon in chapter 3.5. By diluting the carbon-intensity of the European energy mix, it will decrease the European carbon footprint and cut emissions. But how big of an impact will this project have on the European annual $CO_2$ emission?

Table 5: *Overview used when distinguishing the different aspects of the different cases, and in what chapter to find them*

| **Case** | **Name of case** | **Offshore wind** | **Solar** | **Hydrogen production** | **El-cable to market** | **Hydrogen transport to market** | **Local use $H_2$** | **Local use electricity** | **Chapter** |
|---|---|---|---|---|---|---|---|---|---|
| **1** | Wind Case - Electricity only | X | | | X | | | | 4.1 |
| **2** | Solar Case - Electricity only | | X | | X | | | | 4.2 |
| **3** | Wind Case - $H_2$ production | X | | X | | X | | | 4.3 |
| **4** | Wind Case - Supplying Ekofisk | X | | X | | X | X | X | 4.4 |
| **5** | Solar Case - $H_2$ production | | X | X | | X | X | X | 4.5 |

## 4.1 Wind Case - Only electricity

This section summarizes the findings and the results from the possible establishment of an offshore wind farm in the southern parts of the north sea, aiming to export electricity to the German market. The results are based on the market input and cost estimates touched upon in Chapter 3.1. This input combined with the logic of the node network illustrated in figure 16, is processed using the HyOpt model.

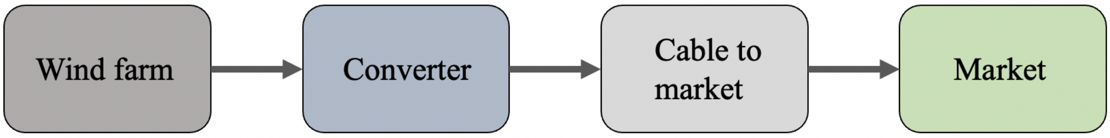

Figure 16: *Simple sketch of the wind case producing only electricity and selling it to the market.*

Based on the market prices for electricity in 2019, the HyOpt model suggest to stay away from investing since the LCOE is higher than the market price.

To reveal the operational aspect of such a system in economic terms as well as its technical production capacities, the model is forced to invest in a 1400 MW wind farm, with an estimated investment cost on 27, 58 bNOK. This reveals the cost gap that needs to be closed, either by reducing the CAPEX due to technology development and mass production, an increase in energy prices or public funding to assure an energy transition that will bring down $CO_2$ emissions.

Table 6 shows the installed capacity for the converter and the cable capacity. The wind farm will never produce at its max. The capacity of the converter will therefore be slightly lower than the capacity of the wind farm. This is due to the optimization model being "greedy" and searching for the most cost-effective solution.

Table 6: *Different key aspects of the energy project when only delivering electricity to the market*

| **Node** | **Installed capacity** | **OPEX [bn NOK]** | **CAPEX [bn NOK]** |
|---|---|---|---|
| **Wind farm** | 1400 MW | 9.17 | 27.58 |
| **Converter** | 1294.86 MW | 0 | 4.49 |
| **Power Cable to Market** | 1400 MW | 0 | 5.18 |

Table 7 shows the economic performance of the full scale investment project. We reveal a negative NPV of 17 bnNOK for project with a total investment and operational costs of approximately 46 bnNOK. The income from selling the electricity on the market is aproximately 29.5 bnNOK.

Table 7: *Overview of key numbers related to the economic feasibility of the project.*

| **Case** | **Offshore Wind** |
|---|---|
| **Discounted income (spot sales electricity)** | 29.46 bn NOK |
| **Wind turbine cost** | -36.75 bn NOK |
| **Converter cost** | -4.49 bn NOK |
| **Cost of power cable to market** | -5.18 bn NOK |
| **NPV** | **-16.86 bn NOK** |
| **Electricity sold** | German market |
| **Discount rate** | 4% |
| **Installed generation capacity** | 1400 MWp |
| **Total annual energy delivered to market** | 5 682 009 MWh |

### 4.1.1 Economic feasibility - Electricity market price sensitivity analysis

By setting the electricity price in the market to the exact level that it was in 2019, the model was able to estimate the NPV achieved by the project when operating in the 2019-market. In the first couple of simulations the HyOpt-model did not seem interested to invest at all. In short, this means that the model deems the project economically non-viable, and opts to not invest at all. To counteract this, the "Existing Capacity" parameter for the nodes called "Wind turbines" was set to 1400 MWh. This let the model calculate the NPV of the project in spite of it being negative. After taking into account the expenses of the converter and the transportation pipeline while utilizing the parameters in table 3, the model calculated a negative NPV of around 16.86 billion NOK. In the search of answering the scientific questions from section 1 regarding whether or not the project could be economically viable if the market prices of electricity were to change, there was added a variable called "levelFactorSpotPriceEl" to the HyOpt-model (see section 3.3.2 ). Continuously running this model with different increases in the market price-level coefficients while the other parameters remained unchanged, yielded a break even (NPV=0) market-coefficient of 1.57. This means that the electricity prices from 2019 would need a 57% increase in order for the project to become profitable.

Comparing this required increase in the electricity market to the actual increase the market has experienced in recent years, it is clear as day that this wind project is economically viable in today's market. As seen in figure 17, the actual market rise experienced in 2021 and the one currently happening in 2022, greatly exceeds the required rise for the project to break even. One can therefore safely assume that if the project were to be built with the current state of the market it would be remarkably profitable.

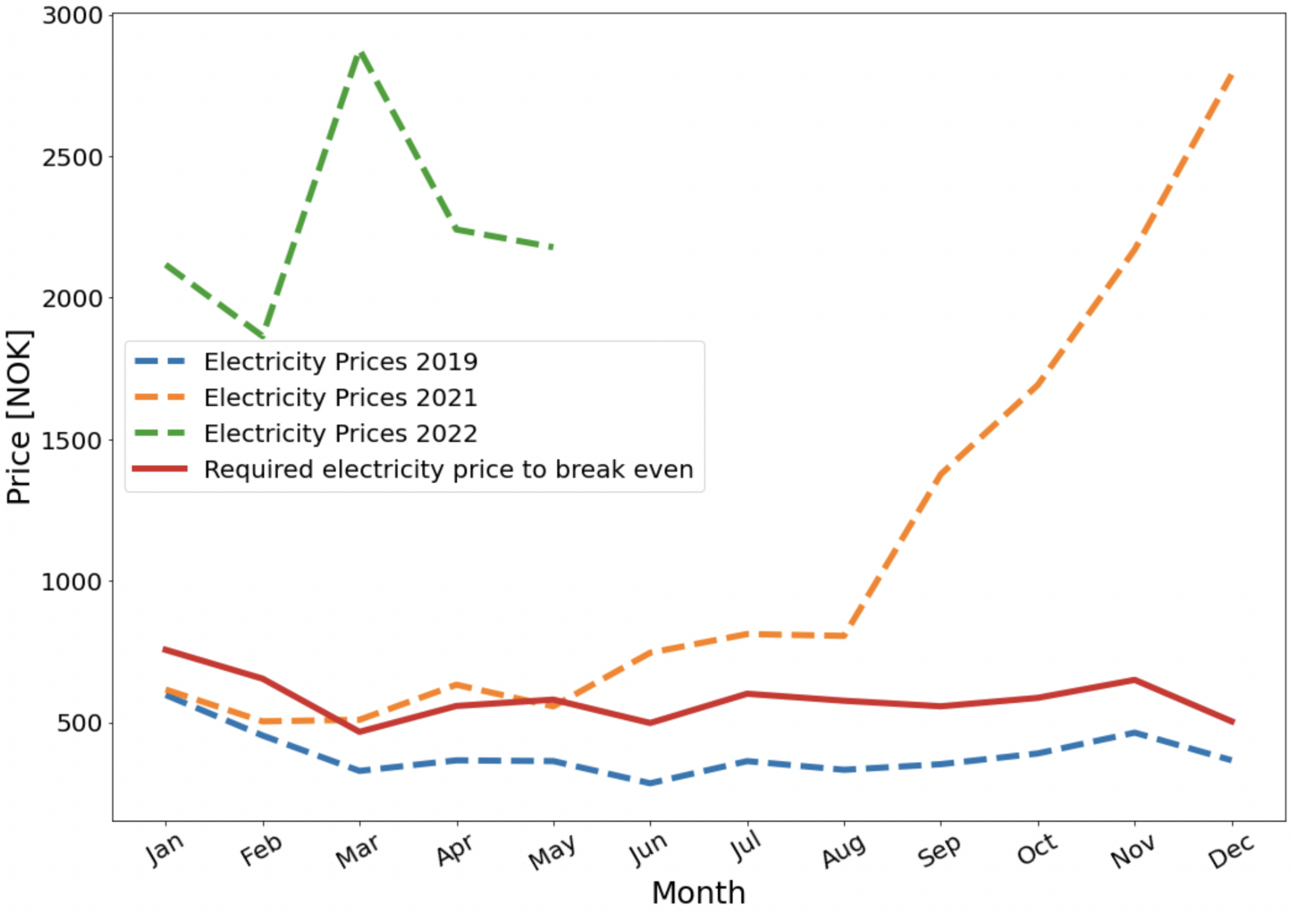

Figure 17: *Required level in the German electricity market for the project to break even. The electricity prices in 2019, 2021 and 2022 so far is included for reference.*

### 4.1.2 Economic feasibility - Required rate of return sensitivity analysis

Another way to push the project in to becoming economically viable, is to manipulate the required rate of return. This is the minimum required return the project has to generate in order for potential investors to be interested in the project. The value of the "Required Rate of Return" varies with who is the potential contractor of the project. If the project were to be undertaken by a company backed by the government, the required rate of return could be set at around 4%, while a commercial company would require a higher rate of return at around 10%.

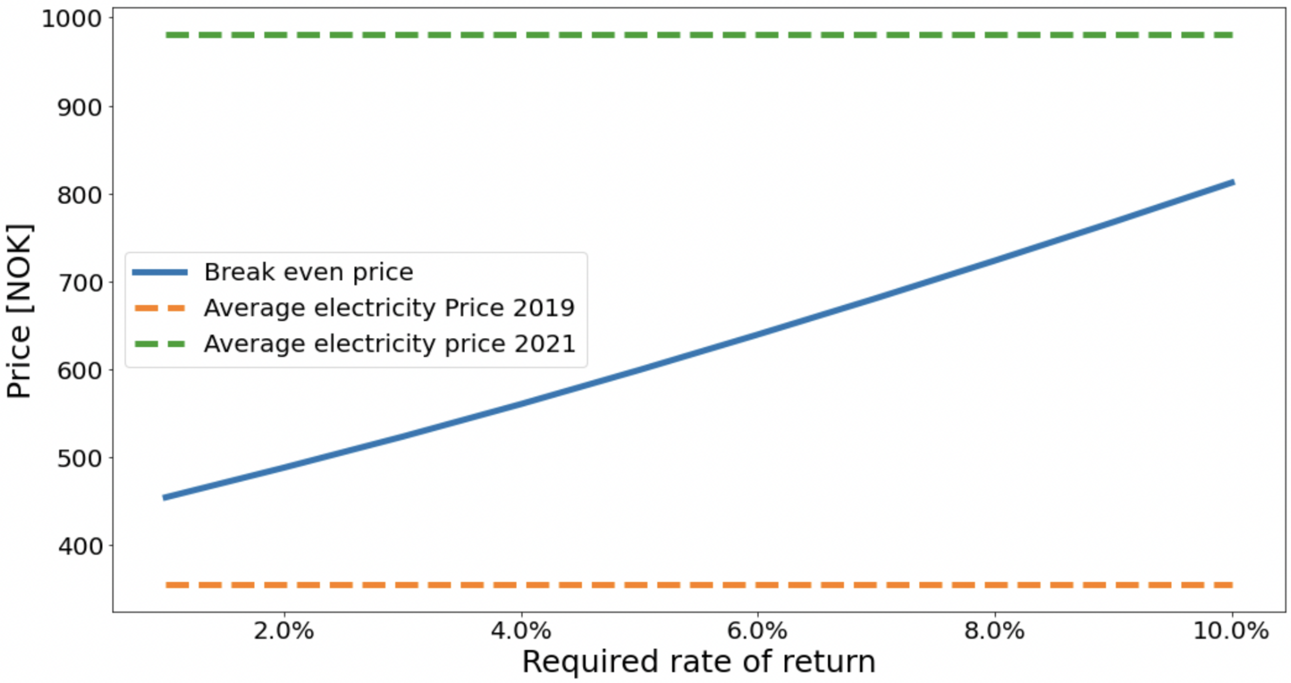

Figure 18: *Average price the electricity needs to be sold at for the wind project to break even at different discount rates. The average electricity prices in 2019 and 2021 is used as a point of reference.*

### 4.1.3 Environmental impact

Even though the wind project seem to generate a negative NPV, it should not be immediately dismissed as a poor project. As seen in chapter 3.5, the European energy mix was operating with a carbon intensity of 231 grams of $CO_2$ pr. kWh in 2020. This equates 231 kg pr. MWh. By using this number, it is possible to calculate how much $CO_2$-equivalents the project can substitute.

According to the model, after all the loss is calculated, 5 682 009 MWh of electricity is shipped to the market annually. If this number is multiplied by the carbon intensity from 2020, it is possible to calculate how much of energy-related $CO_2$ it is possible to substitute with green energy:

$$Substituted CO_2 = 231^{kg}/_{MWh} * 5682009 MWh, \tag{12}$$

This number equates to 1 312 544 tons of $CO_2$ saved annually. Considering that the annual emission of $CO_2$-equivalents in Norway was 49.3 million tons in 2020 [54], this number represents a significant amount. As a reference, this amount is around 2.7 % of Norwegian $CO_2$ emissions in 2020. However, these $CO_2$-equivalents are deducted from the European $CO_2$-accounts where the energy is consumed. An overview of the numeric values utilized in the $CO_2$-calculations are summarized in Table 8

Table 8: *Overview of key numbers related to the environmental impact of the project in terms of $CO_2$ emissions.*

| Case | **Wind - Electricity** |
|---|---|
| **European Carbon intensity** | 231 kg/MWh |
| **Electricity shipped to the market** | 5 682 009 MWh |
| **Annually saved $CO_2$** | 1 312 544 tons |

## 4.2 Solar Case - Only electricity

This section outlines the findings and results from the possible establishment of a large scale solar plant in Algeria aiming to export all the generated electricity to the French market. The results are established from the market input and cost estimates addressed in Chapter 3.1. These data-inputs combined with the logic of the value chain illustrated in figure 19 is processed in the HyOpt-model.

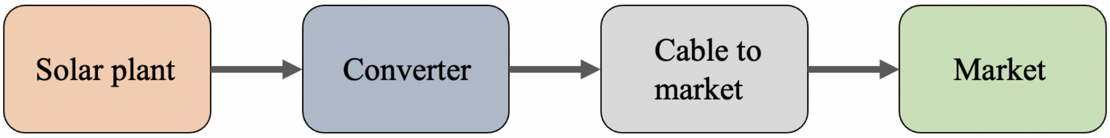

Figure 19: *Simple sketch of the solar case producing only electricity and selling it to the market.*

The plant is designed to be able to produce the same amount of energy each year as an offshore wind farm with a max capacity of 1400MW. Since the production rate is zero during nighttime, the daytime peak capacity has to be higher, estimated to be around 3580 MW.

Based on the market prices for electricity in 2019, the HyOpt model suggests to not invest in this project since the LCOE is higher than the market price. To reveal the operational aspect of such a system in both economic terms and technical production capacities, the model is forced to invest in a 3577 MW Solar plant, with an estimated investment cost on 17, 88 bNOK.

Table 9 shows the capacities the model invests in for the converter and the cable capacity. The solar plant will never be able produce at its maximum, because there will never be optimal irradience conditions over a suspended period of time. This explains why the capacity of the converter is slightly lower than the theoretical peak production.

Table 9: *Different key aspects of the energy project when only delivering electricity to the market*

| Node | Installed capacity | OPEX [bn NOK] | CAPEX [bn NOK] |
|---|---|---|---|
| **Solar farm** | 3577 MW | 3.59 | 28.19 |
| **Converter** | 2863 MW | 0 | 14.32 |
| **Power Cable to Market** | 3000 MW | 0 | 16.56 |

Table 7 shows the economic performance of the full scale investment project. This reveals a negative NPV of 4.73 bnNOK for the project with a total investment and operational cost of approximately 37 bnNOK. Even though the project is non-profitable, it is closer to break even than the wind farm described in chapter 4.1.

Table 10: *Overview of key numbers related to the economic feasibility of the project.*

| Case | **Solar plant** |
|---|---|
| **Discounted income (spot sales electricity)** | 33.42 bn NOK |
| **PV cell cost** | -31.78 bn NOK |
| **Converter cost** | -1.43 bn NOK |
| **Cost of power cable to market** | -16.56 bn NOK |
| **NPV** | **-16.35 bn NOK** |
| **Electricity sold** | French market |
| **Discount rate** | 4% |
| **Installed generation capacity** | 3577 MWp |
| **Total annual energy delivered to market** | 5 881 943 MWh |

### 4.2.1 Economic feasibility

The electricity prices used by the HyOpt model has a significant impact on the profitability of the case being studied. Looking at the NPV from Table 10, it is evident that the solar project will operate at a significant loss if the electricity prices were to stay at the 2019 level. Comparing the NPV of the solar case with NPV of the wind project from Table 7, the values are more or less equal. The solar plant itself has a lower OPEX and CAPEX than the offshore wind farm, but the export cable with twice the distance and double the capacity requirement, evens out the investment costs between the two cases. The HyOpt model perceived the project to be such a poor investment that it initially refrained from investing in the project altogether. To circumvent this, and unlock the full economic details of the project the "Existing capacity" for the solar plant was set to 3577 MWp, similarly to what was done in Chapter 4.1.1.

Even though the project initially was deemed economically non-viable, an increase in the electricity market could alter the viability of the project. Continuously running the model with the parameters described in Table 4 while changing the "Market price-level coefficient" addressed in Chapter 3.3.2 it was determined that the electricity market prices from 2019 would require a rise of 48.9% for the project to break even. Comparing this to the required rise of 57% required to make the wind project from Chapter 4.1.1 profitable it might seem like the solar project is much more desirable from an economic standpoint. However, the electricity produced in the wind cases is sold to the German market, which on average was around 15% lower than the French market in 2019. This means that even though the solar project is more economically viable when only producing electricity, the differences are slightly inflated, and explains the significant variations in the required rise to break even. The average electricity price in 2019 was 409 NOK/MWh for the French market, compared to 356 NOK/MWh in the German market. This difference in market value would equal around 4.25 bn NOK of lost income if the electricity generated from the solar cases were sold in the German market.

### 4.2.2 Environmental impact

Similarly to the case described in Chapter 4.1, this case also has a negative NPV. In spite of the project being infeasible in economic terms, it could still have a considerable impact in terms of cutting $CO_2$-emissions. The HyOpt model calculates that the solar farm will produce and ship 5 881 943 MWh of electricity to the market annually. If this annual energy-export is multiplied by the carbon intensity of the European energy-mix (231 kg/ MWh), addressed in Chapter 3.5, it is possible to calculate the amount of $CO_2$-equivalents this new green energy is able to substitute. By utilizing the same formula used in Equation 12, it is uncovered that the green energy deliverd from the solar plant is able to save 1 358 729 tons of $CO_2$ emissions annually.

## 4.3 Wind Case - $H_2$ production

This chapter presents the findings related to establishing a large scale wind farm with the goal of producing and selling hydrogen to the European market. These results are generated by the HyOpt-model using the data-input established in Chapter 3.1 in conjunction with the node network illustrated in Figure 20.

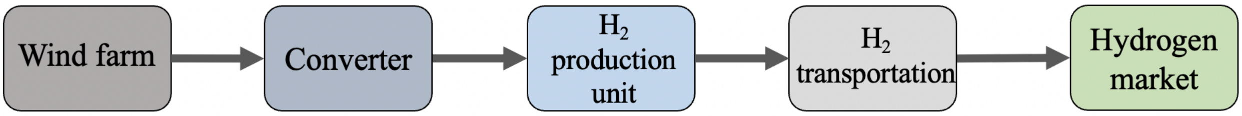

Figure 20: *Simple sketch of the wind case producing hydrogen and selling it to the European market.*

This case aims to illuminate how producing $H_2$ utilizing all the generated energy from a 1400 MW offshore wind farm relates to the case described in Chapter 4.1.

Table 11: *Different key aspects of the wind energy project when only selling hydrogen to the European market*

| Node | Installed capacity | OPEX [bn NOK] | CAPEX [bn NOK] |
|---|---|---|---|
| **Wind farm** | 1400 MW | 9.17 | 27.58 |
| **Converter** | 1025 MW | 0 | 3.55 |
| **Electrolyzer** | 999 MW | 9.27 | 22.29 |

Table 12: *Different costs and capacities the HyOpt has invested in for the wind energy project when only delivering Hydrogen to the European market*

| **Case** | **Wind -** $H_2$ |
|---|---|
| **Discounted income Hydrogen** | 80.44 bn NOK |
| **Wind farm cost** | -36.75 bn NOK |
| **Converter cost** | -3.55 bn NOK |
| **Electrolyzer cost** | -31.56 bn NOK |
| **Hydrogen transport tariff** | -7.31 bn NOK |
| **NPV** | **1.27 bn NOK** |
| **Hydrogen sold** | European market |
| **Assumed Hydrogen price** | 55 NOK/kg |
| **Discount rate** | 4% |
| **Installed generation capacity** | 1400 MWp |
| **Total Hydrogen delivered to market** | 105 524 935 kg |

### 4.3.1 Economic feasibility

This project seems to be more profitable than the cases discussed in Chapter 4.1 and 4.2, generating a small positive revenue. Even though the annual production of 105 M kg $H_2$ generates significant revenue, the cost parameters are quite uncertain. This thesis operates with a flat operational cost of 5 NOK/kg for transport, but this transport cost from an offshore production is uncertain, and must be investigated further. The development of a common transport infrastructure for hydrogen, either by vessels or a pipeline, will give significant input to the value proposition for a project like this. An alternative is of course to transport the electricity to shore, and produce the hydrogen there, but that would entail a 10% energy loss in the transport cables. This option has not been investigated in this thesis.

The market price of 55 NOK/kg is also subject to discussion, but the order of magnitude should be relevant for a future hydrogen market.

### 4.3.2 Environmental impact

As mentioned earlier on in chapter 4, one way to measure the environmental impact of a project is to measure how many $CO_2$-equivalents the energy generated from the project could remove from the current energy mix. When producing $H_2$, the wind farm is able to sell 105 525 tons of $H_2$ to the market each year. By using the calorific value of $H_2$-gas (119.9 MJ/kg=33.3 kWh/kg) it is possible to calculate the energy supplied to the market in the form of $H_2$. This annual energy output to the market equates to 3 513 980 MWh. Comparing this annual energy output from $H_2$-production to the annual energy output achieved when only producing electricity in Chapter 4.1, it appears that the only achieved effect by producing $H_2$ was an annual energy loss of 2 644 350 MWh before reaching the market. This exposes the energy loss in $H_2$ production process, and shows that around 57% of the energy is lost. Even though the amount of net energy is reduced, the energy form of the $H_2$-gas gives it an advantage over electricity when trying to substitute emission-intense gases. This is especially true in the transport industry.

Assuming that the hydrogen is used as a substitute for fuel in the transport industry, and that the reference value used in the comparison is that of the calorific value of diesel (43.1 MJ/kg=11.97 kWh/kg), it is possible to derive how much $CO_2$ it is possible to substitute if the transport sector were to go through with this fuel change. Assuming that all the energy derived from the $H_2$ is going into the transport industry it would be able to substitute 3 513 980 MWh of a fossil fuel like diesel or gas, with green energy. This fuel switch would substitute a substantial amount of $CO_2$ emissions from the transport industry. Calculating these emissions, illustrates why the energy loss in the conversion process might have been worthwhile.

The annual energy output multiplied by the carbon intensity of Diesel (264.53 kg $CO_2$/MWh) yields the annual emissions of $CO_2$. This number equates to 929 554 tons of $CO_2$ annually, but it does not show the full picture. After factoring in the fact that a a hydrogen fuel cell has a higher efficiency (around 45%) than a regular diesel engine (around 35%), the fuel change in the transport industry could cut 1 195 141 tons of $CO_2$-equivalents every year. This is significantly closer to the amount saved when only producing electricity, which for reference was 1 312 544 tonnes of $CO_2$ a year. Even though the wind park with the pure electricity output annually saves 117 403 tons of $CO_2$ more than the $H_2$-counterpart, one could argue that the implementation of a green energy source as the new industry standard in shipping, could have a considerably more positive impact in the long term as humanity continues its mission in combating climate change. An overview of the environmental impact from this chapter is displayed in Table 13 below.

Table 13: *Overview of key numbers related to the environmental impact of the project in terms of $CO_2$ emissions.*

| **Case** | **Wind - $H_2$** |
|---|---|
| Hydrogen sold to the market | 105 524 935 kg |
| Calorific value $H_2$ | 33.3 kWh/kg |
| Annual energy to the market | 3 513 980 MWh |
| Calorific value diesel | 11.97 kWh/kg |
| Carbon intensity diesel | 264.53 kg $CO_2$/MWh |
| **Total annual saved $CO_2$** | **1 195 141 tons** |

## 4.4 Supplying energy to the Ekofisk oil field

The final wind farm case being analyzed is a solution where the newly built wind farm is implemented as a green source of energy for a nearby oil field called Ekofisk. As described in chapter 3.4, it is assumed that the wind farm needs to be able deliver 110 $MWh$ of energy pr. hour all year around. To assure a stable delivery of energy as well as to counteract the variations in production, energy from the hydrogen storage is utilized during extended periods with limited wind. The challenge here is to make the storage tank big enough that it comfortably will be able to supply the platform with $H_2$-based energy while simultaneously keeping the costs as low as possible. Designing the capacity of the elements in these energy systems are one of the major strengths of the HyOpt model, through its ability to combine both technological and economic aspects.

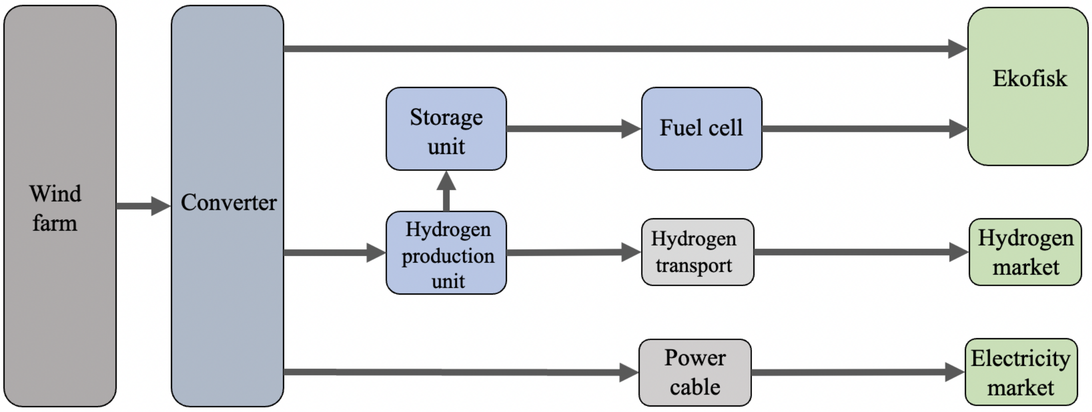

Figure 21: *Simple sketch of the wind case supplying the Ekofisk oil field with electricity and selling hydrogen to the market.*

As seen in table 14, the model suggests to invest in a Hydrogen storage facility with a max capacity of 249 tons of compressed Hydrogen. The dynamics of the delivery requirement from the Hydrogen storage is interesting. For periods with limited wind production, energy has to be provided by the fuel cell reforming the $H_2$ from the storage to electricity. Looking at figures 22 and 23, the peak capacity is nearly utilized once based on the reference wind-profile from 2019. Inspecting the data for electricity generation in that period, the data shows that there is almost no electricity generated for a couple of days in May. Calculating the maximum amount of energy it is possible to store in a 249 ton Hydrogen storage facility, it is revealed that a full storage facility can supply Ekofisk installations for around 45 hours. This means that the $H_2$ storage can supply the platform for around 2 days if there is no wind. Seeing as periods without wind is a common phenomenon, it raises the question as to whether or not the storage capacity should be increased to build a bigger buffer. By increasing the capacity of the storage it is possible to build a buffer that can withstand even longer periods without wind. A buffer will increase the CAPEX of the project. Alternatively, the platform can keep the gas-turbines they are utilizing today, and deploy it as a back up if the hydrogen storage were to be emptied. This can be a significantly cheaper option than extending the storage capacity, but it will have a trade off in terms of emissions.

Table 14: *Different key aspects of the energy project when delivering Hydrogen to the Ekofisk Oil Field*

| Node | Installed capacity | OPEX [bn NOK] | CAPEX [bn NOK] |
|---|---|---|---|
| **Wind farm** | 1400 MW | 9.17 | 27.58 |
| **Converter** | 1025 MW | 0 | 3.55 |
| **Electrolyzer** | 886 MW | 8.23 | 19.80 |
| **Fuel Cell** | 112 MW | 0.12 | 0.28 |
| **Hydrogen Storage** | 249 385 kg | 0 | 1.70 |
| **Power Cable to Ekofisk** | 113 MW | 0 | 0.29 |

Table 15: *Different key aspects of the energy project when delivering Hydrogen to the Ekofisk Oil Field*

| Case | **Ekofisk** |
|---|---|
| **Discounted income Electricity** | 15.63 bn NOK |
| **Discounted income Hydrogen** | 65.76 bn NOK |
| **Wind farm cost** | -36.75 bn NOK |
| **Electrolyzer cost** | -28.03 bn NOK |
| **Fuel cell cost** | -0.39 bn NOK |
| **Converter cost** | -3.55 bn NOK |
| **Cost of power cable to Ekofisk** | -0.29 bn NOK |
| **Hydrogen storage cost** | -1.69 bn NOK |
| **Hydrogen transport tariff** | -5.98 bn NOK |
| **NPV** | **4.70 bn NOK** |
| **Electricity sold** | Ekofisk |
| **Hydrogen sold** | European market |
| **Electricity contract price** | 1170 NOK/MWh |
| **Assumed Hydrogen price** | 55 NOK/kg |
| **Discount rate** | 4% |
| **Installed generation capacity** | 1400 MWp |
| **Total electricity supplied to Ekofisk** | 963 600 MWh |
| **Total Hydrogen delivered to market** | 86 268 330 kg |

### 4.4.1 Economic feasibility

The hourly demand of 110MW from the Ekofisk all year round introduces some interesting dynamics when running the HyOpt model. The increased Electricity contract price of 1170 NOK/MWh is assumed to include both the energy cost as well as the $CO_2$-tax the platforms in the area are avoiding by making the switch from fossil fuels to a zero emission energy source. In reality, some of the investment costs applies to other parties than the owner of the wind farm, but in this thesis it is assumed that all the extra investment costs are within the contractual energy price of 1170 NOK/MWh. Comparing the Ekofisk case to the case discussed in Chapter 4.1 which delivers pure hydrogen to the market, it is evident that implementing a hydrogen storage system in the Ekofisk supply chain could be a significantly more profitable solution for all the parties involved. The NPV is increased to 4.70 bn NOK which is more than three times the NPV achieved when delivering pure hydrogen to the market.

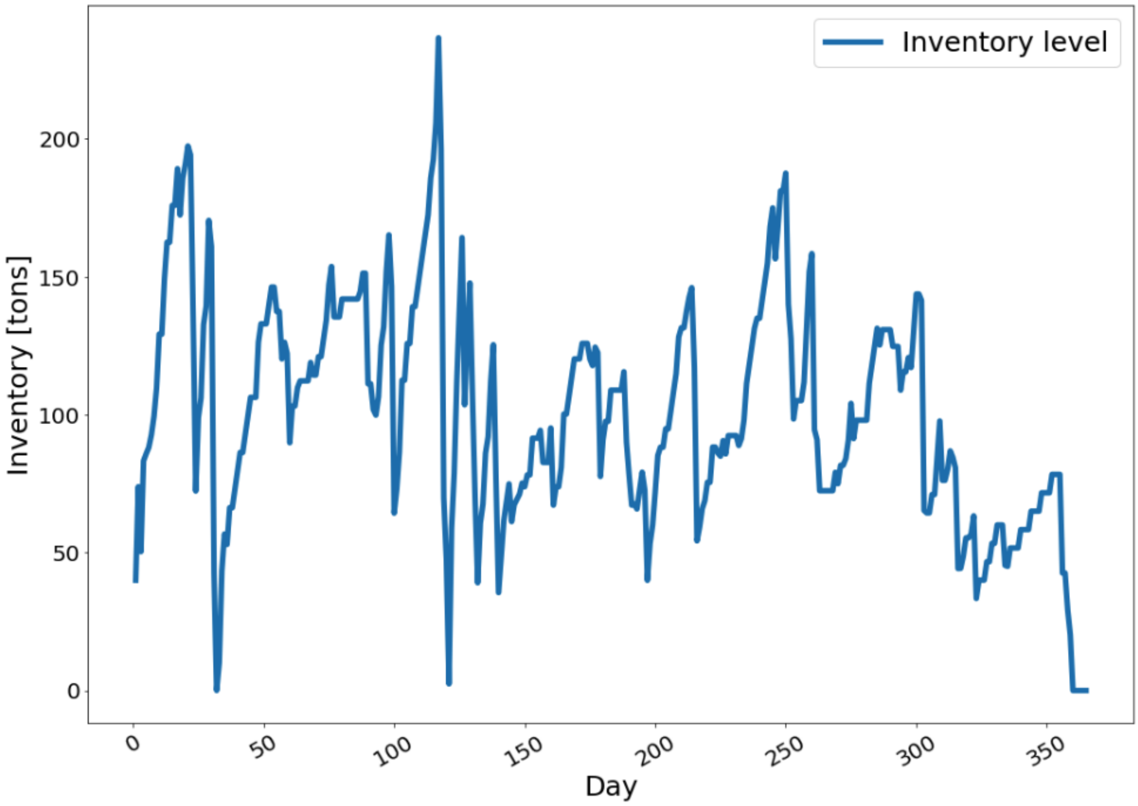

Figure 22: *Inventory level in the Hydrogen storage, and its fluctuations over a period of 365 days when supplying the Ekofisk platform with renewable, zero-emission energy.*

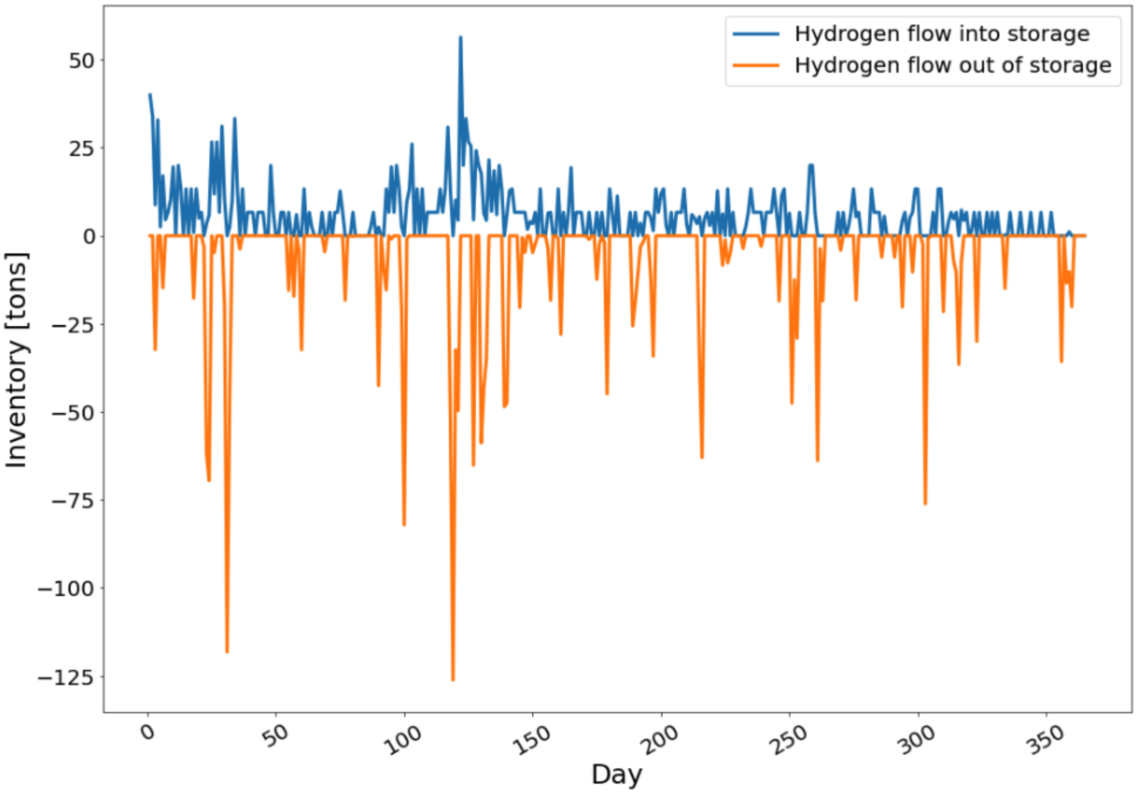

Figure 23: *Inflow and outflow of Hydrogen in the Hydrogen storage tank.*

### 4.4.2 Environmental impact

The environmental impact of the Ekofisk case is similar in nature to that of the $H_2$-case described in Chapter 4.3. Both cases are utilizing wind turbines to produce hydrogen which is then shipped and sold onshore. However, in the Ekofisk case the amount of $H_2$ delivered to shore is reduced to 86M kg, compared to the 105M kg delivered from the pure $H_2$-case. This means that the annual $CO_2$ emissions are reduced by 982 000 tons compared to the 1 195 141 tons saved in the pure $H_2$-case from Chapter 4.3. However, in addition to the 982 000 tons substituted by the hydrogen sold to the market, the Ekofisk case will reduce the estimated $CO_2$ emissions from operating the Ekofisk oil field. According to an emissions-report from 2018 for the Ekofisk oil field [49], the Ekofisk had an estimated $CO_2$ emission of 563 669 tons annually from operating the turbines required to supply the facility with energy. If the wind farm solution was implemented to supply Ekofisk with green energy, the total amount of saved $CO_2$ emissions would be 1 545 669 tons, which is even more than what was saved in both Chapter 4.1.3 and Chapter 4.3.2.

Table 16: *Overview of key numbers related to the environmental impact of the Ekofisk project in terms of $CO_2$ emissions.*

| Case | **Wind - Ekofisk** |
|---|---|
| **European Carbon intensity** | 231 kg/MWh |
| **Hydrogen shipped to the market** | 86 268 330 kg |
| $CO_2$ **substituted by Hydrogen** | 982 000 tons |
| $CO_2$ **saved from phazing out turbines** | 563 669 tons |
| **Total annual saved** $CO_2$ | 1 545 669 tons |

## 4.5 Solar Case - $H_2$ production

This chapter sums up the findings related to the construction of a large scale solar plant in Algeria with the intent to supply electricity to a local processing plant while also producing and selling hydrogen to the European market. These finding are mainly used as a point of reference when analyzing the Ekofisk case from Chapter 4.4. As described in Chapter 3.1.5, the numeric values used when analyzing the solar cases are of a highly uncertain nature due to the limited number of operational large scale solar plants. However, using the data introduced in Chapter 3.1 in tandem with the node network in figure 24 it is possible for HyOpt to come up with an optimal investment and operation strategy that is comparable to that of the Ekofisk-case.

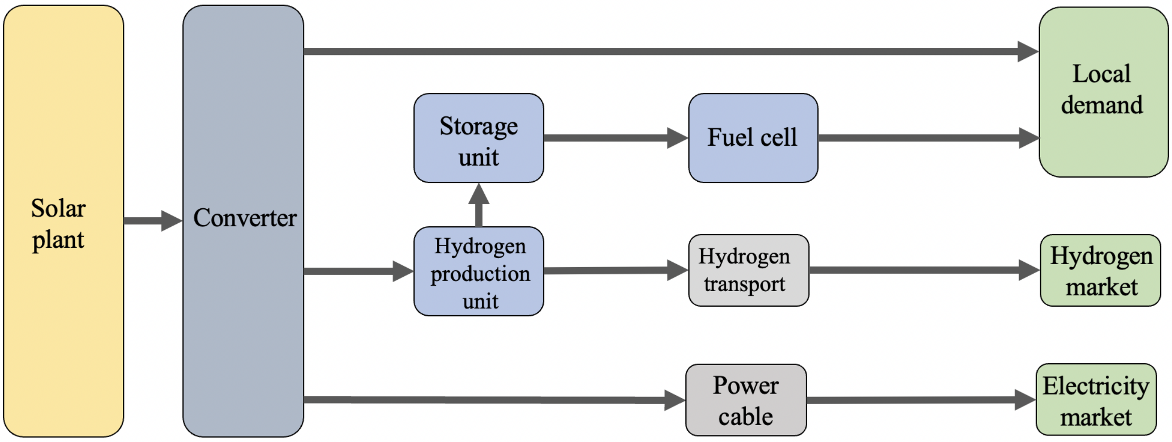

Figure 24: *Simplified sketch of the solar case delivering electricity to a local processing plant, while also selling Hydrogen to the market.*

The HyOpt model utilizes optimization to calculate the optimal capacity of the different components in the energy system. As seen in table 17, the model suggests to invest in a a 2243 MW converter, a 2076 MW Electrolyzer, 110 MW Fuel cell and a Hydrogen storage tank with a capacity of around 98 tons.

Table 17: *Different key aspects of the energy project where a solar farm is delivering Hydrogen and electricity to a nearby processing plant*

| **Node** | **Installed capacity** | **OPEX [bn NOK]** | **CAPEX [bn NOK]** |
|---|---|---|---|
| **Solar plant** | 3577 MW | 3.59 | 28.19 |
| **Converter** | 2243 MW | 0 | 1.12 |
| **Electrolyzer** | 2076 MW | 9.54 | 22.94 |
| **Fuel cell** | 110 MW | 0.11 | 0.28 |
| **Hydrogen storage** | 97 995 kg | 0 | 0.61 |

Table 18: *Different key aspects of the energy project where a solar farm is delivering hydrogen and electricity to a nearby processing plant.*

| **Case** | **Solar - $H_2$** |
|---|---|
| **Discounted demand income Electricity** | 15.63 bn NOK |
| **Discounted demand income Hydrogen** | 57.23 bn NOK |
| **PV plant (CAPEX + OPEX)** | -31.78 bn NOK |
| **Converter** | -1.12 bn NOK |
| **Electrolyzer** | -32.48 bn NOK |
| **Hydrogen transport tariff** | -3.12 bn NOK |
| **Fuel cell** | -0.39 bn NOK |
| **Hydrogen storage** | -0.61 bn NOK |
| **NPV** | **3.36 bn NOK** |
| **Electricity sold** | Local processing plant |
| **Hydrogen sold** | European market |
| **Discount rate** | 4% |
| **Installed generation capacity** | 3577 MWp |
| **Total electricity supplied locally** | 963 600 MWh |
| **Total Hydrogen delivered to market** | 75 071 268 kg |

### 4.5.1 Economic feasibility

Structurally this case is similar to the Ekofisk case from Chapter 4.4, with an assumption that there is a contractual obligation to provide a local processing plant 110 MW from the solar plant hourly throughout the year. The main difference that seperates this case from the Ekofisk case is the means of energy generation. The production profile of the solar plant is very high during daytime, but remains at zero for more than 12 hours a day when the sun has gone down. This means that a higher share of electricity needs to be delivered by the fuel cell in order to accommodate the 110 MW hourly demand from the local processing plant. This change to a cyclical production profile reduces the external export of hydrogen from 86 million tons for the Ekofisk case to 75 million tons for the solar counterpart. This reduction in export means that the solar plant will earn approximately 8.53 bn NOK less from the $H_2$-sales than the Ekofisk-case.

### 4.5.2 Environmental impact

The annual GHG reduction potential related to hydrogen in this case is calculated similarly to the calculations performed in Chapter 4.3. If all the exported hydrogen is used in the transport sector, the project would annually save about 850 232 tons of $CO_2$. Seeing as there is no specific reference for the alternative fuelling of the local demand for electricity, it is hard to determine how much the local electricity export will save. However, there will be an additional effect related to the 110 MW delivered locally.

## 4.6 Comparing the results

### 4.6.1 Levelized cost of energy and hydrogen

When analyzing and comparing the different cases it is important to find comparable metrics. As mentioned in chapter 2.5.3, one such metric is the LCOE and LCOH. The LCOE is a measure of how much one has to spend to produce one MWh of power, while the LCOH is a measure of how much one has to spend to produce one kg of hydrogen. Table 19 shows an overview of the levelized costs for the different cases.

Table 19: *Table comparing the different Levelized cost of Energy/Hydrogen for the various cases.*

| **Case** | **Levelized Cost of Energy/Hydrogen** |
|---|---|
| Wind case - Electricity Only | 598.75 kr/MWh |
| Solar case - Electricity Only | 476.77 kr/MWh |
| Wind case - Hydrogen production | 57.99 kr/kg $H_2$ |
| Solar case - Supplying a local processing plant* | 49.63 kr/kg $H_2$ |
| Wind case - Supplying the Ekofisk platform* | 51.70 kr/kg $H_2$ |

**The cases both have an electricity output and a $H_2$ output. In these calculations, the earnings from the local electricity sales are subtracted from the CAPEX to include this in the LCOH.*

The decision of whether to calculate the LCOE or LCOH is based on the output of the particular case being calculated. If the energy output of a case is measured in electricity, a LCOE calculation is utilized, while a LCOH calculation is utilized when looking at cases with hydrogen as the energy output. However, this approach becomes challenging when analyzing the cases from chapter 4.5 and 4.4. This is because both of these cases produce and sell both hydrogen and electricity. To circumvent this, it was decided to subtract the profit made from local electricity sales from the CAPEX when calculating the LCOH. These local sales assumes that the owner of the energy project, and the local businesses (the Ekofisk oil field or a local processing plant in Algeria) agrees on an electricity price that is significantly higher than the market value. The reason Ekofisk is willing to overpay for this electricity through a contractual agreement is that the supplied energy is 100 % green. If Ekofisk is able to transition into operating on pure renewable energy they will negate the need to pay the $CO_2$-tax. As long as the total price of the electricity Ekofisk buys from the local wind farm is lower than what they would have to pay in $CO_2$-taxes on their current energy mix, their profits will increase. This price has been calculated to 1170 kr/MWh. Another positive takeaway from this deal is that Ekofisk will be able to sell the gas they are currently using to operate the platform, increasing their profits even more.

We anticipate that a common infrastructure for electricity and hydrogen will reduce costs per unit produced, so that the significant investment costs inherent in these cases can be shared with other developers if offshore wind in the North Sea becomes a significant producer of green energy to Europe.

### 4.6.2 Profitability and economics of the cases studied

The estimated value of the basic technology used for large scale plants from offshore wind and Solar plant are comparable and seems to be in the same range of expected profit in the two clean electricity cases (i) & (ii).

Table 20: *Comparison of the profitability and economics of the different cases discussed in Chapter 4*

| **Case** | **Revenue [bn NOK]** | **Total costs [bn NOK]** | **NPV [bn NOK]** |
|---|---|---|---|
| 1. Offshore wind - Electricity spot | 29.5 | -46.4 | **-16.9** |
| 2. Solar plant - Electricity spot | 33.4 | -49.7 | **-16.3** |
| 3. Offshore wind - Hydrogen only | 80.4 | -79.1 | **1.3** |
| 4. Offshore wind - local delivery obligation (110 MW) | 81.4 | -76.7 | **4.7** |
| 5. Solar plant - local delivery obligation (110 MW) | 72.9 | -69.5 | **3.4** |

There are a couple of underlying differences in the two cases. The investment costs related to the export cable is higher in the PV case due to longer distance from the location to France (1000 km vs 490 km to Germany in the Offshore wind case). In addition to the need for higher capacity due to a higher peak production at daytime to have a comparable annual production capacity.

The higher energy price in the French market compared to the German market in 2019, is evening this out with approximately 4 bn NOK. In addition it is less expensive to build a large plant on shore than out in the ocean. With shorter distance to the market, a Solar plant might have an edge economically, under the assumption that it is possible to build in such scale.

The installation cost for the Solar plant is assumed to be 7,9 MNOK/MW while the offshore wind farm has an investment cost of 19,7 MNOK/MW. The maintenance costs of the Offshore wind farms I assumed to be higher than maintain costs of the Solar plant.

Case (3) – where all the wind is used to produce hydrogen offshore, stands out as more profitable than the pure electricity case from offshore wind (1), and that is an interesting observation. The cost parameters of systems not existing in this scale, is of course demanding, and especially the costs related to transport solutions are unknown at present. However, it is obviously interesting to investigate the hydrogen production potential further when discussing large scale offshore wind facilities.
Case 4, sets the stage for a combined solution, where some of the capacity in the wind-farm is dedicated to serve an offshore installation, providing electricity via fuel cells when the wind is not sufficient to cover the demand. The willingness to avoid future $CO_2$ tax, and to go green, will motivate for relatively good energy prices for that share of the production. This will in general strengthen the value of this investment project. The model finds it profitable to use the rest capacity for $H_2$ export to shore, and that is in line with the comparison between case (1) and (3).

Case (5) has a slightly lower value, due to the need for much more use of the Fuel cell, since productions during the 12 hours of darkness a day, will require more extensive use of the fuel cell for a similar delivery obligation as in case (4). The wind farm produces electricity relatively independent of darkness or sunlight and will more often cover the energy need from the platform without needing the hydrogen storage. It is interesting to observe that despite of this, the storage capacity needed is es than half of the capacity needed for the offshore wind case. That is due to higher stability in the energy production from the solar plant, and regular use of hydrogen to serve the delivery obligations when it is dark at night-time.

### 4.6.3 Comparison of emission effects

All the projects discussed in this thesis is set to have a positive impact on the environment. As seen in Table 21, all the cases are estimated to substitute $CO_2$ in a similar order of magnitude.

Table 21: *Comparison of the environmental aspects and impacts of the different cases discussed in Chapter 4*

| **Case** | $CO_2$ **substituted by electricity [tons]** | $CO_2$ **substituted by hydrogen [tons]** | **Total annual saved** $CO_2$ **[tons]** |
|---|---|---|---|
| 1. Offshore wind - Electricity spot | 1 312 544 | - | **1 312 544** |
| 2. Solar plant - Electricity spot | 1 358 729 | - | **1 358 729** |
| 3. Offshore wind - Hydrogen only | - | 1 195 141 | **1 195 141** |
| 4. Offshore wind - local devery obligation (110 MW) | 563 669 | 982 000 | **1 545 669** |
| 5. Solar plant - local delivery obligation (110 MW) | - | 850 232 | **850 232** |

Most of the cases would be able to substitute around 1 million tons of $CO_2$ annually, which is a significant amount. For reference, the Norway has an annual $CO_2$-emission of around 49.3 million tons[54]. These projects are able to cut between 2.4 - 3.1% of the total annual Norwegian $CO_2$-emissions. This shows that all the energy projects that were investigated in this thesis had a significant impact in terms of $CO_2$-emission cuts, regardless if they were economically profitable or not.

In these cases, it is only the reduced emissions in case 4 related to a potential delivery of clean energy to Ekofisk, that will reduce the accounted Norwegian emissions. The rest is export and will benefit the countries using the produced electricity or hydrogen.

# 5 Conclusion

This thesis investigated how effective it is for large-scale wind- and solar plants to implement $H_2$-storage in their value chains, and how this implementation affected economic profitability and environmental sustainability.

The numeric values used in the projects are very uncertain, but there are trends that suggest that the projects might be profitable in the future, without public funding which is currently needed. The main drivers here are related to declining costs due to a change from pilots and "one of a kind" units, to more mass production of equipment needed. The second aspect is related to a possible increase in the market prices, and this combined with a political will to increase the $CO_2$-tax, will give the market incentives to switch to green energy solutions due to a higher profitability than using fossil fuels.

It is fair to anticipate that a common infrastructure for electricity and hydrogen will reduce costs per unit produced, so that the significant investment costs inherent in these cases can be shared with other developers if offshore wind in the North Sea becomes a significant producer of green energy to Europe.

One of the research questions addressed when starting the project, was to investigate if the solar power and offshore wind were comparable in economic terms. The work indicates that they are in the same range of profitability, but with some differences in income and cost structure. The variability in the production profiles of the energy sources is very different.

The work also provides knowledge that indicates that these systems expect to be combined with green hydrogen production in a good way, both technically and economically. The findings in the work is that combining variable energy sources like sun and wind with hydrogen, has a significant potential to increase value to the large scale projects being investigated here,- both for an offshore wind farm in the North Sea and a solar farm in the Sahara desert.

It is also estimated that the global effect of these energy plants, is between 1.0-1.5M tons per year. Using Norway's emissions as a reference, this corresponds to 2.4-3.1% of their total emissions annually. This shows that all cases, regardless if they are economically profitable or not, have the potential to reduce $CO_2$ emissions significantly, and contribute to zero emission energy for a common future.

## 5.1 Further Research

Even though the model framework used in this thesis is a great tool for decision-makers and project managers to assess the viability of a project before the work has started, the model is not perfect. Especially when it comes to the decision-making in storage nodes, there is room for improvement. One way to improve this operating system is to implement an artificial intelligence (AI) with a *Genetic algorithm*. This Genetic algorithm gets its name from the algorithm that is observed in the process of evolution. In nature, this "survival of the fittest" algorithm only allows the "best" offspring to reproduce, securing their "superior" genes for future generations. This is similar to how an AI with a genetic algorithm would operate. First it would run through the model at random, aiming to maximize a preset value, which in this case could be profit or net present value. The model will then review the object value it acquired from its first iteration, and select the highest scoring ones to use as a basis in the next iteration. The model would then in theory improve with every iteration until the optimal solution is found.

Another improvement to the model could be to implement a day-ahead prediction algorithm. These algorithms are used to predict the electricity prices, and could be implemented in one of these energy projects to find an optimal time to sell the produced electricity, maximizing the revenue stream.

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