A study of renewable energy for an offshore ammonia production platform

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Preface

This work was carried out in the framework of a bachelor thesis at the Department of Mechanical and Marine Engineering (IMM) at Western Norway University of Applied Sciences (WNUAS) for the energy technology program in Bergen. The project was in cooperation with Wärtsila, who lead the ZEEDS-project. The project description was developed in collaboration with Egil Hystad from Wärtsilä.

We would like to give a special thanks to our supervisors, Associate Professor Velaug Myrseth Oltedal, and General Manager Egil Hystad from Wärtsilä, for their excellent collaboration and guidance through this interesting project. Also, we express deep gratitude to Associate Professor Jan Michael Simon Bartl, Dr. David Roger Lande-Sudall, Professor Dhayalan Velauthapillai for sharing their expertise and valuable information. To end with we would like to thank external professionals whom we had interesting conversations with, as well as providing us with helpful information, Senior Manager New Projects at Repsol, Ane Bryne Berg; R&D Director at Haldor Topsoe, Pat Han; Captain at Hurtigruten Polarlys, Hermod Nilsen.

WÄRTSILÄ

Abstract

The shipping sector is a significant contributor to global greenhouse gas emissions today. The sustainability movement has led to emission-reducing measures in the smaller vessels such as ferries, but the larger vessels have a longer path to reach net zero emissions. The energy resources available offshore such as wind, wave and solar has yet to reach their potential. However, there are some challenges related to technology development and efficiency of renewable energy sources, which leads to problems of electrifying an offshore platform. Having an electrified ammonia fuel production hub across shipping paths might speed up the process of reaching net-zero emissions in larger shipping vessels. The aim of this project is to investigate how the shipping sector in Norway can become more sustainable considering the feasibility of present and developing technologies.

The result clearly states that using wind turbines will be the most energy efficient method of producing ammonia. It is found that a combination of wind and wave could be favorable for technology development. Wave energy converters as the only primary energy source would not be feasible today due to the low energy output they can provide. It is also found that electrifying the platform with solar energy will be challenging, considering the poor solar resources in the North Sea. To produce ammonia, it has been found that the most energy efficient method is to use the developing Solid Oxide Electrolysis Cell (SOEC) in combination with the Haber-Bosch synthesis, however the most energy efficient technology today is found to be the Alkaline Electrolysis (AE).

Sammendrag

Skipsfart sektoren er en betydelig bidragsyter til globale klimagassutslipp i dag. Som følge av bærekrafts-bevegelsen har flere tiltak som redusere utslipp i mindre fartøy som ferjer, mens større fartøy har en lengre vei for å nå null-utslipp. De tilgjengelig energi ressursene offshore som vind-, sol- og bølgekraft har ikke nådd sitt fulle potensial. Det er noen utfordringer knyttet til elektrifisering av en produksjons plattform på grunn av den teknologiske utviklingen og effektiviteten til energi konvertere. For å få fort gang i reduksjon av utslipp, kan det være fordelaktig å ha elektrifiserte plattformer langs ruten til de større skipsfartøyene. Målet med dette prosjektet er å undersøke hvordan skipsfartssektoren i Norge kan bli mer bærekraftig med tanke på teknologier som finnes i dag og som er i utvikling.

Resultatet viser tydelig at bruk av vindturbiner vil være den mest energieffektive metoden for å produsere ammoniakk. Det er også vist at en kombinasjon av vind og bølge vil være gunstig for utvikling av energiteknologier og utnytte plassen mellom vindturbinene. Det er funnet at å bare bruke bølgeenergi omformere, ikke vil være mulig i dag på grunn av det lav energiutbytte. Det er også funnet at det vil være utfordrende å elektrifisere plattformen ved å bare bruke sol energi, på grunn av de dårlige solforholdene i Nordsjøen. For å produsere ammoniakk har det vist seg at den mest energieffektive metoden er å bruke Solid Oxide Electrolysis Cell (SOEC) som per dags dato ikke er fult utviklet, i kombinasjon med Haber-Bosch (HB) syntesen. Mens den teknologien som ville være mest energi effektiv i dag er å bruke AE i kombinasjon med Haber-Bosch.

Table of content

Abbreviations and nomenclature

AE - Alkaline Electrolysis

AEP - Annual Energy Production [Wh]

A_{PV} - combined area of PV module [m^2]

A_{swept} - Rotor Plane Area [m^2]

BGO - Bergen

CCS - Carbon Capture and Storage

C_P - Power coefficient

D - Diameter [m]

DC - Direct current

E - Energy [Wh]

EPV - Energy Providing Vessel

FPV - Floating Photovoltaics

GHI - Global Horizontal Irradiation: the total amount of direct and diffuse solar radiation incident falling on a horizontal surface [$Wh/m^2/year$]

HB - Haber-Bosch

H_S - Significant Wave height [m]

IEA - International Energy Agency

IPCC - The Intergovernmental Panel on Climate Change

KKN - Kirkenes

KOH - Potassium Hydroxide

LBPV - Land-Based Photovoltaics

MSD - Marine Special Distillate

Masl. - Meters Above Sea Level [m]

Mbsl. - Meters Below Sea Level [m]

NCF - Net Capacity Factor [%]

NH_3 - Ammonia

N_t - Number of turbines

ORE - Offshore Renewable Energy

PEM - Polymer Electrolyte Membrane

P_R - Performance ratio [%]

P_{rated} - Rated Power [W]

PV - Photovoltaics

P_{wav} - Wave Power [W/m]

RWT - Reference Wind Turbine

SOEC - Solid Oxide Electrolysis Cell

T_p - Peak period [s]

TRL - Technology Readiness Level

T_z - Zero Up-crossing Period [s]

U - Wind speed [m/s]

V - Volume [L]

W- Watt [W]

WEC - Wave Energy Converter

Wh - Watt hours [Wh]

WNUAS - Western Norway University of Applied Sciences

W_p - Watt Peak, the maximum electrical capacity that a solar cell can yield at 25 degrees and irradiation at 1000 W/m^2 [W]

ZEEDS - Zero Emission Energy Distribution at Sea

η - Efficiency [%]

ρ - Energy density [kg/Joule] [L/Joule]

1 Introduction

Global warming is one of the main challenges of our time and is a factor that is progressively affecting small and big decisions. In 2018, maritime shipping contributed to 2,89 % of global CO_2-emissions, equivalent to 740 million tonnes [1]. To reach net-zero CO_2-emissions from the shipping industry by the mid-century, major change is needed. Bernard Looney, CEO at bp, expressed (2020):

"*The technologies required to reach net zero exist today – the challenge is to use them at pace and scale, and I remain optimistic that we can make this happen"* [2]

There are many proposals for solutions to reach net zero for the shipping industry, such as using emission-free fuels, have electrical propulsion by batteries, or using fuel-cells with fuels like hydrogen [3]. The most common solutions for short-distance vessels like ferries, are batteries or hydrogen-fuel-cells [4]. The best solution for larger, long-distance vessels will be to implement an emission-free fuel in the existing engines, as stated in the Mission Possible Report [5]. This will also avoid having to scrap ships that have not yet reached the end of their lifecycle, which is an attractive option for the shipping companies. According to the Energy Transitions Commission it is possible to obtain a 100 % reduction in CO_2-emissions in the near future by using decarbonization technologies, such as ammonia in combustion engines for larger shipping vessels [5].

The development of ammonia engines is prominent in the industry and is planned to be implemented within 2024 by some companies [6]. Wärtsilä is one of the companies that is focusing on building an ammonia engine, and they will have the world's first full scale engine test in 2021 [7]. Wärtsilä has led part of its development work through the ZEEDS initiative (Zero Emission Energy Distribution at Sea) in order to study the use of ammonia as a future carbon free fuel [7]. Egil Hystad, General Manger, Market Innovation at Wärtsilä Marine Business says:

"*The Norwegian culture for collaboration and knowledge sharing across different companies and sectors, is a great support in closing big technology gaps. The assistance, cooperation and funding from governmental institutions are essential to drive the change towards a carbon free future*" [7].

To reach net zero emissions it is necessary to have a fuel that can compete with existing fuels on the marked, meaning it must be produced in the most energy efficient and thus low-cost way. Ammonia is sustainable if the hydrogen is produced by water-electrolysis and if the electricity of the production is delivered by renewable energy sources. Sustainable production, when trying to reach net zero emissions, is the setting for this thesis, and therefore a major part of the study is looking at the renewable energy sources that can be implemented in the North Sea. Renewables such as wind turbines and hydro power have met challenges in the public of Norway, as they are located onshore and damaging the nature. Offshore turbines will have less impact on the environment, and this must be a priority for the developers [8]. Placing turbines or other energy providing instalments offshore will have the advantage of using the Norwegian expertise in the field of offshore instalments [9], as well as exploiting some of the good energy resources to be found at seas.

The vision of the ZEEDS initiative is to strategically place offshore energy production hubs that supply ammonia as a fuel to the existing shipping routes [10]. This initiative is the backdrop of this study. The

ZEEDS production hubs will use the air and seawater surrounding it to produce ammonia. The production will get electricity from the onshore grid or connected renewable energy sources. The produced ammonia will be distributed by a bunkering vessel called the Energy Providing Vessel (EPV), making on-route bunkering possible [10]. Based on a scenario where the Costal Express vessels will convert to using green ammonia as a fuel in a combustion engine, this study evaluates the amount of ammonia required for the eleven vessels per year. This study is looking at a self-sufficient production hub, where the main focus is on the primary energy sources delivering the energy, and the electrolyzers used for ammonia production. The reason for looking into this is that there is a correlation between energy efficiency and how much a company would have to sell the ammonia for. The assessments will provide a comprehensive review to answer the following questions:

How much energy is needed to cover the annual fuel consumption of the Norwegian Coastal Express? And how can current and developing technologies of wind, wave and solar energies be used for electricity production in the North Sea? How many primary energy units are needed, and which combination of them can cover this energy demand? Which electrolyzers are the most efficient and applicable to an offshore ammonia production?

2 Background

This chapter will present the literature study background theory of this thesis. The chapter will start by describing the value chain that contains the different parts of the ammonia production hub. Secondly, as a method to assess how developed the technology is, an explanation of Technology Readiness Level (TRL) is presented. Then, three different primary energy sources (wind, wave and solar) will be described, and how they can deliver electricity to an offshore platform. Thereafter, the process of producing ammonia will be explained, describing the Haber-Bosch (HB) synthesis and three different electrolyzers. Then, ammonia storage and transportation will be briefly explained. Lastly, ammonia in shipping vessels, as well as data and information from the shipping vessel Polarlys, will be presented. It is important to emphasize that the focus will be on the primary energy sources, the ammonia production method, and the ammonia fuel demand of the Coastal Express.

2.1 The production hub

When mentioning '*value chain'* in this thesis, it refers to an energy value chain containing the necessary processes to produce, distribute and consume green ammonia. The proposed value chain of the production hub is a simplified value chain for delivering marine ammonia fuel (*see Figure 2.1)*. The ammonia demand is based on the Costal Express fuel demand, which determines the needed energy in the different steps of the value chain.

Starting from the left, the value chain presented in *Figure 2.1* illustrates three different primary energy sources that is looked at: wind, solar or wave. To produce ammonia, three different electrolyzers for production of hydrogen is looked at, in addition to the air separation unit, desalination unit and Haber-Bosch ammonia synthesizer. The next step of the value chain is the storage and distribution, but the energy demand and losses for these steps are not accounted for in the calculations. The last step of the value chain is to deliver ammonia fuel to the Coastal Express.

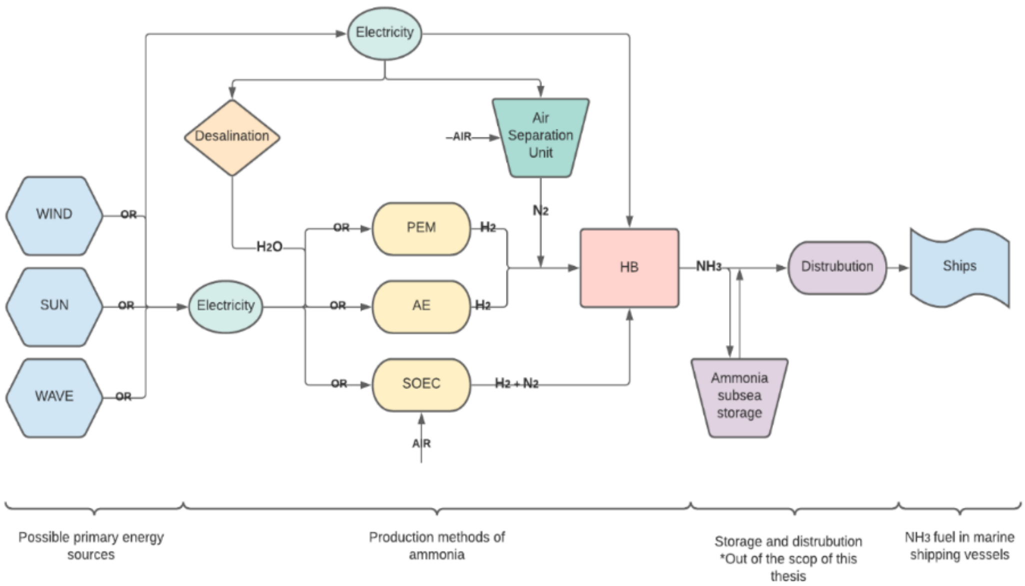

Figure 2.1- Value chain for the production hub for ammonia fuel production.

The ammonia production hub will be located on a platform in the North Sea next to a renewable offshore energy farm. It will be built as two-level platform same as in the ZEEDS vision [10].The platform will be boxed in to have the possibility of installing PV-panels for electrical energy production. The first floor will contain the electrolyzers for production of hydrogen, whereas on the second floor the ammonia synthesis will take place. In this case, the size of the hub depends on the production scale needed to supply the Costal Express fleet. However, in this thesis the platform is assumed to have the dimension of a medium sized oil platform of approximately 125m times 75m [11]. Going forward any further design and layout of the production hub will be out of the scope of this thesis.

2.2 Technology readiness level, TRL

The technology readiness level (TRL) shown in *Figure 2.2,* is a tool used to determine the phase in which the technology lies in the developing process. It is sorted by numbers from 1 to 9 whereas the former is when the technology is a "basic concept", and the latter is when the product is "commercialized". The stages in between represent different development stages of the technology. In this study, the assessed technologies are evaluated based on the TRL tool, as this will help to compare how far the development of the technologies are.

Technology readiness level (TRL)								
1	2	3	4	5	6	7	8	9
Basic concepts	Conceptual design	Preliminary design	Detailed design	Benchmarking/lab testing	Prototype	Field test	Pre-production	Commercialized

Figure 2.2- Technology readiness level (TRL). Inspiration taken from [12].

2.3 Wind energy

This sub-chapter will present information about how wind turbines work, wind farms and wind conditions. It will also present the data and equations used in the wind energy result chapter.

2.3.1 Wind energy background

Norway has large wind energy resources, with highest wind speeds offshore or at the coast. Utilizing Norway's offshore wind energy to produce ammonia offshore could be a solution in locations where the capacity of the power grid is too poor or not existing. In 2020, 9.9 TWh of electricity was produced from wind in Norway, meaning that wind power accounted for a little more than 6 % of total power production [13]. The international focus on wind energy has helped the technological development of wind turbines making them more efficient and robust [14]. The following chapters gives an overview of how Norway's wind resources can be utilized in a value chain for producing ammonia offshore.

How does a wind turbine work?

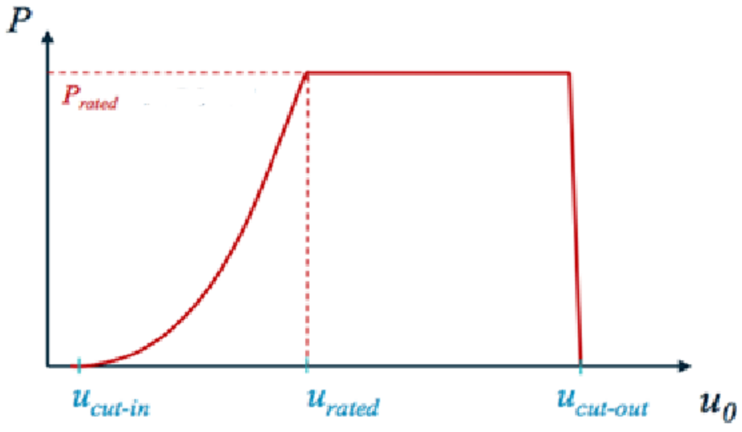

Figure 2.3- Power curve for wind turbines

Wind turbines produce electricity by converting kinetic energy from the wind into electrical power. The theoretical maximum power that can be extracted from the wind is 59 %, as described by the Betz limit [15]. Each wind turbine is characterized by a power curve, which illustrate the relation between wind speed (u) and the amount of electrical power generated [16]. As such, the power curve indicates how much electrical output each of the turbines have at different windspeeds, see *Figure 2.3.* The power curve is divided in to three regions, 1) cut- in wind speed, 2) rated wind speed, and 3) cut- out wind speed. These regions represent the wind speed at 1) which a turbine begins to generate power, 2) generates its rated power, and 3) stops generating power. The rated power of a turbine is the theoretical output of maximum power. However, the energy that a wind turbine will produce depends on both its wind speed power curve and the wind speed frequency distribution at the site. The annual energy production (AEP) is how much power the wind turbine can extract from the wind, and depends on numerous factors including wake losses, wind speed, down-time, maintenance etc. The capacity factor, CF, is a ratio between the actual energy output over a period of time to the maximum possible electrical energy output over that period [17].

Wind farms

An array of wind turbines in the same area is called a wind farm. Modelling the layout of a wind farm require extensive optimization to avoid unnecessary wake losses [18, p. 4]. Wake losses comes from the upwind turbines, which causes a reduction of wind speeds at the downwind turbines. Additionally, vortices from the tip and rotor are the main source for turbulence in the wake. Turbulence increases the fatigue loads onto the rotor, and additionally reduces the power output. To minimize these wake effects, wind direction and spacing distance between each turbine are among the factors needed to be considered in a wind farm optimization. As a rule of thumb, the inter-turbine separation needs to be minimum 8 to 10 times the turbine diameter (8-10D), in each direction [19]. This leads to a lot of empty space in a wind farm.

Wind conditions in Norway

Figure 2.4 [20] *s*how that Norway's wind resources are among Europe's best. Norway's wind resources are very good compared to Germany and Denmark, both of which have well-developed wind power [21]. Norway is in a unique position for utilizing wind power, as placing one wind turbine in Norway can generate more electricity than if the turbine were in a country with less favorable wind resources.

The primary reason behind this is that Norway's latitude often coincides with the polar front, where cold air from the north hits hotter air from the south. The wind mainly moves from west to east at our latitudes, meaning that the coast facing the open sea in the west causes wind to blow in-land, with strong winds that have blown unhindered over the open sea. Areas with high mean wind speeds and steady wind conditions over the year are attractive locations for utilizing wind energy. The government has recently opened areas for license applications for offshore wind in Utsira Nord and Sørlige Nordsjø II [22]. Utsira Nord is an area of 1010 km^2 not far off the coast, while Sørlige Nordsjø II extends to the boarder of Denmark's economic zone over an area of 2591 km^2. It is chosen to use wind data from both locations shown in *Figure 2.5* [13] to further investigate the different conditions that may affect the energy production.

Figure 2.5 - Utsira Nord and Sørlige Nordsjø II. Photo: NVE [13]

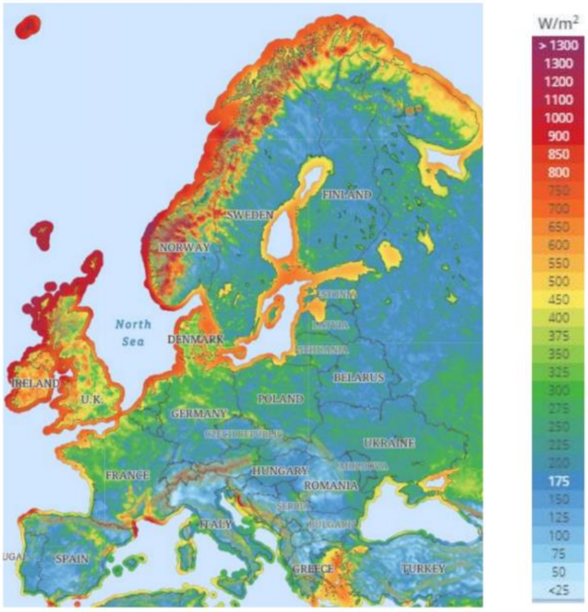

Figure 2.4 - Wind resources[W/m²] in Europe (where blue is the least and red is the most) [20]

Chosen wind turbines for calculations

The objective is to use a wind turbine that is larger than todays commercialized turbines, (TRL=9), where the largest commercialized wind turbine today is 14 MW [23]. To make calculations of the power generation, it is necessary to choose a turbine size and use this turbine's technical specifications and power curve in the calculations. The technical specifications of the chosen turbines are shown in *Table 2-1,* and consists of a 5 MW turbine (XEMC Darwind XD115 5 MW), and an 8 MW (Vestas V164- 8.0 MW) and a 15 MW (IEA 15MW Reference Wind Turbine). The power curves are shown in *Figure 2.6*, where the red, green, and blue curve respectively presents the 15 MW, 8MW, and 5MW turbine. As a result of the rapid growth in the industry and the amount of time it could take to realize this type of project, it is chosen to use data of a 15 MW IEA reference wind turbine[24]. The 15 MW turbine is a Reference Wind Turbine (RWT), meaning it is an open-access design of a wind turbine used as a baseline for calculations [24]. It has therefore been chosen to use the 5 MW and the 8 MW turbine verification of the data of the 15 MW RWT, as they are actual turbines. This turbine will be used to calculate the number of turbines necessary to fulfill the energy demand to produce ammonia to the Costal Express vessels. The TRL of this reference turbine is much lower than most turbines, around 5-6, as this type is yet to be commercialized.

Technical specifications	5 MW turbine [25]	8 MW turbine [25]	15 MW reference turbine [24]
Specific rating [W/m^2]	481,4	378,7	332
Cut-in wind speed [m/s]	4	4	3
Cut-out wind speed [m/s]	25	25	25
Rated wind speed [m/s]	14	13	10,56
Rotor diameter [m]	115	164	240
Hub height [m]	90	120	150
Rated power [MW]	**5**	**8**	**15**

Table 2-1 -Technical specifications for wind turbines for 5 MW, 8 MW, 15 MW .

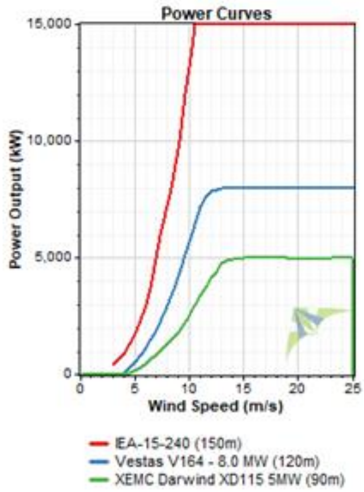

Figure 2.6 - Power curves for three different wind turbines. Source: Windographer [25]

Wind measurement data

The measured windspeed data that will be analysed in this thesis are delivered by NORA3, a taskforce that has reanalysed wind data from Utsira Nord and Sørlige Nordsjø II in a span of 15 years (2004-2018). NORA3 is developed by *Meteorologisk* Institute by Hilde Haakenstad and is shared in cooperation with *Bergen Offshore Wind Centre* by Birgitte R. Furevik. Equinor has also contributed to the development of the dataset. The project who is partly financing the development of NORA3 is WINDSURFER.

2.3.2 Wind calculations

The wind calculation method is visualized in *Figure 2.7* The program Windographer is used for the calculations of Annual Energy Production (AEP) and Net Capacity Factor (NCF). The qualitative data was gathered from a dataset of wind data, NORA3 was uploaded as a text file into Windographer. Thereafter, the 5 and 8 MW turbines power curves were collected from the wind turbine library inside Windographer. The 15 MW RWT turbine was inserted into the turbine library by plotting a reference turbine's power curve and given data such as hub height, rotor diameter and rated power. The wind data from the locations, Sørlig Nordsjø II and Utsira Nord, is measured at 100 meters above sea level

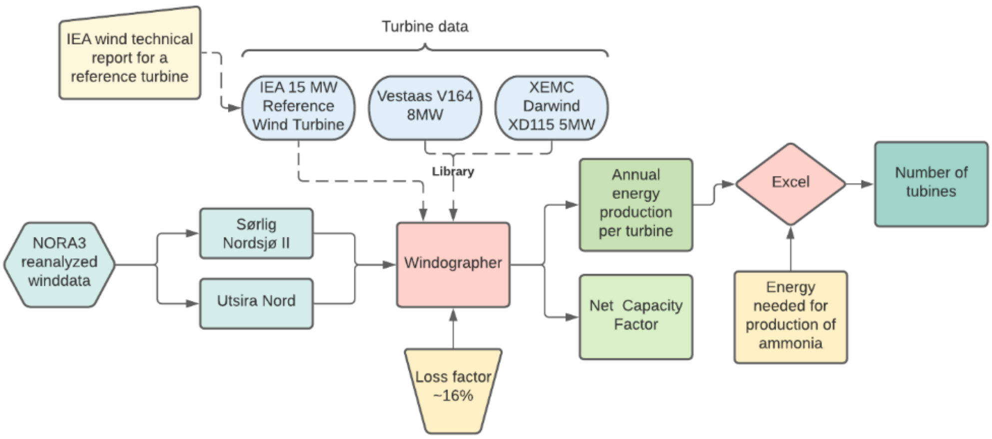

Figure 2.7- Flow chart for wind calculation method.

(masl.). To make it compatible with each of the turbine's hub heights, the extrapolating function in windographer was used to extrapolate it to 150, 120 and 90 masl.

Windographer calculates the AEP, (*see Equation 1*) from a wind-timeseries in the data-set input in intervals between the cut-in and cut-out wind speeds which is when the turbine produces power. Where the rated power, P_{rated} of the wind turbine is the maximum power extraction. To calculate the AEP Windographer uses different variables: The power coefficient (C_p) is multiplied with the density of air (ρ), the rotor plane area (A_{swept}), the incoming wind speed (U_{wind}) and the number of hours in one year which is 8760 h.

$$AEP\ [Wh] = C_P * 0{,}5 * \rho * A_{swept} * {U_{wind}}^3 * 8760h \tag{1}$$

The NCF is the ratio between actual power output and theoretical power output and is calculated as shown in *Equation 2.*

$$NCF\ [\%] = \frac{Actual\ electrical\ power\ output}{Theoretical\ output\ of\ maximum\ power} * 100 = \frac{AEP}{P_{rated} * 8760h} * 100 \tag{2}$$

Excel is used to calculate the number of turbines, N_t using *Equation 3.*

$$N_t = \frac{E_{production}}{AEP_{per\ turbine}} \tag{3}$$

2.4 Wave energy

This chapter will present the wave energy resource, as one of the possible offshore primary energy sources. Firstly, wave energy theory will be presented, as well as a description of the chosen technology for this thesis. Lastly, the method of calculating the energy output for the technology will be described.

2.4.1 Wave energy background

The energy in waves comes primarily from the wind moving the water surface level, pushing it along the globe [26]. Gravity, surface tensions and inertia forces make sure to restore and spread the waves across the ocean. Waves can otherwise be created by other factors such as distant weather, gravitational pull from the moon and sun (tides) or underwater disturbances. Today, there are many ways to predict and simulate wave with various levels of accuracy. These programs, if advanced enough, can predict how waves interact, propagate, and dissipates and much more [26].

Trying to exploit the energy found in waves can be an essential contribution to the worlds expanding energy need. An IPCC report from 2012 stated that the theoretical potential in wave power was 29 500 TWh/yr for the world's oceans, meaning that the power potential is significant [27]. However, not all parts of the ocean can be used because of fishing, protected areas, and general availability. In 2019 only 4,2 MW were installed [28] – which is 0,000125 % of the theoretical potential of wave energy. Since the early 2000, there has been a steady growth of wave energy installations. The new installations are often single units, which reflects that there is not yet an industry to launch large arrays of wave energy installations. This is because wave energy is not commercially competitive to supply electricity to a onshore grid [29], and often ends in a financial loss.

Wave conditions in Norway

The Norwegian offshore ocean is characterized by rough winters and calmer summers, with a relatively large variation in wave direction [30]. In terms of the global average, the North Sea has a high medium mean wave power, see *Figure 2.8* [30], averaging at 40-60 kW/m [31]. The oceans of the North Sea are mostly characterized by wind-generated surface waves and swell waves [26]. When trying to extract power from the waves, installations in the North Sea would need to be quite resilient against rough seas. Most of the wave data that exist from the Norwegian coast is based on simulated wave modelling, and not directly measured data [26]. This is because measuring the different parameters of the ocean can be expensive, and therefore not prioritized.

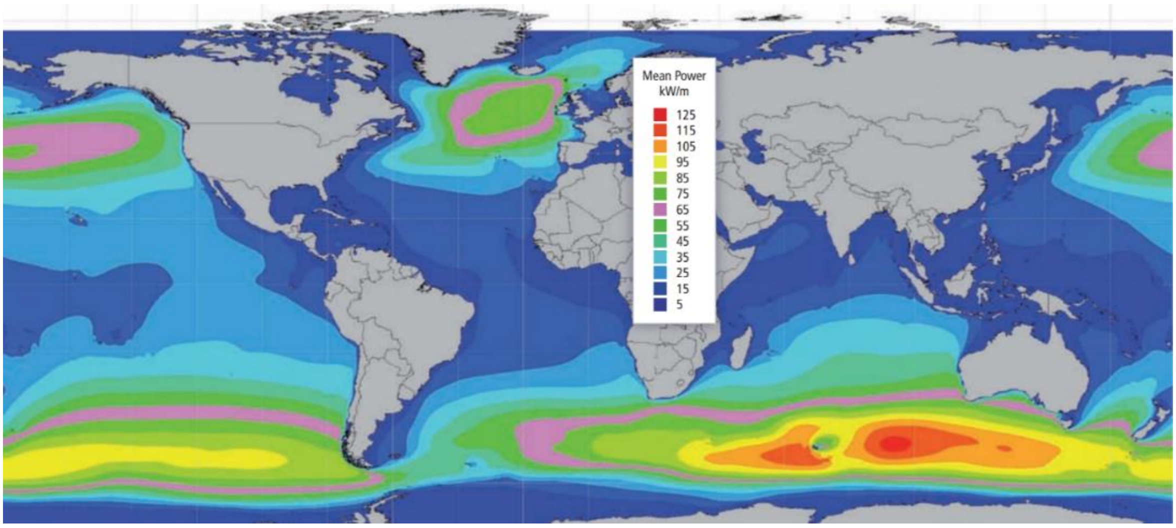

Figure 2.8 - Global offshore annual wave power level distribution, taken from Renewable Energy Sources and Climate Change Mitigation from the IPCC (2012) [30]

Wave Energy Converters, WECs

Wave energy converters (WEC) have been developed since the 70s, however the lack of success in the field is due to the difficulty of extracting enough energy in a financially feasible way, and at the same time survive the rough sea [32]. WEC technology can be divided broadly into three categories, *see Figure 2.9* [33], [34]*:* Oscillating water columns *(2-10a),* overtopping devices (2-10b) and oscillating body systems *(2-10c)* [34]. This thesis will focus on a technology that falls under the category of oscillating body systems. Oscillating body systems are either floating or submerged devices and is generally divided into rotational (most pitch systems) or translational (mostly heaving systems), see *Figure 2.9c.* The oscillating systems are often efficient at deeper waters, as they are not being

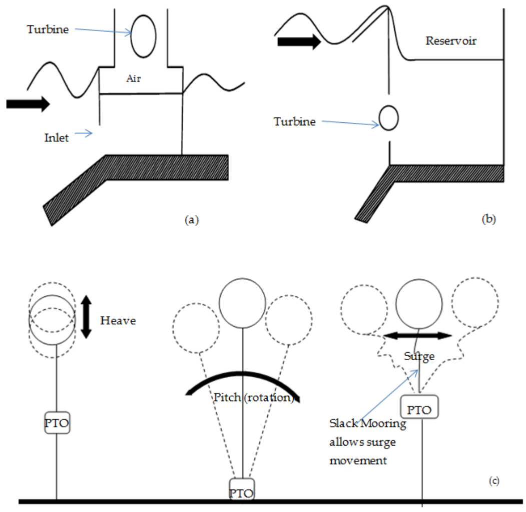

Figure 2.9 - Classification of wave energy converter (WEC) extraction technology: (a) oscillating water column, (b) overtopping devices, and (c) oscillating bodies. [34]

disturbed by the seabed. Rotational, or pitching, systems base their generation from the pitching motion by aligning the system to the wave-direction. The motions that a floating object is subjected to, are shown in *Figure 2.10.* Heaving systems extracts power by heaving buoys and are often fixed to the sea-bed. Big depths might be a problem for mooring solutions for the buoys, so another heaving device can be a floating multibody system that extracts power from two or more bodies oscillating out of sync.

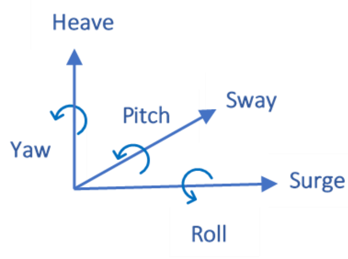

Figure 2.10 – The six degrees of freedom that a floating object is

Most WEC installations have a TRL of 6-7, where the most developed technologies have been developed and launched at a small scale. No WEC have been commercialized yet, as they have a difficulty of becoming economically competitive to other energy sources. In other words, the technology is developed, it is just not techno-economically feasible [35].

Limitations with WEC

Waves are very irregular in amplitude and transmits power through many variables such as height and period [34]. However, the converters need to be robust enough to handle extreme wave heights as this often are the conditions of the open seas. WECs need direct conversion or a mechanical linkage to be able to extract the energy from the waves and may be limited by the slow frequency of waves compared to other technologies using generators like wind turbines. In other terms, converting the kinetic wave energy to electrical energy is not particularly efficient in most of today's proposals [26]. Maintenance can also be problematic as many of the WEC are deployed offshore, as it is very costly. The corrosive nature of the ocean salinity, biofouling and the major forces can strain the units, consequently they need maintenance on a regular basis [34]. The local marine life may also be disturbed by the WEC installation and operation, of course more so if the units need to be moored.

Chosen WEC – M4 multibody WEC configuration

The calculations will be based on a moored six-float line absorber (M4) from Manchester University[36]. This is a WEC under the category of floating multibody systems. Out of the different M4-combinations tested in the study, the chosen M4 used in this thesis is the 6 float 123b combination, see *Figure 2.*11 [36]. The M4 experimental system was downscaled to 1/40th part of the designed system, designed for conditions outside of Ireland. This scaling might not be the best for the Karmøy-location in the North Sea and will need optimizing. The M4-multifloat have not been tested for power generation, thus, there are no data of energy yield. The power is calculated by a given Capture Width Ratio (CWR), which express how much of the available wave power is absorbed and converted. The values used for this configuration are shown as a graph in the results, see *Figure 4.2.*

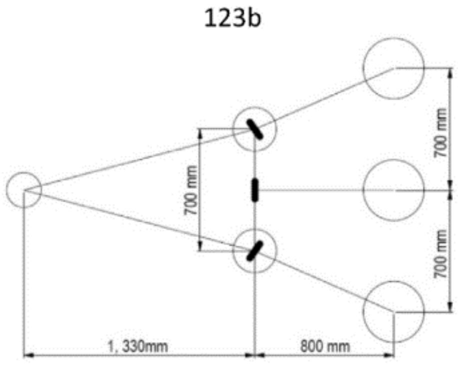

Figure 2.11 - Schematic of the M4- 6 float (123b) configuration with dimensions for laboratory scale.

The reasoning behind choosing this WEC is that the M4 is proven to withstand rough weather similar to the North Sea and is able to extract power from a broad spectrum of frequencies [32]. Another reason is that the M4 was a well-documented and tested WEC, having publicly available data. The M4 WEC-configuration has a TRL of 4-5 (lab-testing and benchmarking), although it has not yet been tested for power production.

Location and wave data – Karmøy

The sea state-data was obtained from outside Karmøy [37], located in the North Sea (latitude 59.15, longitude 5,15), which is in close proximity to Utsira. The data was obtained from MetOceanView [37], an ocean weather forecasting program used for marine industry and operations. Simulated occurrences of sea states are a forecast of the waves, given in variables of peak period, T_p, and significant wave height, H_s.

2.4.2 Wave calculations

To calculate the wave energy the equations are based on the parameters of significant wave height, H_s, and the peak period, T_p. The wave calculation is the most extensive calculation in the thesis and can be viewed in *Appendix D.1-D.2 and E.1-E.2.* To obtain the annual energy production of the proposed WEC, *Equation 4* and all other calculations was used in excel. A flowchart has been made to better illustrate the steps of the process, see *Figure 2*.12.

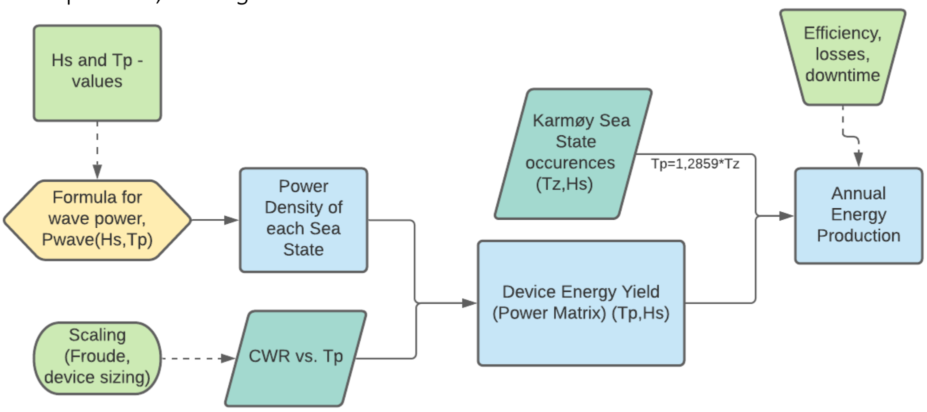

Figure 2.12- Flowchart visualisation of the method used to calculate the wave energy production.

$$AEP\ (H_s, T_p) = CF * Sea\ State\ Occurences\ [\%] * Device\ Yield\ [kW] * 8760\ h \tag{4}$$

AEP is the annual energy production, and CF, or capacity factor, takes in to account the general efficiency of the module such as transmission losses, downtime for maintenance and repair, as well as mechanical losses. The sea state occurrences [%] describes the frequency of each sea state, documented through one year [37]. The device energy yield [kW] is a power matrix for the M4 device, given based on factors of significant wave height, H_s [m], and peak period T_p [s].

The Karmøy sea state occurrences were given as predicted values of T_z and H_s, but needs to fit the format of H_s and T_p. The relationship between T_p and T_z are given with the interpretation of JONSWAP numbers [38], seen in *Equation 5*.

$$\frac{T_z}{T_p} = 0{,}6673 + 0{,}05037\gamma - 0{,}006230\gamma^2 + 0{,}0003341\gamma^3 \tag{5}$$

Where T_z is the mean zero-upcrossing period, T_p is the peak period of the recorded waves and γ is the spectral peakedness factor in the JONSWAP spectrum. The sea state occurrences have to be portrayed in percentages, if described otherwise.

The device energy yield was obtained by finding the power density of each sea state and multiplying this against the capture width ratio, CWR, and wavelength, L. The power density of the sea states was found with *Equation 6* for power in wave [39]:

$$P_{wav}(H_s, T_z) = \frac{\rho * g^2 * T_p * H_s^2}{64\pi} \tag{6}$$

Where P_{wav} is the power in irregular waves [W/m], based on the density, ρ [kg/m^3], of the ocean, the gravitational constant, g, and T_p and H_s.

A CWR vs. T_P-curve (*see Figure 4.2)* was obtained from a test done in a wave lab in Manchester [36] for the wanted M4-configuration. This data was used to see how much the device would capture of the wave-power in the location. The data had been scaled with Froude similarity criterion, and the test model was scaled with a factor of 40 (1:40). As the CWR is a dimensionless number, it is not affected by the Froude criterion. Time, or in this case the period T_P, needs to be scaled by $\lambda^{0,5}$. *Equation 7* [40] describes this relationship, where T_{PM} is the period for the modelled scale, T_{PF} is the fully scaled period and λ is the scaling-factor.

$$T_{pM} = T_{pF} * \sqrt{\lambda} \tag{7}$$

The next step is to find the corresponding wavelength to the different periods. For deep waters this is done with *Equation 8* [39], for each period.

$$L = \frac{g * {T_p}^2}{2 * \pi} \tag{8}$$

Some data might need to be interpolated, and this is done using linear interpolation [41][30], as seen in *Equation 9*.

$$y = y_1 + \frac{(x - x_1) * (y_2 - y_1)}{x_2 - x_1} \tag{9}$$

2.5 Solar energy

This chapter will present the last primary energy source in this thesis. The chapter will firstly present the background theory of solar energy resources. Lastly, the calculation method of the solar PV panels will be described.

2.5.1 Solar energy background

This thesis must also consider the most abundant renewable energy resource - the sun. In 2019, 724,1 TWh of energy production was covered by solar renewables [2]. Whereas Norway only contributed with 0,1 TWh [2] where the most common method was solar photovoltaics (PV) panels. Today there are little applications for offshore solar energy, most of which are installed directly on a platform structure or other offshore structures. Solar energy technology is generally divided in to 2 main types: thermal solar energy and photovoltaic solar panels (PV).

Thermal Solar Energy

Thermal solar energy exploits the suns heating properties, where the sun is heating up a fluid that will be used to either generate electricity through a turbine or use the heated fluid directly for central heating [42]. Thermal solar energy can be used in various ways and is generally divided in to passive or active systems. The active systems usually direct the sunrays toward a specified point that creates a high temperature, whereas a passive system absorbed the solar energy directly for usage such as space heating [42]. Due to the cool climate, thermal solar energy exploitation is not applicable for offshore usage on the coast of Norway.

Photovoltaic Solar Energy – PV

Exploiting the sun using photovoltaic panels is the commonly applied method. The working principle is to utilize the radiation from the sun to free electrons in a semiconductor, which creates a direct current (DC) [42]. The semiconductor consists of a crystalline solar cell, usually consisting of silicone semiconductor. This is doped with small doses of another material – such as boron or phosphorus. It was not until the mid-2000s that PV-technology experienced a broad commercial interest, which was mostly driven by notable reduction in technology cost, rising electricity prices and an increase in user engagement [43]. In many countries this growth was also supported by incentives and support mechanisms. In 2018, PV solar energy contributed 2,4% of the worlds energy demand, or approximately 600 TWh [44].

Implementing a solar energy production application for offshore usage in Norway is limited by the poor solar resource. For this reason, PV technology gives the highest power output, and will be evaluated in this thesis. A general problem with having PV technology offshore, is the salinity of the water and air. For instance, the PV technologies will often have a salt-coat on the surface, which will decrease the efficiency of the module [45]. The applications would also have to withstand the harsh, windy weather. Today there are many variations in PV technologies, most prominent of them is the 1) standard PV panel, 2) thin film PV, and 3) floating PV panels.

1) Fixed PV installations for offshore usage

There are not many sources of offshore implementations of solar PV panels directly on the platform. Besides from the saline air and harsh winds, it is expected that the panels have the same conditions as land-based PV-panels, and is able to function on the same level. The general efficiency of solar PV-panels today is at 13-21 % [31].

2) Thin Film PV

Thin film PV is a type of PV that stands for approximately 7% of the used PV technology [42]. They are typically a few micrometers (µm) thick and are composed of the same materials as in a normal crystalline PV. They have a lower efficiency than PV panels, with efficiencies at around 10 % [42]. One of the proposed usages of thin film PV is sticking them on the surface of a PV panel, and has been documented to increase the efficiency by only 4-5% [45]. Nonetheless, thin film PVs are one of the solar technologies that is being researched and developed today, such as the OceanSun floating units [46]. As there are many commercialized thin film technologies, they have a general TRL of 9. When it comes to floating thin film for offshore usage, one Norwegian technology (OceanSun) has the TRL of 2-3 [47].

3) Floating PV-panels (FPV)
In 2018 there was 1,1 GW_p installed floating devices in the world [48], where most of the installations were located in water reservoirs or dams. Floating PV panels (FPV) comes with the fortunate side effect of decreasing the reservoirs water loss due to evaporation and are therefore often located in areas that have a less water resources. Generally, it is reported that FPV have a better efficiency than land-based PV in warmer areas, due to cooling effects of the water [44]. How much more efficient the panels are is very individual, and is based on type of PV, floater-structure, and location.

FPVs stands for just a fraction of the solar energy production, although usage in calm waters have a TRL of 9, meaning that they are commercialized. Usage in rough waters, or offshore usage, have on the other hand a TRL of 5 [49]. This is due to the large cost of offshore applications, and the low energy yield compared to other technologies. There are some experimental offshore FPV project in Norway planned, such as Equinor and Saipem's XSIGHT project [49]. The XSIGHT project is going to be an 80x80m pontoon structure covered in PV-panels, due to be tested by the end of 2021 outside of Frøya. This test-project creates the basis of our FPV calculations.

Solar conditions in Norway

Although Norway has little sun during the year and seems inefficient to install solar energy technologies in the northern climate, it has the advantage of its cool climate. The cold climate increases the overall efficiency of the PV panels, as they would not overheat [48]. At the west coast of Norway the global annual horizontal solar irradiation (GHI) is documented to be 715 KWh/yr/m^2 [50]. The number is taken from the Meteotest database, and will act as a general estimate of yearly irradiation. Placing the panels at the right tilt angle affects the performance of the panels, if it does not have a responsive tilt system integrated. A general rule of thumb is to set the tilt angle the same as the latitude of the location, give or take a few degrees [31].

Chosen values based on industrial standards

Solar calculations will be based on industry standards for technical PV-specifications, and not one specific PV panel. The reasoning of this is that few panels have been used for offshore applications, and their recorded performance ratios may be a bit high. Performance ratio (P_R) reflects how well the module performs due to losses by factors like electrical, shading, mismatching, temperature, soiling and such. For commercialized PV panels, P_R is between 77 to 82 % [51]. Since the FPV units will be exposed to wave-splatter, varying tilt angles and shading due to waves, their performance ratio is expected to be on the lower side (77 %). The fixed installations on the other hand have less variables affecting their performance ratio as they are placed quite high up, their tilt angle is fixed, and have generally less losses compared to an FPV. Therefore, their performance ratio is set on the higher side (82 %). Availability of the system accounts for the downtime and unplanned outages, and a standard value of this is 95 % uptime [48]. Standard PV module efficiencies are around 13 to 21 % for silicone technologies [51], and a higher value is assumed as it will be expected to choose state of the art PV modules.

2.5.2 Solar calculation

The calculation for solar energy from PV-panels is one of the more simplified calculations, used to visualize how much energy the PV-panels will generate. All the calculations can be read in *Appendix A.*

$$AEP = A_{PV} * Av * \eta_{PV} * P_R * GHI \tag{10}$$

When calculating the Annual Energy Production (AEP) for the solar energy, Excel will be used. *Equation 10* [31] contains all the factors that solar energy production is based on. A_{PV} is the combined area of all the PV-modules, Av is the availability of the installation, meaning downtime for maintenance and electrical shortages. η_{PV} is the module efficiency, and P_R is the performance ratio, concerning factors that affect the performance of the module. GHI is the abbreviation for the annual global horizontal irradiation and is a measurement of the suns radiation. This method is visualized in *Figure 2*.13.

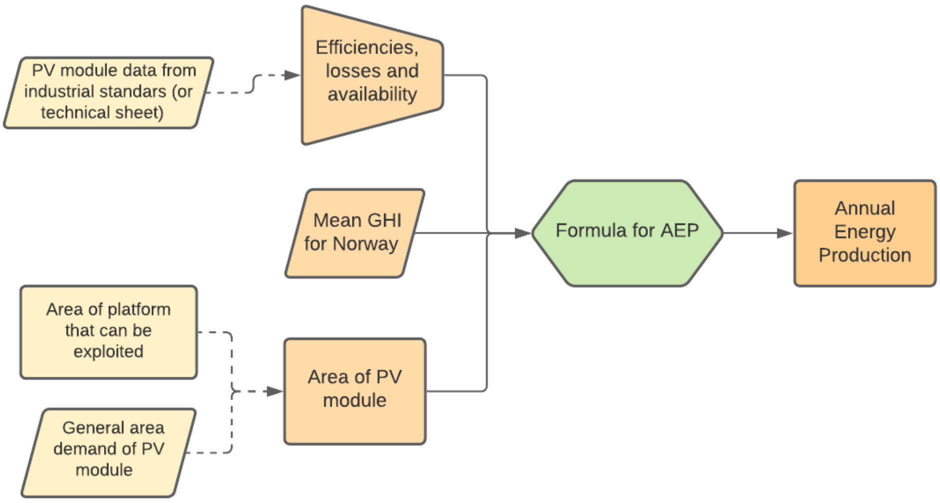

Figure 2.13- Flowchart for calculation of solar energy production.

2.6 Combining Offshore Renewable Energy

This chapter will present the benefits and disadvantages of combining primary energy sources in an area. There will also be presented a simplified method of how to optimize a given offshore space by using two or more energy sources.

2.6.1 Combining energy sources

There are many incentives pointing towards combining different offshore renewable energies (ORE) sources at the same area. Generally, combining multiple electricity generating technologies are in many ways a positive thing. Installing anything offshore must be thoroughly planned and is more time-demanding and costly than for onshore installments [35]. Planning for more than one technology in the same area will then lighten the workload that is needed for planning, logistics and other needed applications or documentation. Aspects like installment of substations for electrical wiring, grid connections and shared mooring for floating units will also become cheaper when shared, as opposed to the systems being separately installed [35]. These factors massively bring down the cost of the project, but only if the different technologies are to be installed either together, separately, or not at all. If the question is to install a wind farm alone or a wind farm together with a wave farm, the project would not be cheaper in the latter option.

Combining different technologies will make it possible to optimize empty space in a farm, which can be a rare commodity due to environmental laws and arrangements of the Norwegian coast [52]. Marine life can be highly impacted by offshore installations, especially if they are constructed onto the seabed. Minimizing or reusing offshore installment-areas will then be less destructive, and more sustainable for marine life.

When looking at combining the different primary energy technologies described in the previous chapter, a defining factor is the supply of electricity. The purpose of the primary energy sources is to deliver enough energy to the production platform. Depending on the type of electrolyzer and their response time, a stabile supply of energy is often a factor for the production-efficiency. Renewable energy sources are known to be quite unstable, so meeting this need from the production can be difficult. The intermittency problem can however be solved by installing a battery-reserve or by choosing a fast-responding electrolyzer.

Combining all three methods have been deemed unnecessary in this thesis, and so combinations of two energy sources will be looked at. As mentioned in *chapter* 2.3.1, wind farms needs at least 8D-10D inter-turbine separation, and contain a lot of empty space. Combining either Wave Energy Converters (WEC) or Floating PV-panels (FPV) with a wind farm, would be a good space optimizer, as it is beneficial to utilize the full potential of the concessional area [53]. A wind/WEC combination would make for a soothed power output, as wave climate peak trails the wind peaks, and thus generating longer peaks of power. There are also benefits to a wind/solar combination, mainly because wind and sun have typically alternating periods, meaning that there is more sun when there is less wind, and vice versa [54]. However, there is a low contribution from sun compared to wave due to a lower capacity and rated power output. The same argument can be made for a wave/solar combination as for the wind/solar combination, as the wave and wind climate is similar [31]. A counter-argument for wave/solar is that the two types both generate lower numbers of energy than a wind turbine and will therefore need larger number of units to provide an energy demand.

Optimization with the means of maximum energy extraction in an offshore area, have to take into account several factors such as meteorology, wave behavior, wake effects, type of energy extraction and how they interact, etc. [35]. Such a detailed optimization is an important part of the planning of an offshore energy implementation and is far too complex for this thesis. Nonetheless, a simplified method of this will be used, as described in the succeeding chapter.

2.6.2 Calculations for combining energy sources

To optimize a given area used for multiple offshore renewable energy technologies, two methods will be explained in this sub-chapter. The 'hole'-method is the method chosen to give the basis of the calculations, as this is the easiest to calculate. Although the 'protective'-method is the best for protection against the harsh weather but needs a bit more parameters and complex calculations to use. For this thesis, the co-location will contain either wind turbines + Wave Energy Converter (WEC), or wind turbines + solar Floating Photovoltaics (FPV).

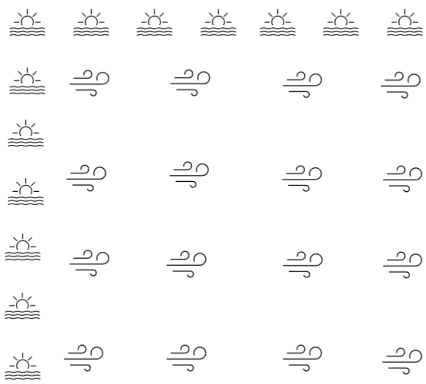

Figure 2.14 - Schematic of the 'protective'-method. represents the wind turbines, and represents either a WEC or an FPV-unit. Inspiration taken from [35].

'Protective'-method

The 'protective' method of space-optimizing displayed in *Figure 2.14,* is basically using either WEC-units or FPV-units to shield the turbines from the on-coming waves [35]. Placing a row of WEC/FPV units on the two sides with the most common wind direction will create a milder wave climate 'inside' the wind farm. The WECs will deflect much more of the wave power than the FPVs, as they 'absorb' and convert the power into electrical power. This space-optimizing can be used to ease the strain on the wind turbine monopiles, making them last longer.

'Hole'-method

The 'hole'-method of space optimization, viewed in *Figure 2.15,* consists of clusters of WEC/FPV units being placed in-between the wind turbines [35]. This placement will also absorb some of the wave power, easing the strain for the wind turbines, but not as much as the 'protective'-method. This method, however, will make for a simpler calculation, where the approach is to firstly place the needed number of turbines in an array, then calculate the numbers of 'holes' between the turbines. The last step is to place one single or multiple units in these 'holes', based on the size of the WEC or FPV units.

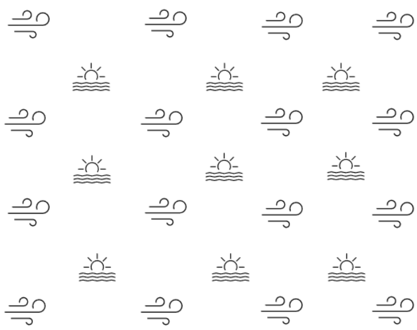

Figure 2.15 – Schematic of the 'hole'-method. represents the wind turbines, and represents either a WEC or an FPV. Inspiration taken from [35].

Calculating the energy coverage by either WEC or FPV units

Using the 'hole'-method to calculate how many WEC or FPV units can be fitted inside a wind farm array, *Equation 11* is used in the excel worksheet (*see Appendix A:).*

$$Coverage\ by\ \ X\ unit_{WEC\ /\ FPV} = \frac{AEP_{x\ units}}{E_{NH3\ production}} * 100 \tag{11}$$

This equation looks at the coverage [%] done by X amount of WEC or FPV units. X is how many units are fitted in one hole, multiplied by number of holes between the turbines. Coverage is found by taking the Annual Energy Production of X units ($AEP_{x\ units}$) and dividing it by the energy demand for the given ammonia production method ($E_{NH3\ production}$).

2.7 Production of ammonia

This chapter will present different production methods of ammonia, where three different electrolysis methods will be explained. It will also present the equations used in the result chapter.

2.7.1 Ammonia background

Grey ammonia	Produced from natural gas
Blue ammonia	Produced from natural gas, but with CCS
Green ammonia	Produced from green hydrogen with renewable sources

Table 2-2; Ammonia categorised in colour by production method and emissions.

Production of ammonia is a well-known process and has been used as a base substance for agricultural fertilizer for over a century. Ammonia is also used for plastic, as a refrigerant gas, chemicals, and explosives. Where about 80 % of the annual global ammonia production is used for fertilizers[6]. However, offshore production of green ammonia has not yet been studied broadly. Ammonia does not contain carbon, which means that if renewable energy is used to power the production, it can be made with no CO_2-emissions. There are several ways of producing ammonia, where gas reforming to supply hydrogen to the Haber Bosch process is the most common method today. The production methods can be distinguishing between three categories of ammonia, each with its own colour designation[55], see *Table 2-2*. In this report, however, the focus is on green ammonia, and blue ammonia production will be presented.

Properties of ammonia

Ammonia can be used as a fuel, as a hydrogen carrier and energy storage medium. General properties of ammonia are shown in *Table 2-3.* Ammonia is a gas at atmospheric pressure and room temperature (20 °C) and can easily be liquefied either by compression above 8.6 bar at 20 °C or cooling to -33 °C [6].

	Ammonia
Energy content [MJ/kg]	18,60
Energy density [Kg/L]	0,76
Volumetric energy density [MJ/L]	14,14

Table 2-3 - Properties of ammonia [44], [6].

Blue ammonia

Blue ammonia is produced from natural gas, where the CO_2 emissions from the production of hydrogen is captured and injected into an underground reservoir for permanent storage, this is called Carbon Capture and Storage (CCS)[6]. Implementing CCS in the hydrogen production can reduce the CO_2 emissions by 50-95 % with gas reforming [56]. The hydrogen is produced by gas reforming of natural gas, which can be done with various methods, where steam reforming of natural gas using water vapor is the most common method [57].

There are several challenges connected to having a steam reforming plant. One challenge is cost and the need to establish large facilities to achieve economic scale. It is estimated that a small-scale plant with the capacity to produce 150 kg H_2/day will have 7 times high cost of production than a large-scale steam reform plant [56]. Another challenge is that it operates under high temperature and pressure, which comes with greater risk and safety requirements. These factors will limit the relevant sites for such production. Gas reforming is assessed by others and proves to be inappropriate offshore, therefore it is chosen not to go any further into blue ammonia production in this thesis [58].

Green ammonia

Yara in Porsgrunn has recently announced that they are planning to make a full- scale green ammonia production plant, this will result in an annual emission reduction of 800 000 tonnes of CO_2 [59]. Unlike blue ammonia, production of green ammonia is made entirely from renewable electricity, air, and water[55]. This means that green ammonia has zero CO_2-emissions. Green ammonia is produced through the Haber-Bosh process with green hydrogen produced by electrolysis of water. Electrolysis of water is the process of using electricity from renewable energy to split water into hydrogen and oxygen. Having an offshore ammonia production offshore would require running the seawater through a desalination device to get pure water to the electrolysis[60].

Production of Hydrogen

There are several methods of water electrolysis, covering different characteristics. Three technologies are highlighted as currently or in the future as the most promising, the Proton Exchange Membrane electrolysis (PEM), Alkaline Electrolysis (AE) and Solid Oxide Electrolysis Cells (SOEC). The latter has not yet been scaled up or commercialized. The efficiencies for the different electrolyzers are shown in *Table 2-4*, as well as the efficiency for the HB- Process. As the efficiencies vary from company due to type, usage, location, and scale, there is used an average efficiency of the electrolyzers.

Process	Efficiency
HB	0,87 [56]
SOEC	0,85 [6]
AE	0,735 [61]
PEM	0,715 [61]

Table 2-4 – Efficiencies for the different electrolyzers and Haber-Bosch process.

Alkaline electrolyzer, AE

Alkaline electrolyzers (AE) have been used for more than 100 years in hydrogen production and is therefore a mature technology. The efficiency of this electrolyzer typically range from 65 - 82 % [61]. AE operates at temperatures at around 60 – 80 °C and uses potassium hydroxide (KOH) as electrolyte, which is a highly concentrated alkaline aqueous solution [62]. This electrolyzer would therefore require transport and storage of KOH to the offshore production site[60]. The alkaline electrolyzer struggle with operating at very low current densities. This makes it difficult to combine with unstable renewable energy sources, since the response time of the control of the process is long compared to the expected power variations [60]. This makes it difficult to combine with unstable renewable energy sources, since the response time of the control of the process is long compared to the expected power variations. The flow chart process of ammonia production for AE-HB and PEM-HB is illustrated in *Figure 2.16.*

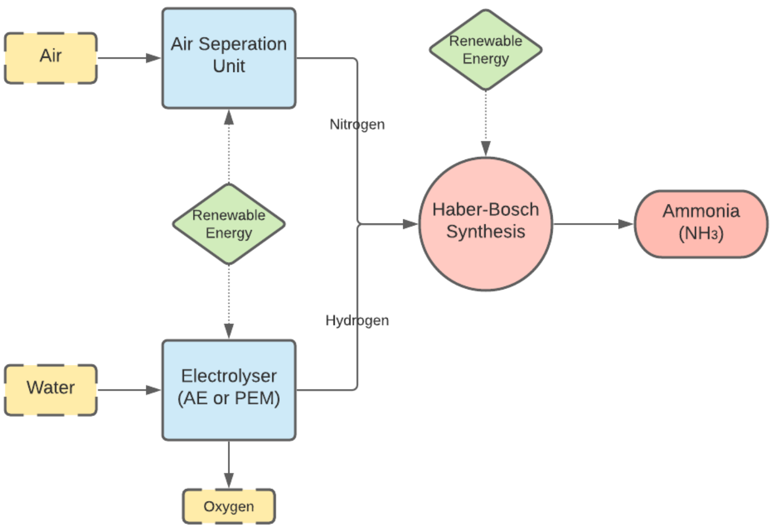

Figure 2.16- Flow chart of Ammonia production using AE-HB or PEM-HB process. Inspiration taken from [61].

Proton Exchange Membrane electrolysis, PEM

Proton Exchange Membrane, PEM electrolyzers uses a polymer as the electrolyte and operates at a temperature around 60-80 °C [61]. The efficiency of the electrolyzers typically ranges from *65-78 %* [61]. The PEM electrolyzer work at a high current density, which allow more compact electrolysis unit. In addition is the response time for PEM fast, where the dynamic load range from zero to above 100 % of capacity in time of milliseconds[6]. Due to low pH, there is a corrosive environment in the PEM electrolyzer, this means that precious metals must be used, which is expensive.

Solid oxide electrolyzer, SOEC

Haldor Topsoe is currently developing a solid oxide electrolyzer demonstrator that integrates a solid oxide electrolysis cell (SOEC) to produce ammonia synthesis gas. The electrolyzer has not yet been scaled up or commercialized [6]. SOEC operates at high temperatures, typically 700-800 °C. The high operating temperatures results in favourable thermodynamics and reaction kinetics, resulting in electrolyzer efficiencies that cannot be achieved with other electrolysis technologies [63]. The production with SOEC process is illustrated in *Figure 2.17* [64], and inspiration is taken from Haldor Topsoe [64]. This electrolyzer differs from AE and PEM, where there is production of both hydrogen and nitrogen in the same unit before the Haber Bosh process [55]. The waste heat from the Haber Bosh synthesis is utilized in the SOEC, which results in an overall energy efficiency at 90 % [6]. Furthermore, SOEC separate oxygen from air without an air separation unit, and no rare and costly metals are needed.

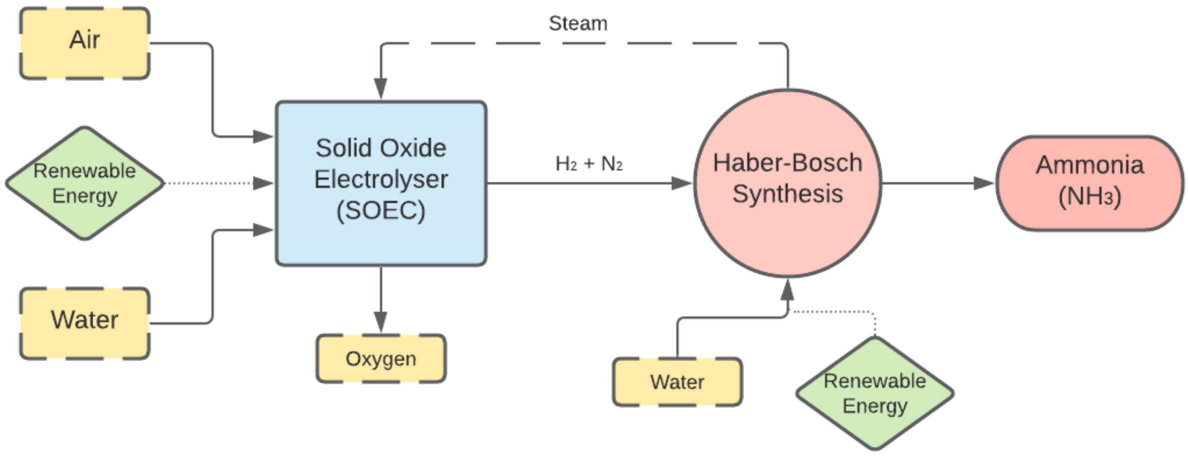

Figure 2.17 - Flow chart of production of ammonia using a SOEC-HB process. Inspiration taken from [64].

Haber- Bosch process

Figure 2.18 shows a schematic illustration of the Haber-Bosch industrial plant [65] . The Haber- Bosch (HB) process begins with hydrogen gas and nitrogen gas are, reacting under high pressure and temperature [66]. The hydrogen and nitrogen are inserted into a compressor, that compresses the gasses to 200 bar. The gas mix enters a converter which heats the gases up to around 450°C. The converter contains a catalyst made of iron, which is used to speed up the reaction, and heat the pressurized gases up to around. At this point the reactants has formed ammonia, but there is still some unreacted hydrogen and nitrogen. After this, the gas is inserted to a cooling tank where ammonia, hydrogen and nitrogen is cooled, and the ammonia is turned into a liquid and collected. The unreacted reactants will go back into the converter, so more ammonia can be produced. This process is repeated several times until most of the hydrogen and nitrogen have been transformed into ammonia [66].

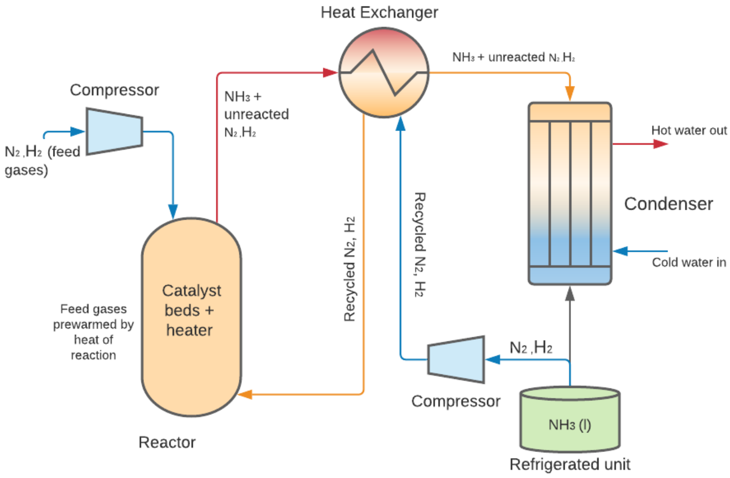

Figure 2.18 – schematic of an industrial plant for a Haber-Bosch synthesis. Inspiration taken from [65].

2.7.2 Production calculation

To calculate the energy input needed to produce ammonia, it is necessary to know the quantity of ammonia that is needed for the fleet of coastal passenger vessels yearly ($NH_{3_{consumption}}$). Standardized values were used as a hypothesis to validate and to adjust the result. The calculation method is illustrated in a flow chart, see *Figure 2.19.*

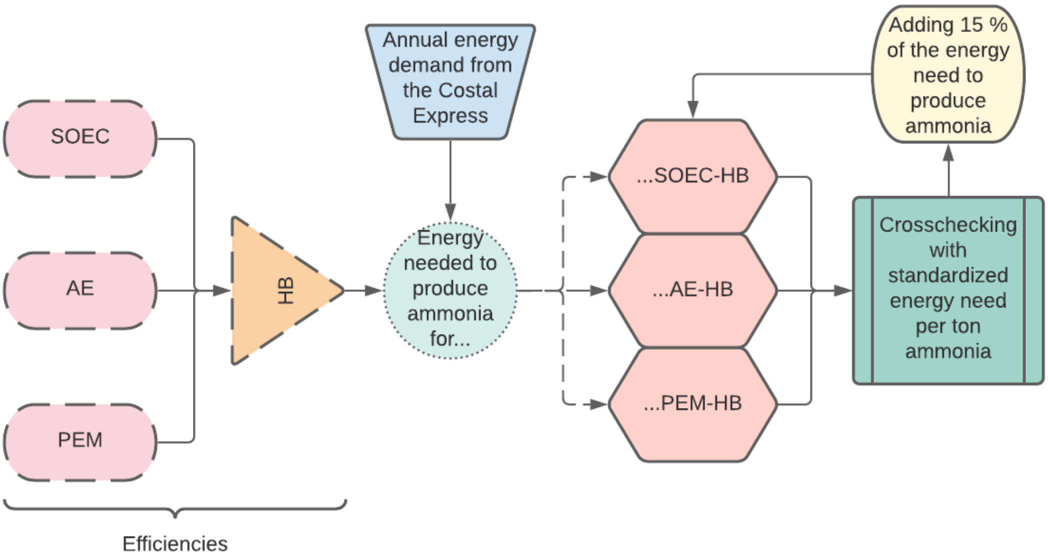

Figure 2.19 - Flow chart for calculating energy needed for ammonia production.

The total efficiency ($\eta_{\text{production}}$) is a product of the electrolyzer and Haber Bosch efficiency *(Equation 12)*. Lastly, adjusting with a 15% loss in energy in the supporting systems to find the energy needed to produce ammonia ($E_{NH_3 production}$) with the different electrolyzers *(Equation 13)* [67].

$$\eta_{\ production} = \eta_{\ electrolysis} * \eta_{\ H-B\ process} \tag{12}$$

$$E_{NH_3 production} = \frac{\left(\frac{NH_{3_{consumption}}[\text{ton/yr}]}{\eta_{\ production}}\right)}{0{,}9} \tag{13}$$

2.8 Air Separation Unit, ASU, and desalination

In addition to the other appliances for producing ammonia offshore, a desalination unit and Air Separation Unit (ASU) is needed.

The desalination unit is needed since the electrolyzers cannot be operated directly on sea water. Most hydrogen electrolyzers need water with a purification level of 0.5 ppm [60]. Desalination processes today are split into two main groups – thermal desalination and electrical desalination. Today, reverse osmosis is the most used method. If this type of desalination is to be used at an offshore hub, it would demand certain chemicals and solutions that will need to be changed and maintained. But as this is a well-known and developed method, reverse osmosis (RO) would be most fitting for an offshore production hub. As the desalination process require energy, it is assumed that desalination will have an energy consumption of 6 % of the ammonia production in this study [67].

The nitrogen inserted into the H-B process, is obtained directly from air using an air separation unit [55]. Normally will the ASU account for 2-3 % of the process energy used for ammonia production [55]. As the platform is thought to be offshore, the ASU would need washing and drying more often than if it were sited onshore due to salty air [68]. Therefore, will around 6 % of the energy consumption in the ammonia production be used for the ASU [67].

2.9 Subsea storage and Energy Providing Vessel, EPV

The produced ammonia must be stored before getting bunkered on to the ships. Ammonia can be stored in seabed tanks utilizing the pressure of the ocean at 70 meters depth, and the behavior of ammonia at different pressures and temperatures. As mentioned in *Chapter 2.7.1,* ammonia is in a liquid state when it is cooled to -33°C at atmospheric pressure or it can be subjected to 7-10 bar pressure for temperatures below 10°C. For every 10 meters of ocean depth, approximately 1 bar of pressure will be added to any submerged object. With the pressure and the low temperature at such depth, it is calculated that ammonia will remain a liquid at a depth of 70 meters [67]. Using subsea storage, the only energy cost for ammonia storage would be the energy used to pump the liquid down and up again. There is no commercialized solution for this type of ammonia storage today, but NOV is a company currently developing a subsea liquid storage technology [55].

The ZEEDS vision is that the stored ammonia will be bunkered onto an Energy Providing Vessel, or EPV, that will deliver ammonia to fuel the multifuel-vessels inside a range of 100 nautical miles [69]. The EPV's are considered a vital part of the infrastructure that enables ammonia as a marine fuel. This type of vessel does not exist today, and will be a pioneer in its field. The EPVs are designed to avoid "traffic jams" in the main hub area [56], as the receiving vessels are being bunkered on-route. As ammonia is a chemical with less energy than most used marine fuels today (like Marine Special Distillate or Heavy Fuel Oil), the bunkering rates would be consequently more frequent for vessels with the same tank size. The EPV and subsea storage are important parts of the value chain, but as they have little impact on the total energy demand for ammonia production, they will be disregarded in the further calculations.

2.10 Ammonia in marine vessels

This sub-chapter will present information the vessel Polarlys, and the data used for calculating the ammonia demand of the Costal Express fleet. It will also present the risk and concerns of using ammonia as a fuel and ammonia in combustion engines.

2.10.1 Marine coastal passenger vessels

In this thesis the energy demand of Polarlys, a coastal passenger vessel, is investigated to give an indication of the total energy demand from the Coastal Express. This will indicate how much electricity the primary energy sources will have to deliver to the production of the ammonia demand.

Hurtigruten - Polarlys

Heavy fuel oil (HFO)		
Energy content	[MJ/kg]	40,60
Energy density	[kg/L]	0,885
Volumetric energy density	[MJ/L]	35,93

Table 2-5-Properties of heavy fuel oil

The Costal Express travels round-trips Bergen (BGO) - Kirkenes (KKN) every day with a fleet of eleven ships, this equals to 365 trips yearly or 33 trips per boat each year. The present fleet has a variation of age starting from the first ship built in 1964 and the last in 2009 [70]. They transport goods, mail, and passengers to 34 different ports. All the ships have two main engines (crosshead motor with type designation: B&W DM 742 VT2BF-90) [70], two auxiliary engines and a boiler for hot water that requires energy. Bunker fuel once every trip in Bergen, however they can travel nearly two trips with a full 21 000 L storage tank [71]. They use Shells Marine Special Distillate (MSD) diesel[72], and the properties of Heavy oil (HFO) are assumed to be equivalent (see *Table 2-5*).

In this study, the fuel consumption of the ship Polarlys is used as a basis for calculations of the energy demand of the Costal Express fleet. This ship was launched in 1996, it can transport 619 passengers each way and has a gross tonnage of 11 341. It can travel at a top speed of 18,5 knots [71]. The measured diesel consumption of this ship is as described in *Figure 2.6.* The given measurements were obtained from Polarlys database [71].

Fuel consumption [L]	Components				
	Main engines[71]	The auxiliary engines [71]	Boiler [71]	Hotel load and supporting systems[1]	Total
Highest	202 266	9 030	4 000	66 127	281 423
Average of 5 trips	191 724	9 381	4 000	66 127	271 232

Table 2-6 - Fuel consumption for Polarlys (BGO-KKN-BGO)

Ammonia engines

There is no operating ammonia engine to this date in shipping, however it is expected that within a few years ammonia can be used as fuel in a combustion engine or fuel cell [73]. One of the biggest advantages of using a combustion engine is that by modifying existing engine installations, it reduces the need to re-new the entire fleet or make expensive and grand conversions of the ships [74]. Wärtsilä is one company that is working on multi-fuel combustion engine based on dual-fuel technology, the first development period is ending in 2023 and aiming for a 30 % diesel and 70 % ammonia related to share of energy content in combustion.

Risks and concerns of using ammonia as a fuel

Various concerns can come up when looking at the possible use of ammonia as a marine fuel. If un-combusted ammonia is in the exhaust, it can create a hazardous gas called nitrous oxide (N_2O) and NOx-gases, however catalysts for the removal of both gases are commercially available [68]. Selective catalytic reduction technology (SCR) is commonly used to remove nitrous oxide, Yara is one company which says the reduction of NOx exhaust is up to 98 % [74] . Thus, the exhaust is not the main issue with ammonia engines.

Ammonia is classified as a toxic substance with high risk for the health by the American National Fire Protection Association (NFPA) [73]. Nevertheless, ammonia is traceable by smell and detectors with concentration below what is considered a health risk, 5-50 parts per million (ppm) of air, but can be tremendously irritating to eyes, throat, and the respiratory tract [75]. No fuel is without danger, and the explosion risk when using ammonia is lower than fuels such as hydrogen and natural gas. There are good and established customs and requirements to handling ammonia on ships today, due to the considerable amount of 20 million tonnes shipped today [73]. Equivalent requirements are needed before ammonia can be used as a fuel[73]. There are ship owners and crew that are uncertain of the consequences of using ammonia as a fuel for ships. There are also other concerns, the IMO International Gas Carrier Code prohibits the use of toxic products as fuel for ammonia carrying vessels[76]. This code needs to be re-evaluated if ammonia is to become a fuel for ships.

[1] Hotel load and supporting systems was not included in given data from Polarlys, this value is estimated from average power consumption of 2500kW [67].

2.10.2 Coastal Express fuel demand calculations

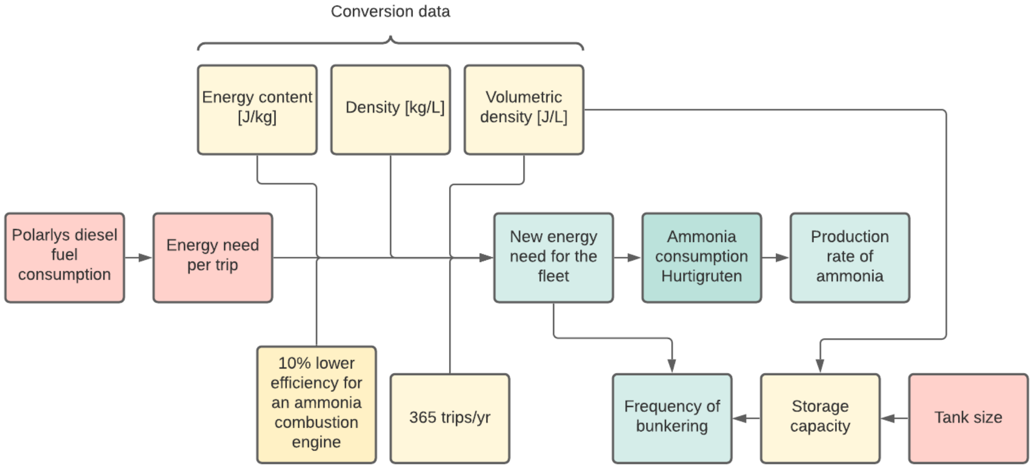

Figure 2.20 - Flow chart for calculating the annual ammonia demand of the coastal vessels in the Hurtigruten fleet.

$$NH_{3\,consumption}[\mathrm{ton/yr}] = \frac{\mathrm{E}_{consumption}[\mathrm{MJ}]}{\rho_{volumetric\ \mathrm{NH_3}}[\mathrm{MJ/L}] * 1000[\mathrm{kg/ton}]} * \rho_{\mathrm{NH_3}}[\mathrm{kg/L}] * 365[\mathrm{trips/yr}] \tag{14}$$

The calculation method is as seen in in *Figure 2.10* and viewed in *Appendix C.* To calculate the potential annual ammonia demand of Hurtigruten $\mathrm{NH}_{3\,\mathrm{consumption}}$ (*Equation 14*) it was necessary to first find the energy consumption $\mathrm{E}_{\mathrm{consumption}}$ per trip for one vessel *(Equation 15).* Further, its necessary to know the energy content of the fuel, $\mathrm{V}_{consumption}$, (see *Table 2-6*) per trip for one vessel and therefor it is multiplied with the volumetric density of heavy fuel oil (HFO), $\rho_{\mathrm{volumetric\ HFO}}$. Lastly, consider the lower efficiency of the ammonia fuelled combustion engine, which is assumed to be 10% less than with the original engine. This is accounted for by dividing by 0,9.

$$\mathrm{E}_{consumption}\ [\mathrm{MJ}] = \frac{V_{consumption}\ [\mathrm{L}]\ *\ \rho_{volumetric\ HFO}\ [\mathrm{MJ/L}]}{0{,}9} \tag{15}$$

It is also necessary to find out the needed production rate of ammonia, $\dot{\mathrm{P}}_{\mathrm{NH_3}}$, by dividing the annual ammonia consumption of the whole fleet in tonnes $\mathrm{NH}_{3\,\mathrm{consumption}}$ by the annual operational hours for the whole fleet, 8760h, see *Equation 16*.

$$\dot{\mathrm{P}}_{NH_3}[\mathrm{ton/h}] = \frac{NH_{3\,consumption}\ [{}^{ton}/_{year}]}{8760\ [h\ /yr]} \tag{16}$$

The frequency of bunkering, $\mathrm{F}_{bunkering}$, needed with ammonia fuel *(Equation 17)* is also calculated. This is done by dividing the annual energy consumption of the entire fleet, $\mathrm{E}_{\mathrm{consumption}}$ on the storage capacity, $\mathrm{C}_{\mathrm{storage}}$.

$$\mathrm{F}_{bunkering} = \frac{\mathrm{E}_{consumption}[MJ]}{C_{storage}\ [\mathrm{MJ}]} \tag{17}$$

3 Methodology

This study is primarily a qualitive study, where data is collected through unstructured interviews and literature such as reports, papers and articles. The thesis also examines data using triangulation, where quantitative data from calculations and measurements is combined with the qualitative data from reports.

3.1 Qualitative data

Primarily, a literature study is conducted for *Chapter 2 - Background*, to give the reader a foundation of understanding the results and discussions of this study. The qualitative data is obtained from literature research and conducting interviews with industry specialists and researchers. The interviews are held to get empirical data, which is data based on experience. This type of empirical data gave an overall picture on the industries, especially for wind, wave and solar. In addition to this, some data are difficult to find in public domain, but is obtained in the interviews. It was challenging to find articles about offshore green ammonia production. The literary research is also gathered from a wide variety of sources, using search engines such as Engineering Village, Science Direct, and Google Scholar. These search engines provide good academic and scientific information on most of the topics. Common search words are “renewable”, “offshore”, “platform”, “ammonia” and “electrolyzer”. The Ammonfuel (2020) [6], Royal Society Ammonia Report (2020)[55] and Mission Possible Report (2018)[5] are reports that is frequently used during the gathering of information. Some sources from the publications/reports were looked into further to see if the sources were reliable.

Using both literature and empirical data is good for backing up hypothesis and suspicions that arises on the way. Interviews with industry professionals might even change the course of the study as a result of their advice, such as choosing the M4-multifloat WEC instead of the Pelamis WEC. Other times the interviews can lighten the workload, such as being recommended a turbine calculation tool (Windographer), instead of doing manual calculation. The qualitative method is however very time-consuming and can often lead to dead ends. Obtaining general information about a subject can be relatively easy but finding details and missing pieces can be time-consuming.

3.2 Quantitative data

Secondarily, the calculation method is conducted for each primary energy source, electrolyzer and the fuel demand. The calculated data is fundamental to support the theory in *Chapter 2.* Choices and assumptions made during the thesis are mentioned throughout the study and in front of each sub-chapter in the results. The quantitative data which the calculations are based on, mainly comes from measured and modelled data such wind speeds, sea states and solar irradiation. Quantitative data concerning technical specifications of components is obtained from; experimental data such as the M4-multifloat capture width ratio; industry standards like the PV-panel specifications and energy for ammonia production; program libraries such as for the 5-and 8 MW turbines from Windographer; raw data from interviews such as the fuel consumption of Polarlys; and industry reference values as for the 15 MW reference wind turbine.

The quantitative data is analyzed mainly in Excel, but for the wind calculations, an analysis tool called Windographer is used. Since the calculations are made with some simplifications, calculated values are compared to standardized values. This method is used to make reasonable and valid results by cross checking sources.

3.3 Sources of error

To be able to complete this thesis in the span of a semester, limitations to the scope of the thesis was made. The limitations that contribute to weaken the results of the study are factors such as only conducting a technology study, only comparing three energy sources, not evaluating different ammonia synthesizers, only looking at the fuel consumption of the Coastal Express fleet and only assessing ammonia as a propulsion system fuel. These limitations can be reviewed as a source of weakness, and other sources of errors are as following:

- The average fuel consumption of diesel is calculated from only five trips of one vessel.
- One vessel makes the ground for the volume of ammonia needed for the whole fleet.
- The fuel requirement will be affected by weather conditions and can therefore vary.
- The standardized value of energy consumption for electrolyzers does not account for offshore usage as this does not exist.
- The wind farm is not optimized to the location and wind conditions.
- The wind turbine layout is not optimized to give the best energy output.
- Reading error when plotting the reference turbine's power curve.
- The sea state data is simulated and not measured.
- The M4-multifloat WEC configuration has not been tested for power production.
- The capacity factor of the WEC was assumed to be economically feasible.
- The solar and wave AEP calculation is simplified and does not account for all factors.
- The technical specifications of PV-panels are standard, and the modules are theoretical.
- The Floating PV-panel unit is only a concept.
- Thrusting sources from the literature study, the relevance of the information might be outdated.
- Personal opinions of interview objects may not be factual.
- A possibility of calculation mistakes using Excel and Windographer.
- Only used space as a factor for optimizing the energy farm.

4 Results of calculations

This chapter will present the calculated results in this thesis. The energy needed from the primary energy sources depends on how much ammonia supply the fleet of Coastal Express vessels demands, and what kind of electrolyzer is applied in the production. The calculations will be presented in reverse order, which means that firstly the Coastal express fuel demand will be presented. Secondly the energy needed for the production of ammonia will be calculated. Then the calculation of the energy needed from the primary energy sources: wind, wave and solar will be presented. And lastly a comparison of the primary energy sources and combinations of them.

4.1 Ammonia fuel demand from the Norwegian Costal Express

Assumptions

- To limit the extent of the calculation the combustion engine is assumed run solely on ammonia and have a 10% lower efficiency than the traditional diesel engine, which is considered a conservative estimate [67].
- The ships vary in size. However, the gross tonnage of Polarlys is an approximately an average representation of the vessel sizes in the fleet.
- It is assumed that all the ships have the same engine type and tank size.

Polarlys energy demand

In this thesis the total fuel demand of the eleven ships in the Norwegian coastal express is sought to be fulfilled, where the fuel consumption data of the vessel Polarlys is measured from five trips sailed between January and February 2021. Hurtigruten Polarlys provided the actual data of the travelled distance and the fuel consumption for each of the components on five different round trips (*Table 2-6*).

Polarlys is found to be approximately the average size of the costal express fleet. This was confirmed by finding the average gross tonnage of all the eleven ships, which is 10 463 which compared to Polarlys' gross tonnage of 11 341 [77]. These are similar enough to give an estimation of the whole fleet's potential ammonia consumption. The highest energy demand, which took place on an 11-day long trip 12.01-23.01 2021, is 3,7 % higher compared to the average demand (see *Table 4-1*). Henceforth, the highest value is used to ensure that the production hub can deliver to the demand.

	Travelled distance [NM][71]	Total diesel consumption [L] [71]	Energy demand per trip [TJ][2]	Energy consumption of the fleet [GWh/yr][3]
Highest	2 668	281 423	11,24	1 139
Average	2 650	271 232	10,83	1 098

Table 4-1 – Calculation of annual energy consumption for the whole fleet of Hurtigruten

The annual ammonia consumption for the whole fleet was calculated as in *Equation 14* and resulted in a need for 220 478 tonnes ammonia per year. To be able to calculate the energy needed to produce this, it was also required to compute the energy consumption of the fleet *(see equation 15*), which equals to 1 139 GWh annually. This energy consumption is the same as the total energy consumption

[2] This takes account for the 10% lower efficiency of the ammonia combustion engine.

[3] This takes account for the 10% lower efficiency of the ammonia combustion engine.

of 70 000 households in Norway. The daily production rate would need to be ~600 ton ammonia per day, and today large scale onshore production (grey ammonia) has capacities up to 3000 ton per day *(see equation 16*) [78].

Polarlys' fuel tank size is 21 000 L, thus the energy storage capacity of ammonia in the tank is around 2,97 TJ compared with diesel which is around 7,55 TJ. The frequency of bunkering (*see equation 17*) would therefore be higher when using ammonia as a fuel. Using diesel, the ships bunker once or twice for every trip [71], while with ammonia they would have to bunker nearly four times per round trip (*see Table 4-2*).

Ammonia consumption of the fleet **[ton/yr]**	220 478
The fleets energy consumption **[GWh/yr]**	1 139
Needed production rate of ammonia **[ton/day]**	~600
Frequency of bunkering per trip	3,8

Table 4-2- Main results from calculations of Polarlys

4.2 Energy demand for the production of ammonia

Assumptions

- The standardized industrial values for production of ammonia have a margin of error of roughly 10 %.
- Since the efficiencies vary depending on the source, the average efficiencies of AE and PEM from multiple sources are used.

Energy input needed to produce ammonia

The electricity input needed for ammonia production will differ depending on what type of electrolysis process is applied. *Table 4-3* shows the energy needed for production of ammonia, where the darkest blue column shows the calculated yearly energy need using *Equation 13*, and they will be referred to as "A". The red column, on the other hand, is calculated with the standardized industrial values, referred to as "B". The results from using the standardized values (B) are used to benchmark the calculated results(A). The industrial standardized value expresses how much energy is needed to produce one ton of ammonia, AE-HB or PEM-HB needs 9,6 MWh/ton ammonia, while the SOEC-HB needs 7,2 MWh/ton ammonia [53]. These values also contain energy needed for all the supporting systems, desalination, and air separation unit (ASU).

	The fleets energy consumption [GWh/yr]	Total efficiency[4]	Desalination & Air Separation Unit	Support systems	A: Energy needed to produce ammonia [TWh/yr]	B: Energy needed to produce ammonia w/industrial standardized values [TWh/yr]
AE-HB	1 139	0,64	+11%	+4%	2,10	2,12
PEM-HB	1 139	0,62	+11%	+4%	2,15	2,12
SOEC-HB	1 139	0,74	+11%	+4%	1,49	1,58

Table 4-3- Energy needed for production of ammonia whit AE-HB, PEM-HB and SOEC-HB

[4] Total efficiency is calculated from HB- efficiency and the electrolyzer efficiency for each paring. The efficiencies are $\eta_{HB} = 87$ % [56]; $\eta_{AE} = 73{,}5$ %[61]; $\eta_{PEM} = 71{,}5$ %[61] and $\eta_{SOEC} = 85$ % [6].

To find how much energy the supporting systems require to produce ammonia, percentage values are applied from both industry sources and using the deductive method. The supporting system are appliances such as ASU, desalination process, and other electrical systems such as water circulation, pumps, ventilation units and factory-building consumptions. These supporting systems represent a total of 15 % of used production process energy. The ASU, as mentioned in *chapter 2.8*, accounts normally for 2-3 % [55], but as the offshore air is highly saline, it will account for 5 % of the total energy consumption. The desalination accounts for 6 %, which is a standard industrial value. Whereas the rest of the percentages goes to other electrical appliances, such as pumping systems, cooling, ventilation, etc.

The Coastal Express average energy consumption per year is found to be 1139 GWh, as shown in *Chapter 4.1,* which is based on an average operation of Polarlys. In order to provide the fleets energy demand, the required energy for different production methods is calculated (A-results). As seen the A-result in *Table 4-3*, show that the demand is ~1,49 TWh/yr for SOEC-HB, ~2,1 TWh/yr for AE-HB and ~2,15 TWh/yr for PEM-HB. The SOEC is clearly the least energy demanding, and therefore the most efficient production method.

The B-values and the A-values of energy consumption of the ammonia production differ slightly but are well within the 10 % margin of error of the B-result. Because of this the B-values validate that the A-values are well estimated. In addition, the A-results of both PEM-HB and AE-HB are very similar, where the AE-HB requires 2,3 % less energy than the PEM-HB process. Consequently, the values for AE-HB and SOEC-HB in the dark blue column are used in the next chapters.

4.3 Energy production from different primary energy sources

The primary energy system is key to make a viable offshore production hub. Therefore, this is the focus of this thesis. In this chapter three primary energy sources will be presented: wind power, wave power and solar power. A low cost of electricity and higher fee for greenhouse gas emissions is noteworthy when choosing the primary energy source, but this is however not considered in this chapter.

4.3.1 Wind power

This chapter will present the results from the wind power calculations, the annual energy production and net capacity factor for each wind turbine size. In addition, how many wind turbines that are necessary for the different value chains when only using offshore wind as the primary energy source.

Assumptions

- Windographer is accounting for a loss factor of around 16 % that accounts for wake effects, availability losses, turbine performance losses and electrical losses.
- Minute interval wind data measurements of windspeed over a 15-year period (2004-2018) is used for calculations.
- Turbine output data for the 15 MW reference turbine was obtained from a power curve and data sheet.
- The wind farm layout assumes a space requirement of 10D (10 times the turbine diameter) inter-turbine separation [19].

Annual energy production and net capacity factor

The potential net annual energy production (AEP) and net capacity factor (NCF) of the three offshore wind turbines are calculated for Utsira Nord and Sørlige Nordsjø II. The results have been obtained by using Windographer, as described in *chapter 2.3.1*. The results in *Table 4-4* shows that Sørlige Nordsjø II has the highest value for NCF for all turbines, which in turn results in a higher net AEP at this location than for Utsira Nord. The net AEP per turbine for both locations differs in a range from 17,9 GWh to 77,4 GWh, dependent on turbine size. The results indicate that the wind conditions in Sørlige Nordsjø II may be the best among these two, for the chosen turbines. Further results will therefore be calculated at Sørlige Nordsjø II to limit the extent of this chapter.

	Utsira Nord: 59.2711N 04.5018E		**Sørlige Nordsjø II :** 56.8040N 05.0016E	
Turbine (hub height)	**Net AEP per turbine**	**NCF**	**Net AEP per turbine**	**NCF**
IEA 15MW – 240 (150m)	~ 70,8 GWh	53,91%	~ 77,4 GWh	58,87%
Vestas V165 – 8.0 MW (120 m)	~ 33,9 GWh	48,38%	~ 37,0 GWh	52,85%
XEMC Darwind XD115 5 MW (90m)	~17,9 GWh	40,77%	~ 19,3 GWh	44,12%

Table 4-4- Calculated net annual energy production and net capacity factor for the given turbines at Utsira Nord and Sørlige Nordsjø II.

The results presented above shows that the 15MW wind turbine has the highest NCF at a value of 58,87 %, which is a quite high value considering that Betz limit is at 59 %[15]. A reason for the high NCF can be that the turbine is a reference turbine, which means it is theoretical and functions as a guidance of turbine properties for the industry. In addition to that, the 15 MW turbine is more optimised than today's turbines. As the Hywind floating wind park recently measured the highest value of NCF of 57,1 % [79], the calculated NCF of the 15 MW turbine is assumed to be reachable.

Total number of turbines needed to fulfil the Costal Express' energy demand at Sørlige Nordsjø II

The total number of turbines required in a wind park to fulfil Hurtigruten's yearly energy demand at Sørlige Nordsjø II is illustrated in *Figure 4.1.* The values are differentiated depending on production method and turbine size, where the different colours in the graph represent the different production methods and the x-axis is divided into the different wind turbines 15 MW-, 8 MW- and 5 MW turbine.

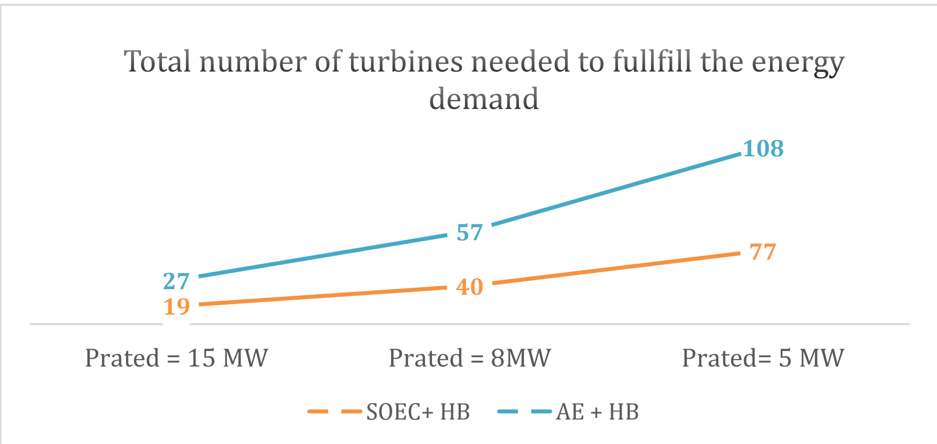

Figure 4.1 - Total number of turbines needed in a wind farm to fulfil the energy demand for each turbine at Sørlige Nordsjø II using SOEC-HB and AE-HB as production system.

This means that an imaginary wind park will need anywhere from 19 to 108 turbines, whereas the production system with SOEC-HB will be the least energy intensive and thus need the fewest turbines. The plan is that the 15 MW turbine will be used in the wind farm, where the number of turbines needed range between 19-27 depending on the production method. If one were to use the AE-HB process with either the 5 or 8 MW turbine the number of turbines needed in the wind farm would be high. These turbines are included in the result to both determine if the 15 MW data result are reasonable. In addition, the 5 and 8 MW turbines give an indication of how many wind turbines one would need to produce ammonia offshore with some of the wind turbine technology today.

Confirming the 15 MW reference turbine data

Table 4-5 show the annual energy production of the different turbines, if the 5 MW and 8 MW turbines hypothetically were wind turbines with rated power of 15 MW. A rated power of 15 MW is equivalent to two 8 MW turbines and three 5 MW turbines. The result shows that when the rated power is equal for all the turbines, the upscaled 8 and 5 MW turbines will not be able to produce the exact same amount of energy as the 15 MW reference turbine. However, the wind speed will differ at the different hub height. This will impact the amount of available energy, and can explain why there is a difference in the amount of energy they produce “per turbine”. Another reason for the difference, as mentioned earlier, is that the 15 MW turbine is more “developed” and can obtain a higher NCF than the two other turbines. Even though there is some difference, it can be explained, and thus the data for the 15 MW is assumed to be accurate and obtainable.

The turbines upscaled to 15 MW rated power	Number of turbines needed to make the turbines equivalent to 15 MW	AEP per turbine at SN2 using the SOEC-HB in the production of ammonia
IEA Reference turbine (15 MW)	15/15=1	77,4*1≈77,4 GWh
Vestas (8 MW)	15/8=1,875	37,0*1,875≈69,4 GWh
Darwind (5 MW)	15/5=3	19,3*3≈57,9 GWh

Table 4-5- Calculation of upscaling to 15 MW rated power to confirm if the 15 MW turbine is valid.

Wind farm layout

The space needed between each turbine and the total space of the wind farm differs extensively in relation to the turbine size, location, and production method. When looking at a square layout farm (see figures in method) with a 10D inter-turbine separation distance the distance between each turbine of 2,4 km, for the lowest number of turbines at 19-15 MW turbines, the total area comes to ~69 km^2. With four numbers of turbines on each row and five number of turbines in the columns behind, and just three wind turbines on the last row.

4.3.2 Wave power

This chapter will present the results of how much energy the chosen M4-multifloat WEC would yield, and how many units would be needed to cover the entirety of the energy demand of ammonia production.

Assumptions

- Using values for the M4 multibody 6-floater 123b [36].

- Mechanical friction losses are negligible for the M4 unit.
- Assuming a value of $\gamma = 3{,}3$, as this is a general value for the North Sea [39].
- The capacity factor is 33%, based on a study done on the M4 [32].

The annual energy production, AEP, for the M4-unit is calculated from *Equation 10*, as described in *Chapter 2.4.2.* This calculation consists of many steps, and will therefore be described and assessed in an orderly fashion, in this chapter. Firstly, the decisions and formatting of the sea state occurrences will be described. Thereafter, necessary device-scaling will be considered as a part of the device energy yield calculations. Lastly, the AEP results will be presented and reflected will be made.

Sea State Occurrences

The sea state occurrences from Karmøy [37] were predicted wave behaviours, given by parameters of significant wave height, H_s, and zero up-crossing period T_z. As described in *Chapter 2.4.2*, the parameters had to be changed from T_z to peak period, T_p. Solving for values of γ=3,3 in *Equation 11*, the relationship is $T_p = T_z$ *1,2859. The sea states occurrences can be viewed in *Table 4-6* below, and will be used later to describe how often the device would generate power at each sea state.

Hs [m] \ Tp [s]	0,6	1,9	3,2	4,5	5,8	7,1	8,4	9,6	10,9	12,2	13,5	14,8	16,1	17,4	18,6	19,9	21,2	22,5	23,8	25,1
0,25	0	0	0,042	0,122	0,302	0,388	0,376	1,162	0,979	0,311	0,283	0,122	0,102	0,100	0,042	0,032	0,013	0,008	0,003	0,001
0,75	0	0	0,005	0,587	2,401	3,916	3,054	4,479	5,923	2,108	1,742	1,290	0,679	0,673	0,301	0,183	0,086	0,024	0,008	0,005
1,25	0	0	0	0,003	1,367	4,613	4,615	3,726	2,411	1,713	1,552	1,122	0,682	0,748	0,220	0,144	0,039	0,022	0,006	0,002
1,75	0	0	0	0	0,007	1,528	3,727	4,448	2,530	1,205	0,890	0,510	0,403	0,507	0,206	0,143	0,028	0,005	0,001	0
2,25	0	0	0	0	0	0,025	1,376	3,006	3,188	1,279	0,618	0,303	0,150	0,275	0,111	0,105	0,029	0,007	0,001	0
2,75	0	0	0	0	0	0	0,091	1,511	2,523	1,713	0,555	0,191	0,099	0,080	0,063	0,067	0,030	0,011	0,002	0
3,25	0	0	0	0	0	0	0	0,254	1,320	1,833	0,622	0,163	0,052	0,036	0,018	0,028	0,016	0,006	0,001	0
3,75	0	0	0	0	0	0	0	0,013	0,439	1,357	0,758	0,136	0,048	0,028	0,006	0,006	0,007	0,003	0	0
4,25	0	0	0	0	0	0	0	0	0,051	0,669	0,794	0,177	0,039	0,013	0,003	0,000	0,003	0	0	0
4,75	0	0	0	0	0	0	0	0	0,002	0,226	0,645	0,169	0,029	0,008	0,001	0,001	0,003	0	0	0
5,25	0	0	0	0	0	0	0	0	0	0,036	0,384	0,234	0,033	0,003	0,001	0	0,001	0	0	0
5,75	0	0	0	0	0	0	0	0	0	0,004	0,184	0,197	0,029	0,006	0	0	0	0	0	0
6,25	0	0	0	0	0	0	0	0	0	0	0,049	0,152	0,032	0,007	0	0	0	0	0	0
6,75	0	0	0	0	0	0	0	0	0	0	0,006	0,076	0,037	0,006	0	0	0	0	0	0
7,25	0	0	0	0	0	0	0	0	0	0	0	0,023	0,032	0,012	0	0	0	0	0	0
7,75	0	0	0	0	0	0	0	0	0	0	0	0,009	0,023	0,015	0	0	0	0	0	0
8,25	0	0	0	0	0	0	0	0	0	0	0	0,002	0,013	0,012	0,002	0	0	0	0	0
8,75	0	0	0	0	0	0	0	0	0	0	0	0	0,002	0,008	0	0	0	0	0	0
9,25	0	0	0	0	0	0	0	0	0	0	0	0	0	0,002	0,001	0	0	0	0	0
9,75	0	0	0	0	0	0	0	0	0	0	0	0	0	0,001	0	0	0	0	0	0
10,25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,001	0	0	0	0	0
10,75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4-6 - Sea state occurrences in percentages from a location outside Karmøy, given in parameters of T_p and H_s.

Device Energy Yield and device-scaling

The device energy yield was calculated from the generated power matrix, the Capture Width Ratio (CWR) and the wavelength, L, as described in *Chapter 2.4.2*. The device yield describes how much of the available wave power the device can 'capture', and can be optimized by scaling the device in accordance with the CWR and T_P. The CWR for each T_P can be viewed in *Figure 4.2* [36], and is an indication of device efficiency. The device was scaled by a factor of 40 (λ=40), which was the planned design-scaling of the M4 unit [36]. This scaling, however, was not suitable for the location in the North Sea, generating only an AEP of 1 112 MWh per unit (see *Table 4-7).*

The device-scaling had to be optimized for the given location, and maximum power output is reached when the devices length is approximately the same as the corresponding wavelength, L [39]. This wavelength is obtained as a variable of T_p, and the Karmøy sea data had an average period of T_p = 10,74 s. A simple optimization would then be to scale the device so that the highest CWR was aligned with the average period of the location. This resulted in an optimized scaling-factor of λ= 110 (*see appendix B: WEC calculations*). The optimized scaling resulted in a seven times higher AEP than if scaled with a factor of 40, thus needing 7 times less units to cover the energy demand for ammonia production (*Figure 4-8*).

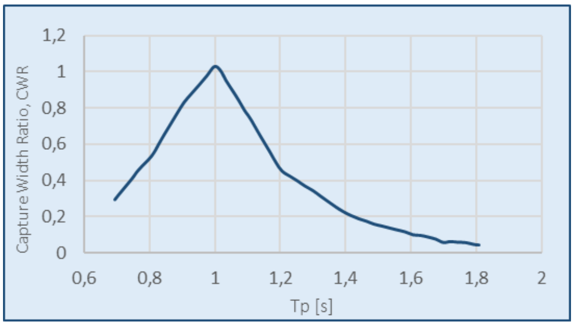

Figure 4.2 - Variation of CWR for the 6 float (123b) configuration given by the period, for $\gamma = 3{,}3$. CWR is the same for all H_s, varying with the period.

Annual Energy Production

When looking at the designed scale (1:40), an array of 1781 units would cover the AE-HB production energy demand, and 1265 units would cover the SOEC-HB production, see *Table 4-7.* To cover the energy demand completely by the WEC with the optimized scaling (1:110), only 266 units (AE-HB) or 189 units (SOEC-HB) are needed, see *Figure 4-8.*

Results for design-scaling M4 (1:40)		
Capacity factor	33	%
Annual Energy Production, AEP	1112	MWh
Units needed for AE+HB	1781	
Units needed for SOEC+HB	1265	

Table 4-7 - Energy output from the optimised scaling of the M4 (1:40) and the resulting number of units.

Results for optimised scaling M4 (1:110)		
Capacity factor	33	%
Annual Energy Production, AEP	7440	MWh
Units needed for AE+HB	266	
Units needed for SOEC+HB	189	

Table 4-8 - Energy output from the optimised scaling of the M4 (1:110) and the resulting number of units.

Using a Capacity Factor (CF) of 33 % may be a bit optimistic for current WEC technology, however it is a fair future assumption for WECs [39]. The CF is based on the industry standard for offshore wind turbines, where if a turbine has a capacity factor above 30 %, it is economically feasible [80]. This statement will be applicable to offshore wave technology when commercially launched, as they face many of the same expenses and limitations as offshore wind turbines.

The linear diffraction modelling that the CWR vs. T_p (*Figure 4.2)* is based on, overestimates the CWR slightly, so the results will be a bit optimistic [32]. It may also be a bit wrong to assume that it is acceptable to scale by a factor of 110, when the design-scaling is 40. Factors that can make the optimized scaling unobtainable, is for example that the devices geometry is not fitted for such large dimensions – and will consequently be less robust against waves and weather. Other factors may be that scaling by a factor of 110 is not economically feasible. As economics are not considered in this thesis, further exploration will not be conducted. A last thing to comment is that scaling solely based on the CWR at the average period may not be the most ideal scale optimizer. To optimize it fully, factors like fatigue, resonant period, wave direction, economics, breaking points, and such, should be considered.

4.3.3 Solar power

This chapter will present the calculated annual energy production of two cases of solar PV-technology: fixed PV-panel installation on the platform, and floating PV-panels. The first PV-technology will be calculated for how much of the production energy demand the panels can cover, while the latter floating technology will have its result visualized as number of units.

Assumptions

- All module data is taken from industry standards.
- Platform will be boxed in and thus have a large roof-area.
- FPV is assumed to have industry standards concerning technical specifications.

In *Chapter 2.5.1* , three different PV technologies was mentioned: PV-panels, floating PV-panels and thin film flexible PV. Thin film PV-technologies will not be further explored as an individual technology, as they have a low efficiency (10 %[42]) and will not be comparable to the remaining two technologies (η~20% [31]). It can be argued that sticking a thin film PV onto an existing PV-panel would increase the total efficiency by 5 %[45], but this will not yield enough energy to be further evaluated.

Calculations for fixed PV installation on the platform structure

The calculated AEP for a fixed PV module, fixed to the platform structure is shown in *Table 4-9*, calculated by *Equation 10.* To present an example of a usable area, a platform hub dimension of 125 m by 75 m have been chosen as the basis of the calculations [11]. As mentioned in *Chapter 2.1,* it is assumed that the platform will be boxed in by surrounding walls and a roof, and that 70% of the roof can be used for PV modules. This roof area will equal to 6 300 m^2 [81]. The technical specifications for the PV-module such as the availability, module efficiency and the performance ratio, have been obtained from industry standards, as described in *Chapter 2.5.1.* The Global Horizontal Irradiation (GHI) is taken from the Meteonorm database [50], which shows that the Norwegian yearly standard is at 715 KWh/yr/m^2. Using the mean value of the solar irradiation does not consider daily fluctuations or yearly variations, but makes for a fair estimated value of solar irradiation.

PV module fixed to the platform		
Total area of PV module	Atp [m^2]	6300
Availability, uptime	Av. [%]	95
Module efficiency	n [%]	21
Performance ratio	PR [%]	82
Annual Global Horizontal Irradiation	GHI [kWh/year/m^2]	715
Annual Energy Production	AEP [kWh/year]	736 891

Table 4-9- Calculated AEP for a fixed PV module.

The fixed installation on the platform will have an AEP of ~737 MWh/year, see *Table 4-9.* This is equivalent to covering 0,046 % of the energy demand for the SOEC-HB production, and 0,033 % of the AE-HB production (*see Table 4-10*). The AEP from the fixed PV panels have a low coverage, almost undetectable. Consequently, choosing a larger platform area or a higher yielding PV-module, will not make a substantial difference to the energy output.

Energy demand for SOEC+HB	TWh	1,489
Coverage by fixed PV	[%]	0,046
Energy demand for AE+HB	TWh	2,095
Coverage by fixed PV	[%]	0,033

Table 4-10- Coverage of production energy demand by fixed PV module.

Calculations for offshore floating PV-units

Floating PV units		
Total area of PV module	Atp [m^2]	6400
Availability, uptime	Av. [%]	95
Module efficiency	n [%]	21
Performance ratio	PR [%]	77
Annual Global Horizontal Irradiation	GHI [kWh/year/m^2]	715
Annual Energy Production	AEP [kWh/year]	702 942

Table 4-12 - Calculated AEP for floating PV modules.

When calculating how much a floating PV unit would yield, it is assumed that the area of the planned test-unit outside of Frøya [49] can be used. The test-unit is planned to be 80 m by 80 m, consisting of several PV-modules floating on a pontoon. Using the size of the test-model, and assuming that it can handle the open, rough, North Sea, one test-unit would measure 6 400 m^2. The technical specifications for the floating PV-modules are based on the same industry standards as for the fixed PV-modules. The values that differ between the two solar calculation, is the performance ratio, as described in *Chapter 2.5.1.* The AEP for one floating PV unit was calculated to be 703 GWh/year, see *Table 4-12*. Calculating for this value, the SOEC-HB would need 2119 FPV-units to cover the entire production energy demand, and the AE-HB production would need 2 982 FPV-units, see *Table 4-11*. To cover the AE-HB-production energy demand, this would equate to 19 million m^2, or about 3 times the size of Gibraltar in Spain [82].

Energy demand for SOEC+HB	TWh	1,489
Units to cover SOEC-HB prod.		**2 119**
Energy demand for AE+HB	TWh	2,095
Units to cover AE-HB prod.		2 982

Table 4-11 – Units needed for the SOEC-HB and AE-HB production of ammonia, when using floating PV.

4.4 Comparison of primary energy sources and potential combinations

The main purpose of this chapter is to summarize the most energy efficient method of producing ammonia. Therefore, it will only be looked at the most efficient production method, which is the SOEC-HB method. It will present a comparison of the different energy sources based on energy produced and TRL (*as explained in Chapter 2.2*). And lastly present an example of the most energy efficient combination of the primary energy sources, wind, wave and solar.

Comparison of the chosen primary energy sources

	Device/ type	Net Capacity Factor (NCF)	AEP per unit [MWh]	No. of devices needed for SOEC-HB production	TRL
Wind	15 MW IEA wind turbine	0,588[5]	77 350	19	5-6
Wave	WEC, M4-multifloat	0,33[6]	7 440	200	4-5
Sun	Floating PV-unit	0,15[7]	703	2 119	2-3

Table 4-13; Comparison of the primary energy sources.

The primary energy sources presented in *Table 4-13* are the results of the different evaluated renewable energy technologies compared. There are considerable differences in the technology development for

[5] Using the 15 MW turbine based on wind conditions at Sørlige Nordsjø [24, p. 15].
[6] M4 multifloat configuration (123b) based on wave conditions outside Karmøy [37].
[7] Based on PV module efficiency at 0,21, availability of 0,95 and a performance ratio of 0,77 [31].

the different sources. Looking at the TRL for the three technologies, the floating PV panels for offshore usage is the lowest, being in the design process (2-3). The M4 multi-float WEC is in the laboratory testing stage and ranging at a TRL of 4-5. The most developed technology is the 15 MW wind turbine, that is at the TRL of 5-6, or the prototype stage. Complementary to the ranking in terms of TRL, and the AEP per unit for each technology (*see Table 4-13*). The offshore wind turbine ranks the highest, with 77 350 MWh annually per units. Next is the M4 WEC with 7 440 MWh, and lastly the FPV with 703 MWh. As mentioned earlier, the capacity factor is the relationship between the actual energy output over a period of time to the maximum possible electrical energy output over that period. This means that comparing the NCF of the three, the wind turbines is measured to run at maximum power more than 58 % of the time in one year, while wave 33 %, and floating solar at 15 %. The comparisons above are a good representation of the status of the technologies in the offshore sector, as well as illustrating the differences in annual energy production.

Combining the primary energy sources

Combining the different ORE technologies has many benefits for producing ammonia offshore, as it is discussed in *chapter 2.6.2*. *Table 4-14* shows the two different scenarios of combining energy sources. It is quite clear that wind turbines are superior in terms of power generation per unit, and is therefore the obvious choice as an energy source. However, it is beneficial to exploit the potential of the concessional area that has been given. It is also advantageous to place WEC/FPV-units between the turbines to lighten the strain imposed by the waves on the turbines structure. The first scenario will combine wind turbines and WEC's, and the second scenario is combining wind turbines and floating PV panels.

Scenario 1	Wind turbines	Wave energy converters (WEC)
Number of devices	16	36
Energy coverage [GWh]	1 221,4 (82 %)	267,8 (18 %)
Scenario 2	Wind turbines	Floating PV-panels (FPV)
Number of devices	18,9	36
Energy coverage [GWh]	1 489,2 (98 %)	25,3 (2 %)

Table 4-14; Combining the primary energy sources.

For optimum power output from the turbines, they need to be fairly spaced, as described in chapter *4.3.1*. This creates a basis of the required space if the energy demand was supplied solely by turbines. To calculate how many turbines can be removed if combined with solar or wave, a hole-method is used.

The hole-method is based on exploiting the 'holes' between the turbines as locations for either WEC units or FPV units see *Figure 2.3*.

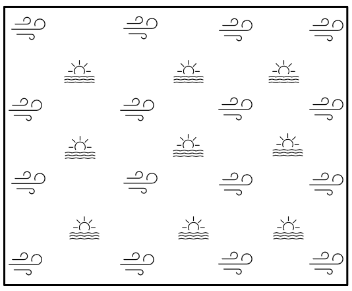

Figure 4.3 The "hole" method.

The proposed system of 19 turbines gives a space of 2,4 km by 2,4 km, with consequently 12 “holes”. Due to the large area of the “holes”, it is proposed that 3 units can be placed per ‘hole’. This gives a total of 36 possible units for a 2,4 km by 2,4 km area. In table 4.15 the energy coverage by 36 FPV or 36 WEC-units are displayed, showing how many turbines can be replaced. For 36 WEC-units, 16 wind turbines are needed to cover the remaining energy demand, thus the wind turbine would not need as much space. The 36 WEC alone could cover 18 % on the energy demanded to produce ammonia (see *Table 4-15*). For 36 FPV-units, only 0,1 turbines can be replaced, proving that solar energies are quite inefficient in the North Sea climate.

One of the main arguments for having a combination of wind and solar is that when there is little sun, there is more wind, and vice versa [31]. If this was the case for 19 turbines and 36 FPV-units, then a worst-case scenario would be that the FPV-units would have to power the entirety of a days’ worth of production. Shown in table 4-15, 36 units would only cover 2 % of one day’s energy demand, thus not supporting the statement concerning solar-wind combination for this case. This way of thinking is not applicable to a wave-wind combination, since when it is not windy the wave resources is not better.

AEP for 36 FPV-units for 1 day	69 331	kWh/day
SOEC energy demand for 1 day	4 079 968	kWh/day
% covered solely by 36 units	2	%

Table 4-15 - Worst case scenario: if 36 units of FPVs need to cover a days’ worth of energy production demand.

5 Discussion

This chapter present the discussion points of the thesis. First, the advantages and disadvantages of ammonia as a fuel in vessels will be discussed. Secondly, it is discussed how the lower energy content of ammonia will affect the implementation of ammonia as a fuel. Then the production of ammonia is discussed, especially concerning the electrolyzers. After that the implications of the different energy sources are discussed. Lastly, the advantage and disadvantages of combining energy sources is debated, as well as recommendation for further research.

A transition to zero emissions in the shipping industry is not impossible. Various reports have shown that using green ammonia as fuel in larger shipping vessels is the best way to reach this goal. The main reasons to use ammonia as a shipping fuel is that it can be produced without CO_2-emissions, it has a relatively high energy density compared to other emission-free fuels, can easily be stored and transportation of the chemical is well-known. The main obstacles of ammonia becoming a marine fuel is availability on-route and the lack of guidelines and customs for ammonia as a combustion engine fuel. Projects like ZEEDS will be a necessity to speed up the development of ammonia as a green, available fuel.

If the Coastal Express vessels used ammonia as fuel, the result shows that each vessel would need to bunker almost 4 times per round-trip. This is due to the lower energy content of ammonia compared to the Marine Special Distillate. One concern about the findings of the frequency of bunkering is that the vessels differ in size, which means that some vessels might have to bunker more frequently and some less. This result indicates that if the shipping sector made the change to use ammonia as a fuel, time used for bunkering would be an issue. However, this can be solved by having several production hubs placed along the routes, and using the EPVs to bunker the ships. The Norwegian Costal Express' energy consumption is only a fraction of the energy needed for the global merchant fleet. To fulfil the global merchant fleet's energy-need with ammonia a whole lot more production hubs would be needed.

To lower the price of the ammonia fuel, it is important to use an energy efficient production method. The results show that the energy efficiency of the SOEC-HB production method is substantially better than for the AE-HB and PEM-HB. AE and PEM are quite similar in terms of efficiency, although AE is the most established method and has a slightly better efficiency in the chosen values. The efficiency of the electrolyzers are a talking-point in the industry, were some sources indicates that PEM is better. One of the arguments for using PEM electrolyzers is that they are more receptible to variable energy sources, due to its fast response time. This is important considering that energy from renewable sources tend to have a lot of intermittency and may cause problems for non-responsive production. The HB ammonia synthesis is state of the art technology and thus a 'better option' has not been evaluated. The result of comparing the energy consumption of the production processes has shown that the difference between PEM-HB and AE-HB are not that significant, and it is more interesting to evaluate SOEC-HB and AE-HB.

The results shows that both SOEC-HB and AE-HB are good methods, however the former is not yet commercially available. As mentioned, the AE response time is long and therefore not very applicable with renewable energy sources. On the contrary the SOEC-HB can combine and alternate different numbers of stacks, which results in a good response time. Another factor is that the lifetime of a SOEC can vary from anything between 2 weeks to 2 years, which is not good, considering that the lifetime of the AE is 10 years. Both SOEC and AE will need clean water to not contaminate the electrolyzers. In addition, AE will need the transport and storage of the electrolyte KOH to the production site. The ASU needs a washing and drying unit regardless of the placement, offshore or onshore. Even so, somewhat more frequent maintenance is needed offshore due to the salty air.

The amount of primary energy units needed to produce ammonia fuel for the Costal Express is one of the main objectives of this thesis. The comparison of energy sources clearly shows that using wind turbines will result in the lowest number of units needed for the ammonia production. Using solar or wave energy results in a much higher amount of WEC and FPV units needed. The high amount of units needed for the wave and solar energy demonstrates that both is not advanced enough yet to deliver enough energy per unit.

Although the results present a combined wind/wave or wind/solar farm, there might not be a need to 'replace' turbines from the farm. This was done in order to visualize how much the wave or solar units would add to the electricity production, but wind turbines alone might be the best option. Wind turbines are, as of today, way more established and developed than wave and solar energies. As mentioned in the results, it is not realistic to use only solar- or wave energy to provide the needed energy for ammonia production. Although the FPV is not desirable in Norway, a wind/solar combination would be very attractive in areas with high solar irradiation, such as near the equator. A combination of wind/wave is clearly the best option out of the two scenarios in the North Sea, because of the strong wind and wave energy resources. However, WEC technology is often installed near-shore, and the current technology may not be mature enough to operate in a large array offshore. This can indicate that neither solar nor wave are good options for offshore usage today. The only arguments left for a combination is to optimize the empty space inside the wind farm, in addition to the reduced strain on turbine monopiles due to the units absorbing much of the impact of the waves.

Further research could be conducted for the optimization of the wind/wave farm in the North Sea and the layout of the production hub, preferably for more factors like wake effects, weather conditions, environmental aspects and much more. One of the thesis' main weaknesses, is that it relies solely on a technological analysis. To strengthen and support the thesis' results, a techno-economic analysis on the whole processes should have been conducted. By doing this, the electricity cost for the energy sources could have been evaluated, which would in terms evaluate the price of the ammonia. Electricity production is a key cost driver for the production of ammonia and its' market survivability. Since the motivation behind the ammonia production hub is to reach net zero emissions in the shipping sector, environmental aspects should be further evaluated. However, since time was a limitation, the scope of thesis was constrained.

6 Conclusion

In conclusion this thesis has found that for the nearest future it is likely that an offshore production of ammonia could be electrified with wind turbines, to deliver the Coastal Express with 220 478 ton of green ammonia annually. It has also been found that combining wind turbines and wave energy converters in a farm can be beneficial for both technology development and space optimization. Solar energy resources are best exploited at hubs placed in sunny areas and wave energy resources have big potential in locations such as the North Sea. The SOEC electrolyzer is not yet fully developed but is the one with the best potential, considering that it is receptible for variating energy supply and has the highest efficiency. Nevertheless, planning and completing a project of installing production hubs would take years, thus the developing technologies such as SOEC, FPVs and WECs might be feasible. The production methods using AE or PEM will also be good alternatives, where AE has the best efficiency of the two, but the PEM would be most likely be better suited in combination with renewable energy sources. Taking all aspect of this thesis into consideration, it is possible to have a fully emission free production hub with technology existing today. Project like this can contribute considerably to reach zero emissions in the shipping sector and allows for zero emission technology to be further developed.

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8 List of figures

9 List of tables

10 Appendices

10.1 List of the appendices

Appendix A - Calculations for PV and FPV

Appendix B - Number of wind turbines and results from Windographer

Appendix C - Polarlys' energy demand and ammonia demand

Appendix D.1 - Device Energy Yield for M4-multifloat for design-scale (1:40)

Appendix D.2 - AEP for M4-multifloat for design-scale (1:40)

Appendix E.1 - Device energy yield for M4-multifloat for optimized scale (1:110)

Appendix E.2 - AEP for M4-multifloat for optimized scale (1:110)

Appendix A – Calculations for PV and FPV

Fixed PV installation

Total area of PV module	A_{PV} [m^2]	6300
Availability, uptime	Av. [%]	95 %
Module efficiency	n [%]	21 %
Performance ratio	P_R [%]	82 %
Annual Global Horizontal Irridiatio	GHI [kWh/year/m^2]	715
Annual Energy Production	AEP [kWh/year]	736 891
AEP in MW	[MW]	0,0841
Energy demand covered SOEC+HB	[%]	0,049
Energy demand covered AE+HB	[%]	0,035

Area of plattform [m^2]	9000
% covered in PV panels	70 %
Total area of PV modules [m^2]	6300

FPV

Total area of PV module	A_{FPV} [m^2]	6400
Availability, uptime	Av. [%]	95 %
Module efficiency	n [%]	21 %
Performance ratio	P_R [%]	77 %
Annual Global Horizontal Irridiatio	GHI [kWh/year/m^2]	715
Area of one unit	A_{FPV} [m^2]	6400
AEP for one unit	AEP [kWh/year]	702 942
Units to cover SOEC+HB prod.		2 119
Units to cover AE+HB prod.		2 982

Appendix B – Number of turbines and result from Windographer

			RWT= Reference wind turbine	
			UN= Utsira Nord	
	AEP og NCF er mean of monthly means		SN= Sørlig Nordsjø	

	IEA 15MW RWT	AE	PEM	SOEC
	Energy needed for production of ammonia [GWh]	2096	2155	1489
	P rated turbine [MW]	15	15	15
	Number of turbines **UN**	30	30	21
	Number of turbines **SN**	27	28	19
WINDOGRAPHER CALCULATIONS	AEP per turbine **UN** [kWh/yr]	70837152	70837152	70837152
	AEP per turbine **SN** [kWh/yr]	77351832	77351832	77351832
	NCF **UN** [%]	53,91	53,91	53,91
	NCF **SN** [%]	58,87	58,87	58,87

	8 MW turbin	AE	PEM	SOEC
	Energy needed for production of ammonia [GWh]	2096	2155	1489
	P rated turbine [MW]	8	8	8
	Number of turbines UN	62	64	44
	Number of turbines SN	57	58	40
WINDOGRAPHER CALCULATIONS	AEP per turbine UN [kWh/yr]	33905272	33905272	33905272
	AEP per turbine SN [kWh/yr]	37036452	37036452	37036452
	NCF UN [%]	48,38	48,38	48,38
	NCF SN [%]	52,85	52,85	52,85

	5 MW turbin	AE	PEM	SOEC
	Energy needed for production of ammonia [GWh]	2096	2155	1489
	P rated turbine [MW]	5	5	5
	Number of turbines UN	117	121	83
	Number of turbines SN	108	111	77
WINDOGRAPHER CALCULATIONS	AEP per turbine UN [kWh/yr]	17858882	17858882	17858882
	AEP per turbine SN [kWh/yr]	19326216	19326216	19326216
	NCF UN [%]	40,77	40,77	40,77
	NCF SN [%]	44,12	44,12	44,12

Appendix C- Polarlys' energy demand and ammonia demand

Hurtigruten's energy demand

Round trip	Distance traveled [NM]
01.01-12.01	2679
12.01-23.01	2668
23.01-03.02	2652
03.02-14.02	2605
14.02-25.02	2648
Average	**2650**

Highest value

* Taking account for 10 % lower efficiency for a ammonia engine

Fuel consumption [L]				
Main engines	The auxilary engines	Boiler	Hotelload	Total
197189	12354	4000	66127	279670
202266	9030	4000	66127	281423
179980	8201	4000	66127	258308
194074	8240	4000	66127	272441
185111	9082	4000	66127	264320
191724	**9381**	**4000**	**66127**	**271232**

Fuel consumption [L/NM]				
Main engine	The auxiliary engines	Boiler	Hotelload	Total
73,6	4,6	1,5	25	104,4
75,8	3,4	1,5	25	105,5
67,9	3,1	1,5	25	97,4
74,5	3,2	1,5	25	104,6
69,9	3,4	1,5	25	99,8
72,3	**3,5**	**1,5**	**25**	**102,3**

Total energy consumption per nautical mile [MJ/NM]	*Energy consumption pr trip for one vessel [MJ]	Energy consumption pr trip for one vessel [kWh]	Ammonia consumption pr trip for one vessel[kg]	Ammonia consumption for the whole fleet [ton/yr]
3751	11165348	3101734	600288	219105
3790	11235334	3121176	604050	220478
3500	10312506	2864814	554436	202369
3758	10876743	3021559	584771	213441
3587	10552525	2931492	567340	207079
3677	**10828491**	**3008155**	**582177**	**212495**

Total energy consumption, whole fleet [GWh/yr]	Needed daily production of ammonia [ton/day]
1132,13	600
1139,23	604
1045,66	554
1102,87	585
1069,99	567
1097,98	**582**

Appendix D.1- Device Energy Yield for M4-multifloat for design-scale (1:40)

Device Energy Yield [kW] for upscaled M4 (1:40)

Hs [m] \ Tp [s]	0,6	1,9	3,2	4,5	5,8	7,1	8,4	9,6	10,9	12,2	13,5	14,8	16,1	17,4	18,6	19,9	21,2	22,5	23,8	25,1
0,25	0	0	0	2	8	12	9	6	4	4	5	7	9	11	14	17	20	24	28	33
0,75	0	0	3	16	71	108	79	55	35	35	47	61	79	99	123	150	181	216	255	299
1,25	0	1	8	45	197	300	220	152	96	96	130	170	219	276	342	417	503	600	709	831
1,75	0	2	15	87	387	588	431	298	189	188	254	334	429	540	669	818	986	1177	1390	1628
2,25	0	3	25	144	639	972	713	493	312	311	420	552	709	893	1107	1352	1631	1945	2298	2691
2,75	0	5	38	215	955	1451	1065	737	466	465	628	825	1059	1334	1653	2019	2436	2906	3433	4021
3,25	0	7	52	301	1333	2027	1487	1029	651	649	877	1152	1479	1863	2309	2820	3402	4059	4795	5615
3,75	0	9	70	401	1775	2699	1980	1370	867	864	1167	1533	1969	2481	3074	3755	4529	5404	6384	7476
4,25	0	12	90	514	2280	3466	2543	1760	1114	1110	1499	1970	2529	3186	3948	4823	5818	6941	8200	9603
4,75	0	15	112	643	2848	4330	3176	2198	1392	1387	1873	2460	3160	3980	4932	6024	7267	8670	10243	11995
5,25	0	18	137	785	3480	5289	3880	2685	1700	1694	2288	3006	3860	4862	6025	7359	8877	10591	12513	14653
5,75	0	21	164	942	4174	6345	4654	3221	2039	2032	2744	3605	4630	5832	7227	8828	10649	12705	15010	17577
6,25	0	25	194	1113	4931	7496	5499	3806	2409	2401	3242	4260	5470	6891	8538	10430	12581	15010	17733	20767
6,75	0	29	226	1298	5752	8744	6414	4439	2810	2801	3782	4968	6380	8038	9959	12165	14675	17508	20684	24223
7,25	0	34	261	1497	6636	10087	7399	5121	3242	3231	4363	5732	7361	9272	11489	14034	16929	20198	23862	27944
7,75	0	39	298	1711	7582	11526	8455	5852	3704	3692	4985	6550	8411	10595	13129	16037	19345	23080	27267	31932
8,25	1	44	338	1939	8592	13062	9581	6631	4198	4184	5649	7422	9531	12007	14877	18173	21922	26154	30899	36185
8,75	1	49	380	2181	9665	14693	10778	7459	4722	4707	6355	8349	10722	13506	16735	20442	24659	29420	34757	40704
9,25	1	55	425	2437	10802	16420	12045	8336	5277	5260	7102	9330	11982	15094	18703	22845	27558	32879	38843	45489
9,75	1	61	472	2708	12001	18243	13382	9261	5863	5844	7890	10366	13312	16770	20779	25382	30618	36529	43156	50539
10,25	1	68	522	2992	13263	20162	14789	10236	6480	6459	8720	11457	14713	18534	22965	28052	33839	40372	47696	55856
10,75	1	74	574	3291	14589	22177	16268	11259	7128	7104	9592	12602	16183	20386	25260	30855	37221	44407	52462	61438

Appendix D.2 – AEP for M4-multifloat for design-scale (1:40)

AEP [kWh/yr] for upscaled M4 (1:40)

Hs [m] \ Tp [s]	0,6	1,9	3,2	4,5	5,8	7,1	8,4	9,6	10,9	12,2	13,5	14,8	16,1	17,4	18,6	19,9	21,2	22,5	23,8	25,1	Sum
0,25	0	0	1	19	209	407	290	620	331	105	129	73	78	96	50	47	23	16	7	3	2504
0,75	0	0	1	824	14939	37033	21186	21501	18002	6385	7124	6929	4689	5849	3245	2413	1357	450	170	124	152222
1,25	0	0	0	11	23613	121167	88916	49689	20354	14417	17631	16752	13079	18059	6568	5279	1718	1150	354	138	398895
1,75	0	0	0	0	225	78673	140756	116243	41859	19873	19828	14929	15138	24017	12093	10279	2381	490	116	0	496900
2,25	0	0	0	0	0	2103	85905	129870	87209	34872	22737	14660	9325	21486	10778	12490	4072	1134	191	0	436833
2,75	0	0	0	0	0	0	8508	97523	103094	69779	30517	13799	9169	9329	9083	11767	6489	2903	572	0	372530
3,25	0	0	0	0	0	0	0	22873	75331	104271	47804	16396	6773	5894	3652	6809	4815	2027	399	0	297044
3,75	0	0	0	0	0	0	0	1597	33359	102767	77540	18255	8361	5989	1535	1875	2639	1350	0	0	255267
4,25	0	0	0	0	0	0	0	0	5008	65075	104339	30498	8633	3714	986	0	1453	0	0	0	219706
4,75	0	0	0	0	0	0	0	0	232	27481	105856	36458	8154	2651	411	502	1815	0	0	0	183559
5,25	0	0	0	0	0	0	0	0	0	5360	76941	61552	11246	1214	502	0	739	0	0	0	157554
5,75	0	0	0	0	0	0	0	0	0	677	44320	62129	11563	2913	0	0	0	0	0	0	121602
6,25	0	0	0	0	0	0	0	0	0	0	14035	56737	15483	4016	0	0	0	0	0	0	90271
6,75	0	0	0	0	0	0	0	0	0	0	1889	33089	20715	4015	0	0	0	0	0	0	59708
7,25	0	0	0	0	0	0	0	0	0	0	0	11452	20834	10035	0	0	0	0	0	0	42321
7,75	0	0	0	0	0	0	0	0	0	0	0	4907	16805	14113	0	0	0	0	0	0	35825
8,25	0	0	0	0	0	0	0	0	0	0	0	1236	11109	12994	2477	0	0	0	0	0	27815
8,75	0	0	0	0	0	0	0	0	0	0	0	0	1785	8995	0	0	0	0	0	0	10780
9,25	0	0	0	0	0	0	0	0	0	0	0	0	0	2513	1557	0	0	0	0	0	4070
9,75	0	0	0	0	0	0	0	0	0	0	0	0	0	1396	0	0	0	0	0	0	1396
10,25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1912	0	0	0	0	0	1912
10,75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Total AEP	**3368713**	kWh
Capacity factor	33 %	
AEP with efficiencies	**1112**	MWh
In MW	0,1269	MW
Prated	0,38	MW

Energy demand from production

AE+HB	1980	GWh
SOEC+HB	1489	GWh

Units needed for AE+HB	1781
Units needed for SOEC+HB	1340

Appendix E.1 – Device energy yield for M4-multifloat for optimized scale (1:110)

Device Energy Yield [kW] for optimum scaling (1:110)

Hs [m] \ Tp [s]	0,6	1,9	3,2	4,5	5,8	7,1	8,4	9,6	10,9	12,2	13,5	14,8	16,1	17,4	18,6	19,9	21,2	22,5	23,8	25,1
0,25	0	0	0	1	2	5	14	37	58	49	42	33	27	22	16	17	20	24	28	33
0,75	0	0	4	9	21	44	130	333	521	445	378	295	247	194	147	150	181	216	255	299
1,25	0	1	10	24	59	122	361	924	1449	1235	1050	819	687	538	409	417	503	600	709	831
1,75	0	3	20	47	116	240	708	1811	2839	2421	2057	1606	1347	1055	802	818	986	1177	1390	1628
2,25	0	4	33	78	191	396	1170	2993	4693	4001	3401	2655	2227	1744	1325	1352	1631	1945	2298	2691
2,75	0	6	50	116	285	592	1748	4471	7011	5977	5080	3965	3326	2605	1979	2019	2436	2906	3433	4021
3,25	0	9	69	162	399	826	2442	6245	9792	8349	7095	5538	4646	3638	2765	2820	3402	4059	4795	5615
3,75	0	12	92	216	531	1100	3251	8314	13037	11115	9447	7374	6185	4844	3681	3755	4529	5404	6384	7476
4,25	0	15	119	278	682	1413	4175	10679	16745	14277	12134	9471	7945	6221	4728	4823	5818	6941	8200	9603
4,75	1	19	148	347	852	1765	5216	13339	20917	17833	15156	11831	9924	7771	5905	6024	7267	8670	10243	11995
5,25	1	23	181	424	1041	2156	6371	16295	25552	21785	18515	14452	12123	9494	7214	7359	8877	10591	12513	14653
5,75	1	28	217	508	1248	2586	7643	19547	30651	26133	22210	17336	14542	11388	8654	8828	10649	12705	15010	17577
6,25	1	33	256	600	1475	3055	9030	23094	36213	30875	26240	20483	17181	13455	10224	10430	12581	15010	17733	20767
6,75	1	38	299	700	1720	3564	10532	26937	42239	36013	30607	23891	20040	15694	11925	12165	14675	17508	20684	24223
7,25	1	44	345	808	1984	4111	12151	31075	48729	41545	35309	27561	23119	18105	13758	14034	16929	20198	23862	27944
7,75	1	50	394	923	2267	4698	13884	35509	55682	47473	40347	31494	26418	20688	15721	16037	19345	23080	27267	31932
8,25	2	57	447	1046	2569	5324	15734	40239	63098	53797	45721	35689	29936	23443	17815	18173	21922	26154	30899	36185
8,75	2	64	502	1177	2890	5988	17698	45264	70978	60515	51431	40146	33675	26371	20039	20442	24659	29420	34757	40704
9,25	2	71	561	1315	3230	6692	19779	50585	79322	67629	57477	44865	37633	29471	22395	22845	27558	32879	38843	45489
9,75	2	79	624	1461	3589	7435	21975	56201	88129	75138	63858	49846	41812	32743	24882	25382	30618	36529	43156	50539
10,25	3	87	689	1615	3966	8218	24287	62113	97400	83042	70576	55090	46210	36188	27499	28052	33839	40372	47696	55856
10,75	3	96	758	1776	4363	9039	26714	68321	107134	91341	77629	60595	50828	39804	30247	30855	37221	44407	52462	61438

Appendix E.2 – AEP for M4-multifloat for optimized scale (1:110)

AEP [kWh/yr] for optimum scaling (1:110)

Tp [s]

Hs [m]	0,6	1,9	3,2	4,5	5,8	7,1	8,4	9,6	10,9	12,2	13,5	14,8	16,1	17,4	18,6	19,9	21,2	22,5	23,8	25,1	Sum
0,25	0	0	2	10	62	166	476	3762	4968	1345	1042	349	245	188	60	47	23	16	7	3	12772
0,75	0	0	2	445	4467	15094	34791	130477	270587	82093	57660	33320	14726	11419	3885	2413	1357	450	170	124	663481
1,25	0	0	0	6	7061	49385	146014	301530	305934	185370	142690	80551	41078	35260	7865	5279	1718	1150	354	138	1311383
1,75	0	0	0	0	67	32066	231143	705400	629175	255517	160473	71788	47545	46893	14480	10279	2381	490	116	0	2207813
2,25	0	0	0	0	0	857	141068	788094	1310825	448368	184020	70495	29288	41952	12906	12490	4072	1134	191	0	3045761
2,75	0	0	0	0	0	0	13971	591802	1549591	897193	246981	66353	28798	18215	10876	11767	6489	2903	572	0	3445510
3,25	0	0	0	0	0	0	0	138801	1132286	1340675	386896	78843	21271	11509	4373	6809	4815	2027	399	0	3128704
3,75	0	0	0	0	0	0	0	9690	501409	1321342	627555	87781	26260	11694	1838	1875	2639	1350	0	0	2593432
4,25	0	0	0	0	0	0	0	0	75276	836710	844443	146653	27116	7251	1181	0	1453	0	0	0	1940083
4,75	0	0	0	0	0	0	0	0	3483	353337	856728	175310	25610	5176	492	502	1815	0	0	0	1422452
5,25	0	0	0	0	0	0	0	0	0	68917	622710	295974	35323	2371	601	0	739	0	0	0	1026635
5,75	0	0	0	0	0	0	0	0	0	8702	358693	298749	36318	5688	0	0	0	0	0	0	708151
6,25	0	0	0	0	0	0	0	0	0	0	113592	272823	48630	7841	0	0	0	0	0	0	442886
6,75	0	0	0	0	0	0	0	0	0	0	15288	159110	65064	7839	0	0	0	0	0	0	247300
7,25	0	0	0	0	0	0	0	0	0	0	0	55067	65437	19593	0	0	0	0	0	0	140097
7,75	0	0	0	0	0	0	0	0	0	0	0	23596	52781	27556	0	0	0	0	0	0	103934
8,25	0	0	0	0	0	0	0	0	0	0	0	5942	34890	25371	2966	0	0	0	0	0	69169
8,75	0	0	0	0	0	0	0	0	0	0	0	0	5607	17563	0	0	0	0	0	0	23170
9,25	0	0	0	0	0	0	0	0	0	0	0	0	0	4907	1864	0	0	0	0	0	6771
9,75	0	0	0	0	0	0	0	0	0	0	0	0	0	2726	0	0	0	0	0	0	2726
10,25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2289	0	0	0	0	0	2289
10,75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Total AEP	**22544518**	kWh
Capacity factor	33 %	
AEP with efficiencies	**7440**	MWh
In MW	0,8493	MW
Prated	2,57	MW

Energy demand from production

AE+HB	1980	GWh
SOEC+HB	1489	GWh

Units needed for AE+HB	266
Units needed for SOEC+HB	200

AEP for 36 M4-units for 1 day	733778	kWh/day
SOEC energy demand for 1 day	4 079 968	kWh/day
% covered solely by 36 units	18	%

AEP for 36 FPV-units annually	267 828 875	kWh/year
SOEC energy demand	1 489 188 443	kWh/year
Percentages covered solely by 36 unit	18	%

SOEC-energy demand covered by turbine	1 221 359 568	kWh/year
Number of turbines needed	16	
Turbine AEP	77 351 832	kWh/year