A concept study on offshore floating hydrogen production, storage, and offloading

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Preface

This master thesis has been prepared at the Department of Physics and Technology at the University of Bergen (UiB) as part of the integrated master's program in Ocean technology. It is a combined thesis with Velaug Myrseth Oltedal as supervisor from the Western Norway University of Applied Science (HVL), Ivan Østvik representing the industry and Martin Fernø as supervisor from UiB.

My personal motivation for this thesis has been a strong interest in combining the field of ocean technology with renewable hydrogen production from offshore wind. I would like to take advantage of this opportunity to thank my supervisors for their guidance and support, letting me combine these fields of interest. With my supervisor's good contact network, the thesis resulted in a complementary and motivating thesis. I want to thank LMG Marin and Sevan SSP for their flexibility in providing me with guidance and experience in naval modelling and analyses. Thanks to TechnipFMC, Behyond, Chart Industries, Gexcon, Aabø Powerconsulting, H2Carrier, North Ammonia, Yara and Greensight for relevant and necessary data input for my literature research and analyses.

Finally, I would like to thank my fellow students and family for their motivation, help and good discussions. Days would not have been the same without Friele, Freja, WOD and Juni.

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Abstract

To achieve the target of 50% reduction in emissions in the maritime industry within 2050, hydrogen-based fuels produced from renewable electricity must become commercially available on a large scale. Floating offshore wind provides a renewable energy source for large scale hydrogen production. Hydrogen production on floating production storage and offloading unit (FPSO) creates an opportunity for large-scale hydrogen production from high-capacity floating wind farms.

This thesis evaluates two types of FPSOs for offshore large-scale hydrogen production: one ship-shaped and one cylindrical shaped. The concept of offshore hydrogen production, storage and offloading is defined and compares the storage options liquid hydrogen and ammonia. Area and weight estimations of the required processing equipment dictate the expected maximum hydrogen production capacity on these FPSOs. The concept is further analysed with a response analysis to understand the environmental loads and resulting motions that can affect the operation of the hydrogen-producing FPSO.

The FPSOs can facilitate large scale production capacities up to 172 tons/day with liquid hydrogen storage, twice as large as the hydrogen production capacity with ammonia storage. Offshore ammonia conversion and storage are mature applications compared to hydrogen liquefaction in an offshore environment, where large-scale production and the high offloading rates are limiting factors. Motions of the hydrogen process equipment on deck cylinder FPSO are less significant than for a ship-shaped FPSO. The selected hydrogen production approach must prioritize between large production capacity associated with new technology development (liquid hydrogen) or rapid implementation with smaller production rates (ammonia).

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Nomenclature

Abbreviations

H_2 = Hydrogen

LH_2 = Liquid hydrogen

NH_3 = Ammonia, NH_3

ALK = Alkaline Electrolyser

PEM = Proton Exchange Membrane

PEMEL = Proton Exchange Membrane Electrolyser

SOEL = Solid Oxide Electrolyser

MW = Megawatt

MWh = Megawatt hours

kW = Kilowatt

kWh = Kilowatt hours

JONSWAP = Joint North Sea Wave Analysis Project

LNG = Liquid natural gas

LPG = Liquid petroleum gas

IMO = International Maritime Organisation

IEA = The International Energy Agency

tpd = Tons per day

LCOE = Levelized cost of Energy

Symbols

H_s = Significant wave height

T_p = Spectral wave period

T_z = Spectral wave period

m^2 = Square meters

m^3 = Cubic meters

ω = Wave frequancy

ζ = wave amplirude

1 Introduction

1.1 Motivation

The climate crisis is well documented in the sixth assessment report by the Intergovernmental Panel on Climate Change (IPCC) [1]. The world's temperature is increasing, and the world will face more extreme and more frequent storms, heatwaves, and heavy precipitation in the years to come. The Paris agreement's goal of a maximum of 1.5 degrees of global warming will be exceeded [1]. The consequences of not reaching global warming of 2 degrees have led to an urgency to reduce human-made emissions. The Green Deal commission in the EU has increased its targets by at least 55 % emission reduction in 2030 compared to 1990s levels [2]. Shipping, transport, and industry sectors have followed carbon neutrality or zero-emission goals. In 2018 the International Maritime Organisation (IMO), the most influential regulator in shipping, has set a target of cutting the shipping segments' greenhouse gas emissions by 50 % by 2050 [3]. Measure for reducing emissions in the shipping industry is changing from conventional fossil fuels to zero-emission alternatives

Electrification is one of the most effective ways to obtain zero-emission in most sectors. The International Energy Agency (IEA) states that hydrogen, with its high energy density, will have a leading role in achieving net-zero emissions by 2050 [4]. Hydrogen produced from renewable sources provides a solution to high gravimetric energy fuel as hydrogen emits only water and oxygen. As a fuel, hydrogen can cut emissions in heavy-duty transport, shipping, aviation, and trains where batteries are limited for electrification. In shipping, hydrogen and hydrogen-based fuels such as ammonia and methanol provide a solution to cut emissions from smaller vessels to large ships with longer voyages [5]. Hydrogen can also play an essential role in hard to abate sectors, cement, steel, and chemical production [4].

Hydrogen's opportunity to cut emissions is emphasised in the EU's "Green deal", which launched a progressive hydrogen strategy in July 2020. The goal is to increase hydrogen production from 6 GW to 40 GW within 2030 [6]. However, producing hydrogen without emissions requires large amounts of renewable energy and water. A rule of thumb is that to produce 1 kg of hydrogen, 55 kWh electricity and 9 kg water is required. With an increasing demand for renewable power to electrify a range of sectors, new renewable power solutions must fundament the hydrogen production facilities.

Offshore wind is a rapidly growing industry which utilizes the energy potential far from shore. The potential of offshore wind is divided into shallow (< 60 m) and deep-water wind turbines (60-2000 m) [7]. Deepwater turbines are referred to as floating offshore wind. Floating wind turbines in deeper water have the opportunity to unlock an excellent wind potential. According to International Energy Agency (IEA), the offshore floating wind has the potential to supply the world's total electricity demand 11 times in 2040 [7]. Hence, hydrogen production from offshore wind provides a solution to the need for renewable energy sources, hydrogen production sites and water resources.

If hydrogen and other low emission fuels are to become commercially available on a large-scale and implemented in the maritime industry within 2050, research and innovative solutions for production and infrastructure are needed. A new and innovative concept is hydrogen production on a Floating, Production, Storage, and Offloading unit (FPSO). FPSO is a commercialised oil and gas production unit with a large storage capacity and deck area to accommodate large-scale hydrogen process equipment. The floating properties make an FPSO suitable in combination with floating offshore wind further away from shore in deep water. With local bunkering possibilities or by bunkering vessels to ports, offshore production facilities can reduce space occupation issues in ports where new infrastructure is needed. The FPSO concept can potentially reduce costs and energy loss compared to transporting the fuel to ports from land-based production facilities and power cables from a floating wind farm to shore.

By studying a large-scale hydrogen production on an FPSO, the thesis aims to contribute to implementing hydrogen as zero-emission fuel in the shipping industry.

1.2 Literature review

There is not a substantial body of research investigating aspects of large-scale offshore hydrogen production from wind. Meier published the first work on hydrogen production in the North Sea [8]. The study assessed the required electrolysis technology and did a cost analysis. Meier concluded that the electrolysis must have a minimum capacity of 100 MW to produce economically feasible hydrogen. From 2020 to 2022, the number of articles addressing the technical and economic sides of producing hydrogen from offshore wind has increased. This section focuses on the article with relevant objectives regarding hydrogen production from floating offshore wind.

Ibrahim et al. proposed three hydrogen production concepts coupled with floating offshore wind by assessing the electrolysis technology, floating wind platform design and hydrogen transmission to shore [9]. The paper concluded that decentralized solutions are complex compared to centralized, in which centralised hydrogen can open doors for more cost-effective options for the emphasized components in the study. A centralised production is defined as production at one dedicated platform supplied with electricity from the wind farm. In contrast, decentralised hydrogen production takes place on each wind turbine installation (Figure 1-1).

Figure 1-1: Difference between decentralised (left) and centralised (right) hydrogen production units [10].

Ibrahim et al. found that hydrogen pipelines are considered the best transmission option from floating concepts to shore. Calado and Castro support hydrogen pipelines over electrical cables. They found the main advantage of having hydrogen production offshore is the cost reduction related to losses in submarine electrical cables. Submarine cables were found to have a loss of 5 % versus 0.1 % related to the transmission of hydrogen in pipelines[11]. This is relevant to the concept of producing hydrogen from a wind farm instead of transporting the electricity to shore.

The paper by Calado and Castro further reviews economic assessments on hydrogen production from wind. The literature review shows that costs are expected to decrease with technology development evolving longer lifetimes, more efficient electrolysers, and lower costs [11]. The review emphasizes that hydrogen production coupled with wind is feasible from an economic perspective, which is relevant for centralised hydrogen FPSO.

Suitable offloading alternatives are of interest for FPSOs. Franco et al. add offloading pathways to the economic assessment of offshore hydrogen production from wind. They found the levelized cost of hydrogen transporting liquid hydrogen and ammonia with ships outcompeting hydrogen compressed pipelines longer than 150-250 km [12]. Hank et al. found the energy efficiency of different ways of converting renewable energy through electrolysis and further processing into gas or liquid fuel. The assessment of LH_2 and NH_3 transport to shore by ship resulted in total system efficiency of 47.7-52.4% for NH_3 and 52.4-57.9% for LH_2[13]. The energy-intensive hydrogen liquefaction process is the most energy-efficient but only a few per cent better than the NH_3 conversion. The NH_3 process benefits from the less energy-intensive liquefaction process and the efficient nitrogen supply from the air. The similar energy efficiency of the production process means that liquid hydrogen and ammonia are comparable.

A master thesis by Sekandar adress an FPSO as a concept and is the most relevant among the papers presented in this literature review. The objective was to develop a conceptual design of an FPSO producing hydrogen from wind power with conversion to ammonia[12]. The FPSO concept included ammonia production and offloading to a liquid petroleum gas (LPG) carrier. The concept was validated with a simulation of the production and use in Matlab. Further work was found to take the concept to the embodied design phase.

Most of the studies presented in this section are technological reviews on state of the art combined with economic assessments. However, there is a piece of missing information in the literature on whether the offshore environment affects the hydrogen production feasibility regarding waves, wind, and currents that make motions on the FPSO. What motions can be expected for a large-scale concept, and how does it influence the production process? Are there other concerns of a floating production unit which should be addressed to further develop this concept? This is supported by Ibrahim et al., who state that *"electrolysis response to offshore conditions needs validation"* [9]. Electrolysers are the central part of hydrogen production from wind. Hence, this is an important aspect and a gap of knowledge in the literature.

1.3 Technology status

As the research finds offshore wind and hydrogen feasible, it has gained international interest. The international interest supports a market potential in future decades coupling offshore wind and hydrogen. Many consortia have been announced in the latest years, with big industry partners investigating distinct typologies for hydrogen production on bottom fixed platforms [13]. To utilize the potential of offshore wind, dedicated floating units for hydrogen production are also under development. The technology status of offshore floating hydrogen projects is further described in this section.

Projects are under development for future large-scale deployment. Most of the projects are currently in the demonstration phase, with pilot projects installed in the near future. A pilot project which will be deployed in 2022 is a floating hydrogen pilot plant led by Lhyfe. The aim is to validate the offshore hydrogen production technology before commercialising large-scale floating plants in 2024[14]. DOLPHYN is another project which aims for large scale floating wind and hydrogen, with its first offshore large-scale site under development[15]. DOLPHYN will launch a prototype by 2024 consisting of a semi-submersible 2 MW floating wind turbine with hydrogen production on the wind turbine base.

The two pilots for floating hydrogen plants are both decentralised concepts. The P2X concept by H_2Carrier is the only announced concept that includes the hydrogen conversion onboard a ship[16]. They plan to produce hydrogen from wind power on a retrofitted Liquid Petroleum Gas (LPG) carrier, offloading directly from the ship.

To summarise, a growing portfolio of projects combines floating and fixed bottom wind and offshore hydrogen production. The broad difference in the presented projects is worth noticing, which is logical because combining hydrogen and offshore wind is a brand-new field with no standard solution. Innovation and new thinking are essential to developing the best solutions, which this thesis will contribute.

1.4 Objective

The literature review shows that studies have dealt with producing hydrogen from offshore wind. However, no articles have approached the hydrogen technology's ability to operate in a maritime environment on an FPSO. In the urge to implement zero-emission fuels in the maritime industry, the research objective of this study is to develop and evaluate the feasibility of offshore large scale hydrogen production, conversion, storage, and offloading on an FPSO. With input from industry partners within hydrogen and marine applications, these are the research questions investigated in this work:

1. How to produce, store and offload hydrogen offshore?
2. What production capacity can be expected on an FPSO?
3. What motion from a floating unit must the process equipment be designed for?

With this objective, the thesis combines the knowledge of naval engineering and hydrogen technology. This by focusing both on the FPSOs motion and the process equipment layout on the FPSOs deck. No studies with this approach have not yet been published, which highlights the relevance of providing this knowledge in a forwarded field of interest.

1.5 Approach and thesis structure

To answer the first question in the objective, a technology review is performed as a background for further analysis. Question two finds the expected production capacity on FPSOs with a quantitative area estimation. Hydrodynamic response analysis will obtain quantitative motions from FPSOs to answer the last objective.

The thesis is divided into three main parts: "Concept analysis", "Area and weight estimation," and "Response analysis" (Figure 1-2.). Firstly, chapter 3 presents and analyses the concept of offshore hydrogen production, including the technology review. Chapter 4 is an area and weight estimation, where the methods and results are presented and discussed. The weights yield input to the response analysis in chapter 5, including method, results, and discussion. Lastly, the conclusions of the thesis is presented in chapter 6. The thesis structure is illustrated in Figure 1-2.

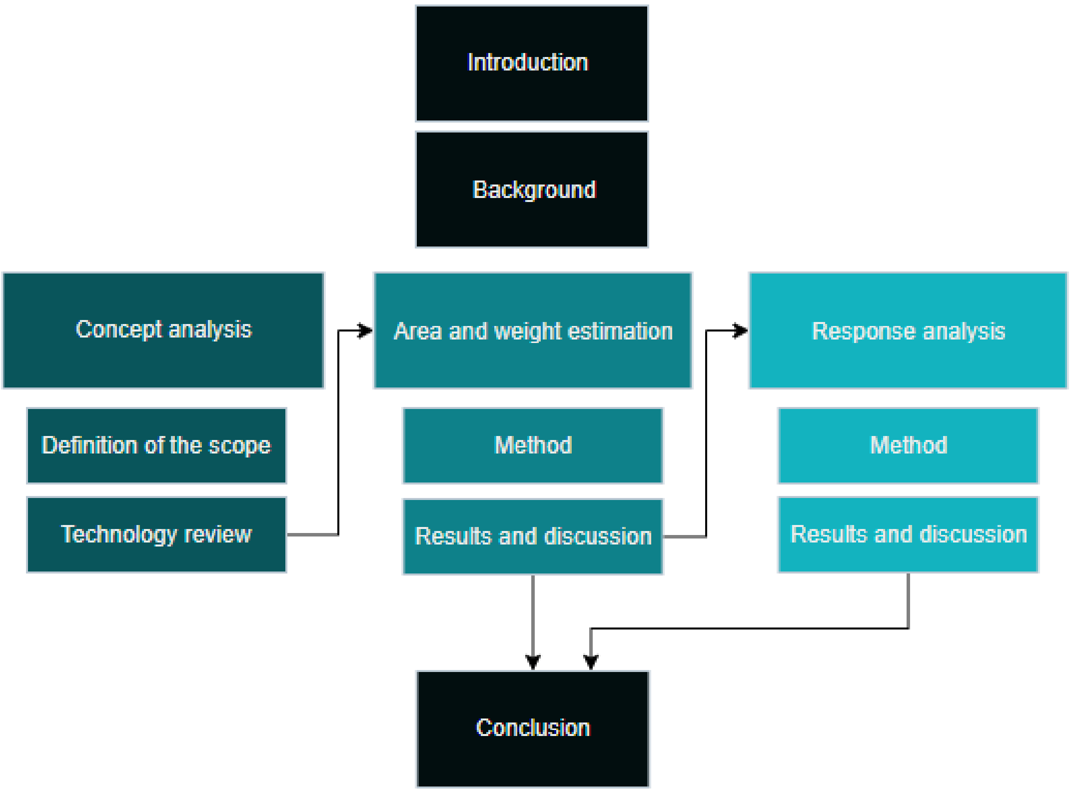

Figure 1-2: Structure of the report into three main parts, including essential sub-sections.

2 Background

This section will cover relevant background for the objective of the thesis, namely hydrogen production and the theory behind hydrodynamic response analysis.

2.1 Hydrogen and production methods

Hydrogen is an attractive fuel option for heavy transport and electricity generation applications[17]. It also offers ways to decarbonise a range of hard to abate sectors, including chemical, iron and steel production[4]. With its high energy density, hydrogen can be used to cut emissions, but must be handled with care. Hydrogen is an energy-intensive, reactive gas with a high burning velocity. It makes hydrogen very likely to ignite and combust if gas leakage occurs. The reactiveness is a combination of a flammable range of 4-75% oxygen and low ignition energy [18]. Significant safety measures must be implemented to develop hydrogen applications, production, and infrastructure. The essential properties of hydrogen described are listed in Table 2-1.

Table 2-1: Selected properties of hydrogen [18]

Properties	Hydrogen
Density at 0°C, atm	$0.090\ \frac{kg}{m^3}$
Boiling point	-253°C
Flammable range in air	4% - 75%
Minimum ignition energy	0.017 mJ

Hydrogen is produced from various sources, as the primary target or as by-products in industrial processes such as ammonia, methanol, and oil refining. The energy source and emission of the production method categorise hydrogen by colour. With over 95% of the hydrogen produced, the leading hydrogen production worldwide is from steam methane reforming by natural gas, categorised as grey hydrogen. Producing hydrogen from renewable energy sources through electrolysis categorises hydrogen as green because there are no emissions related to the production. Gren hydrogen is considered in this thesis.

In the case of blue hydrogen, CO_2 is captured and stored up to 95% (CCS), but from a lifecycle perspective, total CO_2 equivalent emissions are only 9%-12% less than for grey hydrogen [19]. The different production methods and colour code categorisation are illustrated in Figure 2-1.

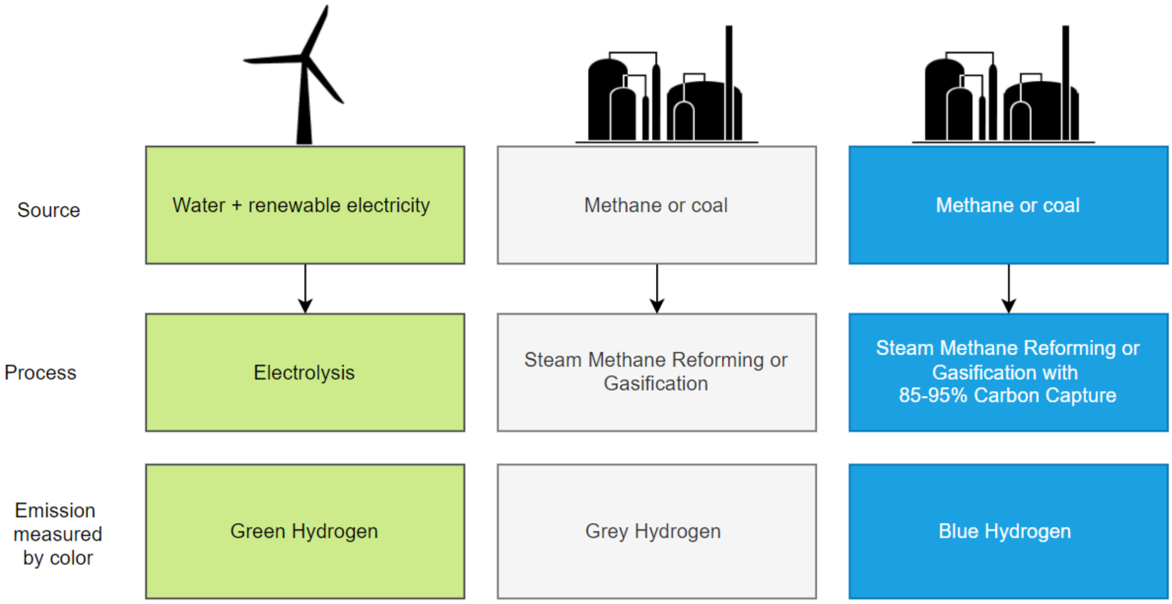

Figure 2-1: Main options for hydrogen production and colour categorisation of green, grey and blue.

2.1.1 Hydrogen produced with electrolysis

When electricity is the source of power, hydrogen is produced through electrolysis. In electrolysis, water molecules are separated into oxygen and hydrogen gas when electricity is applied. The overall electrochemical reaction is illustrated in Figure 2-2.

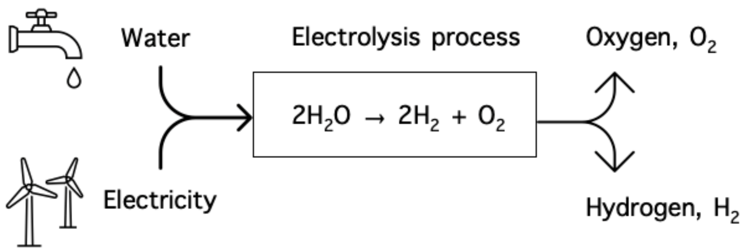

Figure 2-2: Electrolysis with water and renewable power input, oxygen and hydrogen as output.

The applied electrolyte and temperature classify three main water electrolysis technologies. Low-temperature electrolysis technologies on the market are Alkaline Electrolysis (ALK) and Polymer Electrolyte Membrane Electrolysis (PEM). Solid Oxide Electrolysis (SOEL) is the most mature High-temperature electrolysis.

Alkaline electrolysis (ALK) represents a mature low-temperature electrolysis technology and has been applied for large scale production in the industry since the 1920s [20]. The concept of the technology and the chemical reaction is illustrated in Figure 2-3. The electrodes are immersed in an aqueous alkaline electrolyte (KOH) solution in alkaline electrolysis, normally lye[21], which ensures efficient process conductivity. Hydrogen is produced with a general system efficiency of 51-60% of the lower heating value (LHV) and with 10-30 bar [21].

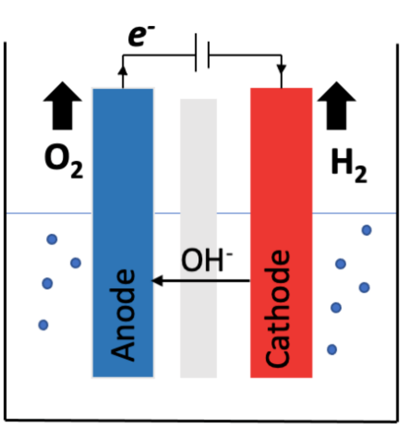

Figure 2-3: Alkaline electrolysis inspired by [21]

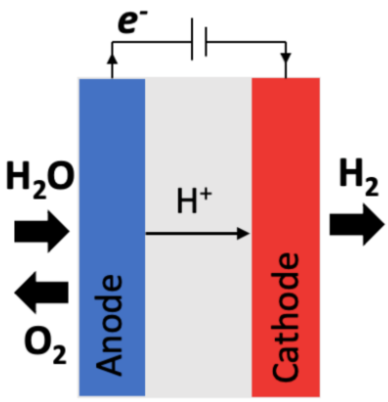

Figure 2-4: PEM Electrolysis inspired by [21]

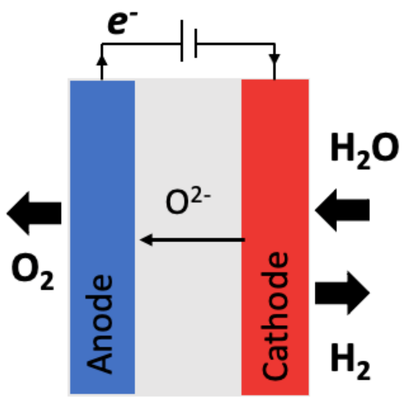

Figure 2-5: Solid Oxide electrolysis inspired by [21]

Polymer Electrolyte Membrane Electrolysis (PEM) has a solid polymer membrane that separates and exchanges the protons between the two electrodes, illustrated in Figure 2-4. It operates at a lower temperature. The technology can operate at high current densities because of the solid electrolyte. This makes PEM electrolysis a more compact module than ALK and produces hydrogen at higher pressure[21]. The system efficiency is 46-60% LHV with the output pressure of 20-50 bar [21].

The last technology, Solid Oxide Electrolysis (SOEL), is a high-temperature electrolysis technology (Figure 2-5). Compared to ALK and PEM, this technology is only applied in a few commercial applications and is the least mature of the technologies. SOEL operates at a high-temperature range of 700–900 °C, with steam as water input. The system efficiency is 76-81%$_{LHV}$, with an output pressure of 1-15 bar [21]. SOEL is a promising technology in industrial processes, with higher efficiency than ALK and PEM if spill heat is used. Still, the total efficiency of the electrolyser decreases as the steam or heat required in the process must be generated from additional electrical heating. Therefore, SOEL is a less usable application on an FPSO.

2.2 Hydrogen storage and conversion

Hydrogen is an energy carrier and potential application for storing, moving, and delivering energy produced from renewable sources. Energy can be converted to hydrogen and back to electricity when needed. Hydrogen can also be stored in significant quantities and looks promising to be the lowest-cost option for storing electricity over extended periods [4]. Long-term storage is arguably necessary for the transition to renewable energy sources as it is a way to address unreliable renewable sources of energy.

Hydrogen's most suitable storage method is based on gravimetric and volumetric energy density, concerning applications and costs. The low volumetric energy density makes hydrogen more storage efficient by concentrating it by compression, liquefaction or bound on other chemical substances. The two main categories of storing technologies for hydrogen are physical and chemical storage methods [22]. The physical storage methods change hydrogen's physical properties eighter by compression or liquefaction of the hydrogen (LH_2). Chemical storage is hydrogen bound in other materials with high hydrogen content [22]. These are, for instance, chemical hydrides like ammonia (NH_3), methane (CH_4), hydrogen in a liquid organic hydrogen carrier (LOHC), or metal hydrides.

2.2.1 Compressed hydrogen

Compressed hydrogen storage is the conventional method of storing hydrogen in applications such as vehicles, refuelling stations and other industrial processes [23]. The energy density of the stored compressed hydrogen depends on the storage pressure. At standard pressure the density is 0.089 kg/m^3 [24]. High pressures are required to achieve higher densities of hydrogen in the gas state. Pressure vessels are usually designed for 700 bar in transport applications, and density increases to 39.3 kg/m^3[25]. With increased pressure, the pressure vessels are exposed to the risk of hydrogen embrittlement due to permeation being accelerated by increased pressure [23]. Storing hydrogen at great pressure needs expensive advanced materials such as glass fibre-reinforced and carbon fibre [23] instead of steel to maintain the strength and reduce the weight of the storage tanks. The low volumetric energy density of gaseous hydrogen requires large storage volumes and storage tanks are not an option for storing large quantities of hydrogen[22]. Storage of compressed hydrogen in salt caverns, pipelines or compressed underground reservoirs are methods currently under development [23].

The thesis will focus on storing hydrogen as liquefied and as ammonia. These storage methods have higher densities and is more suitable for maritime applications.

2.2.2 Liquid hydrogen

Storing hydrogen in a liquid state has a density of 70.8 $\frac{kg_{h2}}{m^3}$ which is around 800 times higher than compressed at standard temperature and pressure [24]. It is a promising and efficient way of storing a large amount of hydrogen to facilitate the demand for high volumetric energy density in maritime applications[23]. Properties of liquid hydrogen are listed in Table 2-2.

Table 2-2: Properties of liquid hydrogen (LH_2).

Properties	Hydrogen
Density at -253°C, 1 atm [24]	$70.8\,\frac{kg}{m^3}$
Volumetric Energy density, 4 bar [25]	$7.5\,\frac{MJ}{l}$
Gravimetric energy density, 4 bar [25]	$120.0\,\frac{MJ}{Kg}$

Hydrogen is liquefied by refrigeration to -253°C. The liquefaction process includes cooling gaseous hydrogen to its boiling point and then stored in vacuum isolated storage vessels. The energy needed to liquefy 1 kg of hydrogen is around 12 kWh/kg_{H2} [27], or approximately 1/3 of the usable energy in one kg of hydrogen (33.33 kWh/kg_{H2}). The basic concept of the liquefying process is illustrated in Figure 2-6. The process includes a pre-compression bringing hydrogen to a feed pressure of 10-30 bar, several steps of cooling with heat exchangers and end with the Joule-Thompson valve, which brings hydrogen down to the required temperature[26].

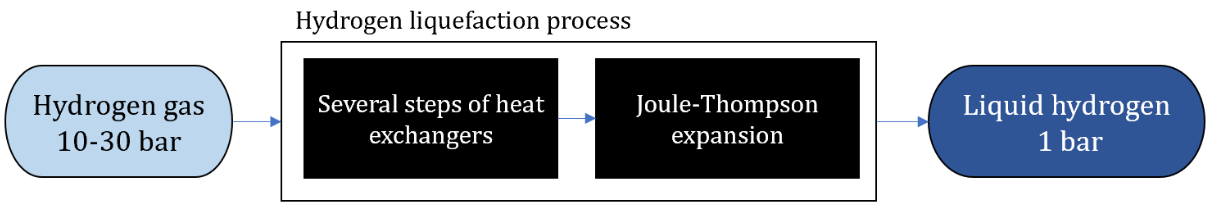

Figure 2-6: Illustration of steps in the hydrogen liquefying process line. Input pressure of hydrogen is 10-30 bar, and through the liquefying process, including steps of heat exchangers and a Joul-Thompson expansion, hydrogen is liquefied to -253 degrees at 1 bar.

Today, the liquefaction technologies are the helium Brayton cycle or the Claude Cycle[26]. They commonly use liquid nitrogen to precool the hydrogen before further cooling stages. The Helium Brayton Cycle uses helium as cryo-cooling for quantities up to 3 tons per day (tpd) [26]. For larger liquefaction capacities, re-cycled hydrogen and helium are used as cooling mediums (Claude Cycle). Claude Cycle has an energy consumption of 10.8-12.7 kWh/kg_{LH2} and is a slightly more efficient cycle than the Brayton with 12.3-13.4 kWh/kg_{LH2} [26] The hydrogen pressure is 15-20 bar in Claude Cycle and requires higher investment costs than Brayton, where pressure is 10-15 bar [26].

According to Krasae-in et al., there were 30 LH_2-plants in operation in America and Asia in 2010 [27]. An LH_2 plant by Air Products In USA, New Orleans, has the largest production of 34 tpd [27]. The number of plants supports that liquefaction is a well-proven and mature technology. Developing more energy-efficient and large-scale liquefaction plants is currently under development. The short-term goal is to reduce the energy consumption from 12 kWh/kg_{LH2} to 7.5 to 9 kWh/kg_{LH2}. In short to medium term, the predicted capacity will increase from today's 5-34 tpd up to 150 tpd [26]. The future goal for development is 6 kWh/kg_{LH2} on a very large scale, with a production capacity of up to 100 tpd[26]. Turbo compressors are one of the improvements making it possible[26]. Tubo-compressors make compression closer to the isothermal optimum [25], reducing the cost and increasing the liquefaction capacities to above 200 tpd of LH_2.

Liquid hydrogen storage

Liquid hydrogen is stored in storage tanks designed to keep the temperature low and withstand high-temperature changes from filling and unloading [22]. Vaporised hydrogen due to temperature increase in the tanks must be vented out to prevent pressure build-up inside. Boil-off in the tank directly loses the energy needed to liquefy it. Boil-off is measured as a percentage of the total storage content over time [22]. Stage tanks with double walls and a vacuum between the inner and outer shell minimise the heat transfer through convection, conductivity heat and radiation[22]. In addition to insulation, a low surface-to-volume ratio keeps the boil-off low[23]. Therefore, the shape of LH_2 storage tanks is cylinder-shaped and an even larger scale, spherical tanks. The materials of LH_2 storage tanks are generally austenistic stainless steel and aluminium because they are less susceptible to hydrogen embrittlement[28].

2.2.3 Ammonia

Ammonia (NH_3) consists of 82.4% nitrogen and 17.6% hydrogen by weight and is an attractive chemical storage medium for hydrogen [24]. The volumetric energy density is about 1.7 times as high as for LH_2. NH_3 has a density of 121 kg_{H2}/m^3 [24]. Ammonia stores hydrogen chemically with a higher density. The disadvantage is that it is heavier to transport and store because of its higher gravimetric energy density. Ammonia properties are listed in Table 2-3.

Table 2-3: Properties of ammonia

Properties	Ammonia
Density at -33,33°C (1 atm)[29]	682.0 $\frac{kg}{m^3}$
Volumetric Energy density [30]	12.7 $\frac{MJ}{l}$
Gravimetric energy density [30]	18.6 $\frac{MJ}{Kg}$
Gravimetric hydrogen content [24]	17.8 wt%

Ammonia has a wide range of use, for example, in the fertiliser industry and among other chemical industrial processes. The technology and infrastructure around producing, storing, and transporting ammonia are well established[31]. Ammonia can be used as ammonia in different industries or decomposed back to hydrogen. Releasing hydrogen from ammonia is a very energy-demanding process that requires 30.6$\frac{kJ}{mol_{H2}}$, compared to regasification of liquid hydrogen, with an energy input of~ 0.9 $\frac{kJ}{mol_{H2}}$ [24].

Nearly 100% of all ammonia plants synthesise hydrogen and nitrogen with a Haber-Bosh process[32]. Higher availability of natural gas and competitive prices on natural gas in the 1960-1970s, changed the ammonia processes from using green hydrogen to grey hydrogen produced from steam reforming of natural gas[32]. Ammonia is called green when it is produced with hydrogen from electrolysis driven by renewable energy sources. Upcoming projects are changing from steam reformed hydrogen "back" to hydrogen produced from electrolysis. The “Hegra” project led by the fertiliser producer Yara in Norway is a pilot project integrating electrolysers in the Haber-Bosch process [33]. An ammonia synthesis process, including hydrogen and nitrogen production, is illustrated in Figure 2-7.

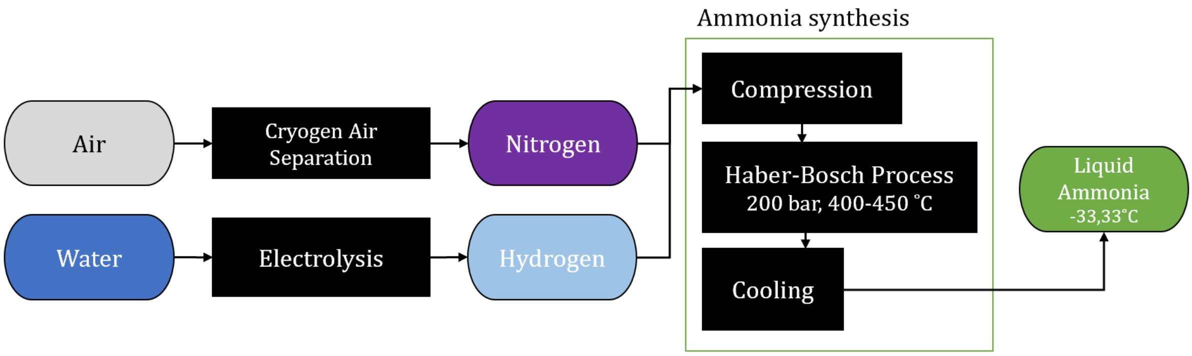

Figure 2-7: Ammonia synthesis illustrated. The feedstock to the Haber-Bosch process is nitrogen and hydrogen, with a liquid ammonia output at -33,33 degrees.

Nitrogen is added to the process synthesized from the air with an Air Separation Unit (ASU). The nitrogen and hydrogen ratio is 1:3 by volume. With a pressure of 10-30 MPa and a temperature of 400-500˚C, ammonia is synthesised with the assistance of an iron-based catalyst [31]. The conversion rate is low, up to 25-30%. By recycling, it is possible to achieve a conversion rate of 98% [32]. The exothermic reaction provides heat to the reaction, and the energy needs in the process yield to feed compression of H_2 and N_2 in the recycle loop[13]. The output is liquefied ammonia at -33.33˚C cooled from the vapour from the cryogenic ASU process from N_2 generation [13]. The resulting energy demand is, therefore, 0.48 $\frac{kWh}{kg_{NH_2}}$ and the energy efficiency of the ammonia process is ~19.6 % LVH [13].

Ammonia Storage

Ammonia is stored gaseous or liquefied depending on the tank capacity [34]. Liquefied and stored at -33. 4°C at 1 atm. or 20°C at 7 bar and has an energy density of 5.2 kWh/kg when liqiuid[34]. Liquefied, the storage tanks do not need to be pressurised, on the other hand, the gravimetric weight is higher. A midway condition between storing ammonia liquefied and compressed is beneficial because low-cost storage tanks can be used while maintaining the volumetric density[24]. Stainless steel and iron are robust to NH_3 corrosion and cryogen properties [35].

2.3 Hydrogen as a maritime fuel

Weight and volume are essential properties of maritime fuels as space is limited on ships. The gravimetric and volumetric energy density describes the energy within a given space and weight. Table 2-4 is a comparison of the different fuels compared. The values for NH_3 and LH_2 are the same as those presented previously, and the table compares them to compressed hydrogen and marine diesel oil.

Table 2-4: Comparison of properties of zero fuels with marine gas oil.

Properties	Liquid Ammonia [24]	Liquid hydrogen (4 bar)[25]	Compressed Hydrogen (350 bar) [25]	Marine Gas Oil [30], [36]
Storage temperature [˚C]	-33.3	-253.0	Ambient	Ambient
Volumetric Energy Density [$\frac{MJ}{l}$]	12.7	7.5	2.8	36.6
Gravimetric Energy Density [$\frac{MJ}{Kg}$]	18.6	120.0	120.0	42.8

Compressed hydrogen as an energy carrier has an energy density of 120.0 MJ/kg (LHV), approximately three times that of marine gas oil of 42.7 MJ/kg (LHV)[30]. Hydrogen's low volumetric energy density makes hydrogen-fuelled ships require large fuel storage onboard than ammonia.

There is no clear winner of the future zero-emission fuel [5]. It is predicted a combination of compressed and liquefied hydrogen for short distances, ammonia, and bio-based methanol for longer distances[5]. The differences are related to operational profiles regarding energy use and time offshore[5]. In deep-sea shipping, ships are larger, and have large propulsion related to steady speed over long distances. With the need for high energy demand and long bunkering intervals, high volumetric energy density fuels, such as ammonia, methane, and methanol, as the most suitable fuels [5].

Hydrogen as a fuel for the maritime sector is used with a fuel cell or an internal combustion engine (ICE). In combustion engines, hydrogen can be the only fuel or used as a dual fuel system [31]. The barriers to hydrogen are the low technology maturity, large onboard space requirements for fuel storage, lack of safety requirements and high investment costs [5]. Green ammonia can be used in both engines and fuel cells as a carbon-free fuel[30]. In combustion engines, ammonia is likely to be blended with commercial fuels because of challenges with ignition temperature and narrow flammability range[31] Direct ammonia fuel cells are carbon-free systems, but nitrous oxide (N_2O) (greenhouse gas) and NOx are emitted and must be regulated [5]. N_2O/NO_x can be removed with filtering technology, and only water and nitrogen exhaustion can be achieved[34]. Hence, the critical challenges for ammonia are toxicity, burning velocity and N_2O/NO_x emissions [5].

2.4 Hydrodynamic response analysis

Floating structures are complex systems that are to be analysed by structural mechanics and hydrodynamics. The thesis mainly focuses on the floater's motions in an operational environment with a hydrodynamic response analysis to be able to analyse the motions hydrogen process equipment will experience on an FPSO. The following chapters present the relevant theoretical background for a response analysis.

2.4.1 Wave spectra

Designing a ship includes the calculation of wave-induced loads on the ship structure. A real sea state is described by a sum of individual regular waves with different frequencies, amplitude, and phases (Figure 2-8). When the sea state is described as a stochastic wave condition, statistical techniques are applied to determine the wave loads on the structure by a wave spectrum. The wave spectrum is used in the structural design process by determining a wave spectrum [37].

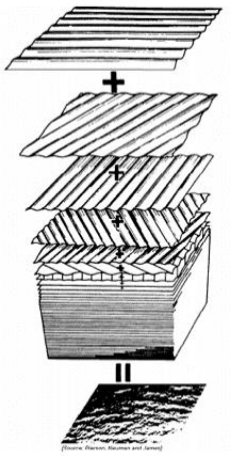

Figure 2-8: Illustration of an irregular sea as a sum of many sinus waves, by Journée & Massie [38]

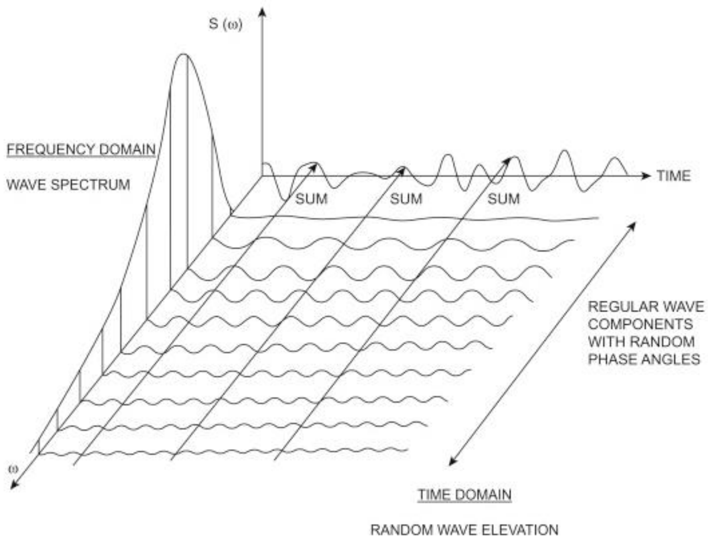

Figure 2-9: A wave spectrum and the relationship between the time-domain and frequency-domain solution of waves by Faltinsen [37].

A wave spectrum is the wave elevation in an irregular sea (time-domain) transformed to the frequency domain. Each wave is described with amplitude, and the phase is transformed to the frequency domain with a Fourier transformation

Figure 2-9). The large sum of regular wave components makes a frequency distribution, the wave spectra. A wave spectrum is a function of the vertical sea surface elevation and describes how the total wave energy varies in the sea state as a function of wave frequency [37]. The method is suitable for finding the most energy-intense wave frequencies for different sea states, which is essential concerning the structure's natural period. If they coincide, it can result in resonance and damage the structure, and whenever possible, the structure's natural frequency is shifted outside this wave frequency region[38]. When the frequency components of the waves become large, the wave spectra' definition is given in Equation (2-1).

$$S_{\zeta}(\omega_i) = \frac{1}{2\,\Delta\omega}\,\zeta_{a_n}^2 \tag{2-1}$$

$$\omega = wave\ frequancy$$
$$\zeta = wave\ amplitude$$

For an extensive record of waves available, statistical data can be computed. Measuring the amplitude of the waves for 30 min to 3-6 hours[39] results in a large sample of waves. The time record of 3-6 hours is determined as a short-term condition, as the period is a relatively short time period. The registration should be 100 times longer than the longest observed wave period [38]. The elevation samples are found to fit a Gaussian or normal distribution, and statistical values can be computed to describe the sea state. These are: the standard deviation or root mean square value, significant wave height H_s, peak period T_p and the up-crossing wave period T_z are obtained parameters. As a function of frequency, the properties in Table 2-5 describe the sea state. They are all computed from the moments under the wave spectra, given by equation (2-2) [38].

$$m_n = \int_0^\infty f^n S_\zeta(\omega)\, d\omega \tag{2-2}$$

ω is the wave frequency

n = 0,1,2… number of moments

m_0 - Zero-momentum. The area under the curve

m_1 - The first-order moment of momentum (static moment)

m_2 - Second-order moment (moment of inertia)

Table 2-5: Statistical properties in wave statistics [40]

Parameters	Formula	Description
σ	$\sigma = \sqrt{m_0}$	The root mean square of the water surface elevation.
H_s	$H_s = \sqrt{4m_0}$	Hs is the significant wave height. It is the average wave height of 1/3 of the highest wave.
T_p	$T_p = T_{m_{01}} = \frac{m_0}{m_1}$	The peak period, at which the wave spectrum has its maximum value.
T_z	$T_z = T_{m02} = \sqrt{\frac{m_0}{m_2}}$	The up-crossing wave period is the time interval between two up-crossings of the mean sea level.

The statistical value is used to find the expected wave heights. If the surface elevation obeys a Gaussian distribution, the wave amplitude statistics is likely to fit a Rayleigh distribution[38]. Rayleigh distribution gives the probability function of which the wave height H occurs by equation (2-3). [38].

$$f(H) = \frac{H}{m_0} \cdot e^{\left(-\frac{H^2}{2m_0}\right)} \tag{2-3}$$

The probability that a wave height h, exceeds a chosen threshold value H_{ω} is given by equation (2-4).

$$P\{h > H_w\} = 1 - P(H_w) = 1 - \int_0^{H_w} f(h) \cdot dh$$

$$P\{h > H_w\} = 1 - e^{\left(-\frac{h^2}{2m_0}\right)} \tag{2-4}$$

Standard wave spectra

Site-specific wave spectra are used in the design process to determine the responses on the vessel or construction. Standard wave spectra represent sea states in different geographical areas and estimate the frequency range in the desired area. Narrow banded spectra are a sea state built from waves with a narrow range of frequencies, and broad-banded spectra are built up from more comprehensive frequencies[38]. In the mid-ocean, where there are no coastal effects on the growth or decay of waves due to shallow waters, the sea state is shown to have a narrow-banded spectrum. These mid-ocean seas are usually fully developed with wind-generated waves, usually with a small period and amplitude [40].

The wave conditions in a sea state can be divided into two classes: wind seas and swell. Wind seas are generated by local wind, while swells are waves that have travelled out of the areas where they were generated. Wind and swell are combined in double peak wave spectra in the Torsethaugen wave spectra used for this thesis response analysis. Torsethaugen is a superposition of two Joint North Sea Wave Project (JONSWAP) spectra [40]. JONSWAP is frequently applied for wind seas for fully developed sea states in deeper waters [38]. It results from the North Sea measurements from 1968 to 1969 [38], hence Torsethaugen wave spectra build on wave data from deep-sea areas in the North Sea [40]. Torsethaugen represents a broad spectrum that can account for more significant responses caused by swell as the wind sea than a JONSWAP spectra. The input parameters for the spectrum are H_s and T_p [40].

2.4.2 Responses on a floating unit

The dynamics of rigid bodies are the combined action of the body's moments, inertia, and external forces[38]. The responses of a ship exposed to environmental loads are described with a response spectre, $S_z(\omega_i)$. The response spectre gives the responses for a marine structure in a short-term duration sea state, similar to a wave spectra. The systems response spectre is the transferer function of the wave spectre multiplied with the systems squared response amplitude operator (RAO) given in Equation (2-5).

$$S_z(\omega_i) = S_\zeta(\omega_i) \cdot [H(\omega_i)]^2 \qquad (2\text{-}5)$$

$S_\zeta(\omega_i) =$ Wave spectre

$H(\omega_i) =$ Response amplitude operator (RAO)

The response amplitude operator (RAO) also noted response amplitude characteristics and referred to a floating structure's response in six degrees of freedom. Surge, sway, and heave is the translation of the ship's centre of gravity in the direction of the x-, y- and z-axis. Roll, pitch and yaw are rotations about the axes [37][38]. Any ship motion is built up from these basic motions illustrated in Figure 2-10. RAO's are used as input data for calculations to define all linear responses. Linear responses are, for example, displacements, velocities, and accelerations used to identify forces acting on the structure or vessel. The derivatives of the displacements find the velocity and accelerations.

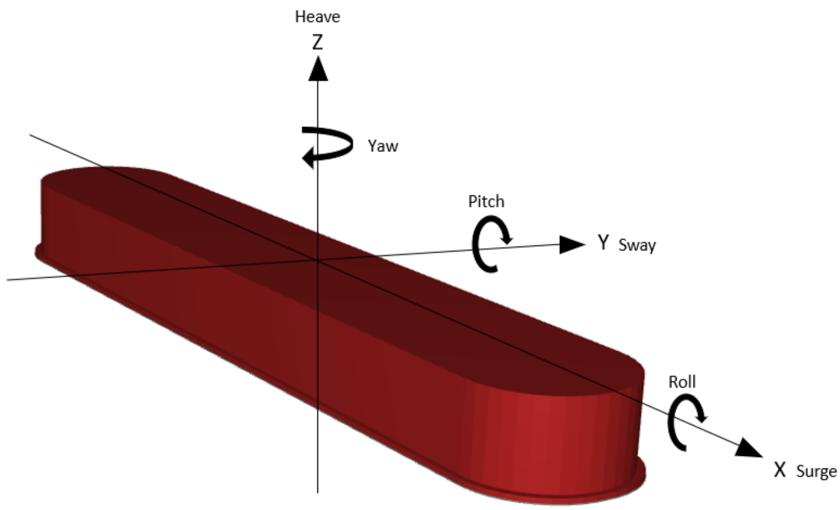

Figure 2-10: RAOs of a floating vessel in six degrees of freedom.

The response spectra built from the RAO and sea state give the wave frequencies that the structure is affected by. Large motions on an offshore structure occur when the response of the wave loads has the same frequency as the structure's natural frequency. This resonance can cause considerable damage to the structure and equipment. Offshore structures and their mooring systems are designed with natural frequencies shifted well outside the wave frequency range of the sea state [37]. The categorical natural periods of motions which affect the design philosophy of the FPSO are given wave period intervals in

Table 2-6, [39].

Table 2-6: "Typical natural periods of deepwater floater" by DNV [39].

Response variable	Natural Periods [seconds]
Heave	5-35
Pitch	5-12
Roll	5-30
Yaw	>100
Surge	>100
Sway	>100

The natural period of 100 s for yaw, surge and sway gives small motions related to these response variables, as the wave spectra usually do not have a peak at 100 s, thus, the most significant responses will occur for heave, pitch and roll.

The problematic motions on floating units are the vertical motions and accelerations. Accelerations determine loads on topside equipment and cargo, and vertical motions can cause slamming and water on deck, resulting in local damage to the structure. The process equipment on a floating unit may also experience limiting factors in operation due to roll and pitch [37]. Liquid sloshing in tanks may be a problem for ships handling liquid cargo. If the natural period of the fluid in the tank reaches the period of the ship motions, this can result in high local pressure and total forces in the tank. Combined with often slight dampening in liquid storage tanks, this is an essential factor in the design of topsides for offshore oil and gas process equipment [37].

3 Concept analysis

This chapter's concept and technology choices form the foundation for the area and weight analysis in chapter 4. This chapter will first define the concept's scope to be analysed in this thesis. Further, the chapter will present a technology review combined with an evaluation of the technologies in each step of the defined scope.

3.1 Scope of the concept

The scope is limited to hydrogen production, conversion, storage and offloading on the FPSO. It excludes analysing offshore wind potential and the distribution to shore, illustrated with system boundary in Figure 3-1. There is a significant market potential for ammonia and liquid hydrogen as marine zero-emission fuels. Consequently, the thesis's scope is limited to converting and storing hydrogen as liquid hydrogen and ammonia (Figure 3-1). Storing hydrogen compressed is considered irrelevant in this study because of the volumetric energy density (cf. 2.2.1).

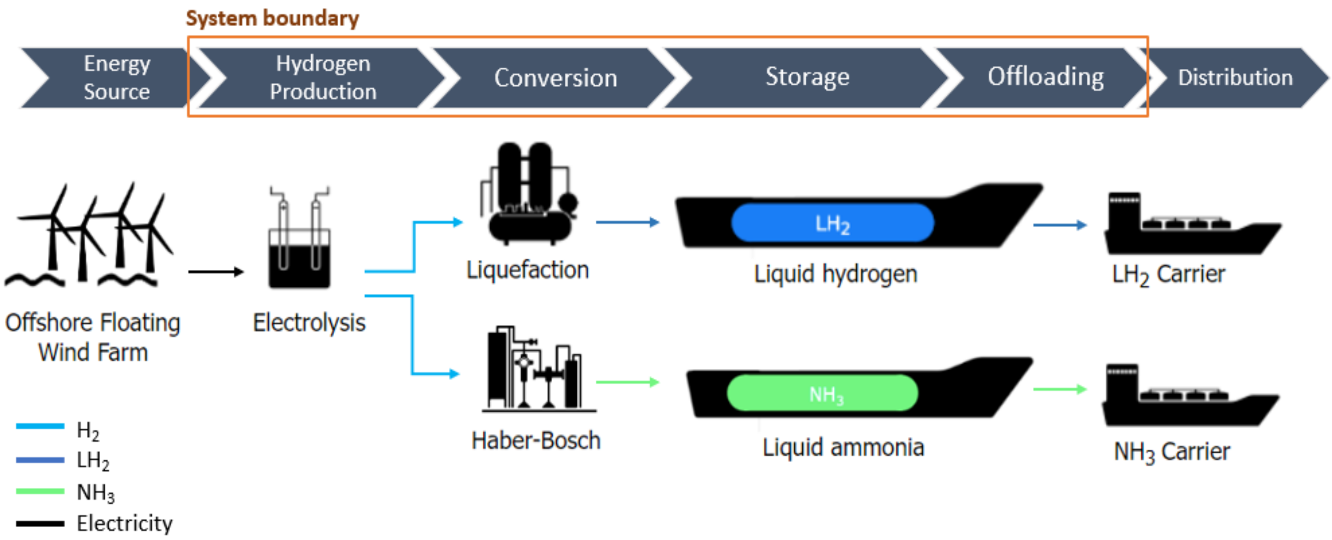

Figure 3-1: Offshore hydrogen production conversion and storage steps as liquid hydrogen or ammonia. System boundary defines the limitation of the scope of the thesis. Icons are provided by Greensight.

3.2 Location and production capacity

The location is essential for input parametria for the response analysis in chapter 5. The North Atlantic Ocean is chosen as it is an area with excellent offshore wind conditions. The North Atlantic Ocean has a wind capacity factor of 57% and is a geographical area of interest for the operation of offshore wind and hydrogen production concepts[41].

The environmental data are used for Statfjord oil and gas field and represent an area with typical Nordic conditions for deepwater (150 m)[42]. The distance from Statfjord to larger ports on the West Coast of Norway is 200-500 km (Port of Trondheim, Bergen and Stavanger) and around 1000 km to major ports of Europe (Port of Rotterdam, Antwerp). The location of the FPSO is relevant for transporting NH_3 and LH_2 to shore as the distance ought to exceed 150-250 km to be cost-efficient [12].

The concept considers large-scale production of hydrogen or commercial scale. Large-scale production has approximately 100 MW electrolysis capacity[34]. Hence, the scope considers a large-scale production size to be at least 100 MW electrolysis capacity. Meier found 100 MW to be economically feasible for hydrogen production in the north sea, supporting the scopes considered size (c. f. chapter 1.2) [8].

The concept is not designed for a specific location and a given wind capacity. It is assumed that the capacity needed for the total concept can be met with proper wind farm design. The limitation has been done to exclude the need to evaluate wind farm size for optimal plant operation regarding costs. For example, designing the total hydrogen production with a lower capacity than the maximum wind production.

3.3 FPSO Typology

The thesis analyses the concept of hydrogen production on floating production, storage and offloading units (FPSO). FPSOs have a large storage capacity and a large deck area to accommodate the hydrogen production equipment.

“Prelude” is the first commercial floating liquefied natural gas (FLNG) facility in operation[43]. Prelude is an example of placing a land-based production unit offshore. With inspiration from FLNG it is reasonable to assume hydrogen production can be placed offshore on an FPSO regarding motions, which is to be analysed in this thesis.

The design of the floating hydrogen production unit is to optimise floating offshore wind potential in deep waters [7]. The floating properties make it possible to change the location of the FPSO. Changing the location depending on optimal wind conditions can be relevant in a future scenario. To limit the scope, the concept in this thesis will consider a permanent located FPSO. Permanently is defined as permanently moored in a fixed location.

FPSOs applied in the North Sea are designed for harsh weather conditions. Responses from wind, waves, and currents result in motions on the process equipment on the FPSOs. Motions, in general, cause fatigue on the equipment. FPSOs in the North Sea must have optimal motion control to increase the operability and lifetime of the process equipment onboard.

The thesis will compare two FPSOs, to represent different layout and response characteristics that can be expected with distinct typology. The two concepts are a ship-shaped design by LMG Marin and a cylindrical FPSO design by Sevan SSP (Figure 3-2, Figure 3-3).

Figure 3-2: A ship-shaped FPSO by LMG Marin. The model shows the for act round fore-aft symmetric hull, mooring lines and topside, including accommodation, cranes, storage tanks etc. [44]

Figure 3-3: Cylindrical design of FPSO deployed in the sea by Sevan SSP. The model shows the topside and how the process equipment is distributed in several decks on the topside[45].

Ship-shaped FPSOs have acceptable motion characteristics if the FPSO lies along with the dominant wind and wave direction. This is possible if the FPSO has a single point mooring system (turret) which makes the vessel freely move around its bow or stern [38]. Turrets are considerable cost drivers on a floating unit, and aval architects avoid this mooring solution whenever possible [46]. If weather conditions allow it, a spread mooring system is usually the preferred mooring option. Spread mooring from four points holds floating units at a fixed position.

3.4 Technology review

This section reviews and evaluates the current hydrogen technology status for maritime applications. This is to understand the concept's maturity and choose technology for the area and weight analysis in chapter 4. The method for the evaluation is a literature review and interviews with field experts and equipment vendors. The review is supplemented with the status of relevant projects. The evaluation has been based on a colour code system (Table 3-3), where the colours categorise the readiness for offshore application. The sub-sections will present the resulting evaluation, and the base for the evaluation will be discussed.

Table 3-1: Evaluation criteria for technology review by colour.

Needs development for offshore application	Minor modifications of today's technology necessary for offshore application	Present technology suitable for offshore application

The technology is evaluated based on the technology readiness level (TRL) in the literature. TRL is defined by the EU horizon 2020 programme 2014-2015[47]. The relevant TRL levels to be discussed in the evaluation are described in Table 3-2.

Table 3-2: Technology readiness levels 5-9 defined [47].

TRL 5	Technology validated in a relevant environment
TRL 6	Technology demonstrated in a relevant environment
TRL 7	System prototype demonstration in an operational environment
TRL 8	System complete and qualified
TRL 9	The actual system is proven in an operational environment

3.4.1 Electrolysis

Electrolysis is the main component in hydrogen production. The electrolysis technologies PEM and ALK are compared to evaluate the best technology for offshore applications. Table 3-3 presents the parameters to be evaluated according to the colour codes.

Table 3-3: Evaluation of the electrolysis technology PEM and ALK for maritime applications. (Orange = Needs development, Yellow = Minor modifications, Green = Suitable for offshore application, cf. Table 3-1)

Evaluation cirterias	PEM Electorlysis	ALK Electorlysis
Ability to tackle variable electricity from wind		
Responses from the maritime environment		
Maintenance		
The footprint of the electrolysis system		
Desalination technology		

With soon to be pilot projects of offshore placement of electrolysis in wind turbines (cf. 1.3), the TRL is evaluated to 7 for offshore application. PEM and ALK electrolysis are technically ready to be placed in an offshore environment with minor modifications. The unsure parameter is the technologies ability to work in offshore motions. Most development is expected for remote operation of the offshore located electrolyser system.

Ability to tackle variable electricity from wind

The electrolysis technologies' ability to operate with variable input from wind power is essential for this concept. The electrolysers system must be flexible due to the varying input power. Flexibility can be defined as the electrolyser's ability to tackle flexible input electricity and short response time [23]. An electrolyser's ability to be flexible depends on the design of the electrolyser's Balance of the plant (BoP). BoP is the complementary system supporting the electrolyser stack, such as cooling or power handling[48][49]. For example, a 1 MW electrolysis system can consist of one large electrolyser or several smaller stack modules. A system consisting of several stacks and power handling systems is more flexible compared to a plant with one large electrolyser and a single power handling system.

Comparing PEM and ALK regarding flexibility, ALK is limited to work with less than 20% of the nominal load[21]. PEMs load range is from 0-100%. ALK can be improved by adding a battery [48]. Further conversion can also be a bottleneck for the flexibility of a hydrogen production concept since the total system might not be able to change its production rate as quickly as the electrolysers. One alternative is an integrated plant design with enough capacity to deal with production variability [48]. This can be batteries storing excess power or hydrogen storage before conversion. Multiple stacks and power supply units can increase operability. Few modules can still work when the capacity is too small for the whole processing equipment to operate.

To summarise, the evaluation yields the BoP of the electrolysis system is the most important regarding tackling variable energy. Hence, PEM and ALK electrolysis are both evaluated as suitable with varying electrical input on an FPSO. Relevant characteristics of ALK and PEM, some discussed and others to be compared, are presented in Table 3-4.

Table 3-4: Overview of characteristics of ALK and PEM electrolysis system [50], [31], [51][21].

Parameter	ALK	PEM
Load range as % of nominal load	20-100	0-100
Warm and cold start-up time*	1-10 min	1 sec – 5 min
Warm and cold shutdown time*	1-10 min	Seconds
Lifetime system	20 years	20 years
Electrolyte	KOH lye	Solid polymer

*a warm startup is defined as the start of the electrolysis system in the pre-heated state. A cold startup is from the ambient temperature. [21]

Responses from the maritime environment

In general, the electrolyser modules, despite technology, must be strengthened to resist the motions from an FPSO. This concerns fatigue resistance in the material because of repetitive periodic motions and environmental conditions. These challenges can be faced by ensuring sensitive equipment is located outside the splash zone and providing external cladding[52].

PEM and ALK have flowing water as input. ALK has an addiction to aqueous electrolyte KOH lye. Flowing liquid can go back and forth in the pipes when significant motion arises. The system must be designed to prevent the water flow in different directions, which can be done by inserting more vents, according to GHS[49].

A question raised is whether motions will affect gas flow in the electrolysers. If hydrogen gas molecules are not transported fast away from the cathode in PEM, this can slow down the production rate. PEM fuel cells are used in mobile hydrogen units, like cars and boats. Fuel cells in these units are experiencing significant motions and do not report limitations to these applications. It is logical to assume that PEMs operation is not affected by the expected level of motion arising on an FPSO. This is supported by ERM's conclusion for using PEM electrolysers in their floating wind turbine concept [52].

Separators are parts of the BoP. Motions within the separator can reduce the separator rate and, thereby, the speed of hydrogen production[49][53]. This can be expected in extreme weather situations. If this is a problem, the electrolysers can be designed to stop hydrogen production in particular sea states. In general, electrolyser vendors can adopt the electrolyser systems to these motions with minor modifications [49].

Maintenance

For electrolysis systems onshore, maintenance requirements are easily manageable. The trend in oil and gas production is autonomous platforms that operate without human attendance to cut operational costs. For electrolyser systems, this calls for the stacks to include sensors, monitors, and calibration systems to be fully autonomous[53]. An autonomous electrolyser unit must also be rugged and stable to fit in offshore systems without daily maintenance. An example of this is the electrolysers' ability to deal with ice formation, which can occur in a northern climate, and material properties to withstand extreme weather and corrosion from saltwater. Covering the electrolyser in a building or container could be a solution.

Stack replacement is a case for both PEM and ALK. In ALK, the corrosive liquid electrolyte has a need for periodic renewal because the electrolyte reacts with impurities in the water leading to corrosion of the electrolyser [54]. With cleaning cycles and changes of the electrolyte, the ALK electrolysers can recover. Pressurized ALK has a lifetime of 20-years and an expected stack replacement after 10-years. Stack replacement is done in 3-hours[49]. PEM suffers irreversible long-term damage from impurities in the water[54]. For a PEM electrolyser, the required stack replacement is once every ten years [52]. It is a scheduled low maintenance activity, with equipment calibration requirements per six months [52]. The lifetime of the electrolysers is expected to increase with additional development. Because of maintenance requirements, PEM and ALK are evaluated as yellow because they both need development towards an autonomous operation.

Desalination technology

Desalinisation technologies are evaluated with high maturity for offshore application because it is applied offshore today. The required purity of the electrolysers is higher than the purity of drinking water. Sea water must therefore be purified through several steps. The purity requirements for PEM electrolysis are higher than for ALK, PEM typical < 10 parts per million (ppm) and ALK, typical 200-500 ppm[42]. A challenge to address is the environmental perspective of brine disposal as residual products from sea water desalinisation. If the concentrations are getting too high for the marine environment, the brine must be stored on the FPSO and discharged in other ways.

The footprint of the electrolysis system

The solid electrolyte in PEM features a more compact modular design and can operate at higher current densities for the same operating efficiencies [54]. ALK has a liquified electrolyte, KOH lye, including KOH lye feed and a storage tank. The KOH handling system adds weight and footprint to the alkaline module. On the other hand, the pressurized ALK electrolyser is smaller due to the pressurized system. Pressurized ALK provides a comparable footprint with PEM.

IEAs have estimated the plant footprint of electrolyser technologies to be 95 m^2/MW for ALK and 48 m^2/MW for PEM [4]. Dimension of the pressurized ALK system provided by GHS result in 45 m^2/MW, but represents only one provider of pressurized ALK. Megawatt modules for PEM and ALK electrolysers are steadily developing with better efficiency predictions, footprint, dimensions, and weights. This is because of the increased interest in large-scale electrolyser production[9].

Today's pilot projects, mostly on decentralised concepts, choose PEM technology for its size[55]–[57]. However, future large-scale applications of PEM will have a challenge regarding PEMs Platinum catalysator. The increasing demand for platinum for the green transition will increase costs for PEM[48].

3.4.2 Liquid hydrogen conversion and storage

The evaluation of the liquid hydrogen conversion process and storage technology for offshore application is presented in Table 3-5.

Table 3-5: Evaluation of liquefaction conversion and storage technology for maritime applications. (Orange = Needs development, Green = Suitable for offshore application, cf. Table 3-1)

Evaluation criteria	Evaluation	Comments
Liquefaction process		Large scale LH_2 conversion needs to be developed
LH_2 storage		Demonstrated in a pilot project

In the evolution of LH_2 plants towards large scale application on an FPSO, the liquefaction process must be developed toward large scale production capacity. LH_2 storage is evaluated as TRL 9 as it is demonstrated stored on a ship.

Liquefaction process offshore

Liquid hydrogen conversion and storage consist of a liquefying process and cryogenic storage tanks. The system includes compressors and a cooling loop. The hydrogen liquefaction process is mature but has not been applied to FPSOs or other floating units [58]. But according to Charts Industries, no components of the liquefaction process are sensitive to motions from a floating unit[58].

The FPSO is supplied with variable wind, and the liquefaction process must comply with the variable input of electricity. The liquefaction process must also comply with variable hydrogen supply because of the variable load on the electrolysers. According to Chart Industries, the compressors are the bottleneck in the liquefaction process. The compressors included in the process can operate at 50-100% of the maximum capacity[58]. Hence, a liquefaction process is flexible variable energy and hydrogen supply, but not as flexible as the electrolysers. Dividing the plant into several sections makes it possible to secure redundancy of the system when the wind power supply is insufficient for 50% operation capacity or when maintenance is requierd[58]. The compressors need maintenance after 25000 hours, and the service period lasts for at least three weeks[58].

Storing hydrogen compressed between the electrolyser and the liquefaction can be another solution. For this solution, a compressor is needed. The best solution must be assessed regarding the operation time of the entire plant and cost analyses.

The limitation in the liquefaction plant for the offshore application concepts is the “large-scale” capacity. Today's largest liquid hydrogen production is 34 tons/day [59]. With a production capacity exceeding 50 tons/day, the present system's compressors will most likely be replaced with turbo-compressors[58]. The turbo-compressor will improve the efficiency and give compression closer to the isothermal optimum [26]. Research and interest in the lagre-scale production of LH_2 among customers are needed to develop liquefaction plants exceeding 50 tons/day [58]. Because of the need for developing the evaluation is “Needs development for offshore application”.

Liquid hydrogen storage offshore

Liquid hydrogen and ammonia must be handled in tank containment systems that can handle pressure and keep the temperature low[5]. Large scale storage of hydrogen is done today, NASA operates the largest LH_2 storage vessels, containing 230-270 $tons_{LH2}$[60]. This scale of storage tanks LH_2 storage tanks has less than 0.1%/day boil-off because of the low surface-to-volume ratio [60]. The boil-off can in the FPSO system be refrigerated if the gas is led back to the refrigeration process. Boil-off can be because of motion inside the tank (sloshing), increasing thermal energy[23]. Boil-off is not considered a problem with a proper system for ventilation and refrigeration of the vaporised hydrogen.

There is one LH_2 carrying ship, a large scale pilot project in operation between Australia and Japan. The H_2 carrier has a tank of IMO type C tank integrated as part of the hull and contains 1250 m^3[61]. A tank Type C is a cylindrical tank designed for pressure handling[5], [62]. Another LH_2 carrier concept by C-Jobs plans to transport LH_2 on deck in spherical tanks with a total capacity of 37500 m^3 [63]. DNV approved June 2021 a new type of storage, a membrane-type containment [64]. Lloyd's Register approved a similar technology for a 50 000 m^3 LH_2 storage tank for a ship developed by Lattice Technology [65]. The approval of principle (AiP) confirms the design as feasible for the prismatic closed volume handling patent for LH_2 as cargo on ships. According to LMG Marin, the membrane tank system is more volume effective than the type C pressure tanks because of the shape, safety distances, and storage capacity[46].

The technology status of LH_2 storage tanks is reviewed to evaluate the TRL level of large scale LH_2 handling on FPSO. TRL is evaluated as 9 for type C tanks and TRL 5 for prismatic membrane-type tanks as it is not demonstrated. The type C tanks are used in the analyses over the prismatic.

3.4.3 Ammonia conversion and storage

The evaluation of the ammonia conversion process and storage technology for offshore applications is presented in Table 3-6. Ammonia processing offshore is evaluated as feasible. Both conversion and storage are mature technologies, possible for large scale.

Table 3-6: Evaluation of ammonia conversion and storage technology for maritime applications. (Green = Suitable for offshore application, cf. Table 3-1)

Evaluation criteria	Evaluation	Comments
Ammonia syntheses process	Green	Can be optimised for production with variable power and feed of hydrogen and nitrogen.
Ammonia storage	Green	Mature technology

Ammonia conversion offshore

Similar to hydrogen liquefaction, the ammonia synthesis plant has not applied to an FPSO. The ammonia synthesis process studied in this concept is electrically driven ammonia production. The general equipment of conventional ammonia processes of steam reforming and partial oxidation [66] is the same as the electrically driven process. It consists of heat exchangers, reactors and pumps, similar to equipment placed offshore today. The equipment of an ammonia plant is assumed to be similar to general equipment included at an oil and gas handling FPSO. Hence, assumed suitable for regular motions on an FPSO. Large scale application of ammonia plat offshore is not a problem compared to hydrogen liquefaction. Onshore ammonia plants have a 1000-1500 tons/day production scale much larger than expected on FSPO (cf. chapter 4.3) [66].

Conventional ammonia plants are designed for 330 days of yearly production [66]. A plant has, on average, 5.7 shutdowns a year due to technical failures and the start-up after a shutdown takes several days [66]. This is a disadvantage if significant motions on the FPSO cause shutdowns.

Nitrogen is the main feed in the ammonia synthesis, derived from the air by a separation unit. Large-scale nitrogen production plants typically consist of liquefaction and separation synthesis units [66]. In a study by Morgan et al. of an ammonia plant for offshore wind, cryogenic air separation was selected as the suitable nitrogen generator. [66]. The concept has a TRL of 9 [67].

Variable energy supply could result in fluctuations in hydrogen feed from the electrolysers and nitrogen supply [66]. This may be a problem because ammonia plants are designed to run on constant pressure and temperature continuously for the entire lifetime[66]. A possible solution to this challenge is buffer tanks between the hydrogen and nitrogen processes and ammonia synthesis processes. A comparison by Rouwenhorst et al. found that the overall system efficiency of ammonia plants without batteries was 57%, compared to 66% for plants with batteries [67]. This shows that an FPSO should account for batteries to increase the efficiency when supplied with variable wind electricity on an FPSO.

On the other hand, Haldor Topsøe, a developer and provider of ammonia plants, stated that variable energy support is not a problem, as they have ammonia plants' designs that handle fluctuations in hydrogen and nitrogen supply[34]. Their technology can work on 10-100% of maximal load without the need for hydrogen or power storage. For a 0-100% load range, the ammonia plant must include batteries and hydrogen storage [34]. In combination with Solid oxide electrolysis technology (SOEL), the efficiency of the ammonia processing can increase by 30% when combining the waste heat from the ammonia synthesis for steam production for the SOEL[34]. Future analysis of optimised operability of an ammonia conversion system on an FPSO should consider SOEL, but not included in the scope of this theis.

Ammonia storage

The main advantage of storing and transporting ammonia is the well-established global distribution network and regulations for ammonia handling compared to hydrogen[24]. Ammonia is globally shipped in fully refrigerated or standard semi-refrigerated gas carriers at -33.33 or 20 degrees [34]. Storing ammonia in a state between liquefied and compressed is beneficial because low-cost storage tanks can be used while maintaining the volumetric density[24]. For this option, ammonia can be stored at ambient temperature but pressurised, still requiring type C tanks, as for LH_2 without the need for liquefaction of the ammonia[34]. On the other hand, Hansen[35] also found the leak rate six times higher for pressurized ammonia compared to refrigerated. A leakage from ammonia can be fatal because low ammonia concentrations are toxic. Because of the safety aspect and the volumetric density, storing ammonia liquid in type C tanks is considered a reasonable solution for an FPSO.

According to Alfa Laval, Hafnia et al., type C pressurised tank for ammonia is a flexible installation which can be integrated into the consolidated design of commercial ship designs[34]. When storing ammonia refrigerated, heat transfer to the tank will lead to some boil-off [66]. A compression-refrigerator loop can restore the vaporized ammonia to return ammonia to the liquid storage tank [66].

Because the ammonia distribution network by ship is well established, storing large scale ammonia is evaluated with TRL 9, suitable for application in FPSO.

3.4.4 Offloading

Offloading concerns transferring liquid hydrogen or ammonia to a receiving vessel that ships the cargo to shore. A good technical solution for offloading is essential in distributing LH_2 or NH_3 with ships to shore. Hence an essential part of the offshore hydrogen production concept's ability to complete. The evaluation of offshore offloading technologies for LH_2 and NH_3 is presented in Table 3-7.

Table 3-7: Evaluation of offshore offloading technology for liquid hydrogen and ammonia. (Orange = Needs development, Yellow = Minor modifications, cf. Table 3-1)

	Evaluation criteria	Evaluation	Suitable offloading technology
LH_2	(Orange)	Less flexible line Isolation and cooling Low offloading rate	Ship-to-ship
NH_3	(Yellow)	Higher offloading rates than LH_2 Can use existing offshore technology with minor modification	Ship-to-ship Platform-based

The best offshore solution of offloading technology for LH_2 is evaluated as the ship-to-ship solution because of the short transfer lines compared to the other solutions. NH_3 has fewer limitations when it comes to adopting existing offloading technologies. The concept from HiLoad is feasible for NH_3 for sea states up to 4 m and can be a suitable solution.

Offshore offloading systems are designed for an acceptable offloading rate for large amounts under normal operational weather and wave conditions[41]. The offloading methods for NH_2 and NH_3 are assumed to be developed toward the well-known offshore offloading technologies. Sæbø et al. have found the offloading technologies that are most likely to be adopted for NH_3 and LH_2 as a Single Anchor Loading system (SAL), a platform offloading, and a ship-to-ship transfer solution [41]. These technologies are used in the operational sea state with 4-5.5 m significant wave height. SAL's central elements are flexible riser and mooring anchored to a single seabed anchor[41]. When offloading with SAL, the receiving vessel can favourable the position in relation to the wind, current and waves. The risk of collision between vessel and platform is low with SAL as the anchor is located at a proper distance from the platform.

In a ship-to-ship offloading method, the receiving ship will connect to the side of the FPSO with fenders or a mechanical arm which holds them in position for the offloading hose to connect[46]. The receiving ship can also connect to the FPSO in tandem with a hose in the bow of the ship, called a bow loading system (BLS) [41]. Bow loading requires reels for handling the offloading hoses on the FPSO.

A platform-based solution must have an additional floating offloading platform beside the FPSO for handling the hoses. Such solutions are to be deployed for ammonia bunkering systems developed by Econnect[68] and HiLoad [69]. The method of offloading with HiLoad is called "tandem offloading" and can be used in sea states up to a significant wave height of 4 m[69]. The required safety distances between the FPSO and receiving vessel offloading hoses is ~150-160 m [69]. Floating platform-based and ship-to-ship transfer offloading have a higher probability of collision between the vessels and require a dynamic positioning system. "Tandem Offloading" provides enhanced safety compared to side-by-side loading [69]. The safety aspects of each solution should be evaluated together with technical feasibility.

Figure 3-4: Offshore offloading concept for LNG from Cylindrical FPSO. The offloading vessel, "HiLoad" connects to the side of the receiving ship when loading LNG from the cylindrical FPSO [69].

An essential aspect of offshore offloading is the dimension for the responses from the harsh offshore environments. Offloading lines must be designed for responses from the receiving vessel and the FPSO on the other end. The lines must include Emergency Release Couplings and Break-Away Couplings to limit spill if drift scenarios[41]. The offloading rate should be dimensioned for most operational time, meaning it can offload the needed volume in a sufficient weather window (max 4-5.5 m Hs). According to Sæbø et al., a sufficient offshore offloading system should be able to transfer the required volume in 1-1.5 hours because the sea state may change in 1.5 hours [41].

There are no established methods for offshore offloading of liquid hydrogen or ammonia[41]. Some companies have been announced in the latest year, specialising in bunkering solutions (shore-to-ship) for hydrogen and ammonia [68][70][71]. Bunkering technology has several similarities to offloading technologies. Offshore offloading must be developed for higher offloading rates and more motions. The evaluation is based on land-based bunkering technology because offshore NH_3 and LH_2 offloading are non-existing.

Safety proportions are the primary concern when offloading, where leakage and spill are critical parameters. The main difficulty of LH_2 offloading is the cryogenic properties. The hoses must be kept at -253°C to prevent boil-off, resist cryogen embrittlement and be flexible to resist fatigue from motions[60]. Moss Maritime did a conceptual design for a bunker vessel for liquid hydrogen. The design philosophy with a design philosophy to minimise heat loss in the transfere achieved by using vacuum insulated piping and short offloading hoses [72]. The procedure reducing loss of LH_2 offloading included draining the hoses to prevent clogging from frozen air and precooling with liquid nitrogen[72].

To minimize the heat loss in the transfer, a ship-to-ship system is a good alternative to offload LH_2 as the receiving vessel connects side-by-side. SAL and Platform offloading would require longer hoses and are assumed to be less suitable for LH_2 offlaoding[41]. A ship-to-ship transfer system adapted from LNG technology was confirmed by vendors that it could be adopted for LH_2 requierments[72]. Modifications of LNG equipment yield higher isolation criteria and material less susceptible to hydrogen embrittlement[75][42].

The offloading rate is another concern. The LH_2 bunkering concept by Moss Maritime has announced a loading rate of 42 tons/hr [72]. The offloading rate is too inefficient for the large scale volumes to be transferred within 1.5 hours. Offloading concept must increase the offloading rate by including additional pumps and offloading hoses.

Ammonia is a well-established value chain, with 120 ports equipped with ammonia bunkering equipment for import and export [34] and the technology readiness level is evaluated as TRL 9. According to the industrial review by Alfa Lava et al., ammonia bunkering operations are very similar to other gaseous fuels, except ammonia is toxic. Adoption of the LNG ship-to-ship solution for ammonia will require a quick availability of ammonia as fuel, according to Alfa Lava et al. [34]. This is supported by the two newly awarded "approval in principle"(AIP) for ammonia bunkering vessel designs for ship-to-ship bunkering in 2022[73]. Hence, the ship-to-ship technology can be expected for offshore ammonia offloading. Platform-based offloading can also be a solution as the Econnect and HiLoad are developed for LNG. SAL solution is less likely because of longer offloading lines. Trelleborg emphasises that hoses need more adaption for LH_2 handling than ammonia[41]. Sevan SSP confirmed that hose vendors had confirmed that offshore hoses were verified for ammonia transferring[74].

The higher density will obtain higher offloading rates of ammonia than LH_2 [41]. Offloading rates for ammonia have not been found. Assuming the offloading rates for LNG technologies are adapted to NH_3, an offloading rate of 5000 m^3/hr can be expected with the HiLoad platform based offloading system[69].

Ammonia offloading technology used on an FPSO is the most technical mature solution. LH_2 is found feasible, but there are currently no commercially available concepts. LNG technology is committed and can adopt for LH_2 use but cannot directly be used. Therefore, the evaluation is that LH_2 offloading technology for offshore use requires more development than NH_3 to be deployed.

3.4.5 Power handling

Power handling is essential to evaluate for several hundred MW to be supplied to the FPSO. Power handling is defined as the power cables connected to the FPSO, the electricity transformers and converters needed to supply the required electricity to the production processes. The power handling system and cables from the floating wind farm are evaluated in Table 3-8.

Table 3-8: Evaluation of technology for power handling on the FPSO. Yellow = Minor modifications, cf. Table 3-1

Evaluation criteria	Evaluation	Comments
Power handling system	Yellow	Heavy and large transformers.
Dynamic cables for floating offshore wind	Yellow	Proven technology, but not between wind turbines and FPSOs.

Most wind turbines generate Direct Current (DC) electricity at approximately 0.69 – 1 kV. Before the electricity is transmitted to shore, it is converted into Alternating Current (AC) and then transformed to a higher voltage level by a so-called step-up transformer. New offshore wind farms have an internal voltage level of typically 66 kV compared to land-based based wind farms with a voltage level of 33 kV [75].

When transferring high effects, a high voltage is used to minimise the resistance in the cables. In discussion with Aabø Powerconsulting, an FPSO with large-scale production, the supplying electricity cables are most likely to be high voltage AC cables to avoid losses [76]. The number of 132 kV AC cables from the wind farm depends on the concept's power consumption. At the FPSO, the electricity is transformed from 132 kV to 10 kV to meet the input voltage for the different sub-systems. The power handling system at the FPSO includes the intake of cables and an electrical housing which contains the transformers and converting system illustrated in Figure 3-5. Converter equipment for each sub-system typically demands a 1 kV AC supply before converting to DC [76]. Electrolysers have a feed voltage of 400 V DC according to the report from the North Sea Wind Power Hub [75], which is the same calculated input power in the Behyon study [10]. Considering that 132 kV AC will supply the FPSO, and the voltage will need to be transformed in two steps. This is because there are no transformers in today's market that can transform 132 kV to 1 kV, according to Aabø [76]. This means that twice as much transformer capacity must be installed compared to the actual. Typically, the transformers can transform down to as low as 10 kV, and further transformers will transform from 10 kV to 1 kV (Figure 3-5).

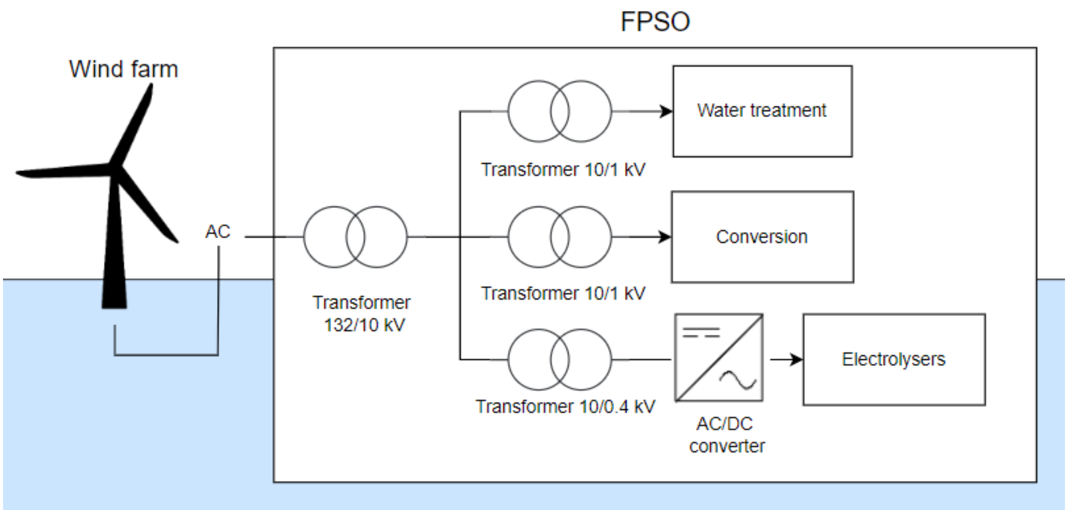

Figure 3-5: Power system onboard the FPSO. The system includes a transformer and AC/DC converter for the electrolysers.

A challenge that must be addressed is the weight and area demanded of the transformers, the cable handling system and switchgear onboard the FPSO. The FPSO must be dimensioned to handle the cable intake and transformation onboard. The consortium "Behyond" has designed a centralized offshore platform with 200 MW electrolysis capacity[10]. Behyond designs for 66kV cables from the windfarm with further transformation 66/10 kV and 10/1 kV to the different process equipment[77]. The 66/10 kV provides a smaller footprint, height, and weight than a 132/10 kV transformer[76].

Since the electrolysers use DC and count for a large percentile of the power consumption, a question to be addressed is the possibility of using the generated DC current directly from the wind turbines, excluding the DC to AC conversion before transferring it to the FPSO. The FPSO must then have the DC transformer 66/0.4 kV to supply the electrolysis system. Other equipment on the FPSO, such as lighting, requires AC. Hence the FPSO must include a DC to AC converter. According to Aabø, high voltage supply from the windfarm means heavy and area demanding DC/AC transformers. High voltage is also challenging for DC transformers as the losses increase. A possibility is to have wind turbines generating lower voltage more suitable for the FPSO, or a 50/50 supply of AD and DC to the FPSO. A comparative cost and technical analysis must be done to find the most suitable solution.

The transmission cables from the wind farm are to be connected to a floating unit, which in turn means that dynamic cables must be utilised. These must have sufficient fatigue endurance to handle the environmental loads from waves and currents during their lifetime. Dynamic cables are a proven technology for 66 kV cables [78] in constructed floating wind farms in Scotland and the upcoming Hywind Tampen located in The Norwegian North Sea. With further development around floating wind, especially in Norway, it is found reasonable to evaluate dynamic cables with TRL 9.

If the concept is to consider higher voltages, the issue concerns material with good fatigue endurance and protection from moisture ingress, according to DNV [78]. The powerlines should have separated connection points and a battery for variable energy supply from the wind farm to secure the system's redundancy. The location of the cable handling system on the FPSO should be accessible for maintenance and possibly replacement[76]. The regulations rule that high voltage cables cannot go through cargo rooms connected hence and the cables is assumed will be connected to the side of FPSOs [74], illustrated in (Figure 3-6, Figure 3-7). This means the deck area does not need to include cable handling.

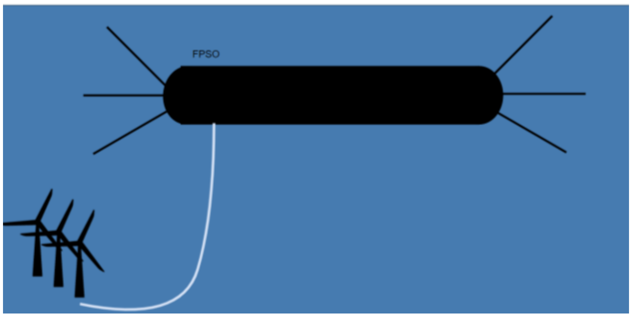

Figure 3-6: Cable intake and mooring on ship-shaped FPSO.

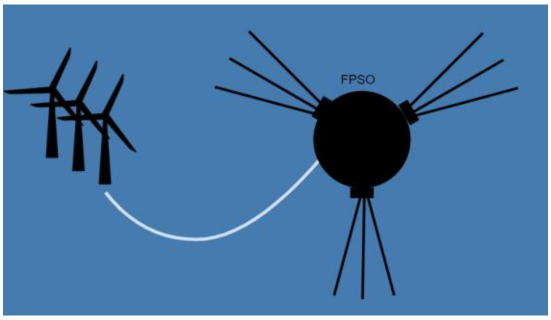

Figure 3-7: Cable intake and mooring on cylinder FPSO.

3.4.6 Summary

A summary of the technical review can be seen in Table 3-9. Storing hydrogen liquefied requires more technology development for offshore applications compared to ammonia. This yields both conversion and offloading technology. Power handling systems are assumed to need minor modifications to be implemented. The GHS as a vendor of electrolysis technologies, Charts Industries representing LH_2 technologies and H2Carriers for NH_3 conversion all had in common little or no knowledge of limiting criteria for their equipment exposed for motions. This emphasises the need to provide knowledge of what motions the equipment can experience on an FPSO and must be designed for.

Table 3-9: Summary of technical review. Orange = Needs development, Yellow = Minor modifications, Green = Suitable for offshore application, cf. Table 3-1

Technology	Technology sub-systems	Evaluation
Hydrogen production	PEM Electrolysers	Green
	ALK Electrolysers	Green
	Water desalination	Green
Liquide Hydrogen	Conversion	Orange
	Storage	Green
Ammonia	Conversion	Green
	Storage	Green
Offloading	LH_2	Orange
	NH_3	Yellow
Power handling	cables	Yellow
	Transformers and converters	Yellow

4 Area and weight estimation

Significant factors in the design of maritime applications are the size and weight of the process equipment. The structure must be able to bear the equipment at the topside and maintain stability. Hence, weight and size are essential factors in the design of an FPSO [41]. This chapter estimates the area and weight based on the evaluated equipment from the technical review. Area estimations are further used to calculate the expected production capacity and the weight estimates provide input for the response analysis in chapter 5.1.2.

4.1 Method

The area and weight estimations aim to give a quantitative assessment of maximum FPSO hydrogen production capacity. The method of area and weight estimates is data collection based on the literature review in the previous chapter. In the absence of data on weight and dimensions from the literature review, the method has included collecting data from collaborative industrial partners: *Behyond, Charts Industries, North Ammonia, H2Carrier* and *Yara*. The method of calculating the maximum production capacity is to scale the area estimates for large production capacities and compare the resulting plant size to the available deck area on the FPSOs. An area layout of the FPSO process deck has been made to ensure the results. The storage volumes for the resulting capacities are further analysed regarding storage capacity in the hull of the FPSOs.

4.2 Area and weight analysis

This chapter's results and discussions are divided into two parts. Firstly, the area and weight estimates are analysed in this sub-chapter. Secondly, the resulting production capacities of the FPSO are presented and discussed.

4.2.1 Area and weight estimates

The area and weight estimates have been grouped into four modules (Figure 4-1): production, conversion, storage, and offloading. The hydrogen production module includes the electrolysis, power handling and water treatment system. The conversion system includes the process equipment for hydrogen liquefaction or ammonia synthesis. It is assumed that all modules except storage tanks are placed on the main deck of the storage tanks.

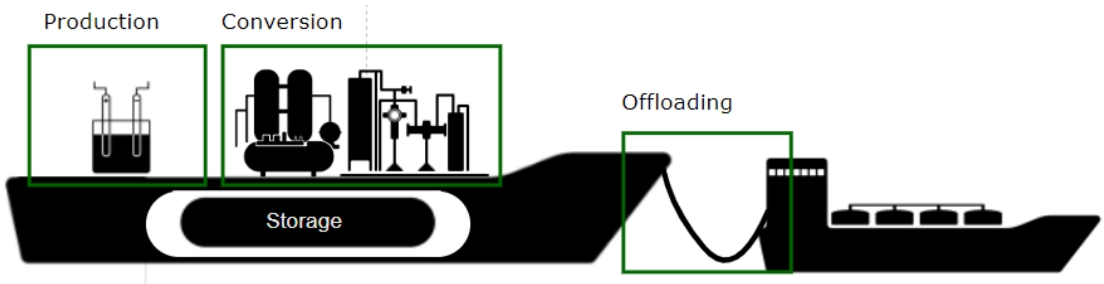

Figure 4-1: Modules for the area and weight estimates. On deck: production, conversion and offloading module. Storage is in the hull of the FPSOs.

The modules' resulting area and weight estimates are presented in Table 4-1.

Table 4-1: Area and weight of the hydrogen production concept with LH_2 conversion and storage.

Modules	Systems	Area	Weigh
Production	Electrolysis	47.7 m^2/MW	17.8 tons/MW
	Water treatment	2.7 m^2/MW	1.3 tons/MW
	Auxiliaries	1.8 m^2/MW	1.1 tons/MW
	Power handling	1.3 m^2/MW	1.0 tons/MW
LH_2 Conversion	Compressors	3.7 $m^2/tons_{LH2}$	125 tons/ 10 tpd [a]
	Liquefying ColdBox	5.6 $m^2/tons_{LH2}$	
	Auxiliaries	26.5 $m^2/tons_{LH2}$	
NH_3 Conversion	ASU	1.7 m^2 /100 MW [b]	180 kg/ $\frac{Nm^3}{h}$
	Haber-Bosch	31 m^2/MW[c]	3300 kg/ $\frac{NH_3}{day}$
Storage	Type C tank	cf. chapter 4.3.3	0.16 $tons/m^3$
Offloading	Ship-shaped FPSO	320 m^2	-
	Cylinder shaped	160 m^2	-

[a] The total weight of the LH_2 module increases 125 tons for every 10 $tons_{LH2}$/day production capacity. See section 4.2.3.

[b] 1.7 m^2 each 100 MW increase in electrolysis capacity.

[c] m^2 each MW of electrolysis capacity.

In addition to the presented area, additional areas are accounted for in the total area analysis. These are 200 m^2 for the explosion wall, 200 m^2 for accommodation building for maintenance workers, 300 m^2 for safety and muster areas [41], and an "unidentified area factor" of 1.1. These areas are the same for all scaling, thus weight is not accounted for in these areas.

The absence of data and comparative literature is emphasized in this analysis. It must be mentioned that since it is the first time this kind of analysis has been done, the result yields many uncertainties, simplifications and limitations, which have been essential in the initial phase of this concept. The area and weight estimates for each module are further presented and discussed in the following sectiones.

4.2.2 Hydrogen production module
Electrolysis system

A small and effective electrolyser module suits an FPSO with a limited deck area. The technology review (cf. chapter 3.4.1) compared the PEM and the alkaline electrolysis technologies and found both suitable for offshore use. PEM, in general, presents a smaller size and weight [4] and combined with more available data on dimensions, PEM electrolysers are chosen for this analysis.

The PEM electrolyze system modules for outdoor applications are typically delivered in 20" or 40'' containers, including all required sub-systems for sufficient hydrogen production, but different vendors and technology lead to variants im the module's size and layout. The dimensions of the PEM electrolysers for the concepts are based on the Hylyzer-100 containerized solution by Cummins (Hydrogenics). In the study *Hybalance*, a layout of a large scale 20 MW PEM electrolysis outdoor plant was presented (Figure 4-2) [79]. These dimensions are used to estimate the electrolysis system for the FPSO concept. The plant consists of 4 x 5 MW electrolysis modules, cell stack and the balance of plan, desalination system, control panel, roof cooling and compressed air [79]. The 20 MW system is 41.5 m long and 23.0 m wide, including the safety distances between each container and sides (Figure 4-2). This resulted in 47.7 $\frac{m^2}{MW}$.

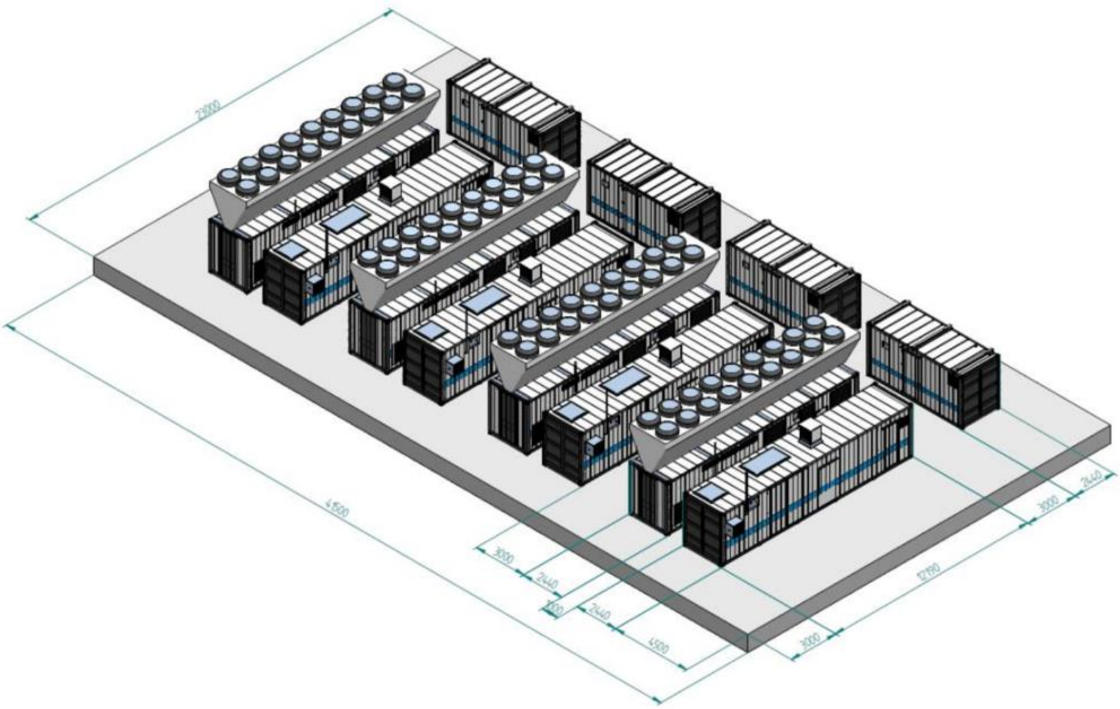

Figure 4-2: 20 MW PEM plant by Hydrogenics as part of the study *Hybalance*. From [79].

This electrolysis estimate coincidence with the predicted PEM footprint by IEA of 48.0 $\frac{m^2}{MW}$ [4]. The area estimate for the electrolysers includes the safety distances from the layout because they will most likely be the same offshore. The containerised system is chosen to protect from salt, ice formation, and other weather conditions. A building can also be a solution, but containers may be more accessible for maintenance if defective containers can be removed directly from the deck.

Desalinisation and balance of plant

An offshore electrolysis system includes a desalinisation system and additional sub-systems for an optimal plant operation (Balance of Plant, BoP). The thesis has been provided data from a study on a centralized offshore platform with PEM electrolysis and BoP by the consortium “Behyond” [10]. They have provided weight and dimensions on their system engineering of the plant, including seawater pumps, power handling units, cooling systems, control units, battery packs for peak shaving, and nitrogen generators for the purging process[77]. The provided data has been used for area and weight estimates of the BoP and desalinisation system. They are grouped into “water treatment” and “auxiliaries”. The water treatment includes the desalinisation unit, water filters, cooling systems, and buffer water tanks. It has a resulting area of 2.7 $\frac{m^2}{MW}$ and weight of

$1.3\ \frac{tons}{MW}$. The auxiliaries group includes a control room, a nitrogen generator for purging, a backup battery for peak shaving and pumps for seawater intake. The area and weight of the auxiliaries group resulted in $1.8\ \frac{m^2}{MW}$ and $1.1\ \frac{ton}{MW}$.

The power system

The power system includes transformers and converters. Switchgear and other power handling system are outside the scope. In the Behyond study, the provided data on the total power system for a 200 MW electrolysis capacity platform is calculated to have a footprint of ~280 m^2, including an AC to DC converter[77]. This is for 66/10 kV transformers. Sevan SSP has provided input based on their designs of substations for offshore wind containing. Their estimates include 66/10 kV transformer and AC to DC converter with the dimensions of 18 m x 14 m and a weight of 200 tons [74]. Based on Behyond's and Sevan SSPs input, the resulting area of the power system is 1.3 m^2/MW. It is assumed that the different equipment will have its own transforming system to supply power at the correct voltage (10/~1 kV) and is not included in the area estimate.

The weight is estimated to be 1 tons/MW by Sevan SSP [74]. The weight estimate does not include the cable handling connection points.

In the technical evaluation in chapter 3.4.5, it was found that the FPSO should be supplied with electricity through several 132 kV AC cables [76]. The power system area is based on the 66 kV estimates from Sevan SSP and Behyon because it represents a comparable estimate. It is evaluated that transforming 132/10 kV will require some increased footprint compared to larger sized transformers than for 66/10 kV. Since more data were found for the 66 kV power system, and since the power system only accounts for a fraction of the total size of the FPSO area, the estimates are found reasonable for this thesis.

Discussion and Summary of the hydrogen production module

The area and weight estimates of the different sub-systems in the hydrogen production module are summarised (Table 4-2) and following discussed. (The same estimates as presented in Table 4-1).

Table 4-2: Area and weight estimates for the sub-systems included in the hydrogen production module.

Hydrogen production module	Area estimates [m^2/MW]	Weight estimates [tons/MW]
Electrolysis system	47.7	17.8
Water treatment	2.7	1.3
Auxiliaries	1.8	1.1
Power handling	1.3	1.0

When using the estimates to calculate the size of large-scale capacities, it assumes linear scaling. The resulting area is multiplied by a factor of 0.8 to account for the large size optimization of the system. This means that the total size of the system will not scale linearly because components such as the cooling system will be more effective for larger systems and do not linearly scale.

To ensure the resulting area estimates for the hydrogen production module, they have been compared with estimates found in the literature. Area estimates for an ALK electrolysis system by Sæbø et al. [41] have been used for comparison. It is reasonable to compare to Sæbø et al.'s results as it is based on calculations from engineers within the field of hydrogen and represents a case for offshore hydrogen production. For the comparison of this thesis, the safety, muster and accommodation areas have been excluded from the estimates by Sæbø et al. The comparison is presented for 100, 200 and 400 MW (Figure 4-3) because the estimate in Sæbø et al. was presented for these capacities.

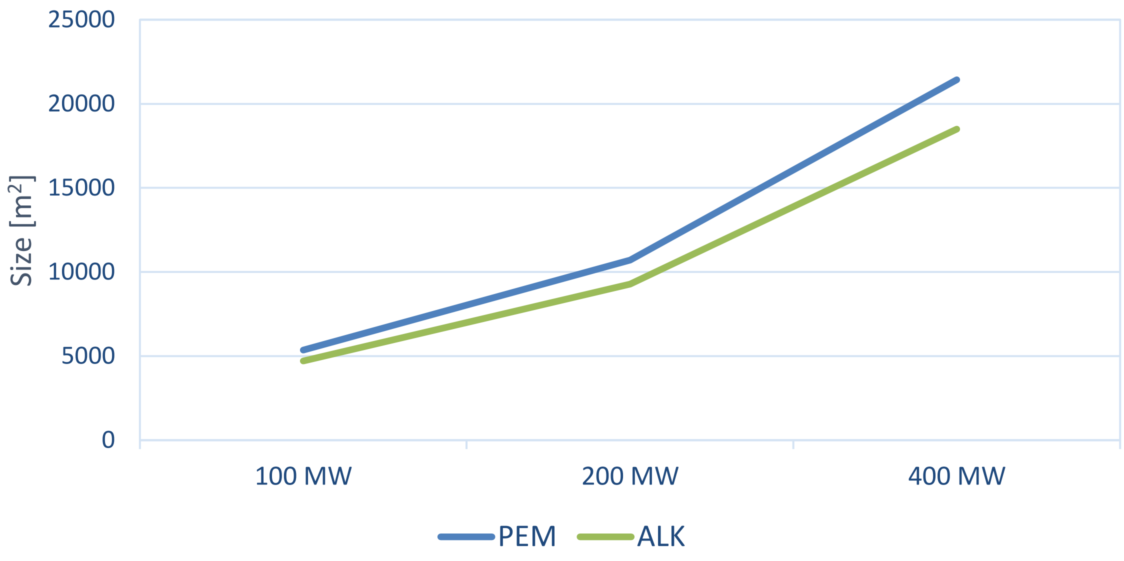

Figure 4-3: Linearly scaling of the electrolysis system for different electrolysis capacities. The thesis area calculations for PEM are in blue, and Sæbø et al.'s estimates for ALK are in green [41].

Although the Sæbø et al. estimates are for ALK electrolysers, it represent a smaller area (Figure 4-3) [41]. The reason can be that the two estimates include different equipment and sizes, for example, a included freshwater storage tanks. The industrial scaling factor for Sæbø et al. also seems to be smaller than 0.8 used in this study. The comparison (Figure 4-3) shows that Sæbø et al. estimates are ~10% larger than the thesis's calculations. The comparison ensures that the hydrogen production module gives reasonable area calculations for large-scale production capacities, even if there are linear scaling uncertainties.

The estimates represent a restricted dataset, representing the only area from a single vendor of electrolysis technology and BoP from Behyond. Comparing several large-scale capacities would give a better qualitative estimate but was limited by the absence of data for offshore hydrogen production systems. However, for the data that was compared, the calculations are shown reasonable as area estimates.

The estimates are based mainly on Behyond's estimates because their system is engineered for an offshore platform. The system design has accounted for limited deck area on an offshore platform and large-scale sized components [10]. Scaling area estimates based on a 200 MW system makes greater capacities more precise than using dimensions of a smaller land-based system.

4.2.3 The liquid hydrogen conversion module

The scale-up of the liquefaction plant exceeding 30 $tons_{LH2}$/day (tpd) is not yet a commercially available product. In the absence of actual data on large scale LH_2 plants, the area estimates assume a linearly scaling of the dimensions of a 10 tpd plant, provided by Chart Industries [58]. The liquefaction plant is divided into three sub-systems: compressors, liquefier Coldbox, and auxiliaries. The auxiliaries include, for instance, liquid nitrogen storage for cooling. The area is estimated from a layout of the 10 tpd plant [58].

An estimate of the weight of the main components and the additional components for a 10 tpd liquefaction plant is 750 tons and 1000 tons for a 30 tpd plant, discussed with Chart Industries[58]. The estimate excludes infrastructural steelwork and interconnecting piping. Using 750 tons as a baseline, each 10 tpd increase in production capacity means 125 tons weight increase. This is the weight of the total liquefaction module. The area and weight estimates for the liquefaction module are presented in Table 4-3.

Table 4-3: Area and weight estimates of liquefaction plant

Liquefaction module	Area estimates [$m^2/tons_{LH2}$]	Weight estimates
Compressors	3.7	750 tons + 125 tons per 10 tpd increased production capacity
Liquefying ColdBox	5.6	
Auxiliaries	26.5	

The estimates of the liquefaction plant are not representative of the general arrangement of the hydrogen liquefaction process as they only represent Chart Industries numbers. When estimating the plant size and weight for larger production capacities, linear scaling of the estimates is assumed. One the one hand, this scaling is based on the 10 tpd plant, there is considerable uncertainty concerning these numbers. The size of large-scale LH_2 plants is not reported in the open literature. Hence, areal and weight results cannot be directly compared with existing data. On the other hand, the scaling has been verified by Chart Industries. They commented that the use of a turbo compressor in a future large-scale liquefaction plant would probably result in an even smaller size and weight of the liquefaction module[58].

4.2.4 Ammonia conversion module

The ammonia conversion consists of nitrogen production and the Haber-Bosch synthesis loop. As a baseline for the area estimates, Yara provided the area of their Haber-Bosch loop as part of their ammonia production plant at Herøya in Norway [80]. The Haber-Bosch loop was estimated to ~4200 m^2 for a plant with a production capacity of 500 000 tons$_{NH3}$/year. The thesis's resulting estimate is 31 $\frac{m^2}{MW}$, where the MW is the electrolysis capacity. It is assumed the estimate from Yara includes all steps in the Haber-Bosh process.

The Haber-Bosch loop dimensions from Yara do not include nitrogen generation as it is based on feedstock from natural gas. An air separation unit (ASU) generating nitrogen is therefore added to the system. The ASU considered is a cryogenic separation unit, as it is an all-electric and mature technology with high volume flow[66]. ASUs are customized units, from containerized modules to blocks. The volume flow of nitrogen defines the size of the ASU units in Linde's datasheet [81]. The nitrogen supply was calculated using the nitrogen density of 1.2506 kg/m^3 at 1 atm, 0° and the 0.8224 wt% of nitrogen in ammonia [13]. A containerized module of type ECOGAN5 from Linde suits the required nitrogen production up to 6000 NH_3/hr. This corresponds to a system designed for 100 MW electrolysis capacity. Higher ammonia production rates need higher nitrogen flows which exceed the maximum nitrogen production capacities for the ECOGAN units. As dimensions were absent in the reviewed datasheets from ASU vendors, the containerized ECOGAN module by Linde has been estimated for larger flow. The dimensions for the ASU unit are found analysing the model picture in the datasheet from Linde. The ASU unit is assumed to be two 40'' containers with a safety distance of 2 m between each container [81]. The footprint is 12 m x 7 m, and the area estimate results in 1.7 m^2 for each 100 MW increase.

The weight of the system has been provided as an estimate of production volume by H2Carrier. The estimates used are 180 $\frac{kg}{\frac{Nm^3}{h}}$ for the ASU unit and 3300 $\frac{kg}{\frac{NH_3}{day}}$ for the Haber-Bosch unit and include a support structure, pipes and other additional systems for application on a ship.

In sum, the area and weight estimates used for the ammonia production module are presented in the following Table 4-4.

Table 4-4: Area and weight estimates for the sub-systems included in the ammonia production module

Hydrogen production module	Area estimates	Weight estimates
Haber-Bosch synthesis	$31\,\frac{m^2}{MW}$	$3300\,\frac{kg}{\frac{NH_3}{day}}$
Air Separation Unit (ASU)	1.7 m^2 each 100 MW increase	$180\,\frac{kg}{\frac{Nm^3}{h}}$

The area estimate for the NH_3 conversion module has been compared with the industry to ensure validity. H2Carrier has a concept of ammonia production on an LPG carrier. They have estimated ~7200 m^2 for the NH_3 conversion module, corresponding to a 140 MW electrolysis capacity [16][82]. The thesis calculates an ~6700 m^2 for a similar system, a ~7 % lower estimate than H2Carriers. This can be because of the estimated size of the ASU or the exclusion of safety distances between equipment. However, the calculating the size for a 100 MW electrolysis capacity is ~6000 m^2 and was confirmed to comply with North Ammonias preliminary area estimates [83]. This comparison indicates that the estimate for a 100 MW ammonia plant is in the correct range. Further linear scaling than 100 MW remains uncertain because no other open sources have been available for comparison.

Clearly, there are most uncertainties about the dimensions of the ASU unit. Nevertheless, the comparisons of the ammonia systems, including the ASU, give reasonable dimensions. Therefore, it has been assumed that the estimates of the ammonia give a realistic estimate of at least 100 MW electrolysis capacity.

4.2.5 Storage and offloading module

A type C tank is found feasible for both LH_2 and NH_2 cf. chapter 3.4. The weight of type C tanks(without cargo) provided by Sevan SSP [74] is used to estimate the weight of the storage tanks. The resulting weight is 0.16 tons/m^3. The area of the tanks is not important for the deck area because it is assumed the tanks can be placed in the hull of the FPSO. However, it is necessary to know the tank volumes to be stored in the hull. The size of the storage tanks is estimated based on offloading interval and max production capacity in chapter 4.3.3.

Dimensions of a cylindrical storage tank are found by the volume of a cylinder added to a sphere. The radius of the tank is limited by the height of the hull of the FPSOs. In the cylindrical FPSO, the diameter cannot be higher than 17 m, which is to be described in chapter 5.1.1. The tanks are assumed to be double containment vessels as a safety precaution if the tank rupture. For safety precaution, an outer tank of 1 m and a safety distance of 1.5 m between tanks is assumed[66]. LMG Marin has estimated that the needed space for the offloading on the ship-shaped FPSO will have a footprint of 320 m^2 [46]. This is based on known sizes of the offloading area on the commercially oil and gas units. The area is for reels handling offloading hose, a crane handling the hose, and mechanical arm or fenders to keep the receiving vessel in position. This is dimensioned as 20 m x 8 m, for two offloading areas, each side of the ship-shaped FPSO. Because of the shape of the cylinder shaper FPSO, only one offloading area with dimensions 20 m x 8 m is needed.

4.3 Results and discussions

The area estimates are linearly scaled and compared with the deck area on the FPSOs to answer what production capacity can be expected on an FPSO. This section presents and discusses the results. The weight of the resulting production capacity yields input in chapter 5.2.1 in the following response analysis.

4.3.1 Deck area on FPSO

When determining the maximum production capacity of FPSOs in the following sections, the deck areas on the FPSOs are a limiting factor. The deck is, in this analysis, defined as the top area of the FPSO.

The deck size of the ship-shaped FPSO is based on the size of the 185 operating and available FPSOs in 2021[84]. The larges sized FPSOs have a length of 250 m- 350 m. For this length, the range in width is 40 – 60 m, which gives a deck area of 10 000 – 21 000 m^2, assuming a triangle (Table 4-5).

Table 4-5:Maximum deck dimensions of the existing ship-shaped FPSO [84].

FPSO	Length [m]	Width [m]	Deck area [m^2]
Ship-shaped FPSO	350	60	21 000

The cylindrical FPSO is based on the FPSO Goliat, which is the largest cylindrical FPSO currently operating in the North Sea [74]. The deck area for hydrogen production on Goliat, which has a circular deck, is 7854 m^2 (Table 4-6). On cylindrical FPSOs, the process equipment needed on the main deck is stalled on several decks in height to increase the usable area [74].

Table 4-6: Maximum deck dimensions of the FPSO Goliat, used for the analysis.

FPSO	Diameter deck [m]	Deck area [m^2]
Goliat cylindrical FPSO	100	7 854

The deck area of the cylindrical FPSO is approximately 1/3 of the deck area of the ship-shaped FPSO. Thus the cylindrical FPSO will have smaller maximum production. It is assumed that the FPSOs considered in this concept study are built exclusively for hydrogen production. The possibility of retrofitting outfaced FPSOs can be mentioned, but is not addressed in this thesis.

4.3.2 Maximum production capacity

The area of the concept of ammonia conversion and liquefaction are presented for the case of 100 MW electrolysis capacity (Figure 4-4). The NH_3 module is 1.8 times larger than the LH_2 module when comparing the two conversion methods for 100 MW electrolysis capacity. The category "other" and "hydrogen module" are the same size for both systems. *Other* includes accommodation, explosion safety wall, offloading area, and safety area. The ammonia conversion module includes the ASU in addition to the Haber-Bosch loop, which results in 55% of the total system. In comparison with the liquefaction module, which accounts for 21%. This emphasises that ammonia storage requires a 34% larger area for the same hydrogen production capacity.

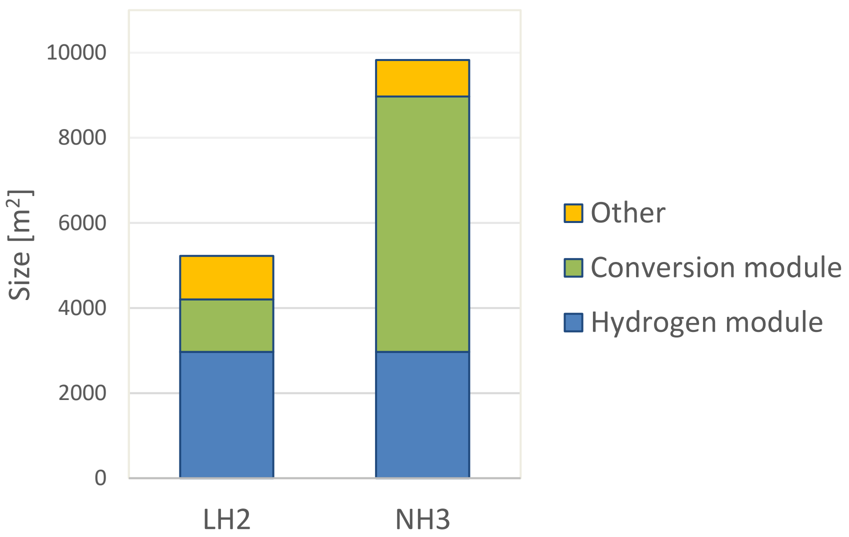

Figure 4-4: Comparing the size of LH_2 and NH_3 conversion with 100 MW electrolysis capacity.

All area estimates are assumed to be linearly scaled to meet the production rate from the hydrogen production module. There are uncertainties in the data estimating the size of both the NH_3 and LH_2 modules. Since the NH_3 module corresponded with North Ammonia and H2 Carrier's size estimates, Figure 4-4 compared the 100 MW electrolysis capacity system. This indicates that storing hydrogen liquefied will have a higher production capacity because it has a smaller footprint.

The production capacity possible on the FPSO is found by scaling the area estimates for different electrolysis capacities. The graph in Figure 4-5 presents the total size of the deck when including NH_3 and LH_2 conversion. The deck size on the ship-shaped FPSO is marked with an orange line, and the cylindrical FPSO deck area is marked with a yellow line.

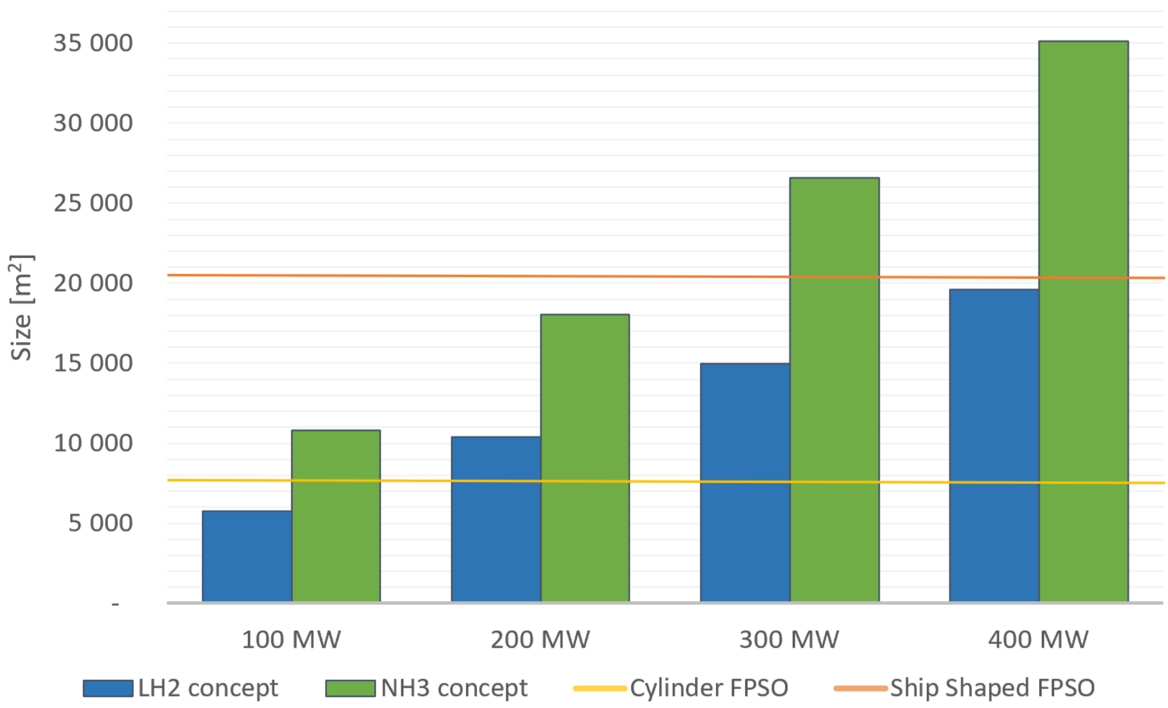

Figure 4-5: Size of hydrogen production with NH_3 and LH_2 conversion compared to the electrolysis capacities of 100-400 MW. The yellow line is the deck area of the cylinder FPSO, the orange line is the deck area of the ship-shaped FPSO.

The size of the total deck area must be coincident with the possible space on the deck of the FPSO. The maximum production capacity of the ship-shaped FPSO is limited to a 200 MW electrolysis capacity with NH_3 conversion. With LH_2 conversion, the maximum electrolysis capacity is 400 MW. For the cylindrical FPSO with a deck area of 7854 m^2, a maximum production capacity resulted in 150 MW for LH_2 and 75 MW for the NH_3 conversion. The electrolyser area is distributed over three decks height to decrease the area demand of the process equipment. On the ship-shaped FPSO, it has been used two decks instead of three. This is because of the larger deck size and the uncertainties of having the electrolysers on several decks. This was discussed with Gexcon, a company that specialises in hydrogen and offshore safety[85]. The electrolysers on several decks must be analysed in terms of possible gas leakages. It requires sufficient ventilation between the electrolysers and the process modules. Ventilation decreases the possibility of explosive gas concentration if leakage occurs [85]. Sufficient ventilation can be achieved by mooring the FPSO wind at an angle relative to the wind direction.

The maximum production capacity concerning available deck area with LH_2 conversion and storage resulted in 172 $tons_{LH2}$/day (Table 4-7). In other words, the result indicates that the unit for LH_2 production needs less area than the NH_3. From the table, the total production in tons/day of NH_3 and $_{LH2}$ is different because of the density. NH_3 has a density of 682 kg/m^3 compared to LH_2, with a density of 70.8 kg/m^3. The energy content(MWh) (or H_2) in the production per day is a more representative parameter to compare and shows that the ammonia conversion needs a larger area to convert the same amount of energy.

Table 4-7: Maximum production capacities with LH_2 and NH_3 conversion on the FPSOs. (ELY is electrolysis)

FPSO	Max. ELY. capacity	Conversion/ storage	Max. production capacity	H_2 content	Energy content
Ship	400 MW	LH_2	172 $tons_{LH2}$/day	172 tons	5743 MWh
Ship	200 MW	NH_3	485 $tons_{NH3}$/day	86 tons	2512 MWh
Cylinder	150 MW	LH_2	65 $tons_{LH2}$/day	65 tons	2153 MWh
Cylinder	75 MW	NH_3	182 $tons_{NH3}$/day	32 tons	942 MWh

In this analysis, the wind farm only supplies the FPSO. The wind farm size is outside the scope but is relevant in discussing the maximum electrolysis capacity installed on the FPSO. It can be assumed the electrolysis capacity should be dimensioned for maximum wind production to avoid loss of generated electricity. Sæbø. et al. estimated the effect of increasing the installed wind capacity relative to the maximum electrolysis capacity for an offshore hydrogen production system not connected to the shore. From a cost perspective, they observed that a small increased installed effect at the wind farm would increase the lifetime of the electrolysers. The 450 MW installed wind for a 400 MW electrolysis capacity, one month of wind data resulted in the lowest calculated Levelized Cost Of Energy (LOCH). The optimal wind farm size relative to the electrolysis capacity is a question of the lowest cost for hydrogen. Hence, not including the size of the wind farm does not affect the estimated maximum electrolysis capacity suitable on an FPSO deck. This is because these concerns can be taken care of by adjusting the wind farm capacity. The wind farm size for optimal operation can be further analysed with a cost analysis, and it can be expected that a wind farm size that is suitable for the concept will have more capacity than for the electrolysers.

Including all other sources of electricity requirements, i.e. the conversion module, the cooling and water treatment would also affect the size of the wind farm. Morgan et al. found a relation of the power requirements for an ammonia plant with PEM electrolysis to be $P_{NH3} = 0.483 \cdot Size_{NH3}$ [66]. $Size_{NH3}$ is the output capacity in tons/day. The electrolysis capacity accounts for 95% of the total size of this power requirement [66]. With this relation, the 200 MW electrolysis capacity plant on the ship-shaped FPSO with 482 ton/day production needs a wind farm capacity of 230 MW. This is similar to 27 floating wind turbines based on the Hywind Tampen wind turbines (8.6 MW). In Norway, the offshore wind concessions are 1.5 GW in the first and second phases [86]. The target is 30 GW within 2040[87]. From this perspective, the 27 wind turbines only account for 15% of the future installed wind capacity of 1.5 GW. On the one hand, the maximum electricity requirement for the ship-shaped FPSO with maximum hydrogen production is relatively small compared to the planned offshore wind concessions. On the other hand, hydrogen production FPSOs coupled with wind farms of larger capacity and cable to shore can be the solution.

Area layout

A preliminary area layout of the process equipment on the FPSO is made with AutoCAD. The area layouts have been made to ensure that the maximum capacities can fit the FPSO decks. On the ship-shaped FPSO, the electrolysis is equally distributed over two decks in height (Figure 4-6Figure 4-7). On the cylinder FPSO, the electrolysers are stalled over three decks in height (Figure 4-8Figure 4-9). Shapes of the different sub-systems are assumed to be squared and made to fit on the deck. The following figures show the main deck as the top figure and the hull as the bottom figure. The drawing represents the FPSOs in a 2D perspective, showing the x-y plane from above.

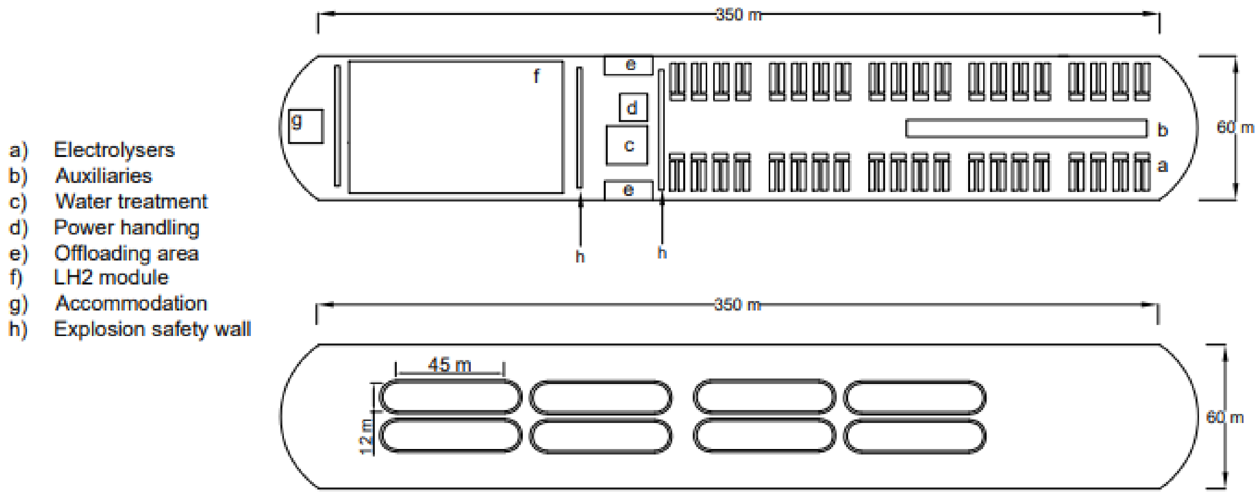

Figure 4-6: Area layout from above of the ship-shaped FPSO. Main deck (top) with 400 MW electrolysis capacity and LH_2 conversion. Storage tanks are placed in the hull of the FPSO (bottom).

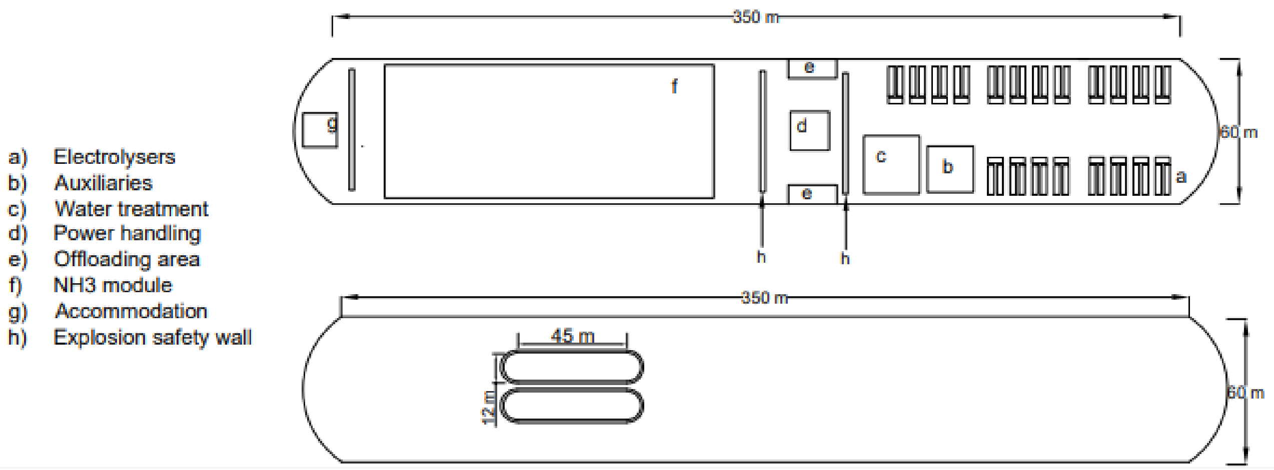

Figure 4-7: Area layout from above of the ship-shaped FPSO. Main deck (top) with 200 MW electrolysis capacity and NH_3 conversion. Storage tanks are placed in the hull of the FPSO (bottom).

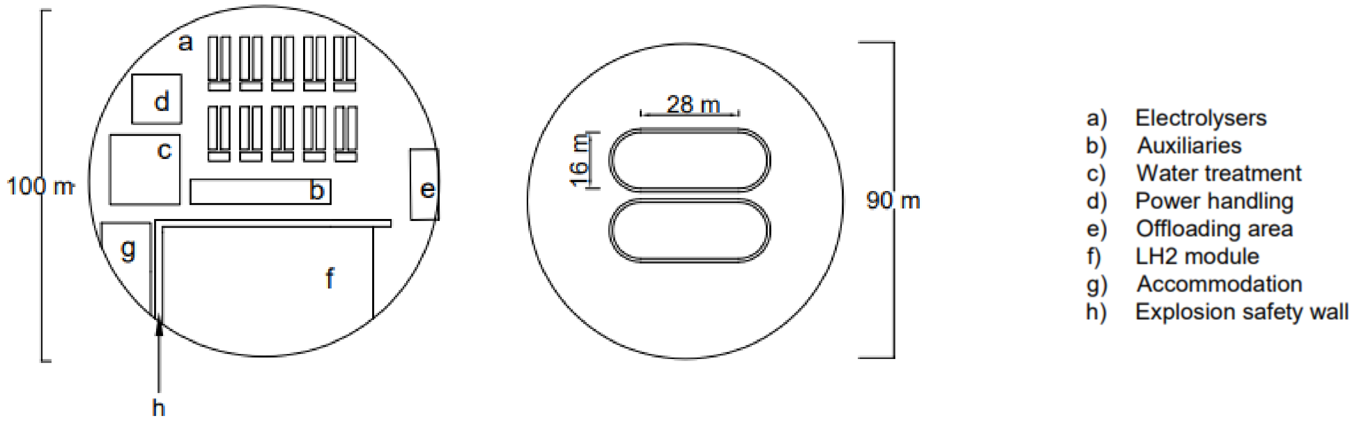

Figure 4-8: Area layout from above of the cylinder FPSO. Main deck (left) with 150 MW electrolysis capacity and LH_2 conversion. Storage tanks are placed in the hull of the FPSO (right).

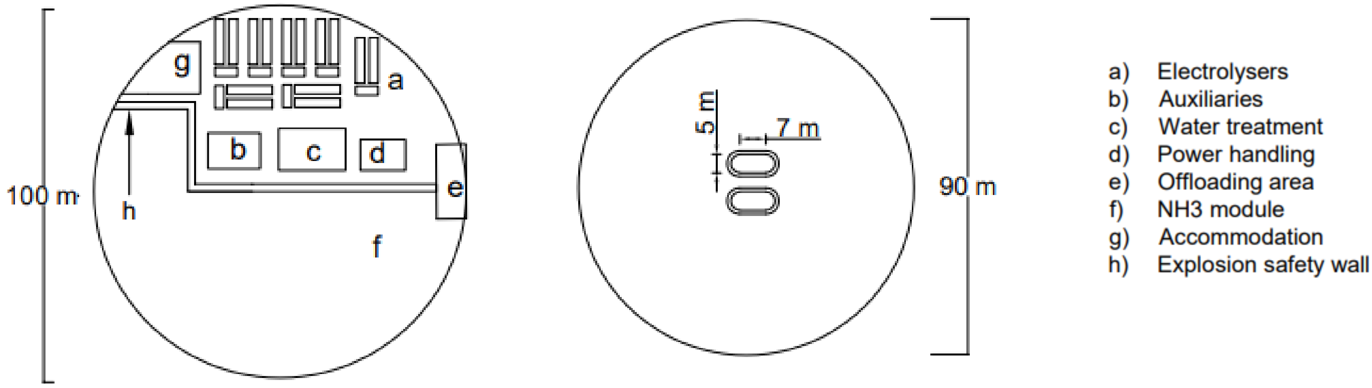

Figure 4-9: Area layout from above of the cylinder FPSO. Main deck (left) with 75 MW electrolysis capacity and NH_3 conversion. Storage tanks are placed in the hull of the FPSO (right).

Overall, the maximum production capacities fit the FPSO decks and verify the calculated production capacities. The shapes on the different sub-systems do not necessarily represent the actual shape of the different equipment. Still, they represent the area of the systems and are assumed reasonable for the aim of the area layout.

The area layout has not taken into consideration the safety measures regarding the actual placement of the process equipment i.e what equipment can be placed next to each other considering safety. Overall safety measures relevant to an FPSO area layout have been accounted for: an explosion wall is added in the handling of gas if there is leakage, and enough spacing between the equipment for safe passages and ventilation.

In further work, there is a need for a safety assessment of the areas between modules, passages for maintenance workers, lifeboats, helicopter deck, emergency exits and other safety measures, which have not been added to the area layout.

4.3.3 Storage

The FPSO must be able to store hydrogen produced between offloading. The production capacity and offloading frequency are the main contributors to the need for storage capacity on an FPSO. The offloading frequency is estimated based on the possible storage volume of the vessel and the arrival frequency of offloading vessels. Offloading is performed when the weather and wave conditions are acceptable, with a maximum significant height (H_s) of 4.5-5 meters. Oil rigs have typically offloaded to a distribution vessel every 7th -10th day if the wave height allows it. In a study by Sekandar, six to seven days offloading intervals are also the optimal offloading interval for ammonia production on an FPSO [88]. Sekandar used a sailing distance for the receiving vessel comparable to the distance from Statfjord to the Norwegian West Coast [88].

From an all-year perspective, the probability of exceeding a significant wave height (H_s) of 4-5 m [41] is between 80-90%. This probability is found using the cumulative distribution of the all-year significant wave height in the Statfjord Late Life Metocean Design Basis by Equinor[42]. The probability level of the significant wave height correlates with the time of the year. In July, the probability for H_s>4-5 m is 0.01%, October and April 10% and approximately 30 %, which is 9.3 days of January. This means that the offloading operations are frequently cancelled due to weather conditions in the winter months.

The unit's storage capacity should take into account for cancelled offloading. Furthermore, suppose the operation of the process equipment is limited by FPSO motions or must be shut down due to weather conditions in the winter months. In that case, additional buffer storage tanks are considered to secure hydrogen supply to the market. The resulting storage capacity for the analysis includes 7-days offloading intervals and 10-day buffer storage (Figure 4-10).

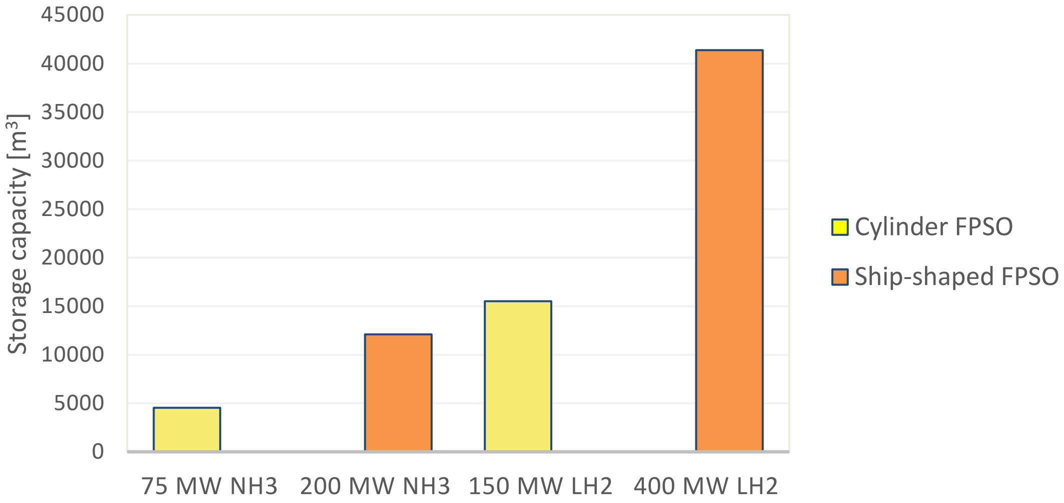

Figure 4-10: Storage capacity required on the FPSOs for 17 days production (7 days offloading interval and 10-days buffer).

The LH_2 tanks are, according to Chart Industries, possible to customize[58] and the LH_2 tanks have been dimensioned to store the required volume without any limitations to size. This assumption yields the same dimensioning tanks for ammonia storage as ammonia storage is well established.

The tanks are dimensioned for 17 days storage capacity. The dimensions of the storage tanks for the cylindrical FPSO were found suitable, with a diameter of 16 m and length of 28 m. The area layout of the hull with storage tanks in Figure 4-7 has included the safety distances of 2 m between tanks with a 1 m thick double wall. For 150 MW electrolysis capacity, the production is 65 $tons_{LH2}$/day and requires a storage capacity of 15512 m^3 (density of LH_2 = 70.8 kg/m^3), assuming steady wind conditions. For the maximum capacity of 75 MW for NH_3 conversion, the 182 $tons_{NH3}$/day results in a storage capacity of 4534 m^3 (Figure 4-10) (density of liquid ammonia = 682 kg/m^3).

On a ship-shaped FPSO, 17 days of storage capacity with 172 $tons_{LH2}$/day requires 41365 m^3. With the hull height of 33 m, the storage tanks for the ship-shaped FPSO are calculated with a diameter of 12 m. These tank dimensions result in eight tanks (Figure 4-7). With ammonia conversion, the required storage capacity is 8243 tons or 12087 m^3. This storage capacity corresponds to around two of the same sized tanks. The density of ammonia results in less volume to be stored but heavier cargo.

It is assumed that it is better with fewer tanks to avoid several connection points because of the risk of leakage. The tank sizes must further be analysed in terms of regulations of maximum storage capacity in each tank, safety aspects of large scale hydrogen and ammonia handling and potential pressure built up in the tanks because of sloshing.

The optimal tank size is a question of the best safety measures, costs, maintenance, and optimal production, which is outside the scope. The tank dimensions only include the tanks and no additional pipes or refrigerating loops for boil-off handling or safety systems. Hence, the tank sizes may not be optimal for a realistic scenario. Nevertheless, the results show that the hull in the cylindrical and ship-shaped FPSOs is large enough for 17-days of storage capacity. The hull has unutilized space, which can accommodate the tank equipment not accounted for. The method of storage tank dimensioning could, in other words, be done with more precise estimates, but the result answers the objective. The estimates are considered suitable for early phase concept development on the FPSO.

4.3.4 Offloading logistics

The feasibility of offloading must be discussed when knowing the offloading interval and volume. The offloading technology should have an offloading rate to transfer the volume in 1-1.5 hours. Considering the ship-shaped FPSO with 172 $tons_{LH2}$/day, a seven-day production interval will require a volume of 1204 tons to be offloaded. The rate for LH_2 offloading is found as 42 $tons_{LH2}$/hr, which equals 28 hours. This capacity must be increased 20 times to reach the 1.5-hour time interval. LH_2 offloading rate must be developed towards a higher offloading rate, or offloading must occur in several rounds. Instead, the ammonia offloading rate is 5000 m^3/hr and equals a suitable offloading rate of one hour when considering the maximum production of NH_3 from the ship-shaped FPSO (485 tons/day).

Another aspect of the concept's feasibility regarding storage capacity, offloading interval and the offloading rate is the capacity of vessels that will carry LH_2 or NH_3 to shore. Since ammonia is transported worldwide by ship, it can be assumed that ammonia carrier ships can be built for this purpose. Semi-refrigerated ammonia is typically constructed for 40 000 m^3 of ammonia [34]. LH_2 carriers are more of concern because the only ship carrying LH_2 is the HySTRA pilot, transporting LH_2 between Japan and Australia [61]. Figure 4-11 provides an overview of the capacity of possible future LH_2 carriers and the seven days production volume of LH_2 to be distributed.

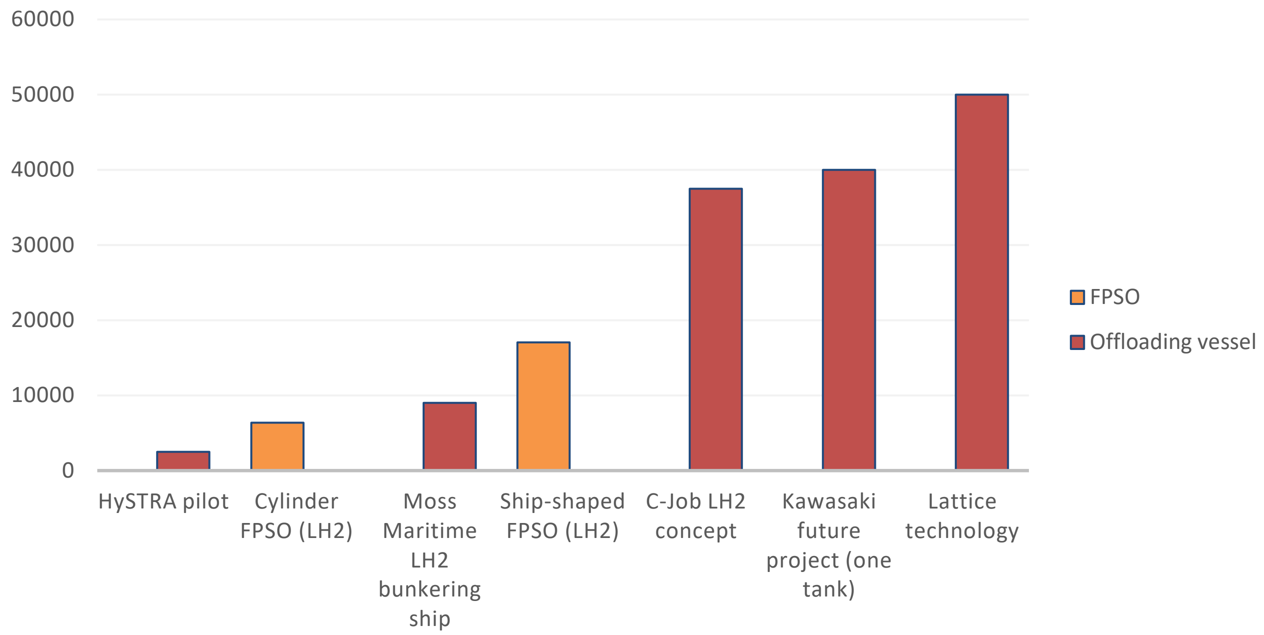

Figure 4-11: The FPSOs storge of seven days production compared with possible LH_2 carriers' capacity in volume [61][65][72].

The overview shows that the concept study by Moss Maritime is suitable for the production capacity of the cylindrical FPSO of seven days [72]. The LH_2 carrier announced by Kawasaki and C-Job is planned with even greater storage capacities, with four tanks of 37500 m^3 - 40000 m^3 [63][89]. With the realisation of these concepts, the distribution of LH_2 with a 7-day offloading interval would be feasible.

The results have shown that the ship-shaped FPSO can store 17 days of production. A 17 days production with 400 MW electrolysis capacity is able to fill a 40 000 m^3 LH_2 carrier. Similarly, the 200 MW NH_3 ship-shaped FPSO needs 12-days of production to fill a carrier of 40 000 m^3. Hence, the FPSOs can store the amount to fill large capacity LH_2 and NH_3 carriers for transport to shore. Still, a limiting factor is the offloading rate required to offload these volumes.

To summarise, the results reveal that storing both hydrogens liquid and NH_3 is feasible regarding available volume in the FPSOs hull. Even greater storage capacities are possible for future announced concepts of LH_2 and NH_3 carriers if the offloading technology is developed for higher offloading rates. A summary of the so far evaluated concept of hydrogen production on an FPSO is presented in Table 4-8. The concepts include production, storage, and offloading, which will be analysed with a response analysis in the following chapter.

Table 4-8: Summarised concept for hydrogen production, conversion, storage and offloading, and max storage capacity for ship-shaped and cylinder FPSO. PEMEL is Proton Exchange Membrane Electrolysis.

FPSO	Cable handling	Hydrogen production	Conversion and storage	Storage capacity (~17 days)	Offloading method
Ship-shaped	Dynamic cables	PEMEL 400 MW 172 tons/day	LH_2 (-253°)	41 300 m^3	Ship-to-ship
Ship-shaped	Dynamic cables	PEMEL 200 MW 86 tons/day	NH_3 (-33.33°)	12 100 m^3	Platform based or Ship-to-ship
Cylinder	Dynamic cables	PEMEL 150 MW 65 tons/day	LH_2 (-253°)	15 500 m^3	Ship-to-ship
Cylinder	Dynamic cables	PEMEL 75 MW 32 tons/day	NH_3 (-33.33°)	4 500 m^3	Platform based or Ship-to-ship

5 Response analysis

This chapter first presents the response analysis method, followed by the discussion and results.

5.1 Method

A hydrodynamic analysis in the form of a response analysis is chosen as the most practical way to find the motions the equipment will experience on the FPSOs. The method was chosen to investigate the responses in a real sea state, used as a preliminary investigation of ships and offshore constructions by naval engineers. The method of the response analysis is described in this chapter.

SESAM software program is used to determine the response analysis on the FPSO. Sesam is manufactured by Det Norske Veritas (DNV). The software is based on the displacement formulation of the finite element method and is suited for hydrodynamic and structural analysis of ships and structures [90]. The main tools within the Sesam software used GeniE (version 8.3.4) and HydroD (version 6.0.0). GeniE features modelling of the FPSOs, and HydroD executes the analysis. Within HydroD the sub-packages Wadam and Postresps are used respectively for the response analysis and presentation of results. The structure of the Sesam Software, including the tools and sub-packages used for the response analysis, is illustrated in Figure 5-1.

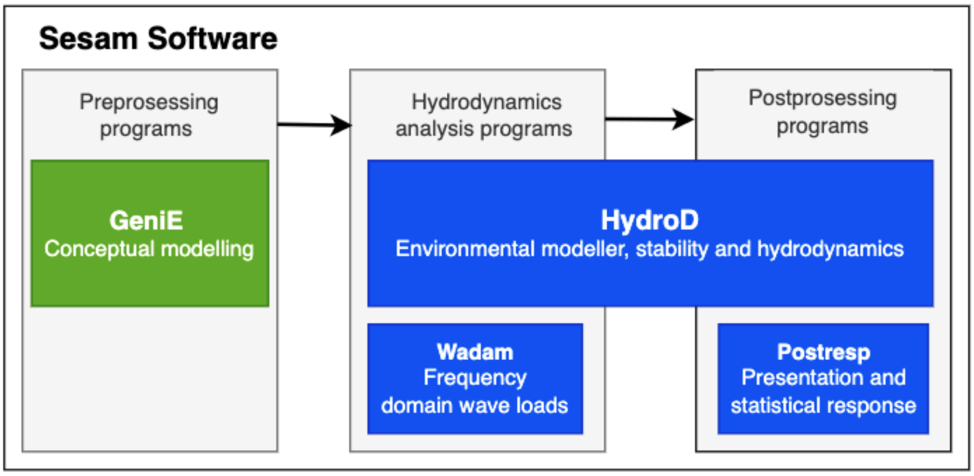

Figure 5-1: Illustration of the Sesam structure and programs for the hydrodynamic analysis. The figure is inspired by the figure "Sesam Overview" in [90].

5.1.1 Modelling of the FPSO constructions

The first step is to model the two different FPSO constructions. The FPSOs were modelled in GeniE prior to the corresponding analysis in HydroD. The ship-shaped FPSO hull is based on an FPSO design from LMG Marin called Robusto [44]. The model consists of a rectangular shaped body with half-circular ends. The fore-aft symmetric hull makes the design robust to incoming waves in several directions. The dimensions are 350 m x 60 m from Table 4-5. The "skirt" at the foot of the hull, together with the rounded act and bow, gives the FPSO a better buoyancy and is more robust to incoming weather directions. The complete model with dimensions is shown in Figure 5-2. The model in GeniE is a simplification of the actual Robusto. The simplifications do not include bearings, plates, or details on the hull, mooring, or topside equipment.

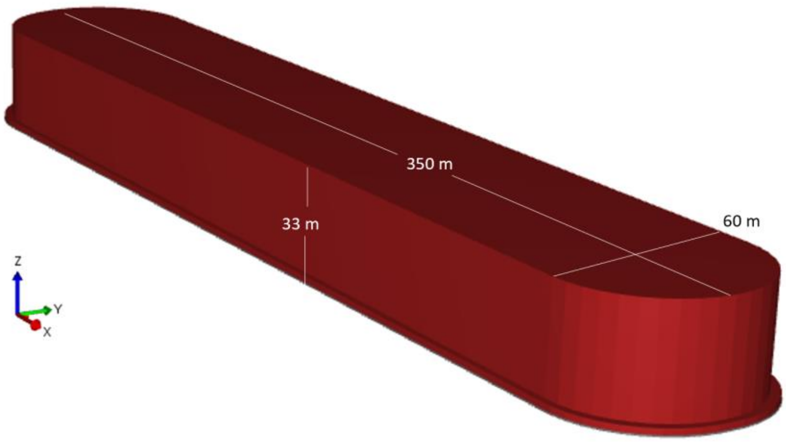

Figure 5-2: Model of ship-shaped FPSO with dimensions.

The model was built in GeniE by dimensions in Table 5-1. The GeniE model was modelled with no thickness or density. All included equipment was calculated based on the weight estimations in chapter 4 and added in HydroD.

Table 5-1: Main dimensions of the ship-shaped FPSO

Main dimensions	Shipshape FPSO [m]
Length	350
Width	60
Height	33
Radius end	30
Skirt height	3
Skirt width	5

The cylindrical design of the FPSO consisted of a cylinder body with a skirt at the bottom and a wider diameter at the deck. The simplification of the cylinder FPSO obeyed the same simplifications as for the ship-shaped. The model represented the shape of the FPSO. A cylinder with an opening through the bottom of the hull. The hole is defined as a moonpool with a radius of 22.5m (Figure 5-4). The model is shown in

Figure 5-3. The dimensions of the cylinder FPSO are presented in Table 5-2.

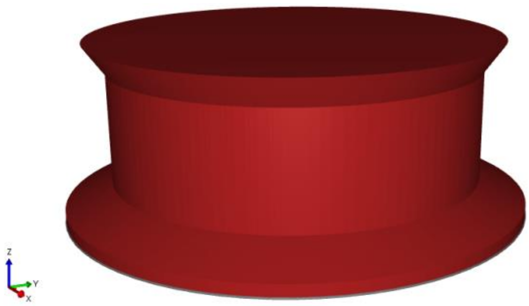

Figure 5-3: Full model of the cylinder FPSO

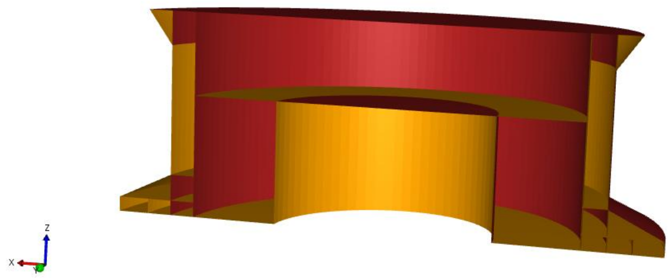

Figure 5-4: Cylinder FPSO in half, showing the moonpool in yellow.

Table 5-2: Main dimensions of the cylindrical FPSO

Main dimensions	Cylindrical FPSO [m]
Height	42.0
Deck radius	50.0
Waterline radius	45.0
Radius skirt	56.3
Moonpool radius	22.5
Skirt height	3.0
Moonpool height	25.0

5.1.2 The approach to weight estimation

Weight is essential regarding the motions and structural limitations of the FPSO. The response analysis is first executed when weight is added to the models and balanced to stability. The input weight for the response analysis is calculated using the weight estimates from chapter 4. After weight inputs, the models were stabilised in HydroD by adding ballast water to obtain the weight needed for the given drafts.

5.1.3 Environmental input

Environmental conditions for the location decide displacements and acceleration of the FPSOs. The environmental condition for input in HydroD was found in the "Stafjord Late life Metaocen design Bases" by Equinor (Statoil)[42]. Statfjord is located in the North Sea with coordinates 6860470,25 north, -200691,62 east, and has a mean depth of 150 m.

The method of obtaining responses is illustrated in Figure 5-5, described in theory chapter 2.4.2. This section describes the environmental parameters used for the analysis and the method of applying these.

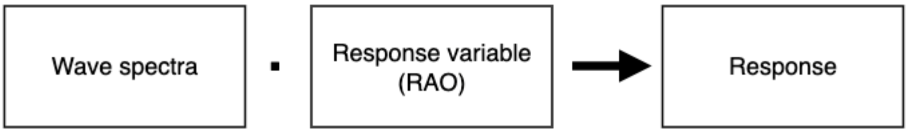

Figure 5-5: Response computation method. Wave spectra multiplied with the response variable give a response distribution.

The response analysis calculated the unit responses for different given sea states. The Torsethaugen wave spectra were used as they accounted for both waves and swell, as described in chapter 2.4.1. Input variables for this wave spectra were the significant wave height (H_s) and spectral peak period (T_p).

The selection of H_s and T_p is based on the offshore standard on "Structural design of offshore ship-shaped units" by DNV [91]. The standard definite ship in operation mode is typically analysed in a maximum sea state (H_s, T_p) and should reflect a minimum of a 1-year return period [91]. The 1-year-return period is defined as the most unfavourable sea state, with the probability of occurrence of 10% each year. As input values for the wave spectra, H_s and T_p are found for a 1-year and a 10-year return period. The H_s and T_p for the 1-year and 10-year return periods were found in table 3.3 in Equinor's Late-life design basis[42] and presented in Table 5-3. The most frequent sea states are used in the offloading analysis to give the expected response values for regular operation, not extreme sea states. Input data for this analysis were collected from table 3.2 in Equinor's design basis [42]. The most frequent sea states used in the response analysis are presented in Table 5-3.

Table 5-3: Sea states for the response analysis. RP1 and RP10 are the Return Period values for 1 and 10 years. H_s is the significant wave height and T_p spectral peak period.

Sea state number	H_s [m]	T_p [s]
1	1.5	7.5
2	2.5	8.5
3	3.5	9.5
4	4.5	10.5
5	5.5	11.5
6	6.5	12.5
RP1	11.0	14.2
RP10	13.0	15.1

5.1.4 Response analysis

The response analysis is based on the behaviour of the FPSOs during a specific design sea state, given as a response spectra, distribution of responses for the frequencies in the sea state. The responses in a sea state are given with a response distribution of a three-hour distribution. To describe the response in the analysis, the 63% percentile of the distribution was used. The method of describing the response with the 63% percentile is defined as the "most probable largest response "of the 3-hour duration. In other words, it is a 63% chance that the highest wave peak in the 3-hour time series will be larger than the most probable largest response[92]. Similar, the probability of non-exceedance is 37%. The probability is chosen as a reasonable estimate of response as it gives a large probability of occurrence. The method of finding the probability is described further.

The probability that n out of N elevations in the record exceeds the highest wave is given in E.q (5-1).

$$P(H_w) = \frac{n}{N} \quad (5\text{-}1)$$

Based on the equation (2-3), which gives the probability that a wave height h exceeds a chosen threshold value $H_{\omega,}$ and eq. (2-4), from the theory, it gives

$$-\frac{h^2}{2m_0} = \ln(n) - \ln(N) \quad (5\text{-}2)$$

$$P(H_w) = 1 - e^{\ln(n)-\ln(N)} \quad (5\text{-}3)$$

When n= 1, and N = ∞ the probability of exceedance of the highest wave becomes:

$$P(H_w) = 1 - e^{-1} = 63\% \quad (5\text{-}4)$$

The most significant response in the FPSOs was calculated for different specific points on the FPSO deck where the response is relatively large. Roll is taken for the side point, pitch for the bow point, and heave for the centre point at the ship-shaped FPSO. The specific points are illustrated in Figure 5-6, and the specific point at the cylinder FPSO in Figure 5-7. The points are 5 m higher than the deck level in the z-direction to represent the height of the equipment modules.

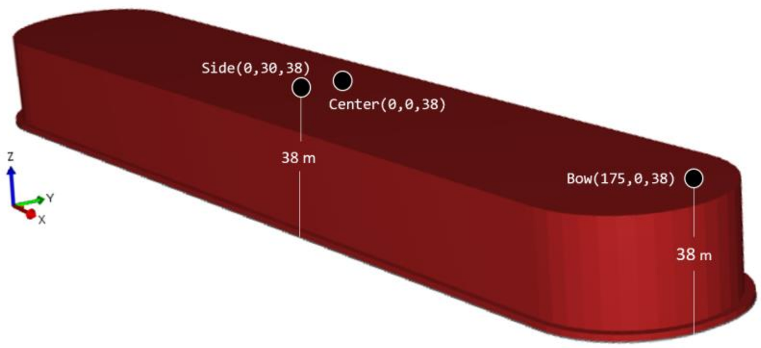

Figure 5-6: Ship-shaped FPSO and the specific points used in the response analysis. Bow for pitch, side for roll and heave in the centre.

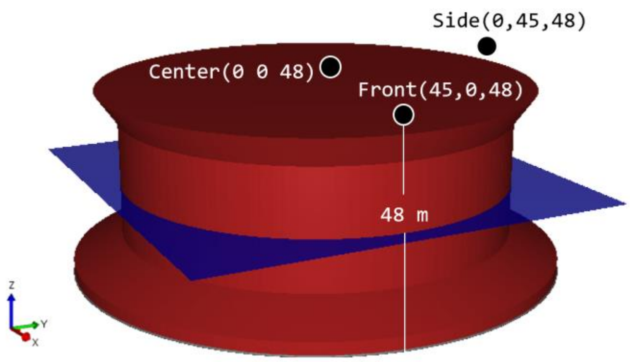

Figure 5-7: Cylinder FPSO and the specific points used in the response analysis. Front for pitch, side for roll and heave in the centre. All 5 m over the deck in the z-direction. The blue square represents the ocean surface.

Lastly, a dampening factor for the cylinder FPSO was added for heave, pitch, and roll, with guidance from Sevan SSP. Heave resulted in 19 000$\frac{kN \cdot s}{m}$, pitch and roll was 9 000 000 $\frac{kN \cdot s}{m}$ [74].

Offloading

The method of analysing the motions for the offloading technology is a response analysis where the combined motions in x, y, and z are found in the offloading locations on the FPSOs.

The cylinder unit typically has one offloading area, according to Sevan SSP[74]. The receiving ship is located in the direction of the sum of wind, waves and current forces in a safety distance ~160 m in radius from the offloading area (Figure 5-8). The receiving vessel will change its location in relation to the FPSO depending on the direction of the environmental forces. Offloading will then be done in the best-suited location relative to the environmental forces in the offloading act. The ship-shaped has an offloading area on each side of the FPSO. The offloading will happen in the dedicated offloading area, a lee side of the environmental forces. Depending on the offloading method, the offloading area includes for example, a crane handling the hoses, reels, or a mechanical arm for station keeping of a receiving vessel with ship-to-ship offloading (cf. chapter3.4.4).

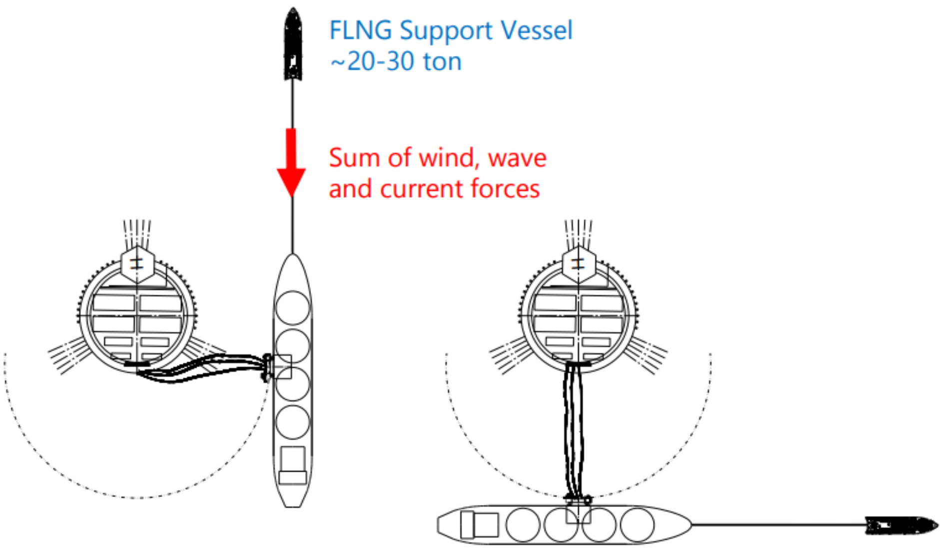

Figure 5-8: Offloading with HiLoad from a cylinder FPSO to a receiving vessel. The bow of the receiving vessel is directed against the environmental forces from two different directions. The safety distance is marked with a dotted line[69].

The combined motions in x, y and z are found in the specific points illustrated in Figure 5-9 and

Figure 5-10. The specific points are located on the opposite side of the weather direction. This gives the displacements in the offloading, which will always happen on the ship's lee side.

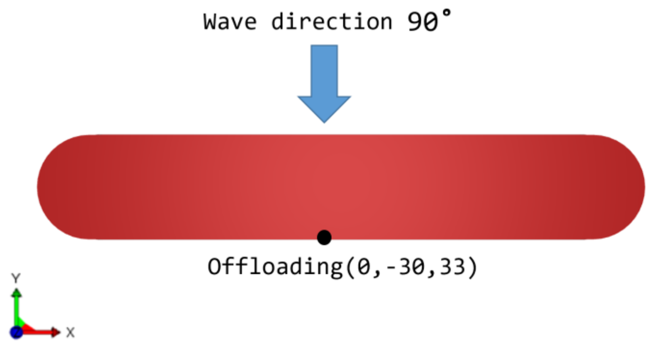

Figure 5-9: Offloading point in response analysis for Ship-shaped FPSO. Environmental loads from 90°

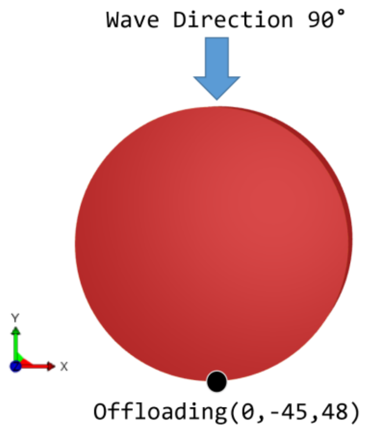

Figure 5-10: Offloading point in response analysis for Cylinder FPSO. FPSO. Environmental loads from 90°.

5.2 Results and discussions

This section presents and discusses the results of the response analysis. The results are divided into “Initial weight calculations”, “Responses on FPSOs”, and ” Expected motions for offloading”.

5.2.1 Initial weight calculations

This chapter presents the initial weight calculations for the response analysis. The weight estimation and stability are important for the responses from the FPSOs. The analysis uses the weight of the LH_2 equipment and storage weight for the 10-days production case, as it has the largest production capacity and weight. The resulting input weights for the response analysis for the ship-shaped FPSO and corresponding z-axis values are presented in Table 5-4. LMG Marin provided the weight of the “additional ship systems” and “hull” [46].

Table 5-4: Mass input and z-value for input coordinates for the ship-shaped model in HydroD.

Equipment	Weight [tons]	z
Topside equipment 400 MW	14 090.0	38.0
LH_2 storage tanks filled	9 547.0	16.5
Hull	60 000.0	20.0
Additional ship systems	8 000.0	32.0
Ballast water	181 140.0	16.5
Total mass	272 777.0	18.8

After stabilising the mode with a draft of 13 m, the resulting ballast water account for approximately 66% of the total weight of the FPSO. The same weight analysis is done for the cylindrical FPSO. The input of hull and additional ship systems are provided estimates by Sevan SSP [74], and the resulting weight inputs are presented in Table 5-5 . Other properties obtained when stabilising the models in HydroD important for the regeneration of the FPSO models are given in the Appendix.

Table 5-5: Mass input and z value for input coordinates for the Cylinder FPSO model in HydroD.

Equipment	Weight [tons]	Z
Topside equipment 200 MW	5 674.4	47.0
LH_2 storage tanks filled	13 542.3	42.0
Hull	30 777.5	17.6
Additional ship systems	1 560.0	42.0
Ballast water	76 883.6	17.6
Total mass	118 437.8	20.0

The estimates for weight need more inputs to give a realistic quantitative result on the weight of the production. The additional weight of piping, ventilation and refrigeration loop was outside the scope and must be added in future work. The safety aspects of containing this large number of explosive substances on the FPSO must be analysed because additional safety measures among explosion protecting walls and lifeboats must be added to the deck and will add weight. From a naval architect's perspective, the difference in the weight or a different centre of mass only means removing or adding ballast water. This supports the method of input of equipment weights as mass points. The ballast of higher density is another alternative when the unit must be heavier to stabilise.

Ballast water is relatively large compared to the total weight in both FPSOs. The hydrogen production and conversion model only accounts for around 5 % of the total weight added to the models and is not a driving factor. Considering that ballast water can be displaced by equipment weight, it follows that additional weight not included in this analysis can be added to both FPSOs later with a good margin.

As the equipment weight has large uncertainties, the balancing method was used to provide a stable model at the given drafts. The draft was chosen with guidance from LMG Marin and Sevan SSP as estimates based on other similar FPSO designs [46] [74]. The optimal drafts should be chosen based on stability analysis, which is outside the scope of this thesis. A stability analysis was not in the scope of the thesis, as the method of stabilising with ballast water gives a stable model to be used for response analysis. Hence, the motions of these models are representative of the initial phase of ship design.

The only correction regarding the stability was getting the correct response variables on the cylindrical unit. This correction was done by guidance from Sevan SSP to obtain correct responses for their design. The resulting centre of mass for the cylindrical FPSO was added 8 m, giving a smaller distance between the mass centre and metacentre. The effect was less amplitude of heave, roll and pitch. Corrections have not been done for the ship-shaped unit as the distance between the mass centre, and metacentre was in the correct range expected for this unit, according to LMG Marin.

5.2.2 Responses on FPSOs

Results

The models are fixed, and the response amplitude varies for incoming wave direction (0˚, 45˚ and 90˚). The resulting responses in the analysis are found for the incoming waves, where the responses in heave, pitch and roll are most significant (cf. Appendix). For both the ship-shaped and the cylinder FPSO, heave has the most significant response for incoming waves from 90°. Ship-shaped has the most significant response in pitch for 45 ° and cylinder FPSO for 0. For both, roll is most significant for 90°. 0° is the x-axis, and 90° is the y-axis.

The limiting factor for process equipment in offshore installations is the responses' acceleration in roll and pitch. The most significant motions in the specific point on the FPSOs are presented as heave, pitch and roll (Figure 5-11). The unit of the response from heave is meter and degrees for roll and pitch. The resulting responses are computed from the 1-year return period and 10-year return period with Torsethaugen wave spectra and non-exceedance of the response level of 37%. Simply put, the most likely response level to occur.

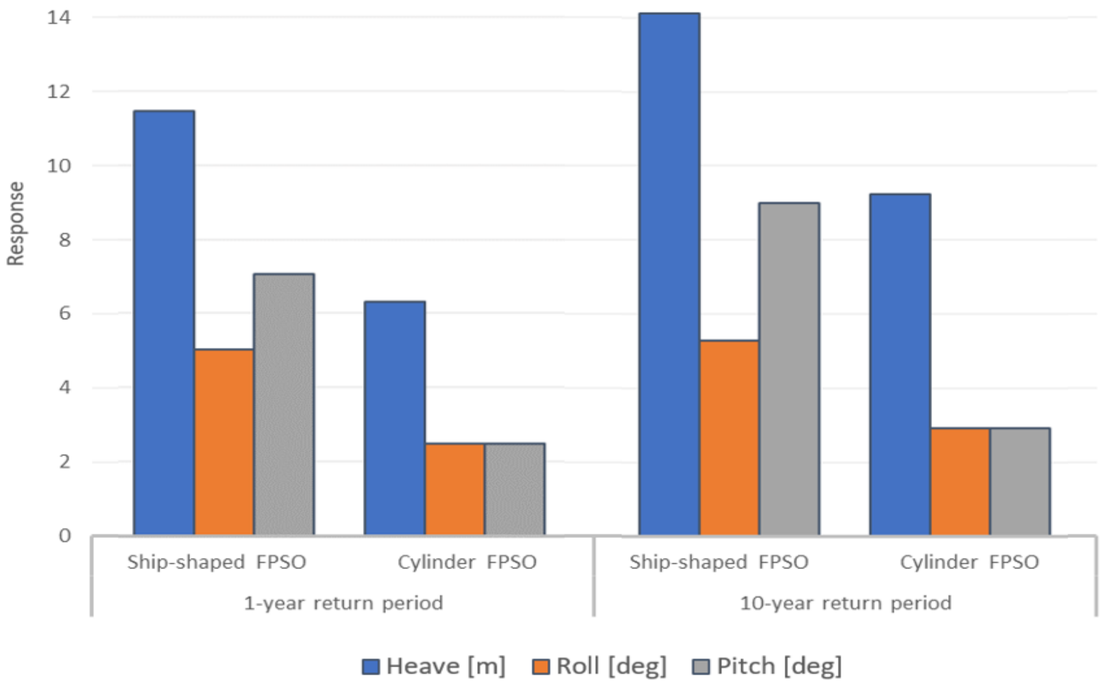

Figure 5-11:Responses for 1-year and 10-year return period in heave, roll and pitch for the ship-shaped and cylinder FPSO. Unit “deg” is degrees [°].

The 10–year return period gives responses for a sea state with more energy, hence the responses are more significant than the 1-year return period. The responses in general increase 2.6-2.9 m in heave for both FPSOs and under 0.5 m in roll and pitch. The response in heave for a 1-year return period is approximately twice as large for the ship-shaped FPSO(11.4 m) compared to the cylinder FPSO (6.3 m).

The ship-shaped has 5.0° in roll and 7.1° pitch compared to 2.5° roll and pitch for the cylinder FPSO. The most critical response for the process equipment is the acceleration in roll and pitch. The acceleration of roll and pitch is presented in Figure 5-12 for the 1-year return period and the 10-year return period.

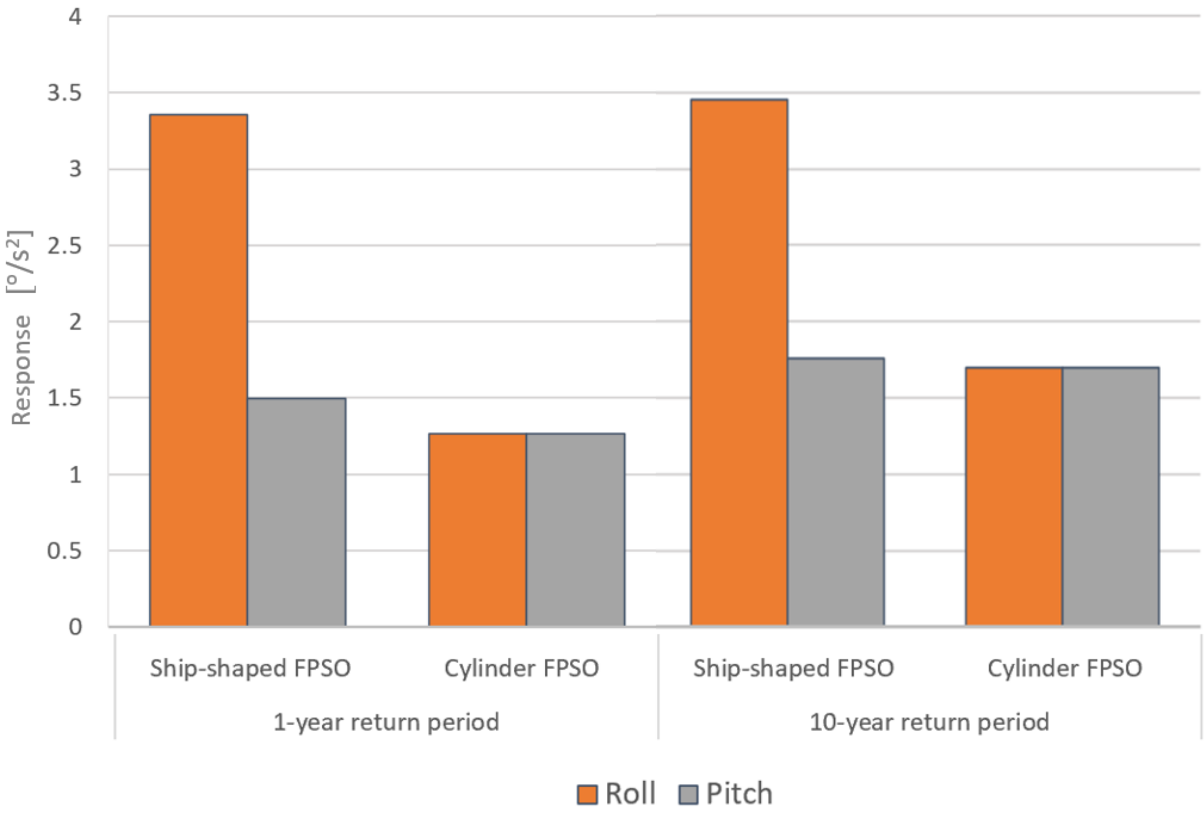

Figure 5-12: Responses in acceleration for 1-year and 10-year return period for the ship-shaped and cylinder FPSO.

The acceleration in roll is most significant for the ship-shaped FPSO. With a roll of 3.5 °/s², the equipment must be able to withstand more change in roll than on the cylindrical FPSO. The cylindrical FPSO has the same response amplitude for both roll and pitch because of the circular shape (1.3°/s²). Based on the results, the equipment must withstand greater accelerations on the ship-shaped FPSO compared to the cylindrical. The results show the acceleration is not significantly changing from the 1-year to the 10-year response. In roll, the difference is ~0.1 °/s² for the ship-shaped and ~0.4 °/s² for the cylinder FPSO.

Discussion

The 3-hour sea state is a method used for initial response calculations. Long term analyses can be done but are not relevant for an initial phase of concept development. The method of 37 % of non-exceedance is an applied method in the naval architecture to compute responses which will occur. A 90% percentile could also have been used, resulting in slightly larger responses but less probability of non-exceedance. It is better to give the responses in 37% non-exceedance, estimating the responses that will occur on an FPSO, hence used for the analysis. The simplification of the model is also a standard method done modelling for initial response analysis as the aim was to have a concept with dimensions and weight that represent realistic FPSO responses. The simplifications do not affect the results but make the models faster to compute.

The responses from the 1- and 10-year return period sea states represent the extreme responses that will happen each year and every 10th year. The results are reasonable estimates for the most significant responses a hydrogen production equipment must be designed for to suspend operation. As the climate is changing, storms will be more extreme and more frequent [1]. From a forward perspective, the FPSOs will be exposed to 10-year extreme sea states more frequently than every 10th year. It can be discussed if the operational design criteria for the process equipment must be designed for more significant motions than before. Therefore, the results give equipment manufacurers a reasonable estimates of expected motions on an FPSO from a yearly and future perspective.

Roll and pitch give minor responses close to the global centre of the units; hence these responses are found in the edge points of the FPSOs. The responses on the edges are more of interest when determining the response that the equipment will experience distributed on the unit. For the ship-shaped FPSO, the specific points are at the bow and the side of the ship, representing the locations with the most pitch and roll motions. If accelerations or motions are too significant for equipment, a location closer to the global centre of the unit will result in less response.

The cylinder FPSO will have less pitch and roll because of the cylindrical shape and have, as expected, less significant responses compared to the ship-shaped. The cylindrical FPSO can be more suitable if the process equipment's operation is limited by roll or pitch than the ship-shaped. The smaller responses can also be a result of the moonpool, which reduces the FPSOs buoyancy or the large dampening factors included. The ship-shaped FPSO has no dampening factors included. According to LMG Marin, exact dampening factors are obtained from model testing, hence inputs for analyses further in the design process[46].

The analysis only considers the heave, roll and pitch and excludes the other response variables, surge, yaw and sway. The additional response variables were excluded because the model does not consider mooring lines and long-period sea states, and these motions are close to 0.

It must be taken into consideration that the motions are the largest that will happen because of the location on the FPSOs, and the incoming waves used in the response analysis for each response. Roll if taken from 90 degrees weather direction and heave from 0, hence the maximum responses from heave and roll will not occur simultaneously. The method of calculating the responses for different incoming weather was to represent the most extreme responses that can occur.. Usually, the wind, current and wave direction are more dominant in some directions. A ship-shaped FPSO will experience incoming waves from 360 degrees directions and moored with the bow in the dominant wave direction can to minimise jeopardizing motions. The response characteristics for the cylindrical FPSO are not dependent on incoming waves' direction because the hull is symmetric.

If there are operability limitations due to certain motions for the equipment, the FPSO can be designed to minimise these motions. An optimisation for the equipment sensitive to the motions or accelerations in roll is the layout on the deck. On a moored FPSO, the equipment can be placed horizontally to the weather direction to minimise roll (Figure 5-13).

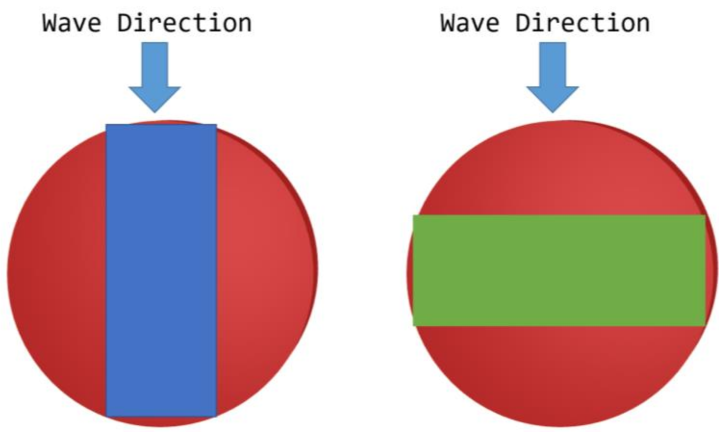

Figure 5-13: Illustration of cylinder FPSO and placing of process equipment. Blue for sensitive roll equipment, green for pitch sensitive equipment concerning incoming waves.

The location of the FPSO in calm waters will also affect the motions. For example, the Mediterranean Sea is less rough than the North Sea. On the other hand, locations with good wind potential mean often rough sea. Offshore wind potential is best far from shore, and also, the transport of offshore produced hydrogen is the cheapest option for distances exceeding 200 km. But the FPSO must also be designed for these extreme conditions offshore. Cost analysis, including wind potential and the increases in extreme weather, could be analysed for further evaluation of the concept.

The results, method and models developed in the thesis can be used to analyse other locations with other sea states. Other floating rigs can also be modelled and used. An example is semi-submersible floating platforms. They are used for oil drilling because they have a small waterline area that reduces wave responses.

The popularity of offshore wind is because the wind farm is out of sight and does not take up space or change the landscape inhabitant neighbourhood. However, the FPSO can alternatively be connected to land-based renewable sources in nearshore locations if motions from the rough north sea limit the production. If electricity is supplied from an onshore gird, the power handling system on the FPSO must be engineered to handle very high, short-circuit currents. This means higher installation cost since more material must be used to cope with the high short-circuit currents, according to Aabø Powerconsulting [76]. Other perspectives are the marine life closer to shore, which can be affected by a large amount of warm water from the cooling loop or the brine from the desalination process. This is also relevant for the offshore FPSO to be further analysed.

5.2.3 Expected motions for offloading

Results

For offloading, the result is the combined motions in y and z-direction. The sea state used in the analysis is 1-6 with H_s from 1.5-6.5 m (Table 5-3), with a probability of non-exceedance of 37%. The results are presented in Figure 5-14 and Figure 5-15.

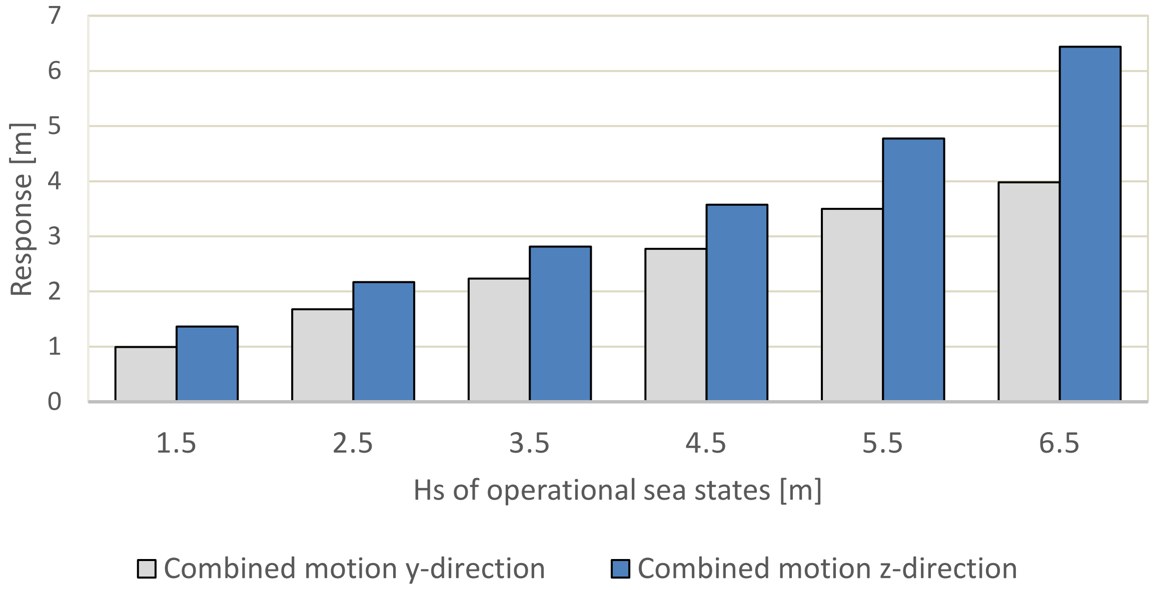

Figure 5-14: Responses for offloading position for shaped-shaped FPSO. Hs is the significant wave height.

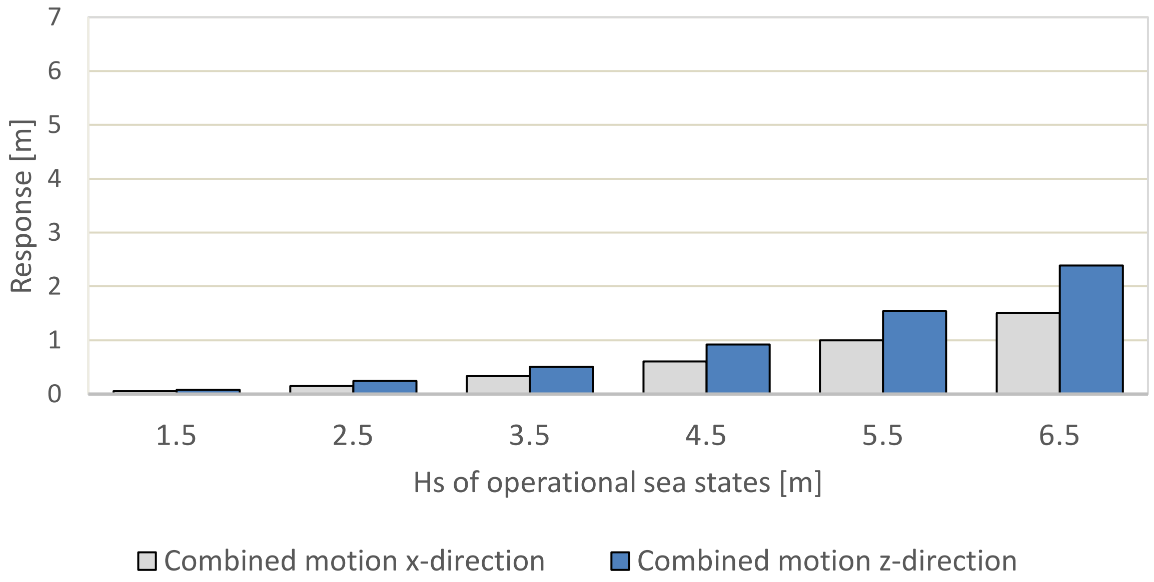

Figure 5-15: Responses for offloading position on cylinder FPSO, Hs is the significant wave height.

Both plots present the motions from the y and z- directions. The motions in the x-direction were 0 because the responses are calculated for incoming waves for 90˚. Comparing the plots, responses are more significant for the ship-shaped unit. The combined motion in the z-direction is 6.4 m compared to the cylindrical, which has an amplitude of 2.4 m with the H_s of 6.5 m. The heave response variable dominates the z-direction. As for the 1-year return period responses, the heave motion is less for the cylindrical unit because of the shape and dampening factors.

Discussion

The offloading analysis determined the motions for the most frequent sea states to give the equipment manufacturers an understanding of the most common responses in operational conditions. The combined motions were found for x,y and z directions to present motions for offloading, as the limitations in couplings and hoses can be compared to these motions. The combined motion includes surge, yaw and sway, but the motion is primarily dependent on the heave, roll and pitch because of the sea states and excluded mooring lines. The mooring would possibly have more influence on both combined motions in x and y as the surge and sway are transitional motions along these axes.

The offloading operational limit is typically a Hs of 4.5 m. At the offshore offloading limit of 4.5 m Hs, the offloading hoses and couplings must withstand motions of up to 3.6 m in the z-direction and 2.8 m in the y-direction for the ship-shaped unit. The cryogen offloading hose or hoses for liquid hydrogen must be very flexible to withstand these motions. The cylindrical FPSO has less than 1 m displacements in x and z-direction for Hs 4.5 m. If hoses and connections are limited by non-flexibility or motions in other ways, the results show that the cylinder FPSO is expected to give better operation time. Further in-depth analysis can give an accurate number of offloading limits and operation windows for a location.

As evaluated(cf. chapter 3.4.4), the best solution for offloading LH_2 is the ship-to-ship solution because of short offloading hoses. In that case, a relativity analysis between the FPSO and the receiving ship must be done. This is because if two floaters are close to each other, other hydrodynamic interactions than wave effects are important to analyse. This requires a hydrodynamic analysis of the two floaters as an integrated system with 12 degrees of freedom [39].

In the initial concept definition in chapter 3, it was assumed a market potential for zero-emission fuels. It lays the foundation of the relevance of this thesis and must be discussed regarding the results. An FPSO can work as infrastructure by transporting LH_2 and NH_3 to shore by a bunkering vessel or fuelling directly for the FPSO by its location. The predicted market for LH_2 is ships and vessels with short distance sailing, such as ferries and fast passenger ferries[5]. Smaller sailing distances compete with battery vessels, which is a better alternative if the hydrogen fuelling infrastructure is not implemented. LH_2 ship bunker directly from an FPSO in an offshore location is not an option considering LH_2 ships operate on short sailing distances. If offloading technologies are developed for higher offloading rates, a dedicated bunkering vessel is an alternative for LH_2.

Ammonia as fuel is predicted for larger ships, even with continental sailing distances [5]. The FPSO can work as an offshore refuelling station located close to popular sailing routes for future ammonia fuelling vessels. The response analysis and the technical evaluation support the market potential for ammonia vessels as a feasible cause for an FPSO refuelling station offshore. But also as a dedicated bunkering vessel with a large storage capacity.

The best storage option is a comprehensive decision that includes market potential, production size, and how to cut emissions. Based on the results in this theisi, the selected storage approach must prioritise between large production capacity associated with new technology development (LH_2) storing or a rapid implementation with smaller production rates (NH_3). On the one hand, market potential decides if there is a need for a large scale production or not. On the other hand, production and infrastructure for zero-emission fuel must be implemented to have a market. It is a classic problem of what comes first, the hen or the egg? The emissions of LH_2 and NH_3 as fuels must also be considered. The carbon intensity of the fuel is only reduced when blending green ammonia with commercial fuels (cf. chapter 2.3). Development is needed for implementing carbon-free ammonia fuel cells. Still, the emitted NOx and N_2O must be regulated [5]. From a climate perspective, to keep global warming under 2 degrees, it can be discussed if the zero-emission LH_2 is the only correct answer? Conversely, a step by step integration of NH_3 to accelerate the development of NH_3 carbon-free systems is another approach to this problem. These are some of the pros and cons of this discussion.

6 Conclusion

Hydrogen production on an FPSO provides a solution for infrastructure for maritime zero-emission fuels. Hydrogen is produced with either PEM or ALK electrolysis technology. The scope is limited to considering hydrogen conversion and storage of liquid hydrogen or ammonia. The necessary technology development for offshore large-scale hydrogen liquefaction and offloading makes ammonia a preferred option in the short perspective. With the rapid need to implement zero-emission fuels and infrastructure for the shipping segment, less development for implementation may be the best solution. In a longer perspective, storing hydrogen liquefied is the most effective production method as it provides more energy produced per area. Storing capacity for 17 days is feasible on FPSOs, considering a 7-day offloading interval and 10-day buffer storage.

The maximum production capacity to be expected on FPSO is limited by the deck area and the storage method. A ship-shaped FPSO with a deck area of 21 000 m^2 can expect a 400 MW electrolysis capacity with liquid hydrogen storage. Storing as ammonia reduces the hydrogen production capacity by 50%. The expected production capacity from a cylindrical FPSO with a deck area of 7 854 m^2 is under the defined large-scale of 100 MW, with ammonia storage.

In a North Sea application, hydrogen process equipment must be designed for larger motions (5.0° roll) on a ship-shaped relative to a cylindrical FPSO, where symmetry reduces the expected motions (2.5° roll). Hence, the FPSO design and shape should be emphasised to minimize motions that can jeopardize hydrogen production. In operational conditions, the offloading technology must be designed for up to 3.6 m vertical and 2.8 m horizontal displacements (ship-shaped FPSO), a possible deal-breaker for the liquid hydrogen because of the limited flexibility and high offloading rates required.

By answering the objectives, the concept is one step further in developing offshore hydrogen production for zero-emission fuels. Motions on FPSOs are supplied to the literature limited by this thesis scope. The expected production capacities are found, and the equipment to be developed for application on an FPSO is emphasised.

6.1 Future work

Future work has been emphasised in many discussions because the results yield many uncertainties, simplifications and limitations, which have been essential in the initial phase of this concept analysis. The main recommendations for future work are summarized in these points. Firstly, it is recommended to add the safety aspects of LH_2 and NH_3 handling and practical area utilisation of several decks and hulls to obtain more accurate calculations of the production capacities expected on the FPSOs. Secondly, new estimates on the conversion modules should be found for linearly scaling exceeding 100 MW, based on input data representing several equipment vendors. Thirdly, techno-economic assessments can further develop the concept by evaluating the best storage method and recommended locations, wind farm size, and market potential. Lastly, the responses from the thesis FPSOs are relevant to evaluating the operation criteria of the process plant. It is recommended to provide vendors and manufacturers with these motions further to map the expected operational criteria for the FPSO plant. Hence the FPSO can be designed for optimal motion criteria.

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Appendix

Resulting properties for the FPSO models after stabilising

Ship-shaped FPSO

Table 0-1: Resulting properties for the ship-shaped model after stabilising.

Properties	Shipshape FPSO [m]
Draft	13.0
Centre of gravity	17.1
Centre of buoyancy	6.5
Metacentre	11.2

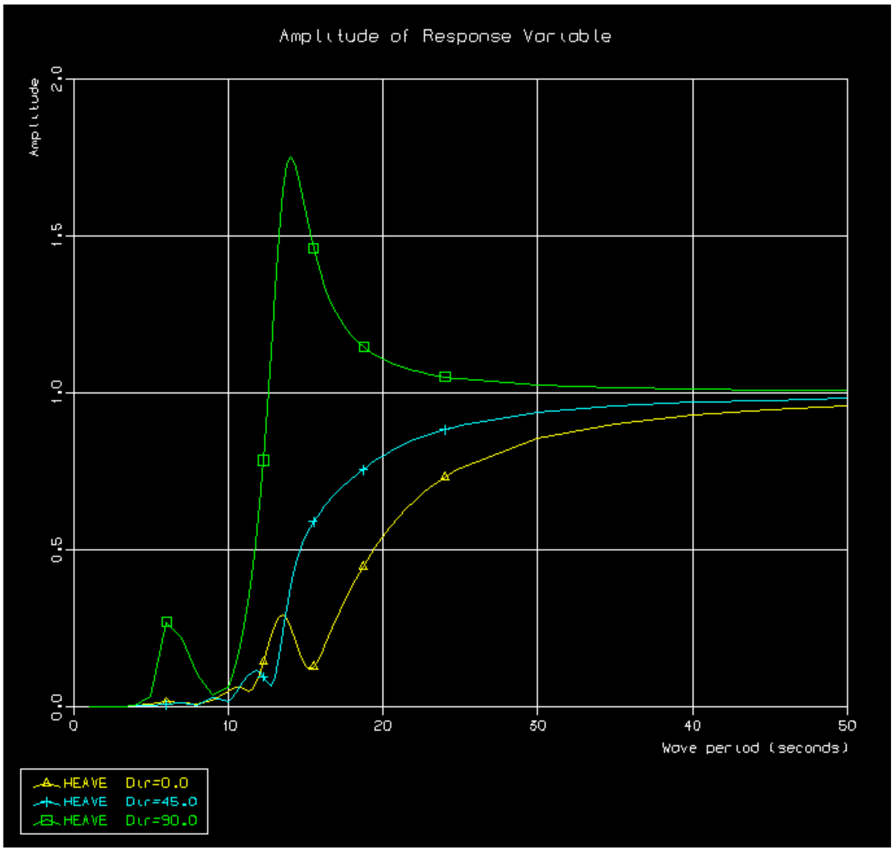
Cylinder shaped FPSO

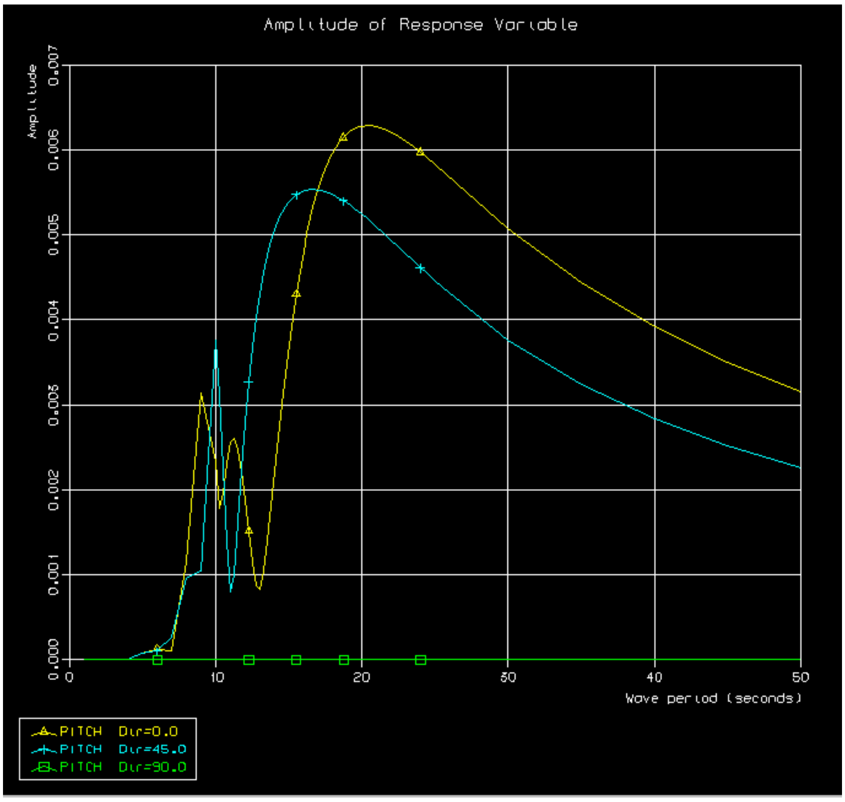
Table 0-2: Resulting properties for the cylinder model after stabilising.

Properties	Shipshape FPSO [m]
Draft	20.0
Centre of gravity	28.0
Centre of buoyancy	8.8
Metacentre	6.9

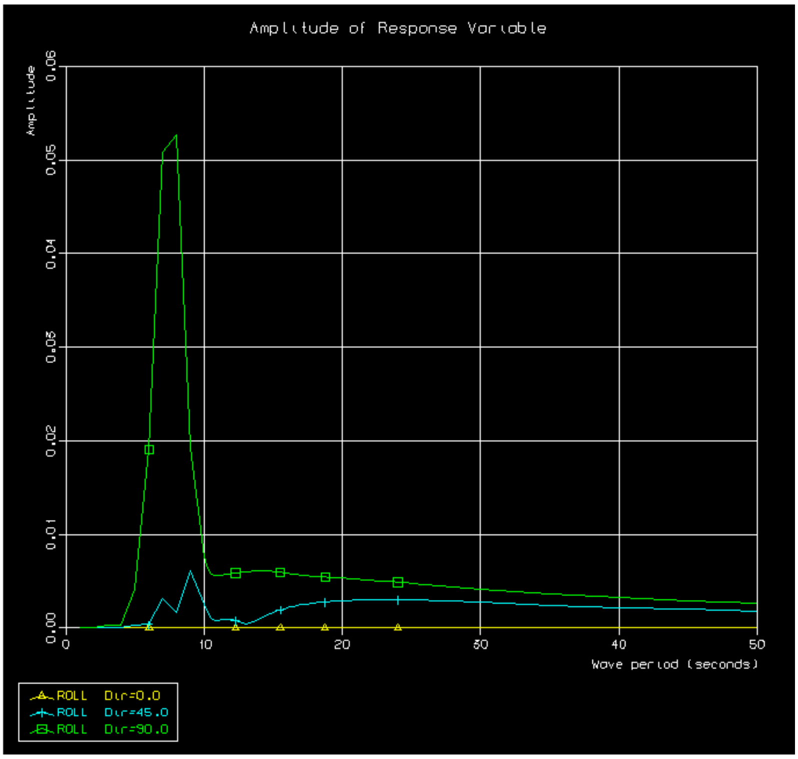
Response variables for ship-shaped FPSO

Response variables for incoming waves from 0, 45 and 90 degrees. The direction belonging to the curve with the largest amplitude for each response variable is used to determine the responses.

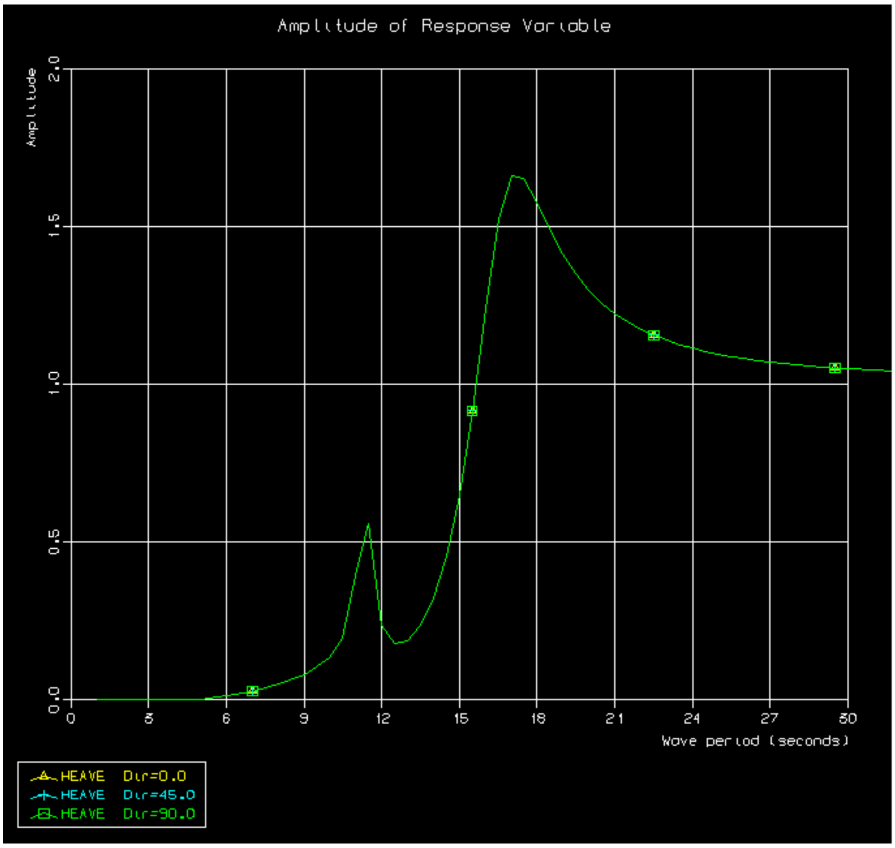




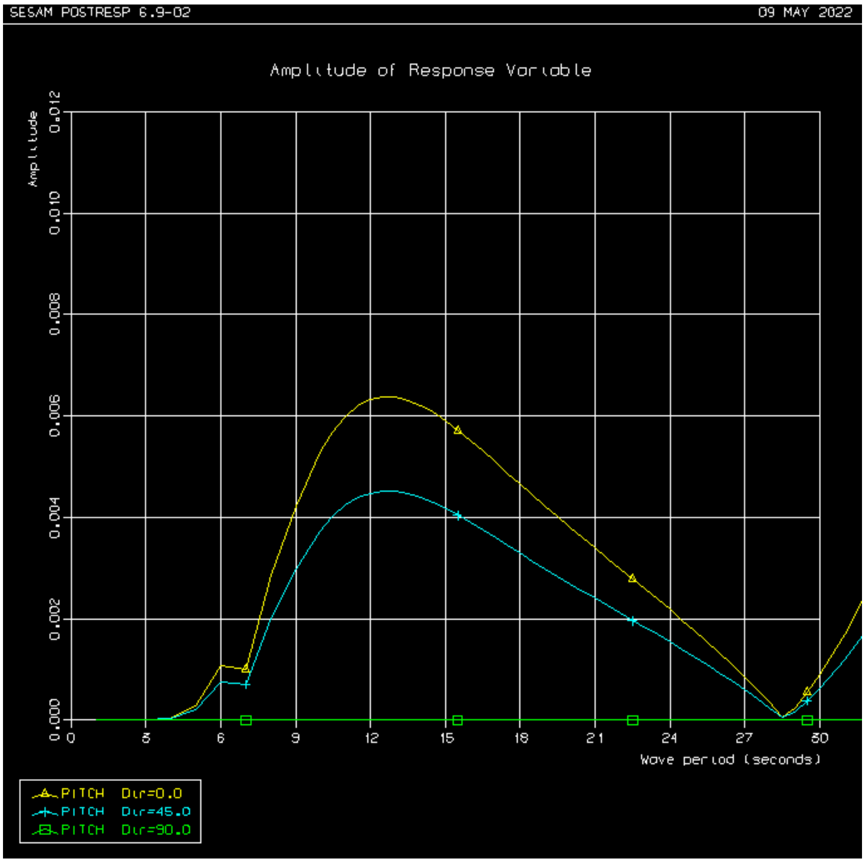
For pitch, the 45 degrees direction is used, as 45 degrees gives the largest response for wave period 10-15 s. This gives the most significant response obtained when multiplying the response variable by the wave spectra.

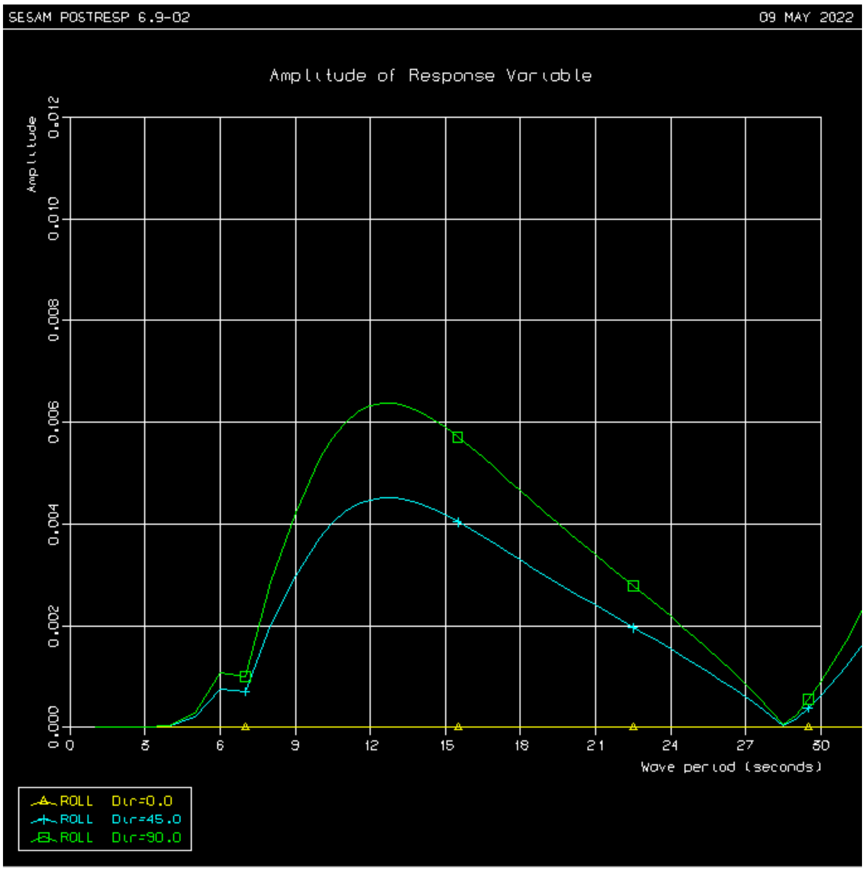


Response variables for cylinder FPSO



Heave for all directions are the same, hence the plot show one green line.


SESAM POSTRESP 6.9-02
09 MAY 2022
Amplitude of Response Variable
Amplitude
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0
3
6
9
12
15
18
21
24
27
30
Wave period (seconds)
PITCH Dir=0.0
PITCH Dir=45.0
PITCH Dir=90.0


SESAM POSTRESP 6.9-02
09 MAY 2022
Amplitude of Response Variable
Amplitude
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0
3
6
9
12
15
18
21
24
27
30
Wave period (seconds)
ROLL Dir=0.0
ROLL Dir=45.0
ROLL Dir=90.0