Sohrab Sekandar

Conceptual Design of Green Ammonia FPSO

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2021

Master's thesis

NTNU
Norwegian University of Science and Technology
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Kunnskap for en bedre verden

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Abstract

The purpose of this thesis is to propose a system that can produce, store and offload hydrogen in a chemical form utilizing renewables. This was done by developing a conceptual design for the problem based on the methodology by Pahl et al. (2007).

The global energy demand has been growing almost exponentially due to growth in population, industrial activity, and advancement in countries. Energy production, mainly the burning of fossil fuels, accounts for around three-quarters of global greenhouse gas emissions. Renewable energy sources such as wind are getting more and more attention and the industry is rapidly growing. The problem of balancing supply and demand is becoming more pressing. Hydrogen could potentially be the new link between production and storage to save both energy and costs. Literature review on different production, storage, and distribution methods shows that there are several ways to combine these methods to develop a system.

The methodology starts by identifying the stakeholders and the needs of such a system. Additionally, through the establishment of function structures and working principles, a solution field was explored. The principles were combined and the compatibility between these was reviewed. They were firmed up into solutions using design tools such as a morphological catalog. These solutions were evaluated using the Analytical Hierarchy Process based on different criteria. The most viable concept was shown to be:

- A floating facility that utilizes renewables to produce hydrogen. The produced hydrogen will be stored as liquid ammonia and transported using LPG carriers.

A proposed model of the production process was established with a description of the chemical principles behind the sub-processes. The next natural step for further work is embodiment design. This means taking the concept into the embodiment design phase, where layout, auxiliary functions, arrangements, and such are found. But another possible route is to use the simulation to evaluate the energy equilibrium and to get an overview and compare how much energy is produced compared to the amount of energy used in the system

Sammendrag

Målet med denne masteravhandlingen er å foreslå et system som kan produsere, lagre og offloade hydrogen ved bruk av fornybar energi. Dette ble gjort ved å utvikle en konseptuell design for problemet basert på metodikk av Pahl et al. (2007).

Det globale energibehovet har vokst nesten eksponentielt på grunn av befolkningsvekst, industriell aktivitet og økonomisk og teknologisk utvikling i mange land. Energiproduksjon, hovedsakelig forbrenning av fossilt brensel, står for rundt tre fjerdedeler av de globale klimagassutslippene. Fornybare energikilder som vind får mer og mer oppmerksomhet og industrien vokser raskt. Problemet med å balansere tilbud og etterspørsel blir mer pressende. Hydrogen kan potensielt være den teknologiske broen mellom produksjon og lagring for å spare både energi og kostnader.

Metoden starter med å identifisere interessenter og behovene til et slikt system. I tillegg, gjennom etablering av funksjonsstrukturer og arbeidsprinsipper, ble et løsningsfelt utforsket. Prinsippene ble kombinert og kompatibiliteten mellom disse ble gjennomgått. De ble utvidet til løsninger ved hjelp av designverktøy som kompabilitetsmatriser og morfologisk katalog. Disse løsningene ble evaluert ved hjelp av Analytical Hierarchy Process på grunnlag av forskjellige kriterier. Det mest optimale konseptet ble funnet å være:

- Et flytende anlegg som bruker fornybar energy fra offshore vindparker til å produsere hydrogen offshore. Det produserte hydrogenet blir lagret kjemisk i form av flytende ammoniakk og transportert til land ved hjelp av LPG tanker

En modell av produksjonsprosessen ble etablert med en beskrivelse av de kjemiske prinsippene bak delprosessene. Det neste naturlige trinnet for videre arbeid er embodiment design. Dette betyr å ta konsept inn i en designfase, hvor layout, hjelpefunksjoner, arrangementer og slikt blir funnet. En annen mulig rute er å modellere prosessen i HYSYS og foreta en simulering til å evaluere energiforbruket.

Preface

This master thesis is part of the Master of Science degree in Marine Technology with a specialization in Marine systems Design at the Norwegian University of Science and Technology, Trondheim. The thesis was written in its entirety during the spring of 2021, and the workload is equivalent to 30 ECTS. The main objective of the thesis has been to develop a conceptual design of a floating system that can produce, store and offload hydrogen in a chemical form utilizing offshore wind energy.

I want to acknowledge my supervisor, Professor Stein Ove Erikstad, for constructive feedback, inspiring discussions and helpful comments during this thesis.

Further, gratitude is extended to Henrik Baardson and Yinson Production AS for their time, guidance, motivating discussions, and always steering me in the right direction whenever it was needed.

Sohrab Sekandar

Trondheim, 10th June, 2021

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Chapter 1

Introduction

The amount of energy produced from offshore wind fields, either exploiting periodical surplus energy or for fields too remote to be connected to the electricity grid, can be used to produce hydrogen. The world energy demand is increasing rapidly and so is offshore wind technology. Several wind farm projects have been completed in the last decade and several more are under development. Hydrogen production from water electrolysis needs only water and electricity as input. It is emission-free if renewable energy is used. It may offer opportunities for synergy with variable power generation, which is characteristic of some renewable energy technologies.

With expanding offshore wind, the further the turbine is from land the greater the electricity connection costs become. In addition, transporting hydrogen over long distances can be up to ten times less expensive than transporting electricity. If there were solutions to produce, store and transport hydrogen offshore, the impact of long submarines piping to the coast will be reduced. Furthermore, having a floating system of this kind versus a stationary platform can potentially outlast its fixed position counterparts by decades. In addition, mobility means that with smaller crews, the ability to dodge adverse weather events, and the mobility to put into port or dock for regular repair and inspection, such system is its own solution to the problem of offshore asset integrity. This will be an essential step in the process of developing conceptual designs for practical application in the maritime and offshore industries.

Overall aim and focus

The overall aim of the thesis is to develop a conceptual design of such a system using the conceptual design methodology by Pahl et al (2007, chapter 6). Even though the design process is fairly limited to conceptual design, a validation in terms of production, experimental and computational testing of concepts in the form of concept selection methods and simulation may be included.

Furthermore, the theory and methodology behind the conceptual design phase will be provided as well as the results when applying the methodology.

Scope and main activities

The thesis should cover the following main points:

1. Provide a systematic overview of the potential offshore wind and hydrogen market and its developments.
2. Give an overview of the potential hydrogen market and its development.
3. Based on a literature review, provide a systematic overview of existing systems and technologies.
4. Develop a conceptual design for the problem based on methodology by Pahl et al. (2007).
   (a) Identify stakeholder and need.
   (b) Abstraction to find essential problems.
   (c) Establishing function structures.
   (d) Searching for working principles.
   (e) Selecting suitable combinations.
   (f) Firming up into solution variants.
   (g) Evaluating solutions using different criteria.
5. Present the obtained results based on the methodology.
6. Propose a model that shows the green ammonia synthesis process.
7. Discuss and conclude, including proposing a plan for continuation.

Chapter 2

Market situation

World energy outlook

Energy production – mainly the burning of fossil fuels – accounts for around three-quarters of global greenhouse gas emissions[2]:

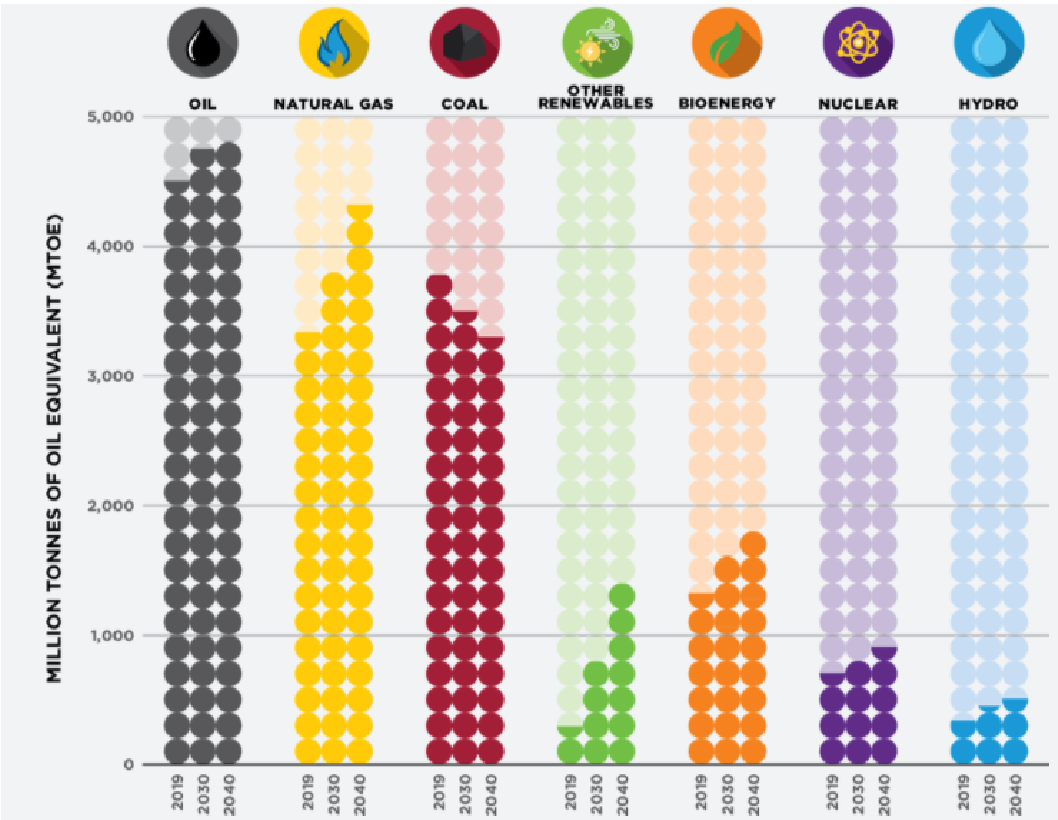


Figure 2.0.1: Global energy mix[2]

To reduce global emissions we need to shift our energy systems away from fossil fuels to low-carbon sources of energy while fulfilling the demand. According to the International Energy Agency (IEA), hydropower will remain as the largest renewable source of electricity, but solar is the main driver of growth as it sets new records for deployment each year after 2022, followed by onshore and offshore wind. In their report, the world's population will increase from 7.7 billion in 2019 to over 9 billion in 2040 - this means that the world's energy consumption will be growing, and the question is if renewable energy can meet the demand and play a key role in the decarbonization of our energy systems in the coming decades.

Energy source

When talking about renewables, which is the most viable option? Which generates more energy? Which is better for the environment? Which is more efficient? There are so many factors and variables that need to be taken into account before answering these questions. Both solar and wind have their advantages and disadvantages.

In short, starting with solar energy, we know that the sun is an enormous and eternal power source. Solar panels won't cause any pollution or environmental degradation when in use. Having a long life expectancy and good reliability, the maintenance costs are small. Having floating solar panels yields zero consumption of soil. In addition, the performance of each panel is higher compared to onshore installations. Using seawater for cooling and ventilation yields much higher efficiency and productivity. On the other hand, solar power is weather dependant. The effectiveness will decrease during cloudy or rainy days, and more significantly, there is no production at night. Furthermore, solar power is less efficient than wind[26].

Compared to solar power, wind can be harnessed both day and night. Offshore wind turbines are also environmentally friendly causing no pollution. The potential of wind energy is enormous, the same goes with its growth. The more attention green energy, the environment, and offshore wind farms get, the more cost-efficient its industry will become. Offshore wind turbines are more efficient than both their land counterparts and solar panels. Offshore wind turbines are generally located a short distance from land, meaning there is nothing that can obstruct the wind compared to onshore turbines installed in mountains, hills, buildings, and so on. The biggest disadvantage of an offshore wind farm is the cost. Wind speed is an unpredictable source and fluctuations in energy production are common. In addition, because of their locations offshore, they are susceptible to damage from high-speed winds during storms or hurricanes and lightning. Furthermore, the impact of offshore wind turbines on the marine environment and surrounding is still a question yet to be answered.

On a **larger scale**, there is no doubt that wind is a far more efficient source of energy than solar. It consumes less and produces more energy overall. To be able to generate the same amount of electricity per kWh, about 48,704 solar panels will be the equivalent to one wind turbine[36]. Wind farms, which are built offshore, can generate more thanks to the constant and strong winds. For commercial-scale power production for the national grid, wind farms seem to be the best solution. In Denmark, 48% of their electricity was generated by wind turbines[38]. While solar energy in Germany, one of the countries with the highest capacity of installed solar panels, only stood for 8.6% of their total consumption[39].

2.1 Offshore wind

Trends and Statistics

Offshore wind energy is a well-established practice, and the first offshore wind turbine was constructed in 1991[3]. Accurate knowledge of the wind field and surrounding wind farms in addition to atmospheric stability is important for wind farms to operate effectively.

Simultaneous with the rapid capacity growth, the wind fields are also being constructed farther away from the coast and grid entry points. Higher wind speeds are located offshore rather than on land, as well as being fewer restrictions in terms of the wind turbine size[6]. However, this poses significant expenses and challenges to the industry. High humidity and saltwater spray shortens service life and causes corrosion and oxidation. This results in construction and maintenance cost far higher than land-based turbines. Despite the high cost, offshore wind energy is the fastest-growing renewable power segment with an annual increase of 28%[4], reaching a global production capacity of 30GW in 2019.

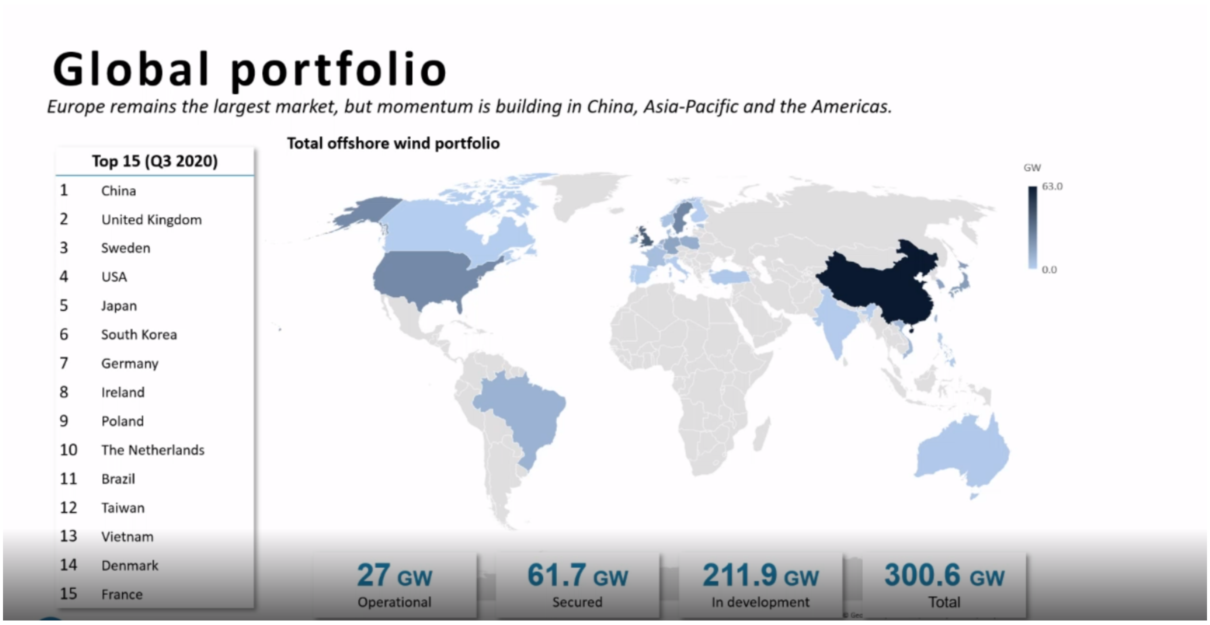


Figure 2.1.1: Global portfolio[16]

Figure 2.1.1 shows the total offshore wind portfolio of installed capacity. The data shows projects that are either under development, operational, or secured over the next years. This yields a total capacity of 300.6 GW[16]. Almost ten times the amount that is operational today. Furthermore, Europe remains the largest market, but momentum is building in Asia and the Americas. Especially in heavy industry countries like China, Japan, and South Korea.

Figure 2.1.2 also shows the same data. The key market is China with several projects under development and predicted to be operational by the end of 2020 and 2021. The main reason behind that is that the Chinese companies don't accept the same tariff deal and amount of investment from the Chinese government by the end of 2021.

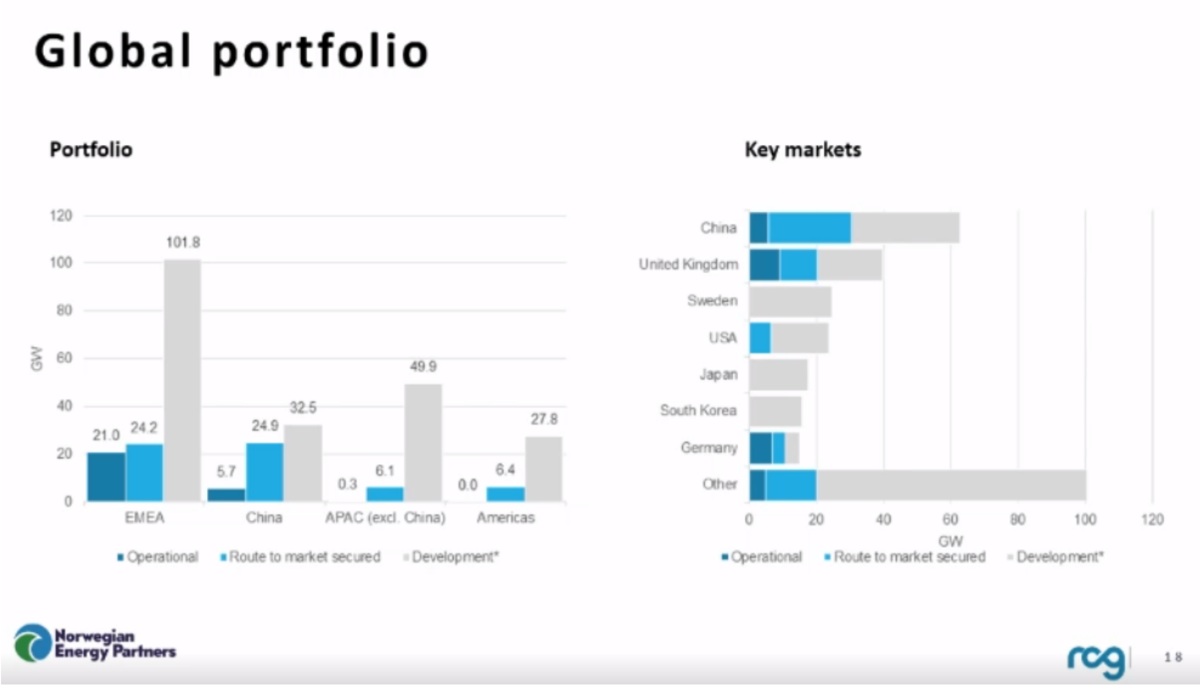


Figure 2.1.2: Global portfolio[16]

Countries like Sweden, the USA, Japan, and South Korea have many projects under development but they lack a route to market strategy.

If we look at the global picture, figure 2.1.3, a cumulative installed capacity increase of 29% is expected by 2025. This means a cumulative installed capacity of 76GW by 2025 with an average of ca. 15GW installed yearly. Across those five years, the investment is relatively flat with a slight decrease in 2023 and 2024. This is mainly due to a decrease in costs, but also because of the high amount of investment in 2021 and 2022 from China. This makes 2024 and 2025 more uncertain. The numbers show a total expenditure of 254 bn EUR in the next five-year period until 2025. That's an average of almost 50 bn EUR/year[16]. Great potential for the market where Norwegian industry can participate and take hold of. Compared to other global markets, like gas and oil, the offshore wind market is relatively new and small. But as we have seen from the previous figures, the potential to be achieved is high, especially after 2025 where even more countries can get involved.

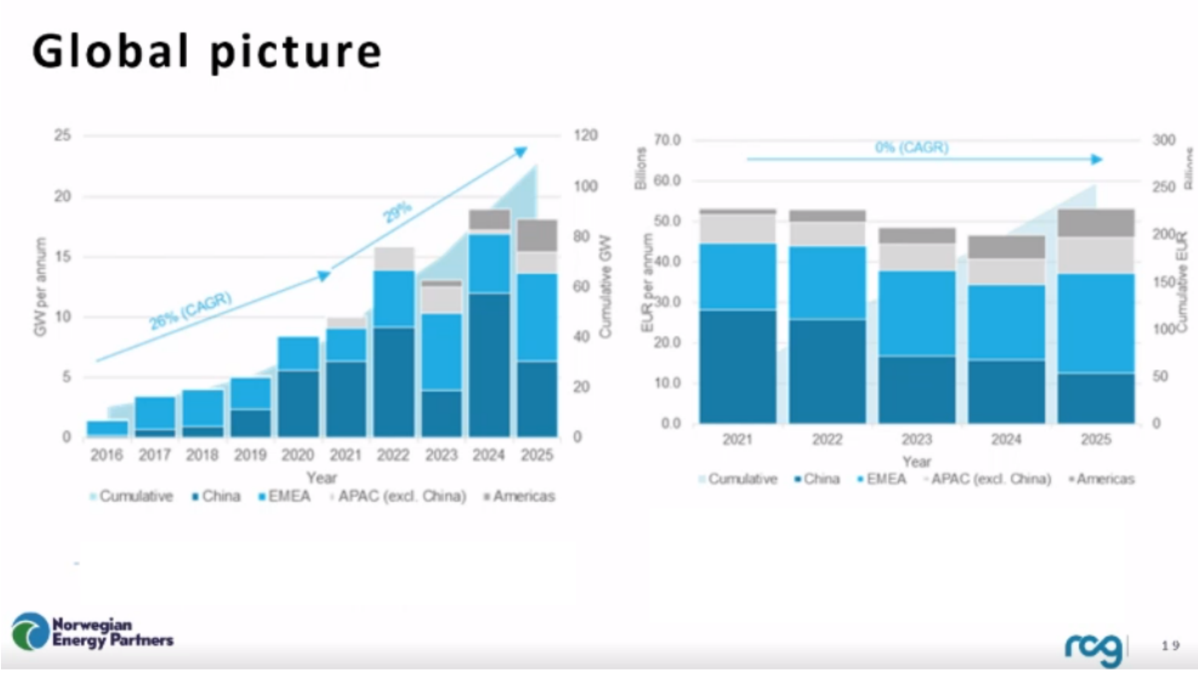


Figure 2.1.3: Global picture[16]

Focusing solely on Europe, figure 2.1.4, there will be a total installed capacity of 144.3 GW[16] in the next couple of years. The United Kingdom has the highest portfolio. There are some extreme activities in the industry in the UK due to attractive incentives from the Government.

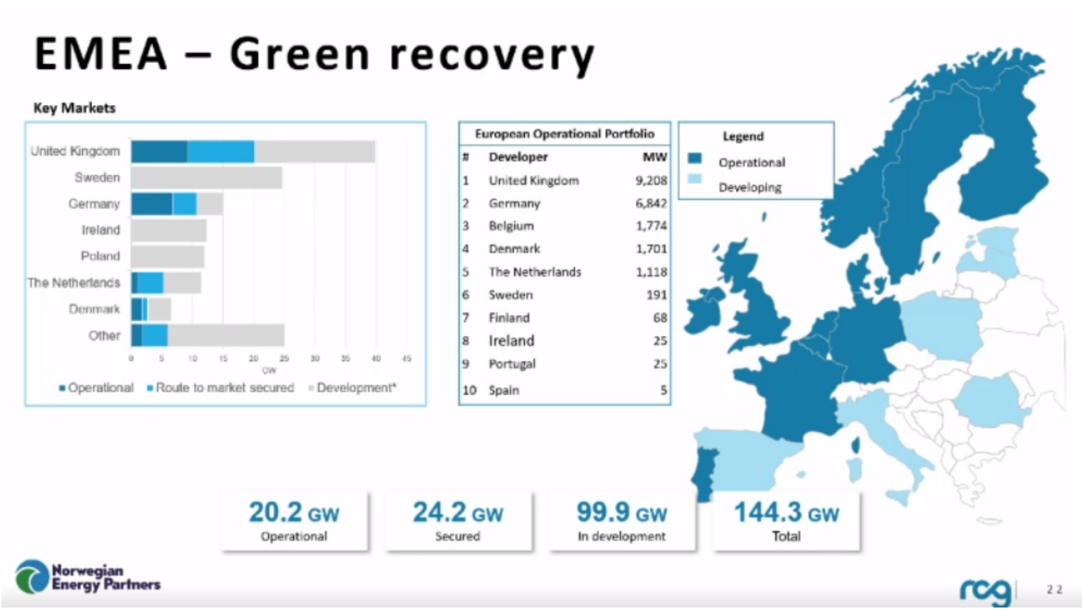


Figure 2.1.4: Market in Europe[16]

As shown in figure 2.1.5, expenditure in Europe is forecasted to increase. A total spends of EUR 98bn is expected between 2021 and 2025 at a compound annual growth rate of 10% and 20bn EUR market per annum[16]. A great amount is forecasted to be developed in the North Sea.

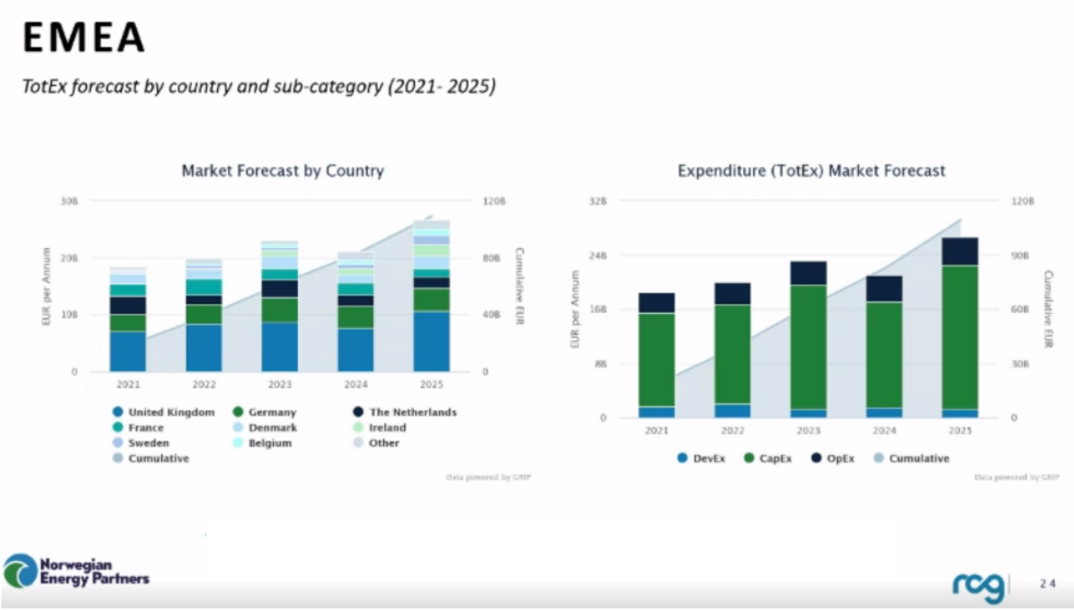


Figure 2.1.5: Expenditure in Europe[16]

The oil and gas industry has always been subject to deep and prolonged cycles of boom and bust and there is no reason to think the future will be any different. This year especially, the industry was hit hard during the coronavirus pandemic where Brent crude fell to the low 20s a barrel[17]. This is where the industries differ. The wind energy industry is less cyclic and more robust, and under this pandemic, there were way fewer cancellations or holds in upcoming projects compared to the oil and gas industry[18].

In the aftermath of COVID-19, governments around the world have deployed extraordinary policy measures to save lives and protect people's livelihoods. The EU announced in June a green recovery package worth EUR 750bn[19]. The goal is to improve energy efficiency, reduce dependence on fossil fuels and invest in preserving and restoring nature. Binding environmental requirements make the loans and grants come with green strings attached.

The future of offshore wind energy will continue to develop regarding efficiency, power, technology, and structure. With new changes and bigger investments, wind can become a leader within the renewables industry. However, for this to happen, the levelized cost of energy(LCoE) for both offshore wind and hydrogen production needs to decrease.

Levelized Cost of Energy

Levelized cost of energy(LCoE) is a measurement of comparing alternative methods of energy production of unequal life spans, project size, different capital cost, risk, return, and capacities. It can be thought of as the average total cost of building and operating for example a wind turbine, per unit of total electricity generated over an assumed lifetime[21]. Calculating the LCoE is related to the concept of assessing a project's net present value. Similar to using NPV, the LCoE can be used to determine whether a project will be a worthwhile venture[20]. Figure 2.1.6 is an illustration of a simple LCoE concept.

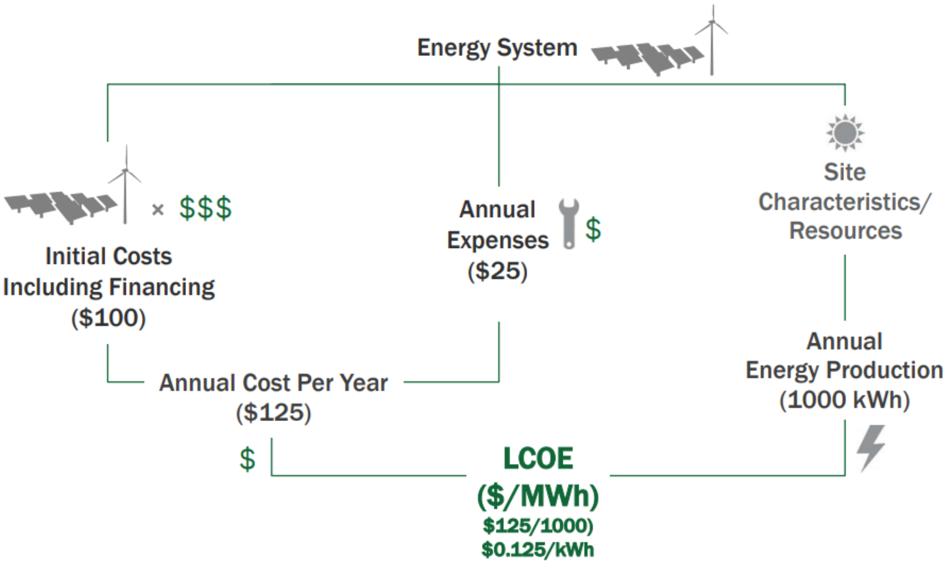


Figure 2.1.6: Simple illustration of LCoE[21]

Cost of energy reduction is a key driver of offshore wind expansion. As regional supply chains are developed and matured, the LCoE will reduce. Figure 2.1.6 shows how the LCoE has changed in the past years and how it is going forward. When Neart na Gaoithe offshore wind farm was announced in 2018, the LCoE was around 120 EUR/MWh, while Moray Firth and Horns Rev 3 is announced to be around 60/MWh. The LCoE is forecasted to reduce as low as in the 40s by 2030[16].

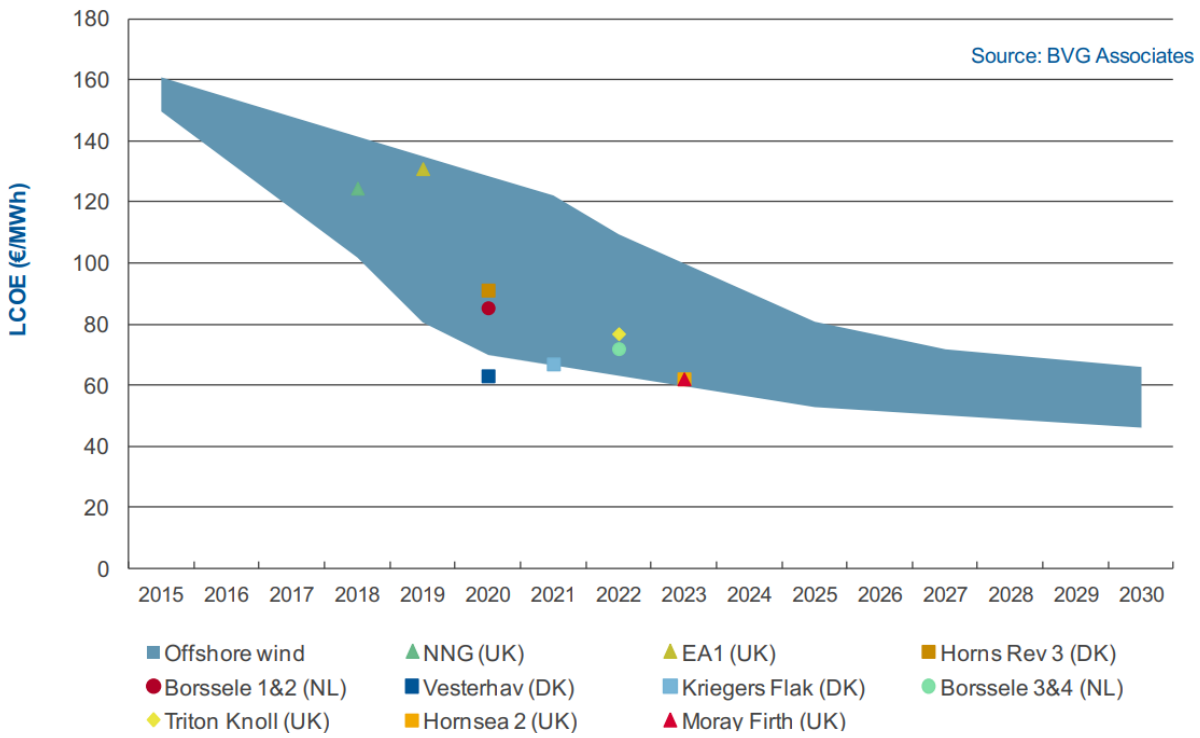


Figure 2.1.7: Development and forecast of LCoE[16]

This cost of energy reduction is a result of an increasingly competitive supply chain (with a reduction in margins), commercializing innovations (especially in large turbines), increasing investor confidence and applying lessons learned on previous projects to increase efficiencies and reduce finance costs[22].

According to BNEF, the global offshore wind average LCoE has dropped 67.5% to US$84/MWh since 2012. Cost reduction of offshore wind is set to continue and expected to hit US$58/MWh by 2025 thanks to the scale provided by GW-level projects, the newly introduced supersized offshore wind turbines, and the reduction in the cost of capital[23].

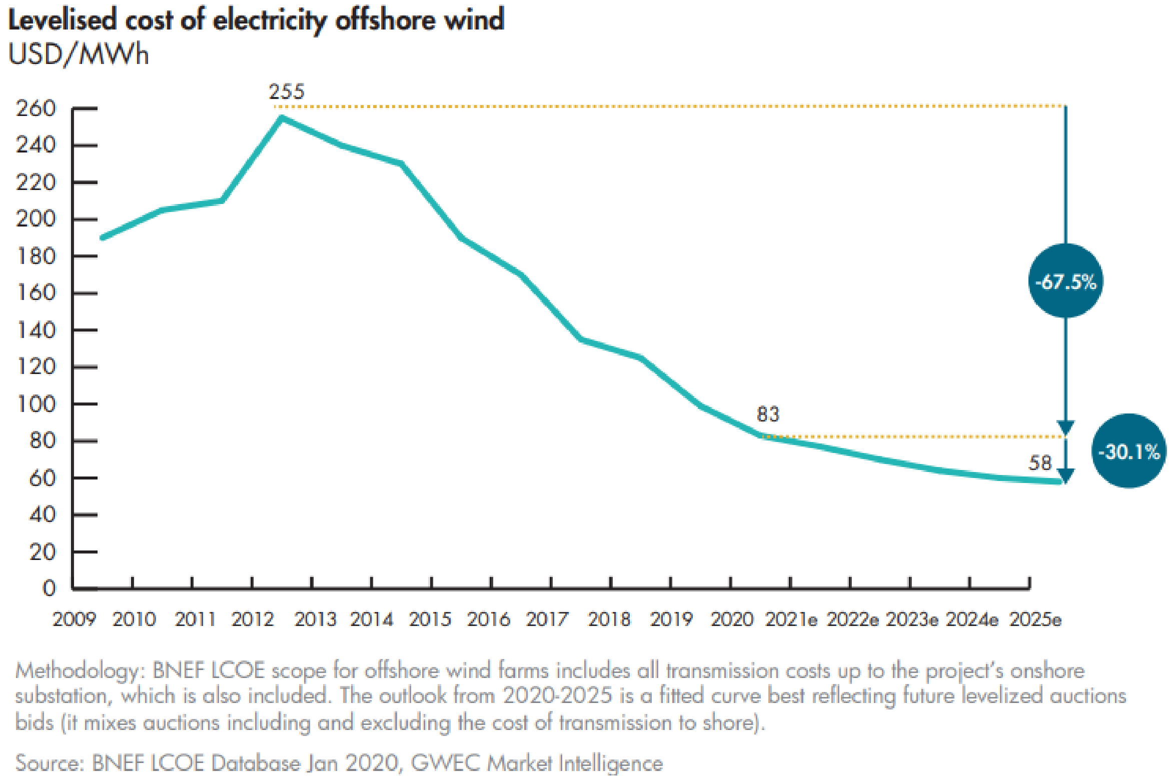


Figure 2.1.8: Cost Reduction of LCoE[23]

In summary, to be able to reduce the costs, the requirement of a strong supply chain in addition to high commitment from governments and the industry is key. As mentioned before, a renewable energy source such as wind is limited due to their intermittent availability. The wind doesn't always blow nor is it always optimal. By introducing hydrogen as the link used as a storage medium to supply energy during high demand the source becomes more viable. The same goes for using excess energy from wind farms to produce hydrogen.

Excess Wind Energy

The problem of balancing supply and demand is becoming more pressing. The grid technology today must be improved to continue to facilitate the increased demand and expanded variety of energy sources. With the considerable amount of investment, research, and analysis of this problem, hydrogen storage technology shows great results and potential as a reliable solution to this problem. Weather-driven power plants such as wind farms adjust the quantity of their product offered on the market according to the resource available. Optimal and beneficial wind and weather lead to an increase in supply in the market, while when the weather is inadequate, electricity is scarce leading to higher market prices. This can be illustrated by looking at figure 2.1.9.

The green curve represents the supply and the red curve the demand. As the weather conditions get preferable, the green curve will shift towards the right. This yields to fluctuations in the market price. When the wind is strong, the production rate of energy pushes the electricity price down, however, when the wind is not blowing the green

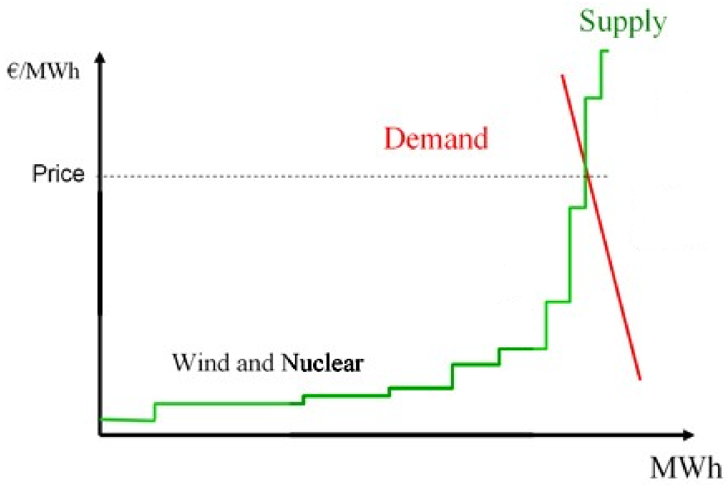


Figure 2.1.9: Power market equilibrium[9]

curve will stay under the demand curve and higher market price.

That's why the cost-effective use of surplus electricity depends on a fine balance between capital expenditure and operating cost of any surplus option on one side and the value of hydrogen on the other side. As the operating hours of a surplus option determine the output of hydrogen, then the value depends directly on this factor.

Chapter 3

Hydrogen value chain

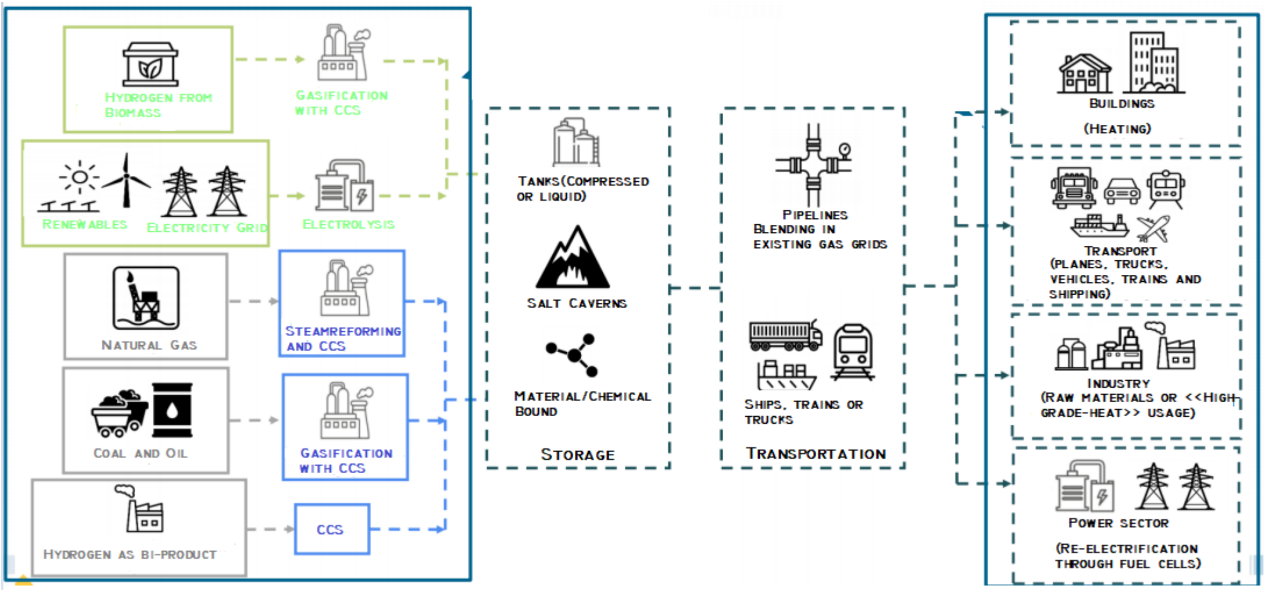


Figure 3.0.1: Value chain for hydrogen[40]

The following chapters introduce the value chain for hydrogen as seen in figure 3.0.1. That includes from the production process to utilization and how each technology differs when it comes to cost and infrastructure.

3.1 Production

Hydrogen alongside renewables and natural gas has an important role to play in the transition to a cleaner energy future. There are three different types of hydrogen – gray, blue, and green with each having its environmental credentials:

	Production method	CO_2 -emission from production
Gray Hydrogen	Reforming from natural gas	Approx. 8 tons per H_2 gas
Blue Hydrogen	Reforming from natural gas using CCS	Up to 90% reduction from gray H_2
Green Hydrogen	Electrolysis from water	No CO_2 -emission (Renewable energy)

Figure 3.1.1: Different types of hydrogen

The aim is to produce green hydrogen to achieve a zero-emission production method, and as shown in3.1.2, and there are several ways to achieve that.

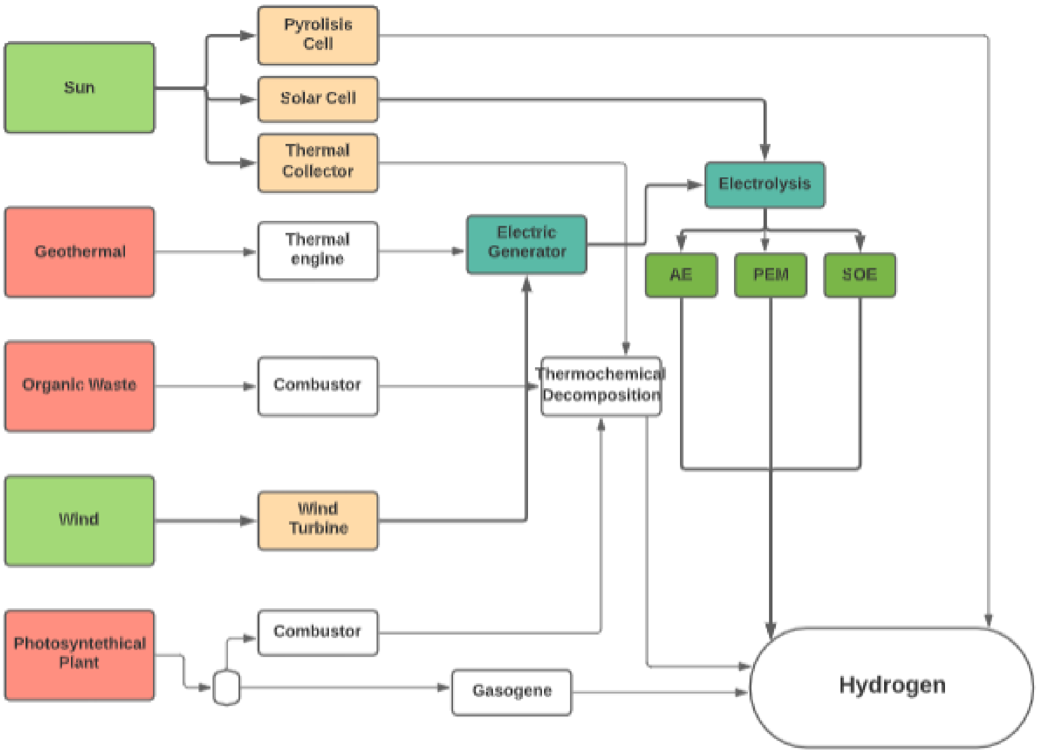


Figure 3.1.2: Potential pathways for producing hydrogen

This section will follow the steps shown in the figure above using wind as an energy source. Starting with an introduction to electrolysis. Then an introduction and comparison to the different electrolyzer technologies will follow. Lastly, a brief discussion on how the cost will vary from one electrolyzer to the other and the critical challenged the production process will meet.

3.1.1 Electrolysis

As mentioned in the previous chapter, almost all of the current hydrogen is produced from natural gas and coal. These processes are responsible for the emission of around 830 million tons of carbon dioxide per year[24]. Using electricity from a renewable source to perform electrolysis of water to produce hydrogen, makes the process emission-free.

Electrolysis of water is the process of using electricity to split water into oxygen and hydrogen gas. Hydrogen gas released in this way can be used as hydrogen fuel or remixed with oxygen to create oxyhydrogen gas, which is used in welding and other applications[30]. Different electrolyzer function in slightly different ways and have different efficiency. The efficiency ranges from 60%-80%[24].

Today, three main electrolyzer technologies exist: Polymer Electrolyte Membrane Electrolyser(PEM), Alkaline Electrolysers(AE), Solid Oxide Electrolyser(SOE). Each of them possesses different technical and economical characteristics.

Polymer Electrolyte Membrane Electrolyser

In a polymer electrolyte membrane electrolyzer, the electrolyte is a solid plastic material. In short, water reacts at the abide to form oxygen. The electrons flow through an external circuit and the positively charged hydrogen ions move across the PEM to the cathode. Hydrogen ions will then react and combine with the cathode to form hydrogen gas[32].

PEM electrolyzers have a compact system design, which means they are relatively small, making them more advantageous than other electrolyzers in dense areas. They have a high production rate and high purity of gases. Since the technology is relatively new and partially established, their overall costs are higher than alkaline electrolyzer.

Alkaline Electrolyser

Oxygen and hydrogen are separated from the water when the direct current is applied to the water. Hydrogen is being generated on the cathode side via the transport of hydroxide ions through the electrolyte from the cathode to the anode. At the anode, oxygen and water molecules are generated[33].

Alkaline electrolysis is a well-established technology that is commercialized and has a low overall cost. In addition to having a low purity of gases, the formation of carbonates on the electrode, the performance of the electrolyzer decreases.

Solid Oxide Electrolyser

Solid oxide electrolysis operates at high pressure and high temperatures 500–850°and utilizes the water in the form of steam[31]. Water at the cathode combines with electrons to form hydrogen gas and negatively charged oxygen ions. What makes SOEs so special, is the fact that the process can be reverted. Which means that hydrogen can be converted back to electricity. This provides a potential service to the grid in combination with hydrogen storage facilities[34].

SOEs are the least developed technology. Several companies are aiming to commercialize the technology. Since the technology is based on using ceramics as the electrolyte, the material costs are low. Operating at high temperatures and high working pressure yields a high degree of electrical efficiency. Since the technology uses steam for electrolysis, a heat source is required. In addition, the technology has a large system design and low durability.

Comparison and summary

Polymer electrolyte membrane electrolyzer is an emerging technology with units available on a commercial basis and is expected to be the prime choice after 2030[35]. Alkaline electrolysis is an advanced, proven technology. Solid oxide electrolyzer is a high-temperature technology. It is promising, but difficult and advanced technology. Each technology has its pros and cons, a summarised table of the different technologies and their characteristics can be found in section 9.1. Using this table to compare the technologies, there is one that stands out. In terms of sustainability and environmental impact, PEM electrolysis is considered the most promising technology. Emitting only hydrogen as a byproduct and having a high pure efficient production of hydrogen from renewable energy sources. Figure 3.1.3 shows their similarities and differences in the process.

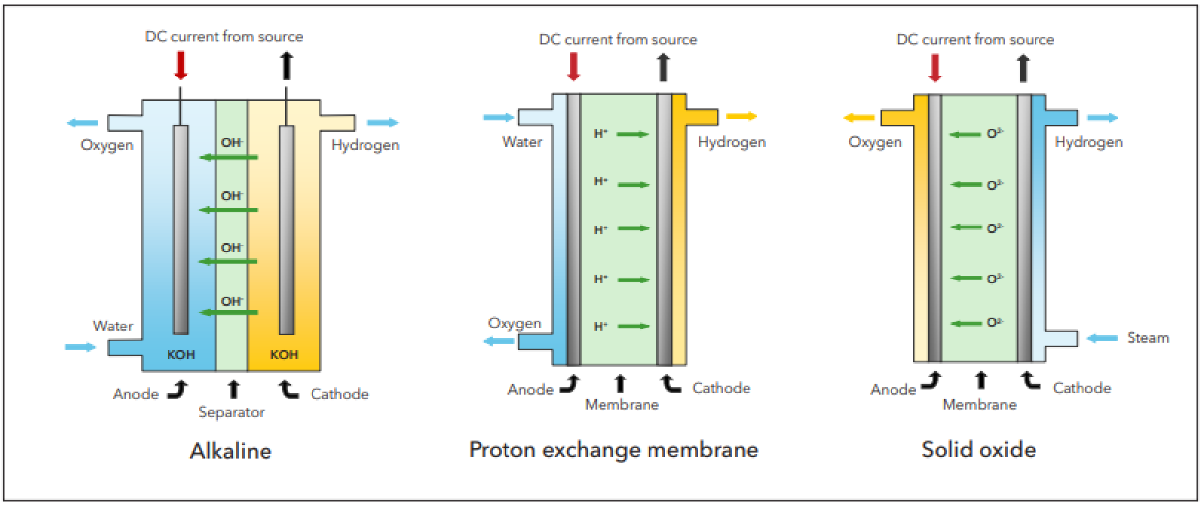


Figure 3.1.3: Principle set-up of electrolysis[31]

Production cost of hydrogen

As mentioned in section 2.1, the idea is to use excess energy to produce hydrogen. Hydrogen production from renewable energy via electrolysis can make a positive contribution to the power grid. The production can be switched off during high-load hours to remedy the power grid without significantly affecting the economy. A challenge with this is that electrolysis plants today have a high investment cost. That means that the number of operating hours must be sufficient and efficient enough to cover the capital cost. This will, in practice, limit the possibility to utilize excess energy. If the full potential of hydrogen from electrolysis in conjunction with non-regulatable renewable energy is to be extracted and utilized, capital costs must be reduced.

The cost is influenced by various techno-economical factors: conversion efficiency, electricity costs, annual operating hours and CAPEX requirements[24]. But analyzing the difference in development in the last decade(figure 3.1.4), there is a clear cost reduction difference.

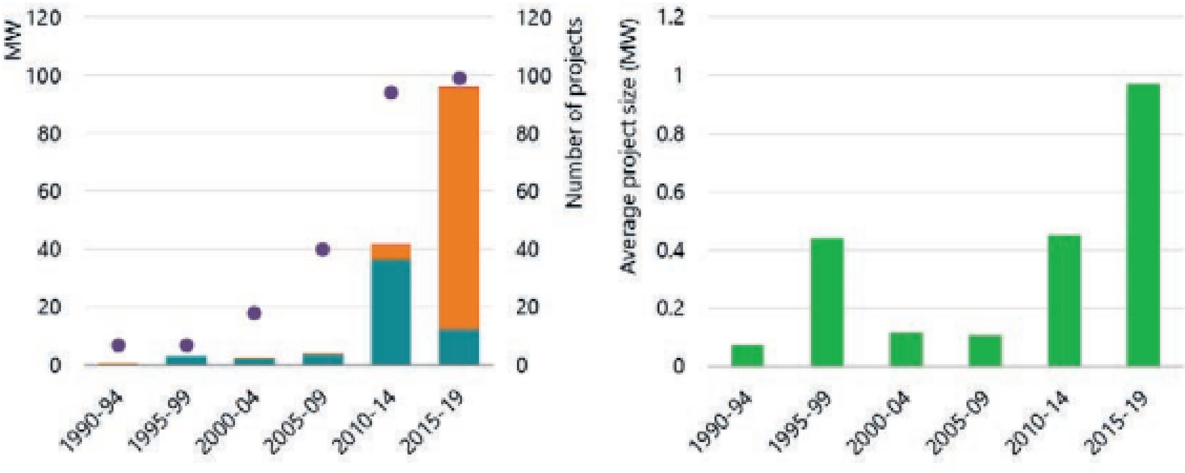


Figure 3.1.4: Development of electrolyser capacity in the last decade[24]

Based on an electrolyzer efficiency of 69%(LHV) and a discount rate of 8%, figure 3.1.5 shows that as electrolyzer operating hours increase, the impact of CAPEX costs on the Levelized cost of hydrogen declines, and the impact of electricity costs rises. Low-cost electricity available at a level to ensure that the electrolyzer can operate at relatively high full load hours is therefore essential for the production of low-cost hydrogen[24].

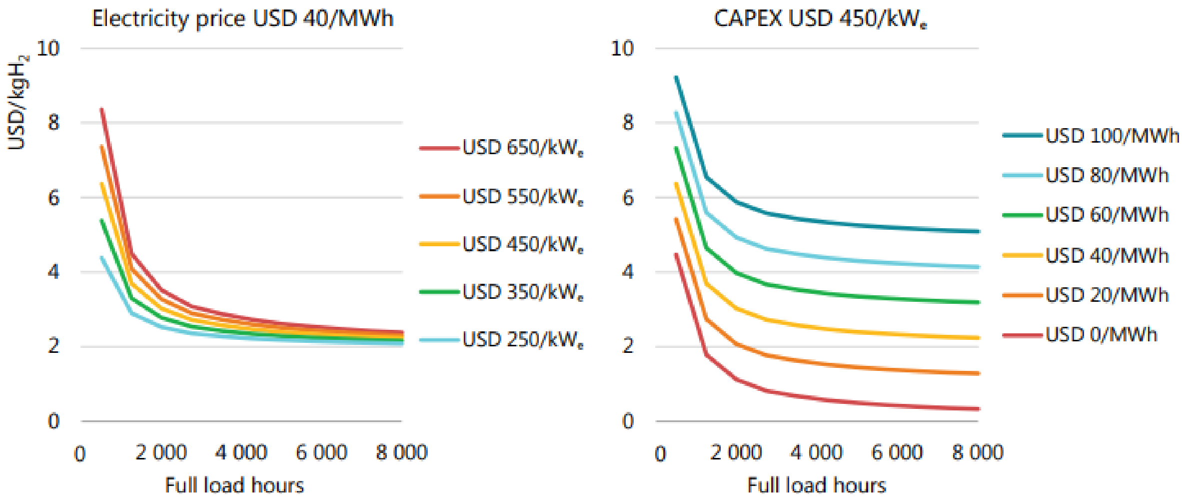


Figure 3.1.5: Future Levelized cost of hydrogen production by the operating hour for different electrolyzer investment costs (left) and electricity costs (right)[24]

With declining costs for wind power, the installation of electrolyzer at optimal and excellent weather conditions could become a low-cost supply option for hydrogen. Furthermore, with the higher desire for green hydrogen, the development of cost-effective PEM electrolyzers is promising:

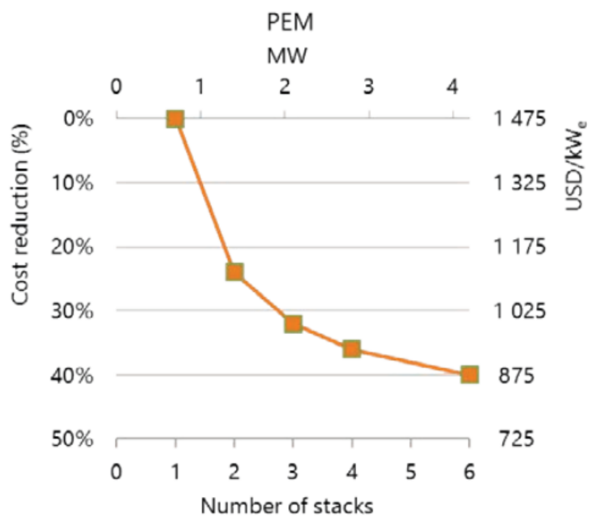


Figure 3.1.6: Expected cost reduction in CAPEX for PEM electrolysers[24]

The figure above illustrates the potential cost reduction in PEM electrolyzer production. Each stack has a capacity of 0.7 MW, and by combining multiple stacks to increase the overall capacity, the expected cost reduction will follow and increase.

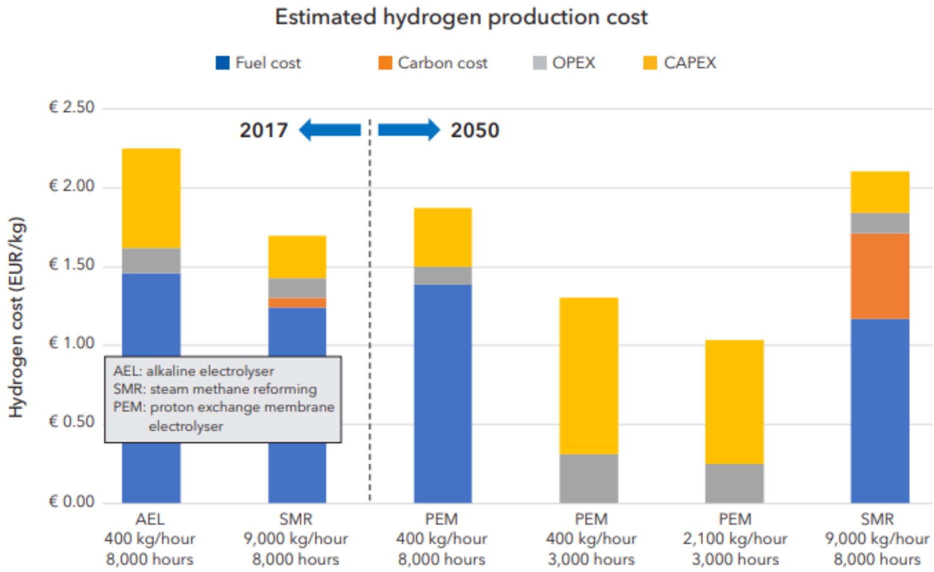


Figure 3.1.7: Expected cost reduction for PEM electrolysers in the future[41]

In addition, according to a report from DNV - based on 3,000 operating hours for a 100MW electrolysis capacity, the estimated cost of hydrogen in 2050 will be equivalent to 7.3 EUR/GJ. The estimation is 15% lower compared to the estimated cost of carbon-taxed natural gas of 8.7 EUR/GJ in the same period[41].

3.2 Storage

Like many other products, hydrogen needs to be stored and transferred to final use. Finding a cost-effective storage method remains an indomitable challenge. Having a low ambient temperature density creates challenges, therefore the development of advanced storage methods with the potential of storing high energy density is a requirement. Today hydrogen is commonly stored in tanks, either in liquid or gas form for small-scale mobile and stationary applications. However, with the projected demand for hydrogen in the future and large-scale and intercontinental operations, hydrogen value chains will require a much broader variety of storage options. This section will cover the different storage methods shown in figure 3.2.1.

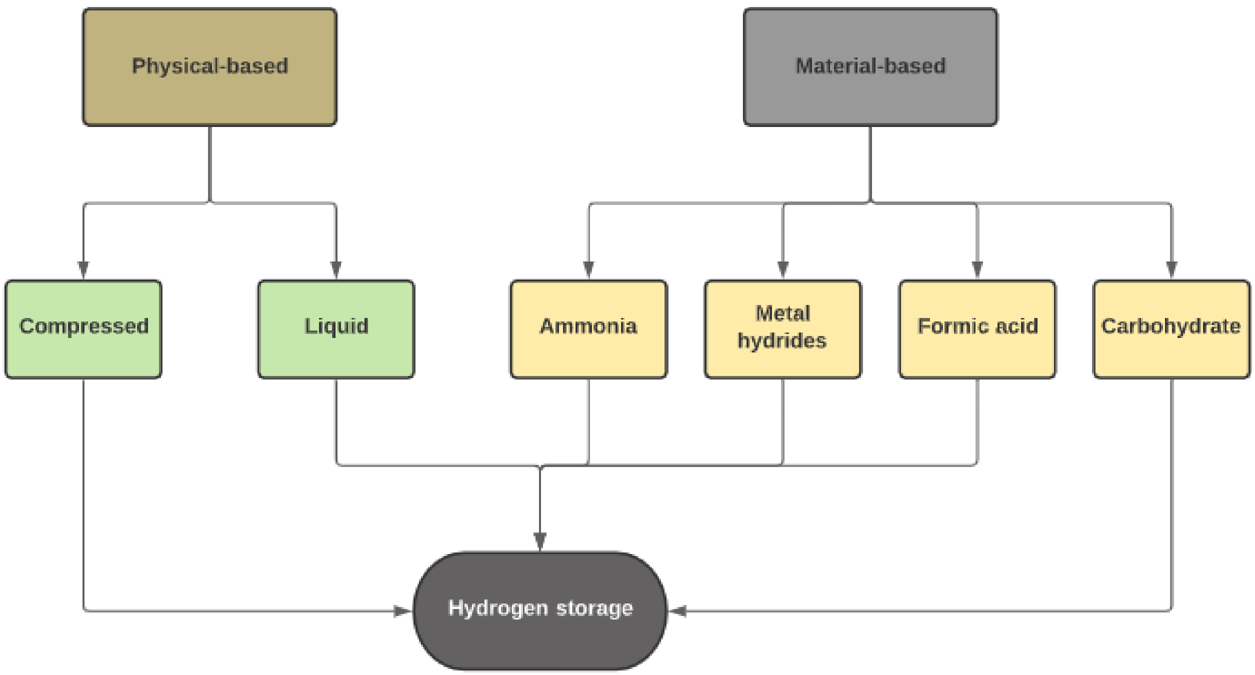


Figure 3.2.1: Storage methods of hydrogen

3.2.1 Physical-based

Physical storage is the most mature hydrogen storage technology based on either compression or liquefaction.

Compressed

Compressed hydrogen storage methods are the storage of compressed hydrogen gas in high-pressure tanks(higher than 200 bars)[42]. This makes it able to be stored in a smaller space while retaining its energy effectiveness which makes it beneficial for fuel purposes[43]. To be able to decrease the volume of hydrogen gas, the easiest way would be to increase its pressure. At 700 bar, hydrogen has a density of 43 kg/m^3 compared to 0.090 kg/m^3 under normal circumstances(pressure and temperature). At this pressure, 5 kg of hydrogen can be stored in a 125-liter tank[44]. Because of its complexity, the compressed hydrogen is stored in tanks that support the mechanical forces. The tanks are usually composed of polymer liner and with a certain composite structure[45]:

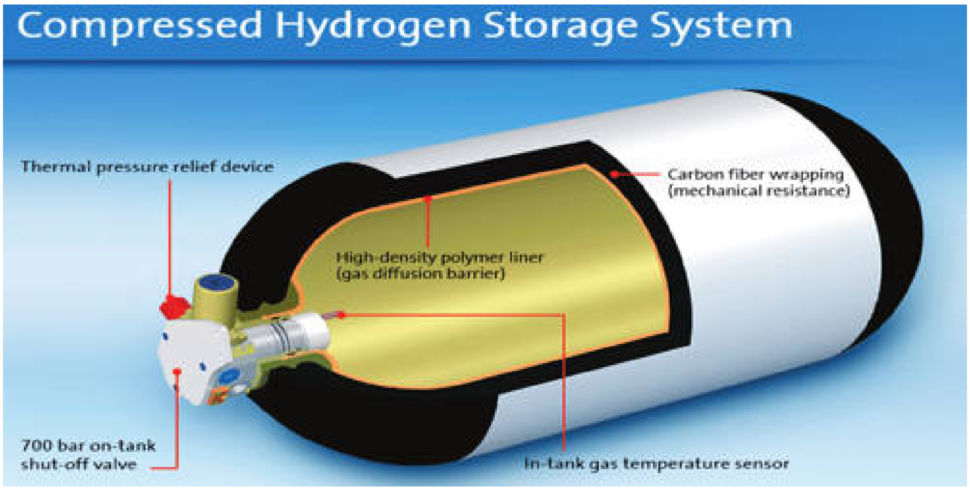


Figure 3.2.2: Compressed hydrogen tank[45]

A critical drawback of these tanks is safety issues when storing high amounts of hydrogen at such large pressures. In addition, another disadvantage of compressed storage is that the energy content of the compressed hydrogen less than the energy content of the gasoline that occupies the same volume[46].

Liquid

To be able to increase the energy density and content of hydrogen, liquefication of hydrogen is a major improvement. This method is achieved by cooling hydrogen to a very low temperature. More precisely, at -252.87°. At this temperature and pressure(1 bar), liquid hydrogen has a density of close to 71 kg/m^3. This means that 5 kg of hydrogen can be stored in a 75-liter tank[44]. This is a great improvement compared to compressed hydrogen.

The technology appears to be very promising due to its volumetric efficiency, but there are still questions that need to be researched and answered. One is the large energy loss during the *boil-off* process. There is a loss of energy when liquefying the hydrogen, but also when the evaporated gas must be vented due to the pressure inside the storage. This loss over time is known as the boil-off. When calculating the percentage of stored hydrogen lost per day, the boil-off rate is introduced. This ratio can be reduced by minimizing the surface-to-volume ratio of tanks by making them spherical and using advanced insulation technology:

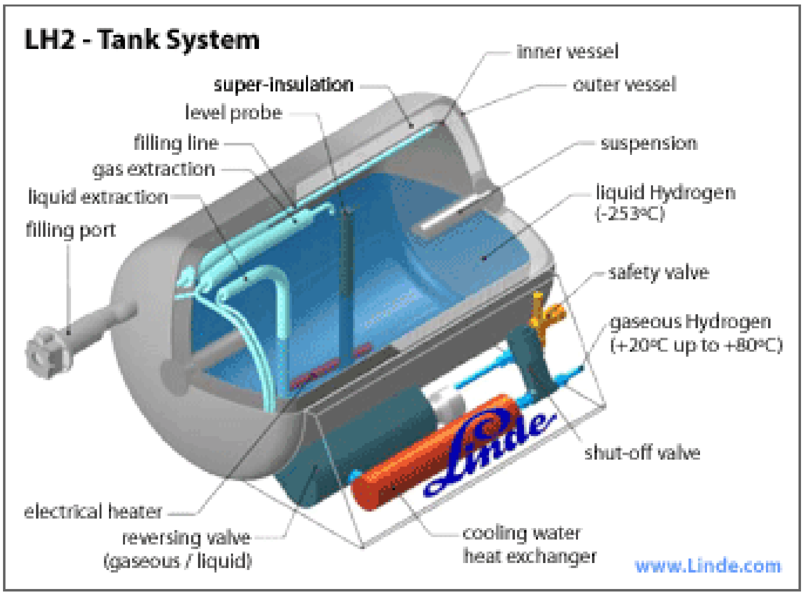


Figure 3.2.3: Liquid hydrogen tank[45]

3.2.2 Material-based

Additionally, to be able to be stored in different states, hydrogen can be stored in a variety of materials using the process of chemical storage.

Ammonia

The most common production route when producing ammonia via hydrogen is the Haber-Bosch process. Due to the exothermicity of ammonia, no heat must be supplied during the process. Its high volumetric hydrogen density, low storage pressure, and stability for long-term storage are among the beneficial characteristics being a potential medium for hydrogen storage[47]. Furthermore, compared to hydrocarbons and alcohols, there is no CO_2 emission at the end-user. The drawback when storing hydrogen in ammonia is first and foremost the production efficiency, it's significantly lower than from fossil fuels, in addition to the toxicity of liquid ammonia[49]. Figure 3.2.4 shows the overall process of ammonia production using wind energy and how it can be utilized again.

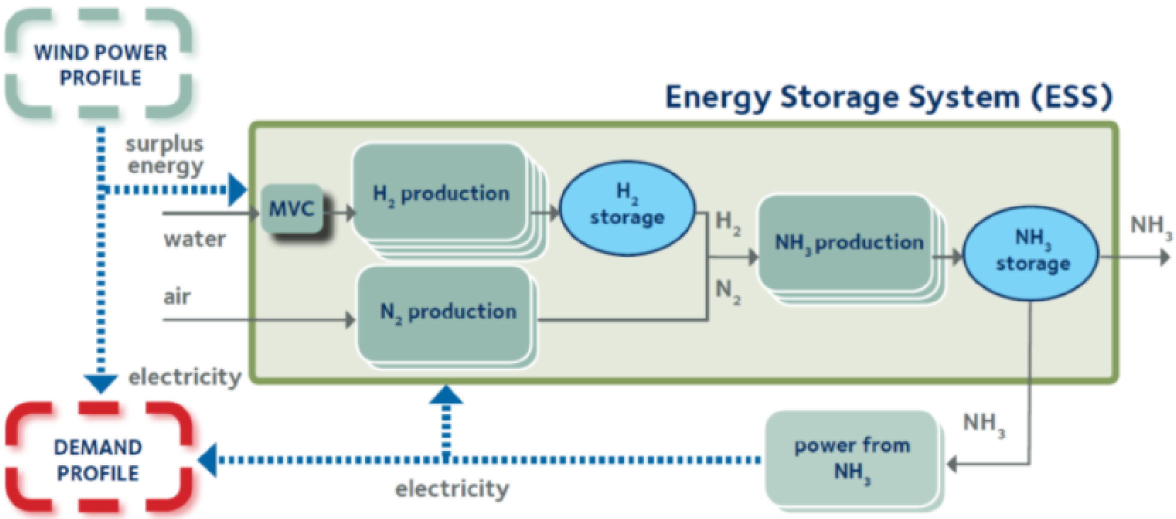


Figure 3.2.4: Overall process of ammonia production[51]

Being the second most commonly used chemical product in the world, the infrastructure when it comes to production, transportation and distribution are quite large[48].

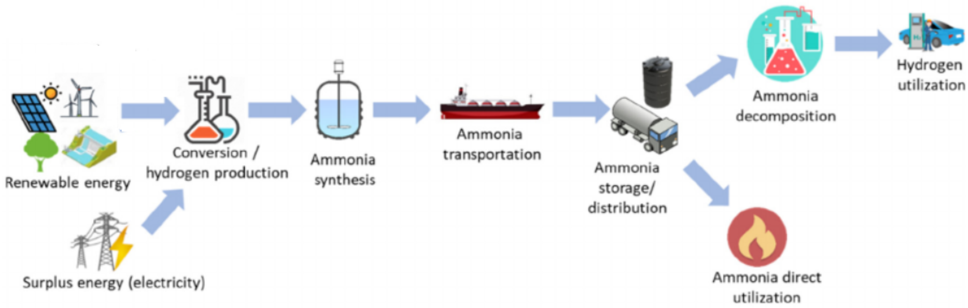


Figure 3.2.5: Production and utiliziation routes of ammonia in the energy sector[50]

Probably the major advantage of storing hydrogen via ammonia is the fact that it can be stored in a liquid state at 25°C and around 10bar in standard steel tanks which are already used for liquified petroleum gas(LPG)[51]. A storage tank with a capacity of 40 000m^3 can supply the electrical demand of 30 000 households(assuming a density of 11.5MJ/liter)[51]. This means that the potential to use ammonia without great environmental impact or technical obstacles is promising.

Metal hydrides

Metal hydrides are compounds containing metal(s) and hydrogen. Solid compounds can store more hydrogen per unit of volume than liquid hydrogen and thus increase safety. There are compounds that can store up to 150kg H_2/m^3 at a 20% in weight[52]. This versatility makes this an attractive alternative for the storage of hydrogen. The strong chemical bond in metal hydrides means that more energy is needed to release the bonded hydrogen. But on the other hand, the strong bond allows hydrogen to be stored at high density even at ambient conditions[53]. However, more research about ionic and complex hydrides needs to be done to find solutions such that the technical and economical aspects are feasible.

Formic acid

This alternative is an interesting twist on zero-emission energy storage for hydrogen. The principle is to store hydrogen as liquid formic acid - HCO_2H. This method could be a significant step towards a cost-efficiency high-scale hydrogen storage method. The relative decomposition of formic acid to yield hydrogen and CO_2 and the comparison of storing compressed hydrogen, the use of formic acid could potentially improve energy density and efficiency[54]. Furthermore, its dehydrogenation compared to ammonia can be performed in temperate conditions. The main challenge of formic acid is the tendency to decompose to CO and water instead of CO_2 and hydrogen upon heating. In addition, compared to other chemical-based hydrides such as ammonia, formic acid has the lowest storage capacity.

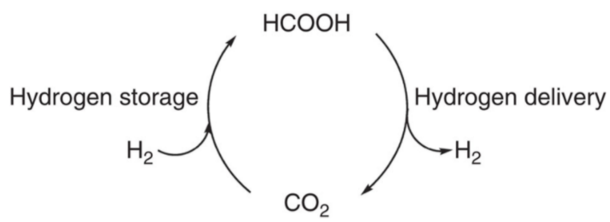


Figure 3.2.6: Formic acid/dioxide cycle for hydrogen storage[55]

Carbohydrates

Due to their lightweight, high surface area, and chemical stabilities, carbohydrates have received a lot of attention and research interest in terms of hydrogen storage. There are mainly three carbohydrates that are seen as potential storage methods - Carbon nanotubes, graphene, and graphene. Each of them with different characteristics. But all three of them are promising hydrogen carriers because of their renewable abundance, low cost, high hydrogen density, carbon-neutrality and high safety[56]. The main challenge with this alternative is that hydrogen needs to be broken into atoms, this required high temperatures that could potentially damage the crystallographic structure of carbohydrates. Further studies and research needs to be done so that the development of carbohydrates for energy storage is feasible.

3.2.3 Comparison

As the demand for hydrogen increase as forecasted, all of the above methods will have the potential to play a major role in storing hydrogen. The table in the appendix 9.2 shows an overview of the properties of different energy carriers.

Tanks storing physical-based hydrogen as either compressed or liquid have a high dismissal rate in addition to high efficiencies of around 99%. This makes them suitable for small-scale applications. Compressed hydrogen has less energy content than gasoline that occupies the same volume. For refueling purposes, compressed hydrogen will require nearly seven times the space as gasoline. And comparing with liquid hydrogen - five kg of compressed hydrogen can be stored in a 125-liter tank while the same amount can be stored in a 75-liter tank as liquified hydrogen. Compressed hydrogen does in fact have a higher energy density than lithium-ion batteries, this yields a greater range in cars or trucks.

Ammonia on the other hand has a greater energy density, which leads to less need for large tanks and the possibility to save a significant amount of space for refueling purposes for maritime shipping. But there needs to be a fine balance between this advantage and high energy loss and cost for conversion/reconversion equipment.

In chemical-based storage methods such as metal hydrides, formic acid, and carbohydrates, the technology is at an early stage of development. This means technologies that provide feasible transportation solutions are complicated and in some cases, expensive. But with increasing interest and technology studies, these methods could potentially increase the density of hydrogen to be stored at atmospheric pressure.

To be able to transport hydrogen over long distances, solutions such as compression, liquefication, or blending hydrogen into larger molecules could be used to transport hydrogen safely and cost-effectively with each solution having its advantages and disadvantages. The optimal solution in the future may include a variation and combination of high pressure, cold gas, and a solid carrier(metal hydrides, formic acid, carbohydrates) to obtain a volumetrically efficient and cost-efficient hydrogen storage system.

3.3 Offloading/Transportation

When hydrogen is produced and stored, then how will it be transported? And what is the link between the storage system and the transportation system? The following sections deal with the present solutions and expected developments for transporting hydrogen affordably and safely. The solutions are varied according to the distance and quantity to be delivered, with logistics concerning pipelines and overseas.

3.3.1 Offshore distribution

The object of offshore transportation is to transport hydrogen over long distances. The main solution has been to transport it in a liquid state. Either as liquified hydrogen or chemical-based through ammonia.

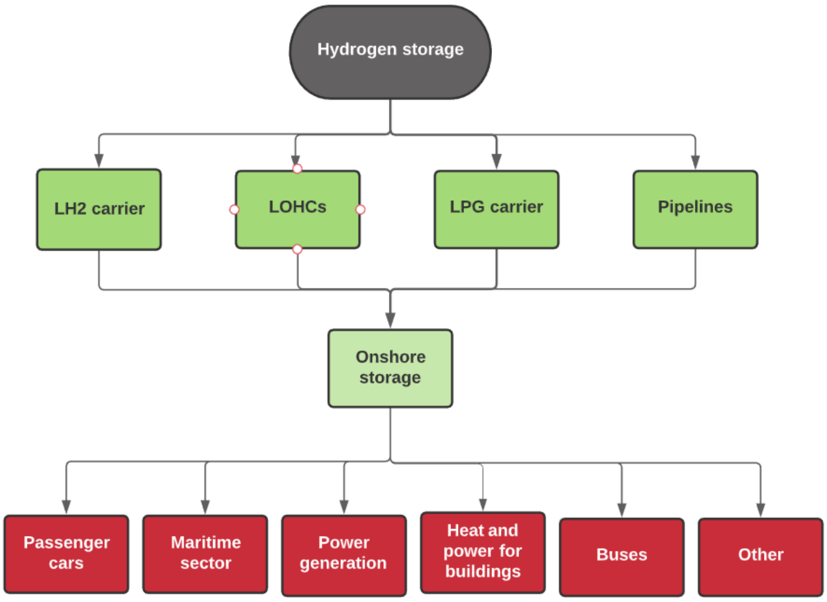


Figure 3.3.1: Transport chain for hydrogen

Liquid hydrogen

Even though a considerable contribution in terms of energy to be used to liquefy was calculated, LH_2 was still recognized as having a lower energy density compared to its most imminent competitor, LNG. Compared to compressed hydrogen, the transport of liquid hydrogen over longer distances is usually more cost-effective because of its high energy content in liquid form.

As the world is rapidly decarbonizing, the need for vessels carrying non-hydrocarbon gases in bulk increases. There are no carriers today that can transport pure hydrogen. But some vessels are under construction today with the ability to transport liquid hydrogen. One of them being the Suiso Frontier that is scheduled for delivery in late 2020. The vessel is designed to transport liquid hydrogen. By cooling the hydrogen to -253°C, hydrogen is at atmospheric pressure and occupies just 1/800 of its original vapor volume[57].

Figure 3.3.2: The Suiso Frontier[57]

Due to its low temperature at atmospheric pressure, high explosive level extended flammable range, and extremely small size compared to other gases, safety measures need to be carefully considered to be able to transport this kind of chemical product offshore: "Liquid hydrogen tankers are designed for gas transport at a temperature of about ≈ -250 °C, i.e. close to the evaporation temperature. Despite the insulation of the cargo tanks, which is intended to limit the entry of external heat, small quantities of heat always enter the tanks and lead to slight evaporation of the gases. This so-called boil-off gas is unavoidable, especially during movements on a ship, and must be removed from the tanks to prevent an inadmissible pressure increase" explains Matthias Flies, Offshore Applications Manager at SAACKE Marine Systems[57] when asked about how the safety systems are going to work. There is the possibility to use this boil-off gas as fuel in the shipping sector in the future. The Suiso Frontier will have a high thermal insulated tank with a capacity of 1250m^3, keeping 75 tons of hydrogen at -253 degrees Celsius for three weeks[57]. Kawasaki Heavy Industries is planning to build larger carriers with a capacity of 160 000m^3 by 2030.

NASA has developed its own tanks that can store a high amount of liquid hydrogen. These tanks can potentially be used for storage/transport use on LH2 carriers. Using Integrated Refrigeration and Storage(IRaS), a system that controls the fluid inside the tank, NASA claims that liquid hydrogen can be stored without any losses. The technology makes sure that the heat leak entering the tank is removed by a cryogenic refrigerator with an internal heat exchanger[60].

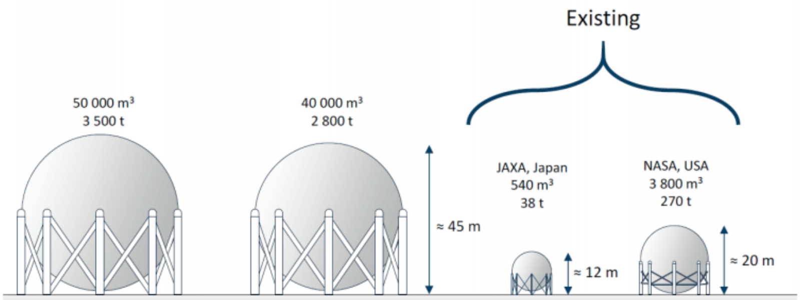


Figure 3.3.3: Tanks with IRaS system[60]

Ammonia

Ammonia, on the other hand, has a more developed transportation chain than hydrogen. Ammonia can be transported using full pressure type, semi-refrigerated type, and fully refrigerated type liquefied petroleum gas(LPG) tankers[61]. This means that practically all LPG carriers can transport ammonia. As mentioned and illustrated in section 3.2.2 , the distribution is quite large. The carrier capacities varies from 30,000m^3 to 80,000m^3 for ammonia trade[62]. Ammonia liquefies at -33°C, a much higher temperature than hydrogen. Due to its density(1.7 times more hydrogen per cubic meter than liquid hydrogen), transportation is much cheaper than liquid hydrogen.

LOHCs

Liquid organic hydrogen carriers are organic compounds such as formic acid that can absorb and release hydrogen from chemical reactions. LOHCs have similar characteristics to oil products and crude oil, this means that they can be transported as liquids without the need for cooling[62]. This means that LOHCs would be the easiest form to transport hydrogen as an oil product tanker can be used. As ammonia, LOHCs cannot be used as final products, which means that there are going to be losses concerning conversion/reconversion.

Figure 9.3.1 in appendix 9.3 shows how selected properties between LH2, ammonia, and LOHCs differ. Especially how much energy the conversion and reconversion are required.

Pipelines

Using pipelines for transportation and distribution of hydrogen is one of the options that are being exploited, but this technology is not always the most convenient and the pipeline network for hydrogen especially at sea is limited. But there is the possibility to blend hydrogen into natural gas by using either export pipelines or transmission pipelines. At Neptune Energy's Q13a oil and gas platform, outside The Hague, the world's first offshore plant for green hydrogen is being build[63]. The concept is to generate hydrogen via electrolysis using wind energy and transport the hydrogen gas molecules via existing gas pipelines. SINTEF and several industrial partners are currently researching a project about safe pipelines for hydrogen transport called HyLINE[64].

The goal is to research clean transportation of hydrogen gas in the existing subsea pipeline infrastructure as well as new pipeline infrastructure.

3.3.2 Cost

All these methods above have their pros and cons - some methods have the possibility to transport a large amount of hydrogen but are limited due to infrastructure and some vice versa. They also differ when it comes to cost and conversion. Figure 3.3.4 shows the cost of hydrogen storage and transmission by pipeline and ship and how the cost of hydrogen and liquefaction and conversion differs. Considering all capital and operating costs, to transport hydrogen in a gaseous state via pipeline for around 1 500km is estimated to be USD $1/kgH_2$. For the same distance, the transportation cost of ammonia is almost half as much. The difference is more clear when comparing the costs of using ships. There is almost a difference of one USD per kg hydrogen transported via ammonia compared to LH2. Comparing the cost of conversion, the difference between liquefaction and ammonia is minimal. The cheapest option to transport hydrogen depends on the method and distance while considering the conversion costs.

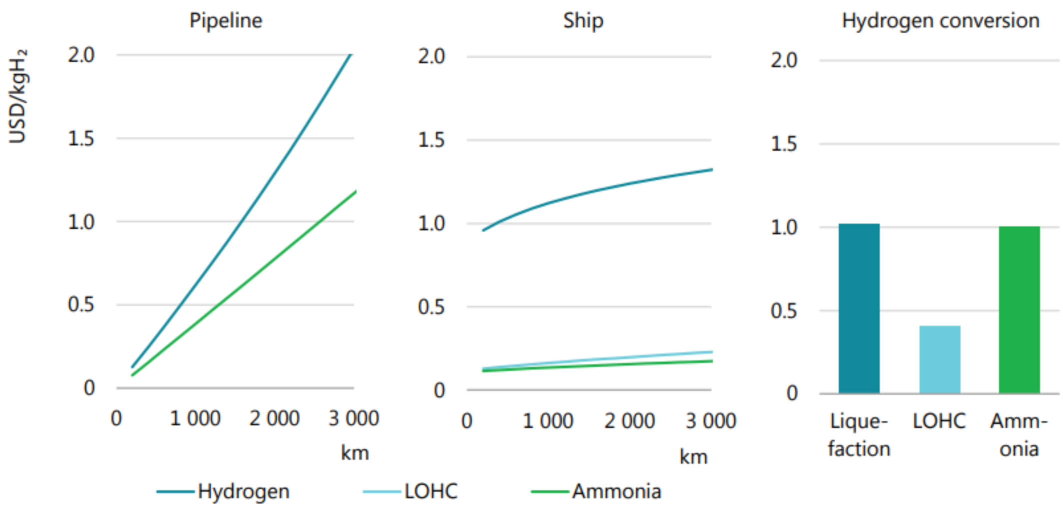


Figure 3.3.4: Cost of hydrogen storage and transmission by pipeline and ship[24]

As shown in figure 3.3.5, if the costs of conversion, transmission, distribution, storage, and reconversion costs are taking into consideration, the full cost will be different.

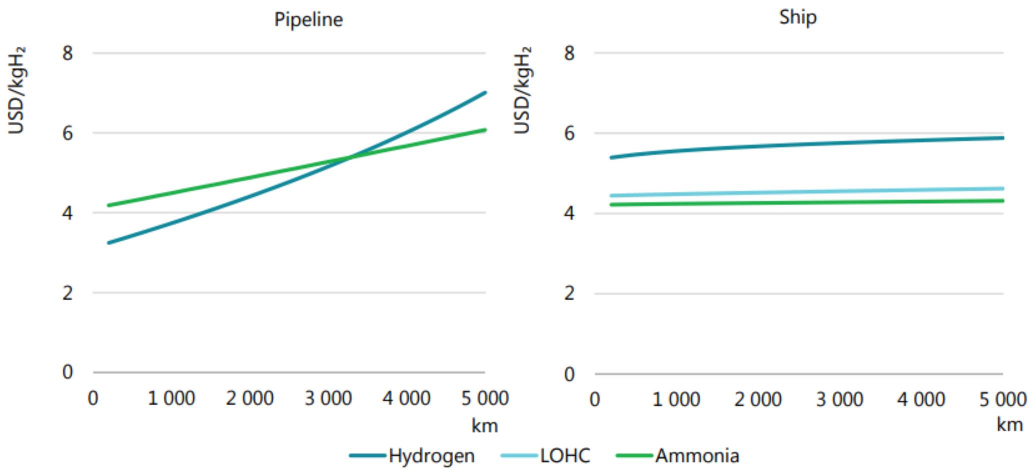


Figure 3.3.5: Full cost of hydrogen storage and transmission by pipeline and ship by 2030[24]

Despite many uncertainties of the cost components and the fact that the cost is affected by the infrastructure available in the exporting and importing countries, IEA estimates that hydrogen gas via pipelines is the cheapest option of distances below 3 500km[24]. Above this distance, ammonia by ship and LOHCs are clearly the cheapest option.

3.4 Utilization

All energy carriers, including fossil fuels, encounter efficiency losses each time they are produced, converted, or used. In the case of hydrogen - after converting electricity to hydrogen, shipping it and storing it, then converting it back to electricity in a fuel cell, the delivered energy can be below 30%[10] of what was in the initial electricity input. This makes hydrogen more “expensive” than other energy storage methods. But on the other hand, with ever new emission regulations, the economical aspect needs to be put aside.

In the absence of constraints to energy supply, and as long as CO2 emissions are valued, efficiency can be largely a matter of economics, to be considered at the level of the whole value chain. This makes hydrogen a viable source towards a carbon-free world.

Demand for hydrogen, which has grown more than threefold since 1975, continues to rise, almost entirely supplied from fossil fuels, with 6% of global natural gas and 2% of global coal going to hydrogen production[10]. And in pure forms, the demand has grown steadily over the past 50 years to around 70 Mt/year today. More than 40 Mt/year is also produced in a mixture of other gases.

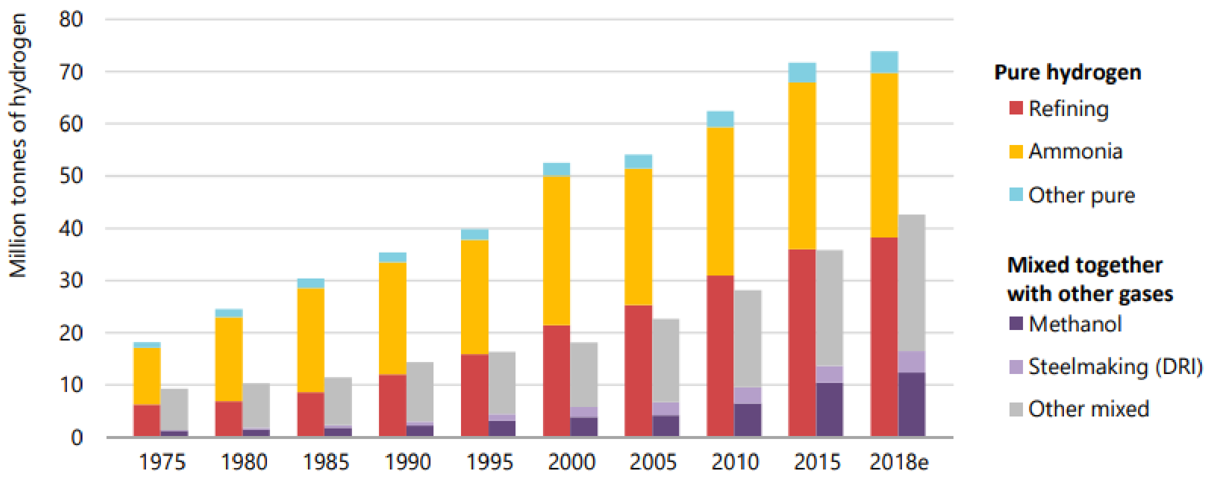


Figure 3.4.1: Global demand for hydrogen in pure forms[10]

There is a big increase in investment support for hydrogen from several countries. Global spending on research, demonstration, technology, and development by different countries has risen over the past few years[11].

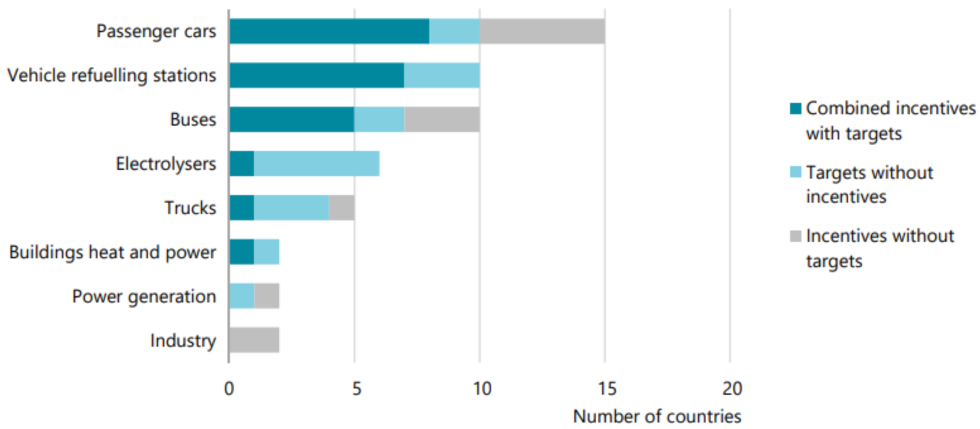


Figure 3.4.2: Growing number of policy support[11]

With the increased interest in renewables these past several years and the declining costs for renewable electricity, interest in electrolytic hydrogen is growing. There have been numerous projects and tests of different hydrogen concepts.

Installing production facilities at locations with huge renewable resource potential could become a low-cost supply option for hydrogen. But even more critically, massive production will require large amounts of electricity. Comparing this to the projected scale-up in offshore wind production today is still not efficient and cost-effective. But with a growing number of policy support from numerous countries and their ambitious emission reduction goals, makes hydrogen one of a suite of technologies that work well together to support the growth of low-carbon energy at the level of the overall energy system[13].

Using Norway as an example, the country has one of Europe's best resources when it comes to renewable energy, both regulated hydropower, and wind. A paper from CenSES estimates that Norwegian wind resources can be expanded to an even larger scale by 2050, mainly for energy export to Europe[14]. Since wind power cannot be planned nor controlled, the interaction with hydrogen provides two positive long-term effects: Firstly, the potential of local electrolysis will provide opportunities to increase the value of the unregulated power by producing valuable hydrogen from excess power. Secondly, taking place in Norway, the potential of local activity will increase.

Furthermore, the position and the overwhelming interest in hydrogen in Norway have not been this high in many years. The Norwegian government has set aside NOK 100 million in 2021 for further research and development in hydrogen technology, in addition to the NOK 120 million, they set aside for use in 2020[15]. Menon Economics published a report about the offshore wind market in Norway. Their analysis shows, among other things, that projects are being realized on a larger scale than previously assumed. This will contribute to a faster cost reduction and in turn, lead to an increased production capacity of 40% in 2050[29]. They predict a net revenue of NOK 85 billion for the wind industry in Norway by 2050. This shows some of the restructuring potentials that lie in the industry.

The EU launched a common hydrogen strategy for the union in July 2020. Leaked drafts of the strategy show that the EU wants to install an electrolysis capacity of 40 GW by 2030[26]. This corresponds to a hydrogen production of 173 TWh. The first phase, from 2020-2024, will aim to establish a capacity equivalent to 4 GW. This will mainly go to decarbonizing current hydrogen production. In the second phase, from 2025-2030, they expect to increase the capacity up to 40 GW. This makes it possible to replace fossil energy with hydrogen for industrial purposes and in the transport sector[26].

Industrial use of hydrogen

Most hydrogen today is used in the refining(33%), chemicals(38%) and iron and steel(3%) sectors[24]. Practically all of this hydrogen is supplied using fossil fuels. In Norway, hydrogen is mainly used for ammonia-, nitric acid and fertile production(YARA, Porsgrunn), methanol production (Equinor, Tjelbergodden), and oil refining(Equinor, Mongstad). The chemical sector accounts for the second-and third-largest sources of demand for hydrogen: ammonia at 31 MtH_2/year and methanol at 12 MtH_2/year[24]. All of these products require the need of natural gas or oil fractions as a hydrogen source, which will eventually lead to CO_2 emission. Using renewable hydrogen instead will significantly reduce amounts of CO_2 and thus open up opportunities for greener products.

Hydrogen for clean transport fuels

Hydrogen can be converted to hydrogen-based fuels, including synthetic methane, methanol and ammonia, and synthetic liquid fuels, which have a range of potential transport uses. For both light-duty vehicles(cars and vans) and heavy-duty vehicles (trucks and buses), there is a strong growth segment. Several car companies produce hydrogen-powered cars. Companies like Hyundai(Nexo), Toyota(Mirai), and Honda(Clarity)[14]. The cars have been reviewed and thoroughly tested for long-haul tests. Despite the tax exemption, the price is still higher compared to diesel/petrol cars. But having a tank that can store 5-7kg of hydrogen, giving a range of 500-700 km and refuel in 3-5 minutes[14], shows promising potential.

In the maritime sector, hydrogen is receiving more and more attention. The Norwegian Public Roads Administration recently commissioned Norled with the development of a hydrogen-powered ferry, which will operate between Hjelmeland-Nesvik-Skipavik in Rogaland[14]. Furthermore, the EU has announced funding for the testing of fuel cells in the MW class. If successful, it should be possible by 2026 to integrate this technology onboard cruise ships that travel in the Norwegian fjords more environmentally friendly. Maritime freight activity is set to grow by around 45% to 2030[24]. Air pollution targets for 2020 and 2050 greenhouse targets are high motivation to promote hydrogen-based fuels. Replacing natural gas with hydrogen/hydrogen mixtures can potentially provide a significant reduction in global greenhouse gases and thus contribute to solving some of the most important societal challenges for Norway, the EU, and the rest of the world by contributing to the global emission reduction, as agreed in COP21[25].

In conclusion, for passenger cars, electric-powered vehicles appear to be the preferred technology, but in heavy-duty vehicles and the maritime sector, hydrogen is a more viable option for achieving emission-free transport. It takes a long time to charge a lithium-ion battery of several hundred kilowatt-hours while refueling a hydrogen tank can be done in minutes. Furthermore, long-haul transport requires a battery capacity that cannot be achieved with the current technology. Hydrogen is therefore highlighted as one of the few possible alternatives to make this segment emission-free.

Chapter 4

Methodology for conceptual design phase

The previous chapter has gone through almost all parts of the hydrogen value chain - from production to distribution - and how these methods and technologies differ from each other when establishing a system that could do all of the above. The main question would be then - who would be willing to pay for such a system and what would be their levels of participation, interest, and influence in the project. Conceptual design is the first stage of the overall design process. This section will provide the theory behind the approach of conceptual design. Parts that will be addressed are the mapping between needs, function and form domains, and superficial stages of the conceptual design process.

4.1 Design of systems by mapping between domains

A system decomposes into entities, each of which has form and function. These entities are the constituents of the system[69]. These entities may be components or subsystems that are either dependent on each other or influencing each other.

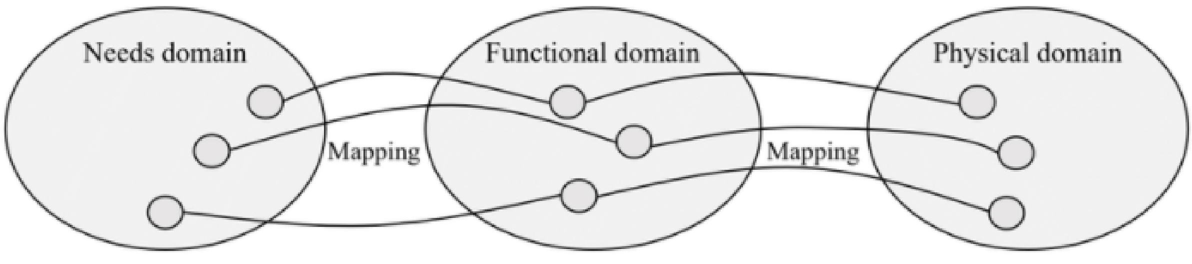


Figure 4.1.1: Mapping between needs, function and form domains[68]

The needs domain represents the space where these needs are identified. The next mapping is the functional domain. Which actions need to be undertaken to meet these needs. The functional domain contains the possible performances and attributes of the design and the overall function which is the intended benefit produced by the system. Since the functional domain contains different performances of the design, the overall function may be divided into subfunctions. After identifying the system functions and subfunctions, the physical domain needs to be identified. The physical domain contains all possible descriptions of the design, in terms of parameters such as length, material, color, etc[66]. The whole idea of mapping is to gather new information when going back and forth between the domains. And use this information to improve the design and solution for each iterative step.

When mapping from the physical domain to the functional domain, the designer analyses whether the form yields the function it is intended to [65]. An evaluation process between the intended functions and the produced functions. The evaluation is important due to not developing unwanted functions or performances.

4.2 Conceptual design process

While Watson[72] differentiates ship design by weight-based and volume-based ship design as a starting point, Levander finds the first stage to be fact-finding and recognition of problems and possibilites[70]. Here the idea is to start the creative process in the design work by recognizing the problems and the possibilities of solutions and needs. Ulrich & Eppinger find the first stage to be to identify the needs, establishing specifications, generating concepts, and selecting concepts[71].

The stages of conceptual design according to Pahl & Beitz is an abstraction to identify problems, function structures, searching for solutions(working principles), combining solutions into working structures, selection of concepts, and evaluation of concepts[65]. Even though the stages are provided systematically, the designer can freely choose the method and path which suits the concepts best. The idea is to use the creative and innovative aspect of design for concept development with a high focus on being an iterative design process.

Comparing the different literature, there is clear that the conceptual design process involves the following stages; Identifying needs, abstraction to identify problems, functions development, search for ideas and concepts, select a suitable concept.

Conceptual design methodology by Pahl and Beitz[65] serves as the structure and foundation of this chapter.

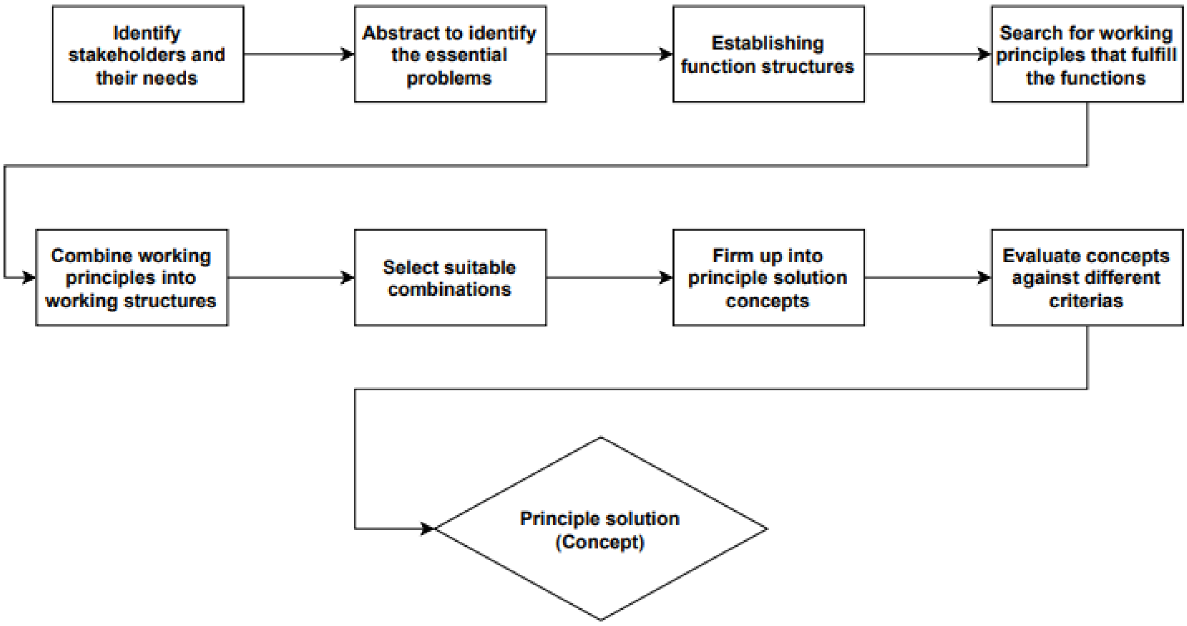


Figure 4.2.1: Steps of conceptual design[65]

Figure 4.2.1 shows the different steps of the conceptual design phase. Starting with identifying stakeholders and needs and ending up at a principle solution. The upcoming section will present all these steps in more detail.

4.3 Identifying stakeholders and needs

Every project and every system that is being designed have stakeholders and beneficiaries. Each of those stakeholders and beneficiaries has differing needs, which means that although a group of stakeholders wants to see a project implemented, their needs and priorities might conflict. Identifying those needs is important throughout the whole process to achieve the success of the project. There are different definitions of what a stakeholder is, but Crawley et al. (2016) find that a stakeholder is someone who has a stake in a project. They are capable of influencing the project owner's needs[69].

Performing a stakeholder analysis helps to understand various stakeholders and to what extent they can affect the project, in addition to identifying their needs. To be able to perform such analysis, data and feedback from the stakeholders are needed. And the goal is to transform their needs into goals and requirements.

4.4 Abstraction to identify the essential problems

Abstraction is a way of extracting the general and abstract information and ignoring the incidental information[65]. The whole idea behind abstraction is to not complicate things when dealing with design with different requirements. The designer should rather focus on what is general and essential. This method can be used to find essential problems by either broadening the problem or by using the requirements list which is a list provided by the customer or stakeholders. The development of such a system that can produce hydrogen using renewable energy is limited, although it has been thoroughly researched, there is currently no ongoing operation, i.e this is more or less an original design. This means that due to the novelty of the task and the lack of a requirement list, the best method of abstraction would be by broadening the problem formulation.

This means that the problem formulation is extended through systematic study of the physical and chemical processes. How hydrogen is produced, what state hydrogen is in, how it converts from one state to another, and how this will affect transportation.

4.5 Establishing function structures

A function structure is an abstract model of the new product, without material features such as shape, dimensions, and materials of the parts[65]. When establishing function structures, the overall goal is to establish the functions that are required and the system boundary of a new design[72]. Additionally, the process has to lead to a design that fulfills the overall function of the system. This function can be divided into main functions and subfunctions as shown in figure 4.5.1.

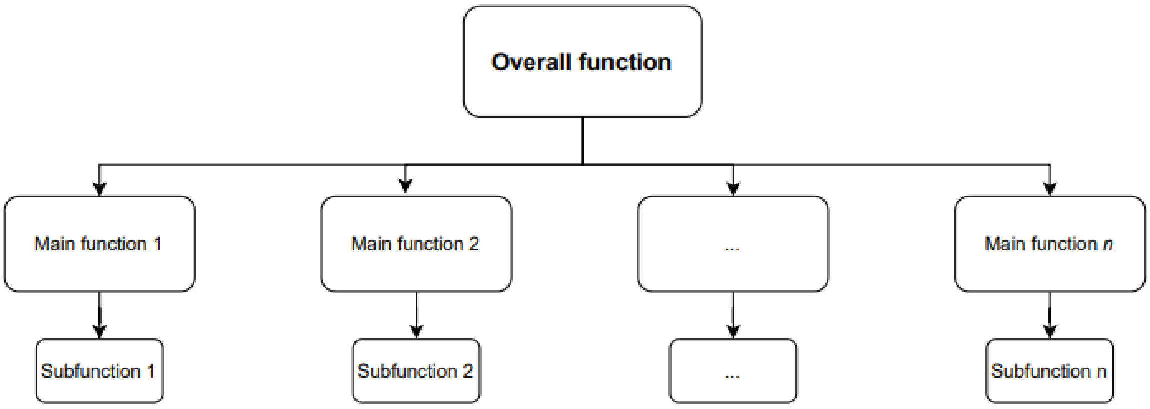


Figure 4.5.1: Illustration of the overall, main and sub-functions

Pahl & Beitz describe the overall functions as the flow of conversion of input to output[65]. As shown in figure 4.5.2. The type of material can be raw, sample, component, or be in a chemical/physical state such as liquid, gas, or solid. The type of energy may be thermal, chemical, electrical, mechanical, in addition to force, current and heat. The type of information can be data, impulse, magnitude, and so on.

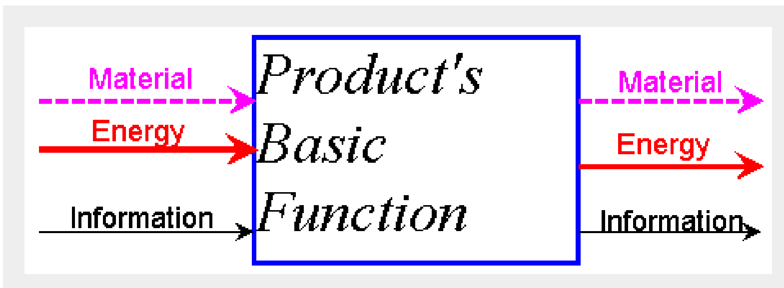


Figure 4.5.2: Generic block diagram[73].

It is worth noticing that each functional description tells what the system does and now how the system performs the function. For instance, the function ”store data” could be accomplished in several ways. There is no point in focusing on how a system accomplishes a function until it is clear what the overall function is and what the system must do.

Establishing function structures is a systematic procedure that starts after establishing the overall function and its corresponding block diagram. Using the steps during abstraction, the procedure starts with deriving a rough function structure by working from the system boundary and inwards while determining the inputs and outputs of the functions. This means that the flow of the output of one of those functions will be the input of the neighboring function.

The overall function depends on the complexity of the problem and the problem formulation. This means that the problem formulation needs to be precise as possible. Furthermore, the relationship between the functions needs to logical to be able to establish the subfunctions such that it can be obtained by studying the input and the output of the flow.

4.6 Working principles

When the needs and functions are identified, the search for working principles(WP) for those functions is initiated. According to Pahl & Beitz, a working principle is a correlation between the physical/chemical effect and a specific function, and also its geometric and material characteristics[65]. This particular stage goes as follows:

1. Searching for and listing working principles
2. Abstracting classification parameters from a list of working principles
3. Arranging the classification parameters and working principles into a design catalog

Firstly, the search for working principles that include the physical and chemical processes along with the necessary geometric and material characteristics needs to start before combining all these principles into a working structure. The search process can be done using different methods such as using different kinds of literature about the offshore industry and the chemical processes involved in this thesis. When finding these working principles, the whole idea is to widen the field of solutions instead of focusing on their feasibility and suitability. It is worth mentioning that if the working principle is unknown, it should instead be derived from the physical effects such as from the type of energy.

Secondly, when the list of working principles has been found, the analysis of the solutions, their characteristics, and any similarities in physical or chemical principles is started. These principles are called classification parameters and are found through discursive methods: systematic search with the help of classification schemes using types of energy, working movements, and working surfaces, as well as the use of a catalog on varying forces[65]. When both the working principles and the appropriate classification parameters have been found, then it will all get arranged to create a design catalog. The design catalog is a matrix containing the classification parameters in the columns and rows, and the working principles in the cells as shown in figure 5.4.1.

Sub-functions \ Solutions		1	2	…	j	…	m
1	F_1	S_{11}	S_{12}		S_{1j}		S_{1m}
2	F_2	S_{21}	S_{22}		S_{2j}		S_{2m}
⋮	⋮	⋮	⋮		⋮		⋮
i	F_i	S_{i1}	S_{i2}		S_{ij}		S_{im}
⋮	⋮	⋮	⋮		⋮		⋮
n	F_n	S_{n1}	S_{n2}		S_{nj}		S_{nm}

Figure 4.6.1: Basic illustration of a design catalogue with WPs and functions[65].

As mentioned in the previous section, we can clearly see why the need of a precise function description is necessary when searching for WPs. Furthermore, the designer should use their intuition and creativity in addition to being conservative when excluding solutions.

Combining working principles into working structures

Combining the working principles happens when all the working principles have been found and can be used to fulfill the overall function. This is done by combining one working principle from a function with the working principle for a neighboring function into a working structure. By systematically doing this, a solution can be found for each function and the working structure can be used to fulfill the overall function. When this is done, an overview in the form of a morphological matrix shown in figure 5.4.1 can be assembled. Furthermore, by adding the physical and chemical principles to the matrix, the solution might give some information about the solution and its performance.

To be able to do this process thoroughly, the measurement of the physical and geometrical compatibility of the working principle when combining them needs to there to get an efficient and thorough flow of energy[65], material, and information. This can be used by using a compatibility matrix by searching for combination possibilities between classification parameters of subfunctions. As mentioned earlier, when searching for working principles, it does not matter if our solution field is broad, but from now on, our solution field will get much narrower when finding the overall solution and eliminating non-suitable solution variants. Once again this has to be done systematically when picking suitable combinations from a field of theoretically possible combinations.

Lastly, when making the compatibility matrix, a study of how the classification parameters cooperate is made. This is done by either having a simple ”yes/no” option, or by having a more descriptive one. Either way, impossible combinations are shown by a solid cross over the cell while viable solutions have neither of those. The compatibility matrix is used as a matrix for information processing[65] and should be used to get an overview of the different parameters, principles, and functions.

4.7 Selecting suitable combinations

The goal of selecting suitable combinations is about combining all possible solutions found from the solution field and combining these with compatible solutions. This is done by using the matrix for the working principles and the compatibility matrix as a basis. The suitable working structures should be compatible with the overall task and with one another[65]. This leads to either a single working structure or several depending on the combination.

4.8 Evaluation using different criteria

When evaluating the different solutions with each other, it is important to consider the overall aspects of the solution instead of focusing on individual aspects such as cost, feasibility, safety, etc. As projects are rarely defined by only one criterion it is important to define the most influential criteria. There are several criteria to evaluate, this thesis focuses on these:

Cost

The cost of investment and operating cost of the concept. A higher investment need will harm the concept, while a lower operation cost will have a positive influence.

Availability

The availability attribute could have a great impact on the final ranking. In this decision problem, availability covers how often and how fast hydrogen can be delivered.

Flexibility

Flexibility provides an idea of how open the concept solution would be to change. For example, can the transport method be used to transport something else than hydrogen or can the system be used for something else?

Safety

Crew safety is the most prioritized factor during operation, and there should be as few hazardous events as possible. Both construction of the transport system, and safety during operations are taken into account.

Feasability

Feasibility covers how feasible the concept solution is, and how easy it would be to construct. Is it based on already established technology and experience, or does it require large amounts of research and logistics?

Emission

Although this attribute could be included under safety, environmental impact is of such importance that it should have its own attribute. This attribute covers the general emissions from constructing and operating the system, as well as covering the magnitude of environmental consequences if something were to go wrong. If emissions are not low enough, penalties could be given to the company. Moreover, ensuring a low environmental cost is crucial to maintain the company's reputation.

When the most important criteria have been found, a concept selection method (CSM) needs to be chosen. There are several CSMs that can provide an appropriate approach for a particular design situation. Figure 4.8.1 shows some of the CSMs that can be selected.

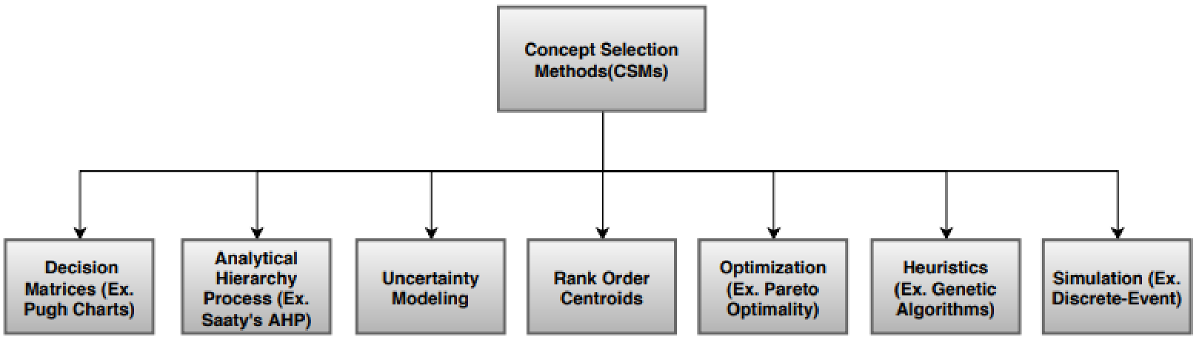


Figure 4.8.1: Some Concept Selection Methods

This particular process will be done through a systematic approach using the Analytical Hierarchy Process(AHP).

AHP

The Analytical Hierarchy Process is a method one can use for turning rankings and preferences between individual attributes and alternatives into numerical weights and scores. The method makes complex decisions based on mathematics and psychology[67]. The process contains three parts: the problem that wants to be solved, all of the possible solutions, and the criteria that will judge the alternatives.

Chapter 5

Conceptual design of facility

This chapter will present the results from using the methodology presented in the previous chapter. It starts with identifying the stakeholders and the needs and opportunities that can be achieved by these solutions. Further, the presentation of abstraction and establishing function structures, which is where the foundation for the solution-space is created. Then the working principles that fulfill the functions are found and sorted accordingly. Next, using compatibility as a criterion, a selection of working structures are found which will then be firmed up. Lastly, these solution variants will be analyzed and evaluated using different criteria.

5.1 Stakeholders need, and opportunities

Stakeholder analysis

Figure 5.1.1 shows an overview of the different stakeholders in the energy industry. This includes everything from the oil and gas sector to local communities.

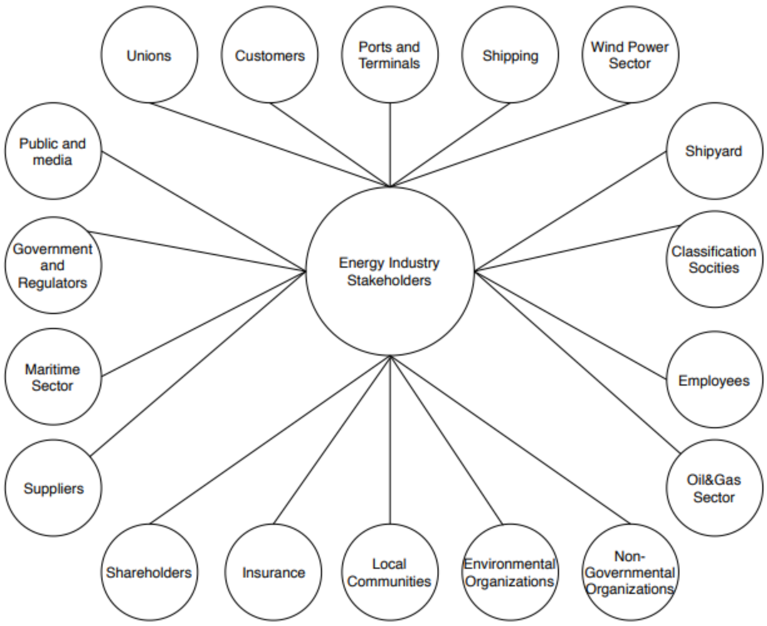


Figure 5.1.1: Overview of stakeholders

To be able to efficiently go through the design phase, the stakeholders and their needs have to be identified. Some of the main stakeholders are shown in table 5.1.1. They are valued by importance where 10 defines the most significant stakeholders. The table shows the different stakeholder requirements and needs for the hydrogen operation. Customers and suppliers need to be satisfied to create an efficient production chain. The hydrogen industry is an industry that has been researched a lot and there has been a lot of development in the sector but there is still a small amount of information accessible for the public concerning this new technology. We live in a time where this green energy solution is of great importance to the public and media. New regulations have to be established which means that classification and regulation companies are stakeholders of importance.

Table 5.1.1: Stakeholders

Stakeholder	Requirements and needs	Importance
Government and authorities	Taxes Creating positions and jobs	**Medium**
Regulators and class firms	Environmental protection	**Medium**
Suppliers	Cash flow Terms regarding contracts	**Medium**
Customers	Providing services according to contract Quality of service and product Delivering service on time	**High**
Shareholders and investors	Safety for crew and environment Operability at all times Optimal efficiency Return of investment(ROI)	**Very high**

It is important to know the stakeholders' expectations as well as the market situation. The various stakeholders are expecting the operation to be run as smoothly and efficiently as possible. As shown in table 5.1.1 the most important stakeholder is the shareholders and investors. They will expect a return of investment and dividends. All stakeholders need to be considered when making decisions in the design and operation phase.

Table 5.1.2 shows a full analysis of the stakeholder's importance level.

Table 5.1.2: Analysis of stakeholders

Stakeholder	Why	How	Interest	Importance
Shipyard	Responsible for assembling systems/vessel.	They install and assembles the systems that are required.	Their work and reliability affects their reputation. If they deliver a top quality product customers may buy more services or products from them	**Medium** - The reliability of the vessel and systems are crucial to uptime and reliability of the system.
Regulators	Set the rules and regulations above the sea surface	Organizations that decides whether or not the vessels are allowed to sail.	Want to sell their services and they want to make sure that the vessels sailing are safe and fit for their type of operations.	**Medium** - Rules and regulations that needs to be followed
Suppliers	Providing systems design for the project.	Contributing to the design of the systems used in extracting hydrogen from wind farms.	They need their system to be as reliable and efficient as possible to benefit and increase their reputation.	**Medium** - Effiecient, reliable and cost effective.
Ship owner/investor	The one with the highest investment in the project and that is responsible for the operations.	Investing in the vessel and is responsible for the cost of building process and maintenance cost.	Main interest is to give the shareholder the most ROI as possible.	**Very high** - This is the person or company that forms the company and sets most of the requirements and needs.
Crew	Ship members using the gear and equipment.	They are employed to use and do maintenance on the system as cost effective as possible.	Reliabilty, effectiveness and safety are key factors when delivering service and to make it as efficient as possible.	**High** - The one with the most use of the system. Income depends on their work and can affect their salary.

When setting out to identify needs, each stakeholder and beneficiary needs to be considered and asked what need the stakeholder has that might be met by the system under consideration. Figure 5.1.2 illustrates the needs of the stakeholder and beneficiaries that have been identified. Notice that the needs are not complete at this stage; that is to keep figure 5.1.2 manageable.

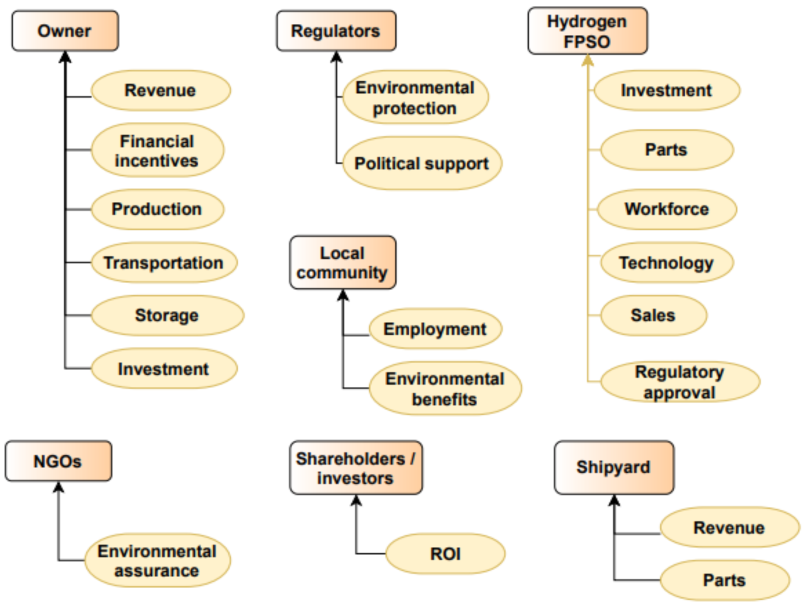


Figure 5.1.2: Needs of the beneficiaries for the system

Notice that figure 5.1.3represents the needs of the stakeholders as a potential flow. This does not imply that it is specified which stakeholders the project has to satisfy, nor does it imply that how the needs of the stakeholders will be satisfied for the chosen concept. Figure 5.1.3 interprets the project as a system. The entities and the relationship between them have been identified.

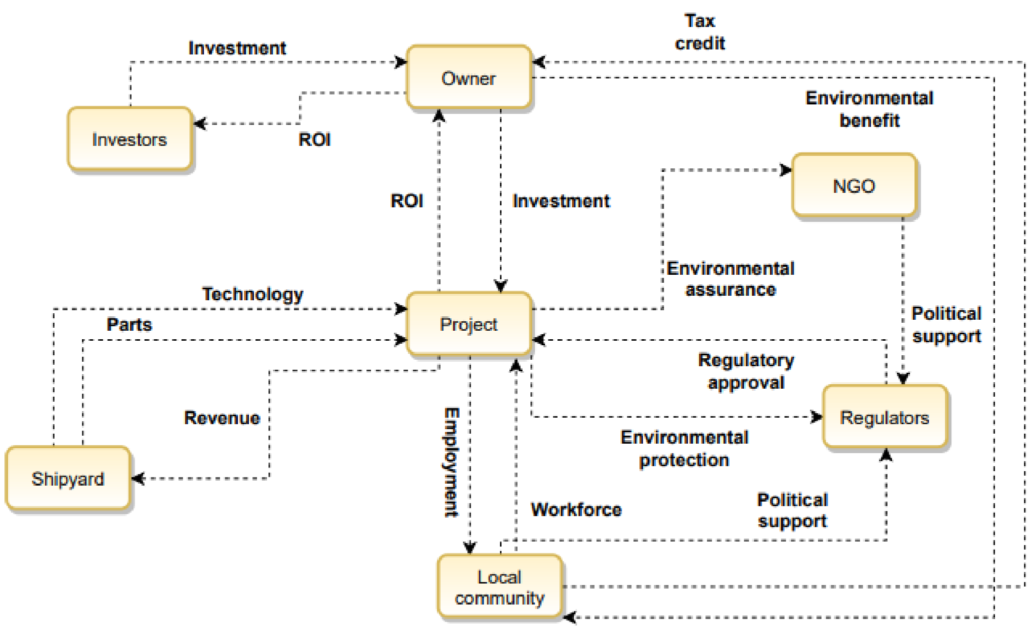


Figure 5.1.3: Stakeholder map for the project, with characteristics of the needs illustrated

Opportunities

Figure 5.1.3 clearly shows that the most important need for the owner is the return of investment - the financial benefit you receive from an investment. This means that the potential of such a system and project should be great. To be able to illustrate the potential, a superficial and simplified needs analysis has been performed.

One of the main questions that need to be answered when analyzing the techno-economical aspect of such a system is whether or not the system should produce hydrogen or transfer the energy directly to the grid. To be able to get an overview of this, large amounts of data need to be gathered and sorted. Gridwatch[74] is a site that tracks the overall energy production in the United Kingdom and registers the data every five minutes. Figure 5.1.4 shows how offshore wind production varied in the UK in 2020.

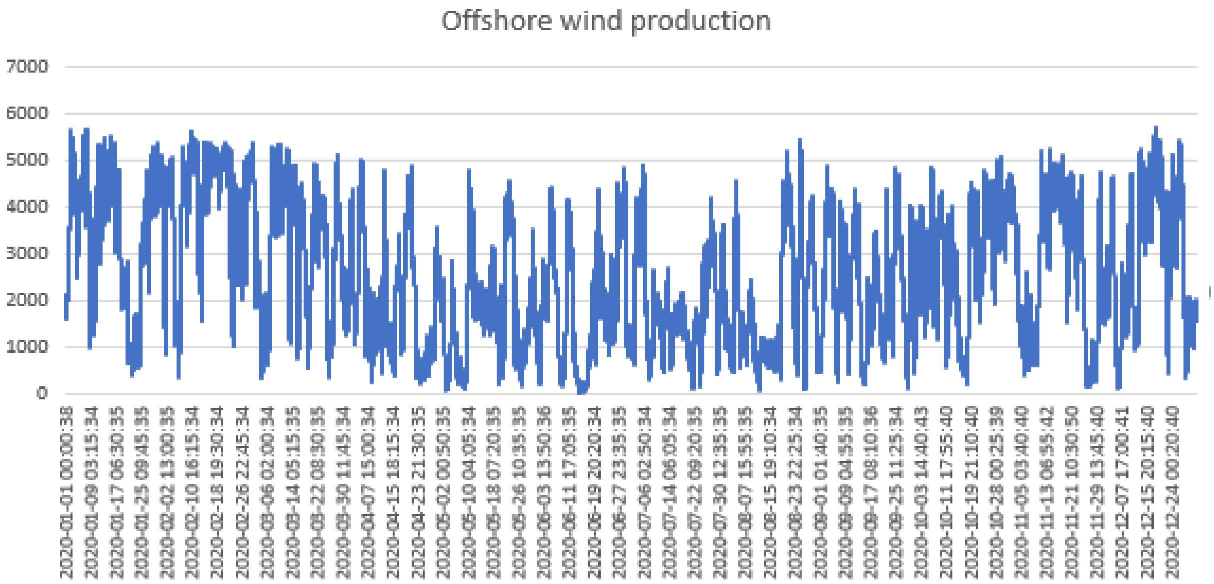


Figure 5.1.4: Offshore Wind Production in the UK 2020[74]

The data set only shows the overall offshore wind production and is not specified to one offshore wind farm. There is also currently no available production data from a specific offshore wind farm such as Hornsea P1[75]. Since HP1 makes up 12% of the national offshore wind energy production, an assumption that the energy production at HP1 follows the same trend as the national production is made. Producing 1 kg hydrogen(which has a specific energy of 143 MJ/kg) requires 50-55 kWh (180-200 MJ) of electricity[76]. This means that by dividing the energy production data by 55, the amount of hydrogen produced in kg is found. The price of green hydrogen varies between $2.50-$6.80 per kilogram today[77]. Multiplying the produced amounts with the median ($4.80), the daily revenue by converting energy to hydrogen is found.

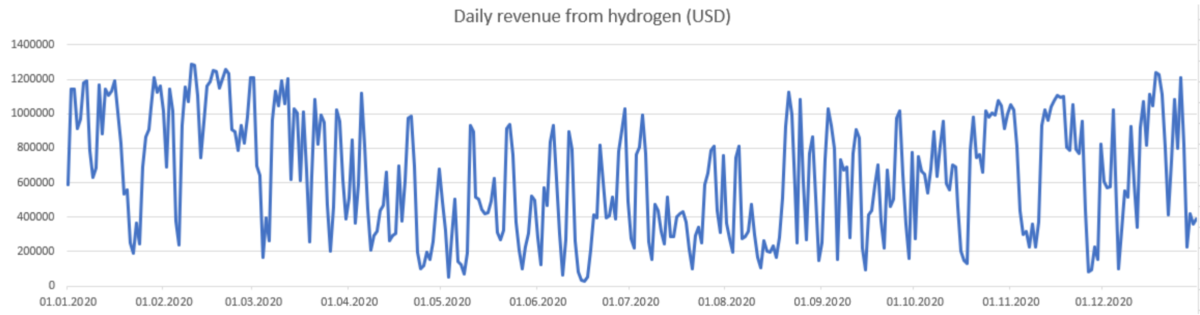


Figure 5.1.5: Daily revenue from hydrogen

To be able to compare the figure above with the daily revenue using electricity, electricity spot prices data from Nordpool[78]. for Oslo in 2020 were retrieved. Multiplying this data with the production data at the specific dates, the daily revenue by converting energy directly to electricity is found.

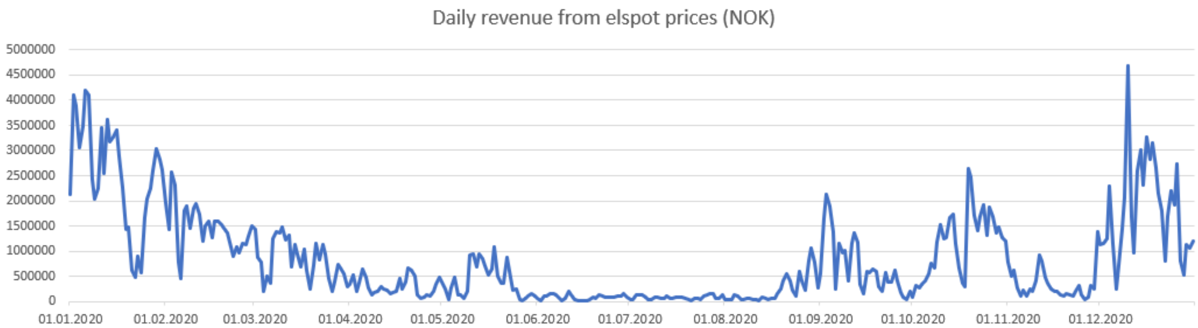


Figure 5.1.6: Daily revenue from electricity

There is a clear distinction between these two plots, especially in the period between May-August. With an average daily revenue from the hydrogen of $\approx$ 4,5 mUSD/day and an average daily revenue from electricity prices of $\approx$ 200 kNOK/day. Both assets are dependent on energy production, so one can make a case for OK predictability for both assets. The difference is that the revenue from electricity also depends on the spot prices. The spot prices vary a lot, and there is a significant difference when comparing prices in November - February with April-August. On the other hand, even though the daily revenue from hydrogen is significant, the cost of materials, production, storage, transportation, and systems will also be significant. It should be noted that these parameters have not been taken into consideration. The electricity spot prices with any surcharges have also not been taken into consideration. Even though this is a simplified analysis, such a system's clear use and potential are shown.

5.2 Abstraction using systematic broadening of problem formulation

As mentioned before, the whole idea behind abstraction is to not complicate things when dealing with design with different requirements. The problem formulation is extended through systematic study of the physical and chemical processes.

The problem formulation will be the basis of this thesis. This means that the problem formulation is extended through systematic study of the physical and chemical processes. How hydrogen is produced, what state hydrogen is in, how it converts from one state to another, how this will affect transportation, and so on. The main objective is set to ”transporting hydrogen from a chosen offshore wind farm to port”. This is a solution-neutral formulation of the objective, this means that the objective that does not favor any particular design.

The next step is to identify the entities that are involved when completing the objective. For the objective to be fulfilled, it is assumed that the facility has the capability to produce, store and offload product to a tanker with the same storage capacity as the facility. The offshore site and port are two different locations and therefore stationary. This means that the only thing that needs to be considered is first and foremost the chemical flow of hydrogen - from electrical energy to hydrogen production using electrolysis. And then the material flow of hydrogen - from facility to port. The questions that need to be answered will then be in which form will hydrogen be produced, how will it be stored, and in what way will be transported. With this information about the entities of the system, the boundaries, and the inputs and outputs, the figures below show how the chemical and material form will change.

Figure 5.2.1 shows how the flow conversion from electrical energy to produced product is determined. The flow starts with electrical energy and H_2O as inputs for the electrolyzer. The electrolyzer will then yield hydrogen in either of these forms as output. The product will be stored at the floating facility in a particular way depending on the chemical form.

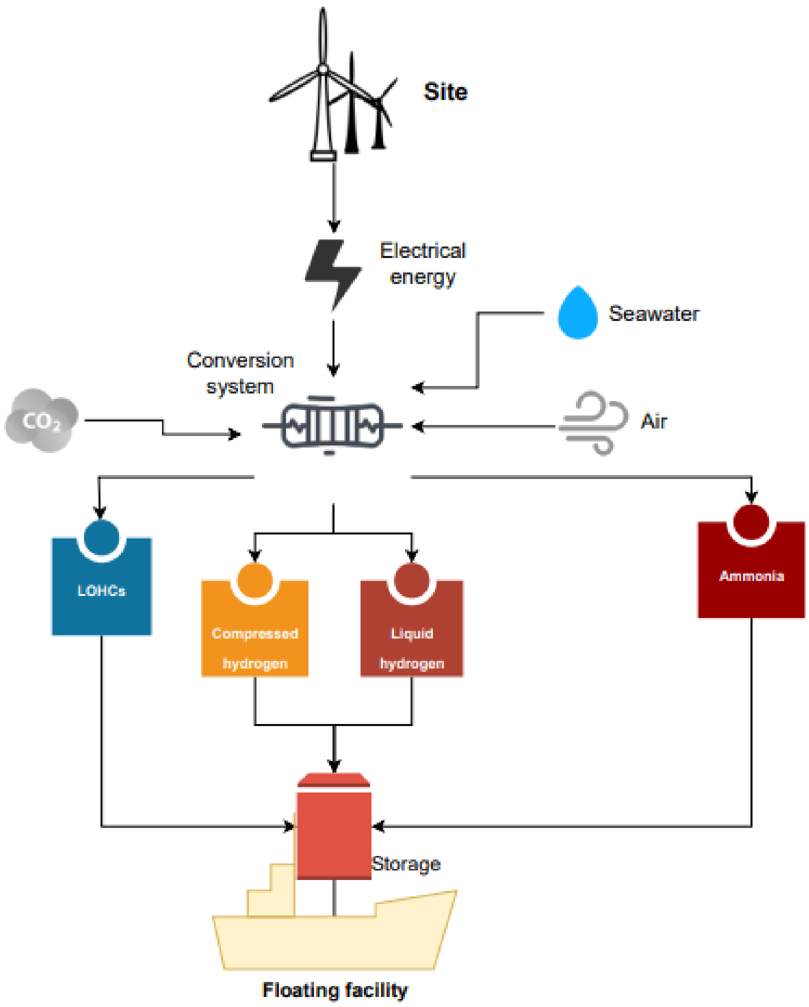


Figure 5.2.1: The chemical flow from electricity to produced product

Figure 5.2.2 shows how the material flow conversion from the storage unit to the port using one of the transportation methods. As mentioned above - the transportation method depends on the chemical form the product is in. The port is not set in a particular location, it is assumed that it is located some distance from the deposit.

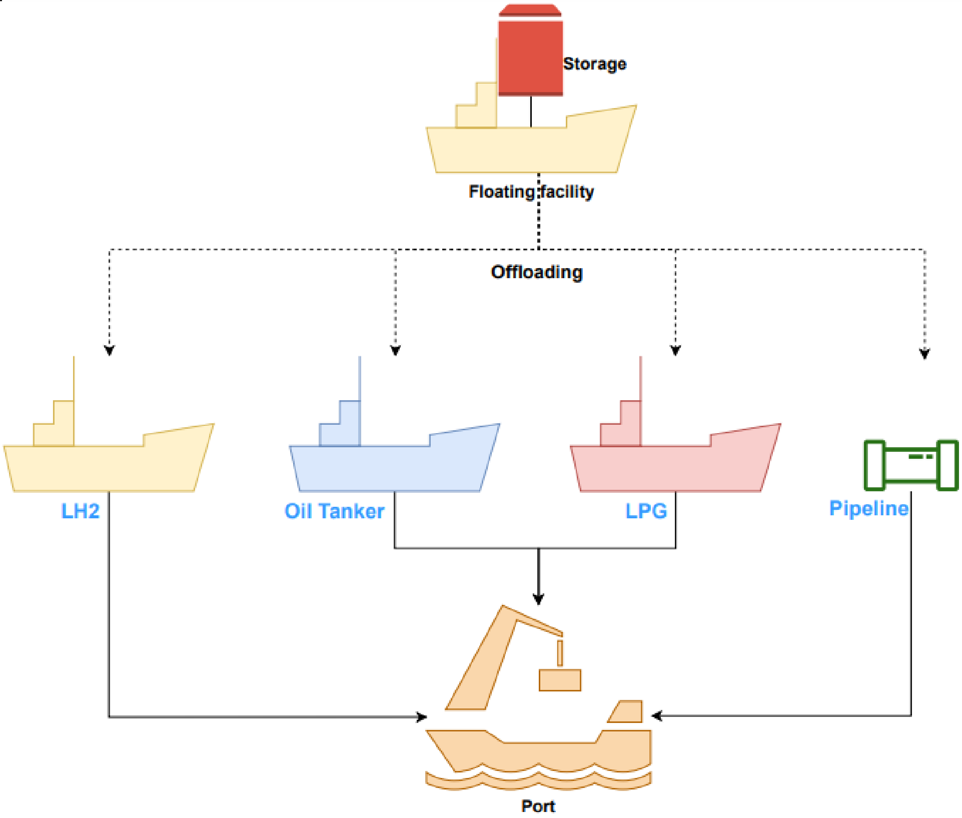


Figure 5.2.2: The material flow from carrier to port

With this in mind, the important stages and processes of the objects have been identified. The process happens in three stages - the chemical flow from electricity to hydrogen, then storing, and lastly transportation to the port. This means that to complete the main objective, these three conversions need to be done. The next step is to identify the main function with underlying subfunctions. This is important to obtain a certain level of consistency throughout the processes.

5.3 Establishing function structures

5.3.1 Overall function

As mentioned in section 5.2, the main objective is to ”transport hydrogen from a chosen offshore wind farm to port”. Hence, this is the overall function that needs to be achieved Figure 5.3.1 shows the overall function with its input and output.

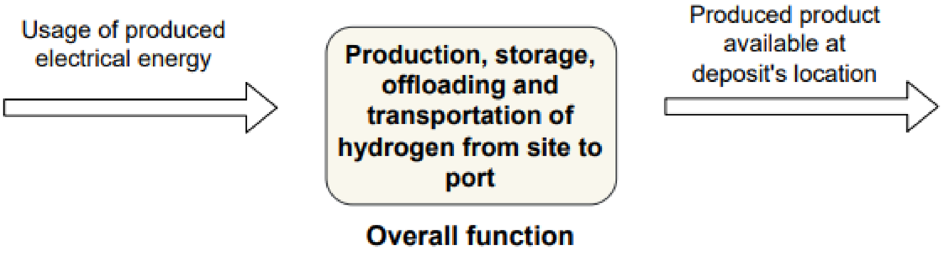


Figure 5.3.1: Block diagram of the input and output for the overall function

The input is the hydrogen will be produced at the site using electrical energy and the output is the produced product available at the port. The overall function is the bold writing inside the box.

5.3.2 Main functions

To be able to obtain the overall function, the main functions need to be identified. This can be done by looking at both the chemical and material flow.

Chemical flow at site

Figure 5.3.2 shows the first chemical flow. The input is the produced electrical energy and the output is the produced amount of hydrogen. The main function is the production system onboard the facility. This means that the system must convert electrical energy available at the site to chemical energy in the form of hydrogen.

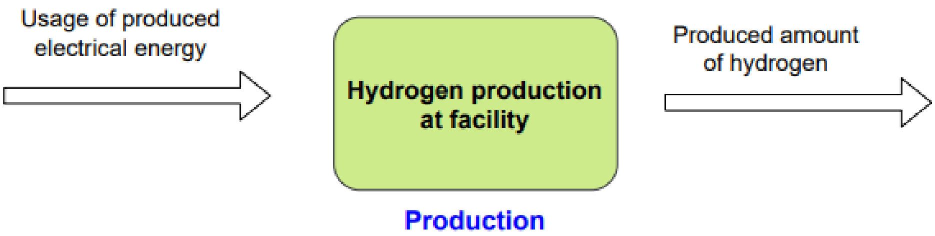


Figure 5.3.2: Block diagram of the input and output for the first main function(MF1)

The next chemical flow is the storing as shown in figure 5.3.3. The input is produced amount of hydrogen and the output is the storing of product at the storage unit. The output is specified as ”storing of produced product”. The reason behind this specification for the output is simply due to the chemical form the hydrogen will be stored in. This could be in either liquid, compressed, LOHC, or Ammonia. This means that the main function is the storing of the produced product.

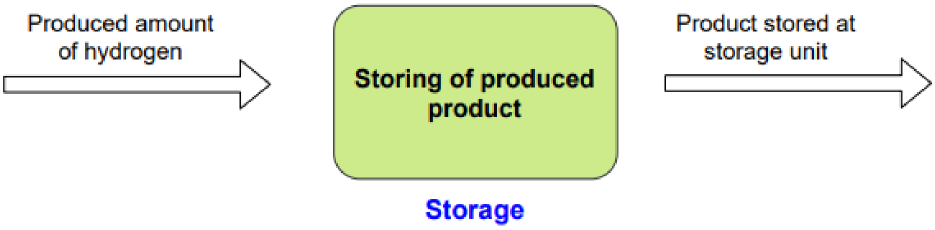


Figure 5.3.3: Block diagram of the input and output for the second main function(MF2)

Material flow from facility to port

Figure 5.3.4 shows the first material flow of the process. The input is the produced product from the storage unit and the output is the storing of product at the carrier. This means that the third main function is the offloading of product from the storage unit at the facility to the carrier. This means that the produced material is moved from one location to another one.

Figure 5.3.4: Block diagram of the input and output for the third main function(MF3)

Figure 5.3.5 shows the final main function. The input is the amount of product stored at the carrier and the output is the same amount of product available at the port or deposit's location. This means that the main function is transportation from site to port. This main function is achieved through two alternatives. The first one being that the carrier transports the amount directly to a port or a specified location and offloads the amount there. The second alternative is that the carrier transports the amount outside a specific location and unloads the amount using bunkering vessels. The second alternative is only viable if the produced product is ammonia. Otherwise, alternative number one is the more neutral alternative. This particular process will be further discussed at the end of this section.

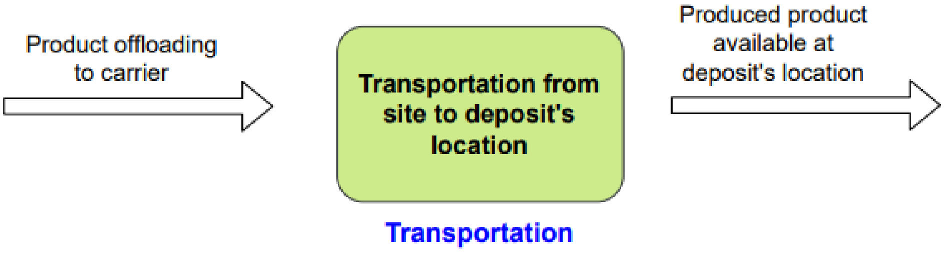


Figure 5.3.5: Block diagram of the input and output for the fourth main function(MF4)

5.3.3 Functional hierarchy

The final functional decomposition study yields four different main functions. The interaction between the overall function and the main functions can be seen in figure 5.3.6. It is worth noticing that the output of the first main function is equal to the input of the next main function due to the principle of flow conservation.

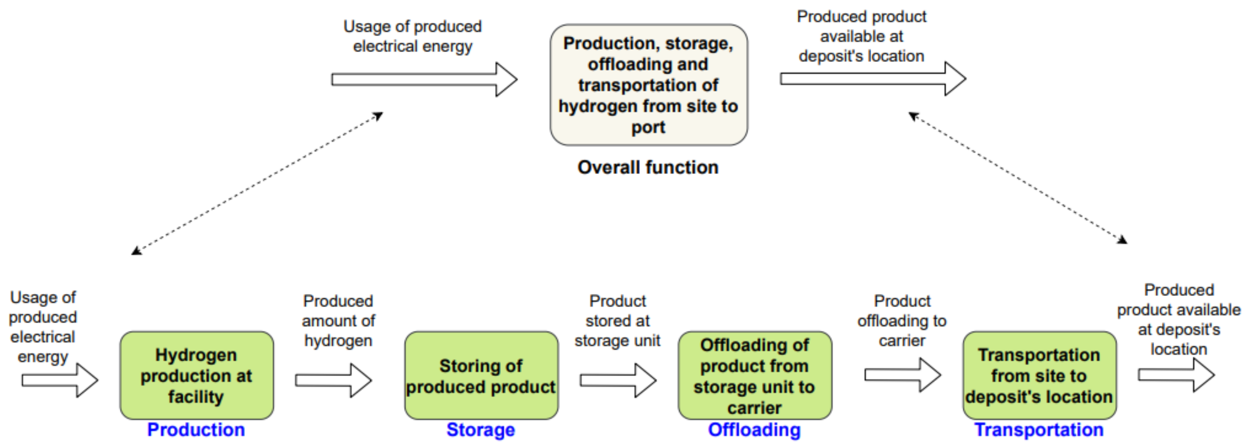


Figure 5.3.6: Final functional hierarchy

5.4 Searching for working principles associated with functions

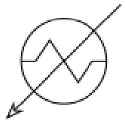
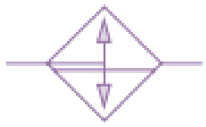
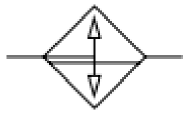
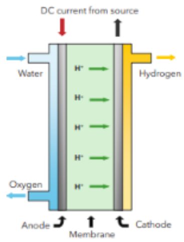
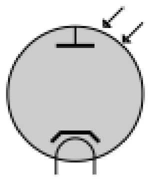
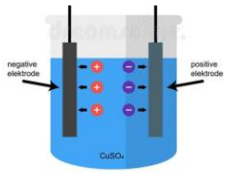
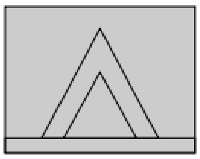
5.4.1 MF1: Hydrogen production at the facility

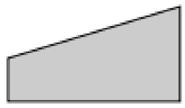
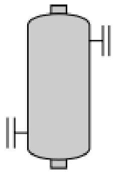
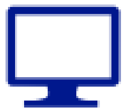
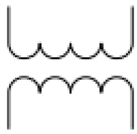
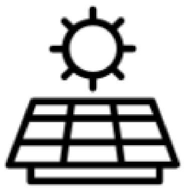
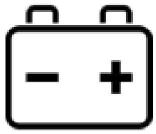
The first main function is the production system onboard the facility. As mentioned in section 3.1, there are several ways to produce hydrogen. All of the viable options can be seen in figure 5.4.1.

	DESCRIPTION	Symbol	Principles
Electrolysis(PEM)	The electrons flow through an external circuit and the positively charged hydrogen ions moves actross the PEM to the cathode. Hydrogen ions will then react and combine with the cathode to form hydrogen gas. The electrolyser have compact system design, which means they are relatively small, making them more advantagous than other electrolysers in dense areas. They have a high production rate and high purity of gases.		• Electrical • Chemical • Mechanical
Natural gas	Stream reforming using natural gas is a cost-effective method for producing hydrogen, first of all because of its availability, but it also has a high hydrogen-to-carbon ratio. This minimizes the formation of by-product carbon dioxide(CO_2).		• Chemical • Mechanical
Biomass	Hydrogen can be produced via pyrolysis or gasification of biomass resources. Biomass pyrolysis produces a liquid product (bio-oil) that contains a wide spectrum of components that can be separated into valuable chemicals and fuels, including hydrogen.		• Chemical • Mechanical
Photoelectrochemical water splitting	This can be done using sunlight to directly split water by using spezialized semiconductors called photoelectrochemical materials, which use sunlight to split water into hydrogen and oxygen.		• Electrical • Chemical • Mechanical

Figure 5.4.1: Working principles for MF1

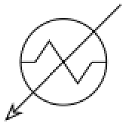
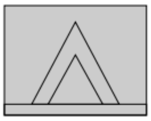
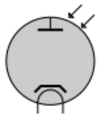
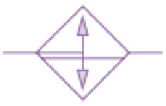
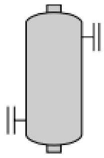
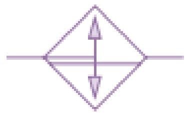
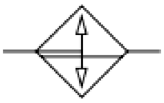
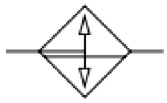
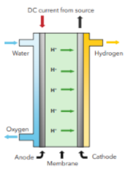
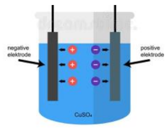
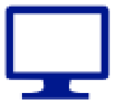
Each of these methods requires both chemical and electrical components for production. The table in the next couple of pages shows an overview of the required components and an illustration.

MECHANICAL	FUNCTION	ILLUSTRATION
Heat exchanger	Removes excess heat from system to ensure proper operation.	
Oxygen phase separator	Separates gaseous oxygen from water exiting the cell stack.	
Hydrogen phase separator	Separates gaseous hydrogen from water exiting the cell stack.	
Cell stacks	Generates hydrogen and oxygen from water using PEM technology.	
Photoelectrolytic cell	Device such as a semiconductor in an electrolytic solution to directly cause a chemical reaction to produce hydrogen.	
Electrolyte	A substance that produces an electrically conducting solution when dissolved in water. The substance separates cations and anions.	
Combustion chamber	Chamber where the fuel/air mix is burned, and natural gas are converted to hydrogen.	

Compressor	Device that increases the pressure of a gas by reducing its volume.	
Gasifier	The objective of the gasifier is to convert biomass- or fossil fuel based materials into gas through chemical reactions.	
Air separator unit	This unit separates atmospheric air into its primary components, typically nitrogen and oxygen.	
ELECTRICAL		
Control room	Provides user interface to control and monitor the system.	
DC transformers	Convert input AC to DC power for PEM electrolysis and to a standard 240VAC.	
Solar PV panels	Assembly of photo-voltaic cells that produces electrical energy using sunlight.	
Battery	Device that stores chemical energy and converts it to electrical energy.	

The components are sorted after which principle they use. It is worth noticing that the components listed in the table are the main components required. Components such as cables, pipes, gauges, and so on are not listed. The production methods and the components are formed and sorted into a solution catalog that shows which components are required in each process.

Many of the components are repeated, with the difference being the method they are used in. For instance, both the electrolysis and photoelectrochemical water splitting require an oxygen phase separator and a hydrogen phase separator. While all of the processes require a control room where temperature, pressure, production, and so on are monitored.

METHOD / PRINCIPLE	ELECTROLYSIS	STEAM REFORMING	GASIFICATION	PHOTOELECTROCHEMICAL WATER SPLITTING
				
MECHANICAL				
				
				
				
				
ELECTRICAL				
				
				
				

5.4.2 MF2: Storing of produced product

The second main function is the storing of the product. As mentioned above, The search for working principles has revolved around the chemical form the hydrogen will be stored in. This could be either in liquid form, compressed form, formic acid(LOHC), or Ammonia. figure 5.4.2 presents the working principles for storing hydrogen.

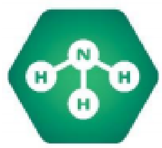
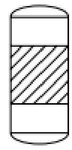
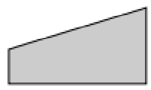
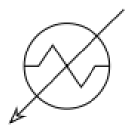
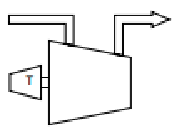
STATE	DESCRIPTION	SYMBOL	PRINCIPLE
Compressed hydrogen	Compressed hydrogen storage method is the storage of compressed hydrogen gas in high pressure tanks (higher than 200 bars). This makes it able to be stored in a smaller space while retaining its energy effectiveness, and this makes it beneficial for fuel purposes.		• Compression • Purification
Liquid hydrogen	To be able to increase the energy density and content of hydrogen, liquefication of hydrogen is a major improvement. This method is achieved by cooling hydrogen to a very low temperature. More precisely, at -252.87°.		• Compression • Purification • Expansion
LOHC	The principle is to store hydrogen as liquid formic acid - HCO2H. This method could be a significant step towards cost-efficiency high-scale hydrogen storage method.		• Dehydrogenation • Purification • Compression
Ammonia	The principle is to store hydrogen as ammonia using the Haber-Bosch process. Its high volumetric hydrogen density, low storage pressure and stability for long-term storage are among the beneficial characteristics being a potential medium for hydrogen storage.		• Compression • Condensation • Purification

Figure 5.4.2: Working principles for MF2

The table on the next page shows an overview of the components required to get the medium from one chemical state to another.

COMPONENT	FUNCTION	ILLUSTRATION
Reactor	A chemical reactor is an enclosed volume in which a chemical reaction takes place.	
Compression		
Compressor	Unit that increases the pressure of a gas by reducing its volume.	
Purification		
Purifier	Removal of impure elements from a medium.	
Dehydrogenation		
Heat exchanger	Device which transfers heat from one medium to another.	
Condensation		
Condenser	Device for reducing a gas or vapour to a liquid by removing heat.	
Expansion		
Turboexpander	Device which a high-pressure gas is expanded to liquefy gases such as liquid hydrogen.	

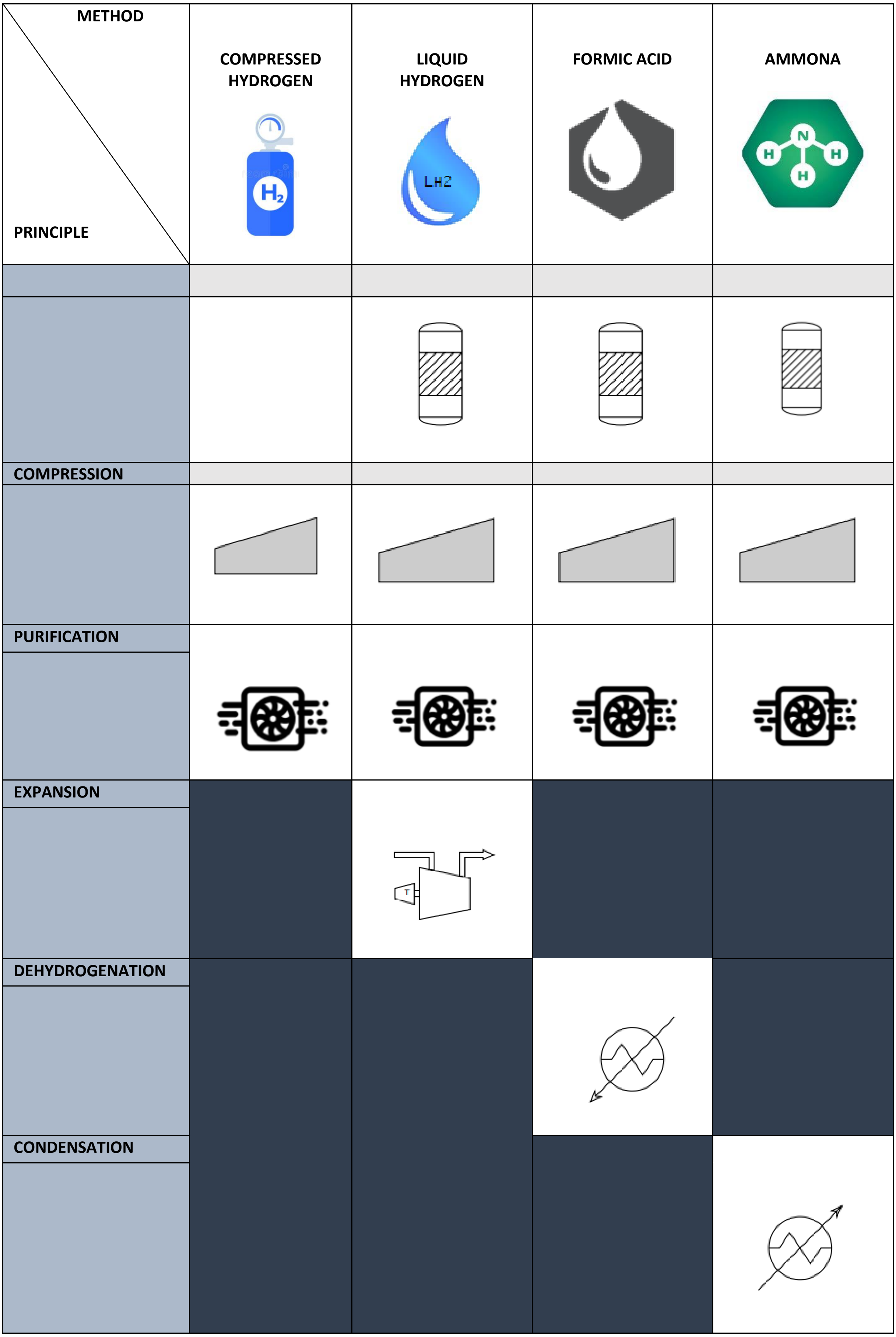
As with the production phase, the storing of hydrogen in these different states are chemical-based. This means that to be able to store hydrogen, the required components are needed. It is worth noticing that the table is showing only the main components in the processes. Other small components such as gauges, tubes, racks, tongs, and so on are not mentioned.

The storing method and the required components are gathered and sorted in the table on the next page. The components are sorted after the physical principle they work in and in which method they are used and required.

Notice that storing physical-based hydrogen as either compressed or liquid in tanks has a high dismissal rate in addition to high efficiencies of around 99%. This makes them suitable for small-scale applications. Compressed hydrogen has less energy content than gasoline that occupies the same volume. For refueling purposes, compressed hydrogen will require nearly seven times the space as gasoline. And comparing with liquid hydrogen - five kg of compressed hydrogen can be stored in a 125-liter tank while the same amount can be stored in a 75-liter tank as liquified hydrogen. Compressed hydrogen does in fact have a higher energy density than lithium-ion batteries, this yields a greater range in cars or trucks.

In chemical-based storage methods such as formic acid, the technology is at an early stage of development. This means technologies that provide feasible transportation solutions are complicated and in some cases, expensive. But with increasing interest and technology studies, these methods could potentially increase the density of hydrogen to be stored at atmospheric pressure.

Ammonia, on the other hand, has a greater energy density, which leads to less need for large tanks and the possibility to save a significant amount of space for refueling purposes for maritime shipping. There needs to be a fine balance between this advantage and the high energy loss and cost for conversion/reconversion equipment.


METHOD
PRINCIPLE
COMPRESSED HYDROGEN
LIQUID HYDROGEN
FORMIC ACID
AMMONA
LH2
N
H
H
H
COMPRESSION
PURIFICATION
EXPANSION
DEHYDROGENATION
CONDENSATION

5.4.3 MF3: Offloading of product from the storage unit to carrier

The third main function is the offloading process from the storage unit to the carrier. Table 5.4.3 shows the most common offloading configurations offshore.

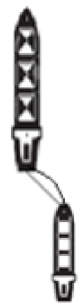
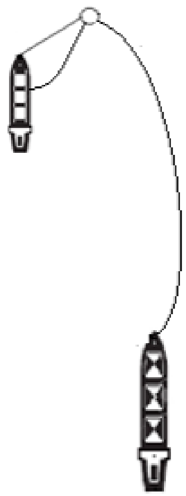
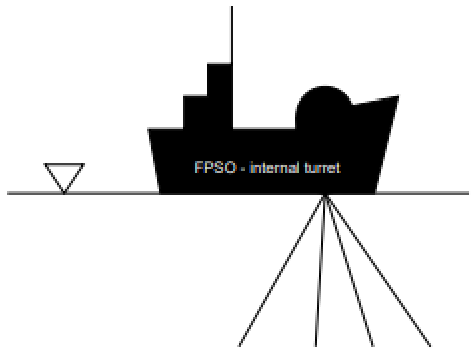
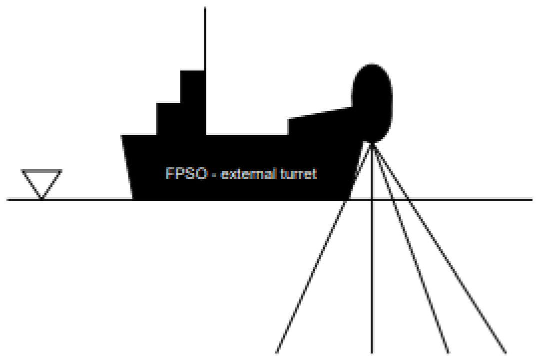
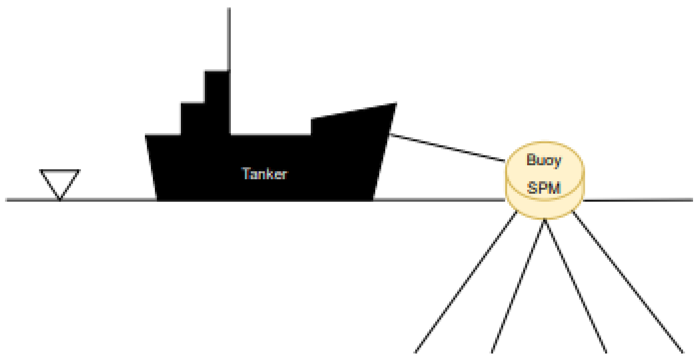
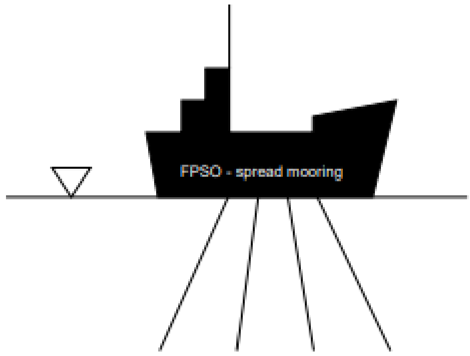
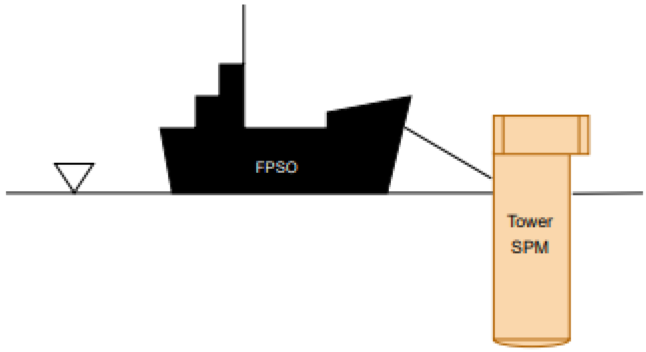
WP3	DESCRIPTION	ILLUSTRATION
Tandem	The shuttle tanker is berthed by a hawser and is loaded using offloading hose from the FPSOs stern. The black line represents the offloading hose and the gray represents the hawser.	
Remote offtake buoy	The shuttle tanker is berthed by a hawser to a remote offtake buoy and loaded through offloading strings at the buoy.	

Figure 5.4.3: Most common offloading methods offshore

It doesn't matter how the offloading process will be done as long as there is no mooring system onboard the vessels. The table on the next page shows an overview of the different mooring systems that are being used today, some description, and an illustration of the system.

SYSTEM	DESCRIPTION	ILLUSTRATION
Internal turret single point mooring (SPM)	This system consists of either an external or internal turret that is integrated to a vessel and fixed to the seabed by means of a mooring system. By having a bearing system, the vessel can rotate around the fixed geostatic point of the turret.	
External turret single point mooring (SPM)	This system consists of either an external or internal turret that is integrated to a vessel and fixed to the seabed by means of a mooring system. By having a bearing system, the vessel can rotate around the fixed geostatic point of the turret.	
Buoy SPM	This system consists of a floating buoy anchored offshore that serves as a mooring point and interconnect for tankers for loading. It is permanently moored to the seabed by means of multiple mooring lines. The system also has a bearing system integrated, which means that the vessel can freely move around the buoy depending on the environment.	

Spread mooring	This system is a multi-point mooring system that moor vessels to the seabed using multiple mooring lines. The bow of the vessel typically heads into the direction where the largest waves are coming from.	
Tower SPM	This system consists of a tower structure that is fixed to the seabed by means of piles or a gravity base. This system works similarly to a buoy with a bearing system that allows the vessel to move freely weathervane around the geostatic part of the system.	

Both the offloading configurations and the mooring systems have their pros and cons. As shown, there are several options for the offloading configurations concerning the mooring system, but it all has to be considered and the following points can be used when determining both the configurations:

- Facility operation and maintenance
- Risk of collision, the spread of fire and oil spill
- Temporary displacements
- Future expansion
- Decommission and abandonment or relocation

The single point mooring system (SPM) allows the vessel to be better equipped for bad weather and thus minimize the mooring loads at all times. This is in contrast to the spread mooring system. In conclusion, the subsea infrastructure and location concerning weather and wind are the most important parameters when defining which system to use.

The offloading configurations have each their own advantages and disadvantages as mentioned before. Some of them are more risk-prone and some are cheaper. As with the mooring system, the selection depends on the environmental conditions, costs, vessel arrangements, and so on. For instance, tandem offloading is commonly used due to being cheap and the most flexible. While remote offtake buoy is used most in weather-prone locations while yielding a higher availability for offloading.

Figure 5.4.4 shows how the different mooring systems will function with the desired offloading configurations. As shown, the mooring system using buoy is crossed over, although it may be a feasible solution, the alternative is way too complex to pursue further. The only mooring systems that will be considered are the external/internal turret SPM, tower SPM, and spread mooring.

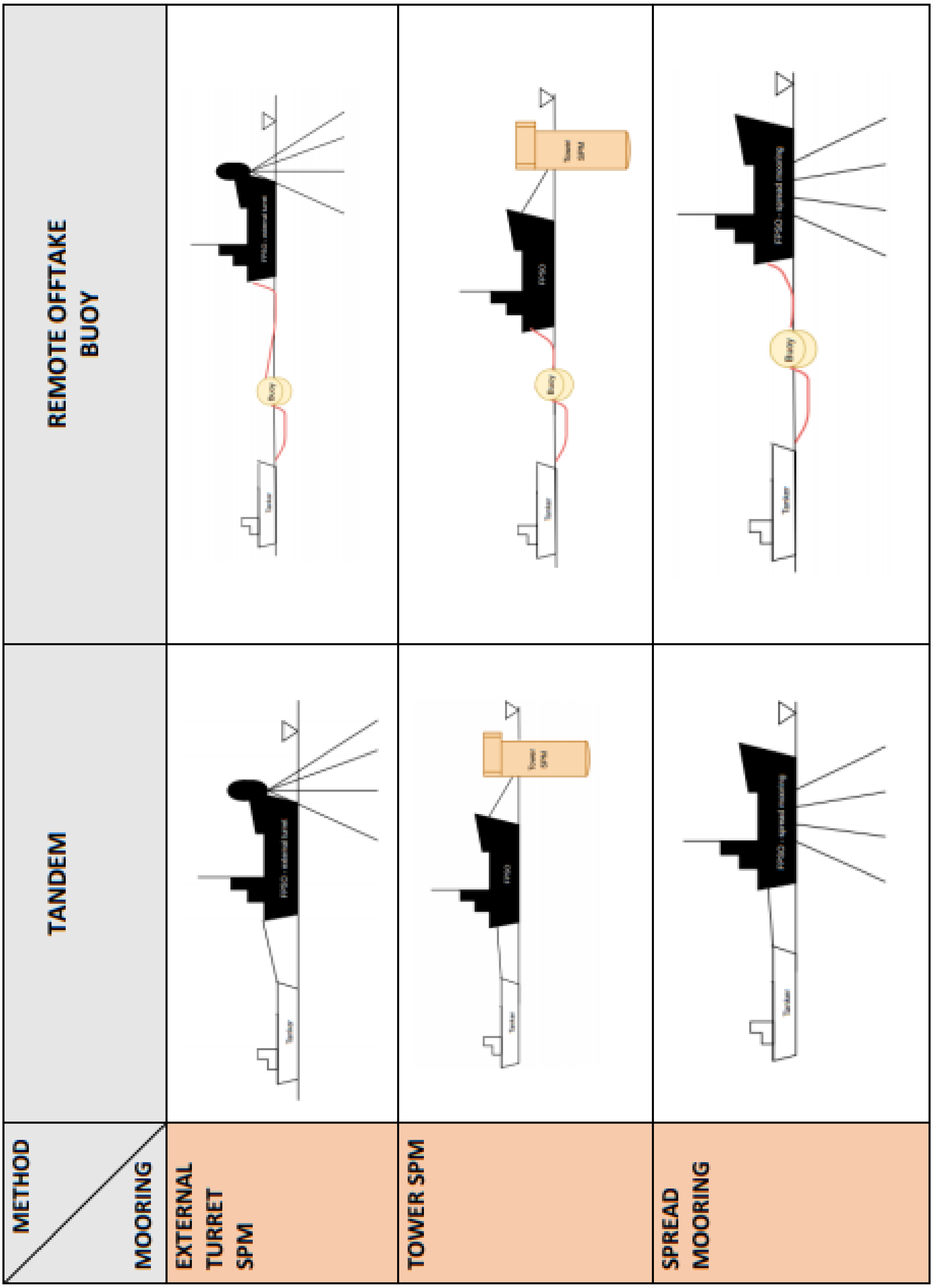


Figure 5.4.4: Solution catalogue for MF3

5.4.4 MF4: Transportation from site to port

To be able to transport hydrogen over long distances, solutions such as compression, liquefication, or blending hydrogen into larger molecules could be used to transport hydrogen safely and cost-effectively with each solution having its advantages and disadvantages. The optimal solution in the future may include a variation and combination of high pressure, cold gas, and a solid carrier(formic acid) to obtain a volumetrically efficient and cost-efficient hydrogen storage system. Figure 5.4.5 presents the different carriers for the transportation of products from the site to the port.

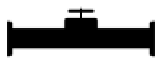
WP4	DESCRIPTION	SYMBOL
LH2 carrier	Carrier such as the *Suiso Frontier* – a carrier with a capacity of 1250 m^3 and the capability to transport 75 tons of hydrogen at -253°.	
LPG carrier	Ammonia can be transported using full pressure type, semi-refrigerated type and fully refrigerated type liquefied petroleum gas. This means that practically all LPG carrier can transport ammonia.	
Oil tanker	LOHCs have similar characteristics to oil products and crude oil, this means that they can be transported as liquids without the need for cooling. This means that LOHCs would be the easiest form to transport hydrogen as oil product tanker can be used.	
Pipeline	Transportation using pipeline using either export pipelines or transmission pipelines is possible by blending compressed hydrogen into natural gas.	

Figure 5.4.5: Overview of the different carriers

Gathering and sorting the chemical state of the hydrogen to the transportation method yields table 5.4.6 and the compatibility between them is shown.

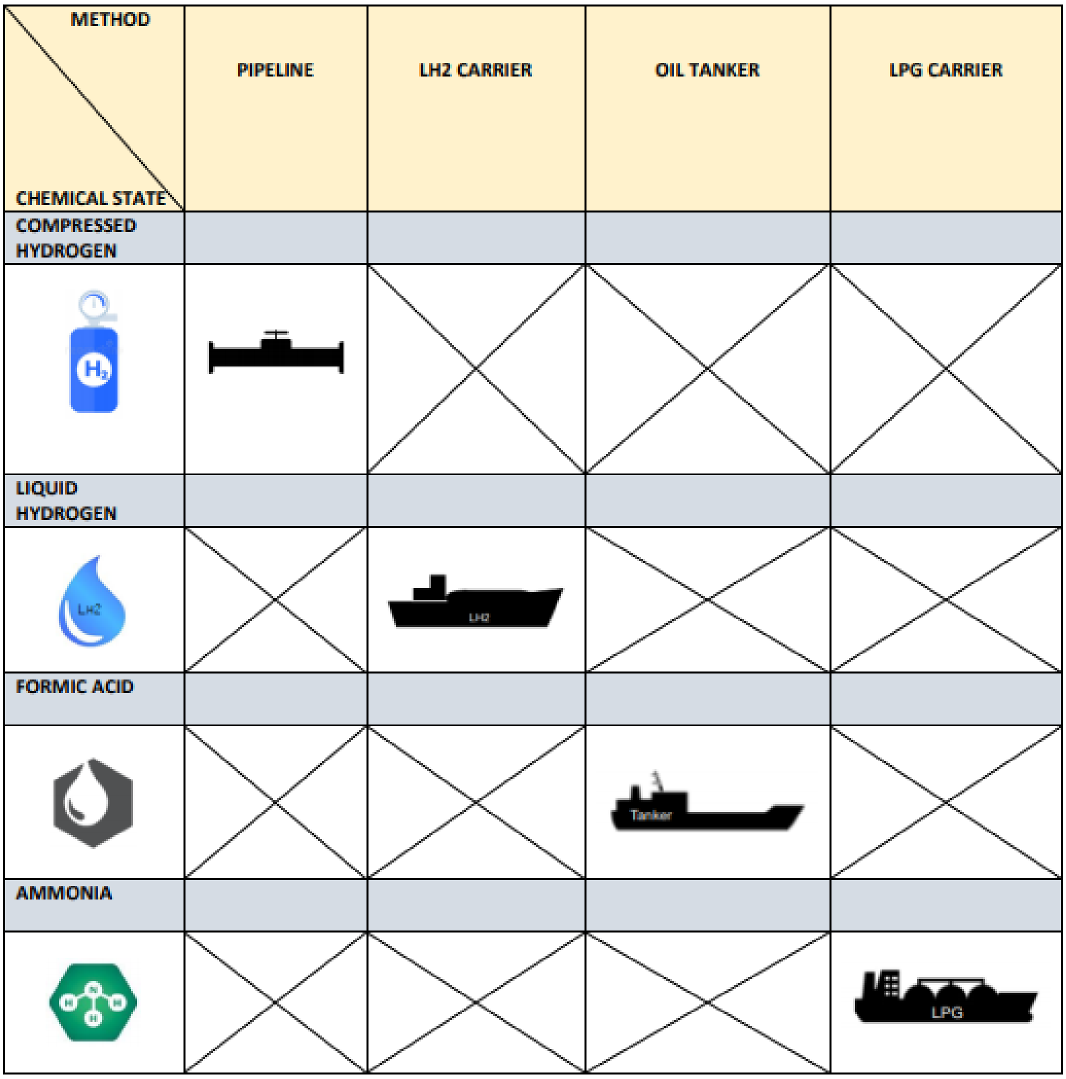


Figure 5.4.6: Compatiblity between carrier and hydrogen

5.5 Combining working principles into working structures

All four different catalogs from the previous section show an overview of the workings principle that fulfills the main functions and its objectives. These catalogs are combined into a single morphological catalog that can be seen in appendix 9.4. This is done to get an overview of the overall function. By doing this, the differences in terms of feasibility and compatibility are more clear when comparing the different principles and methods with each other to obtain a flow of energy, material, and information. This overall catalog will be used as a guiding tool to provide the compatibility matrices between the different main functions. The compatibility matrix is used as a matrix for information processing and should be used to get an overview of the different parameters, principles, and functions. The combinations that can be used using the morphological catalog are many, this means that only the most feasible and most compatible solutions will be highlighted in the compatibility matrices in the upcoming pages.

Compatibility between MF1 and MF2

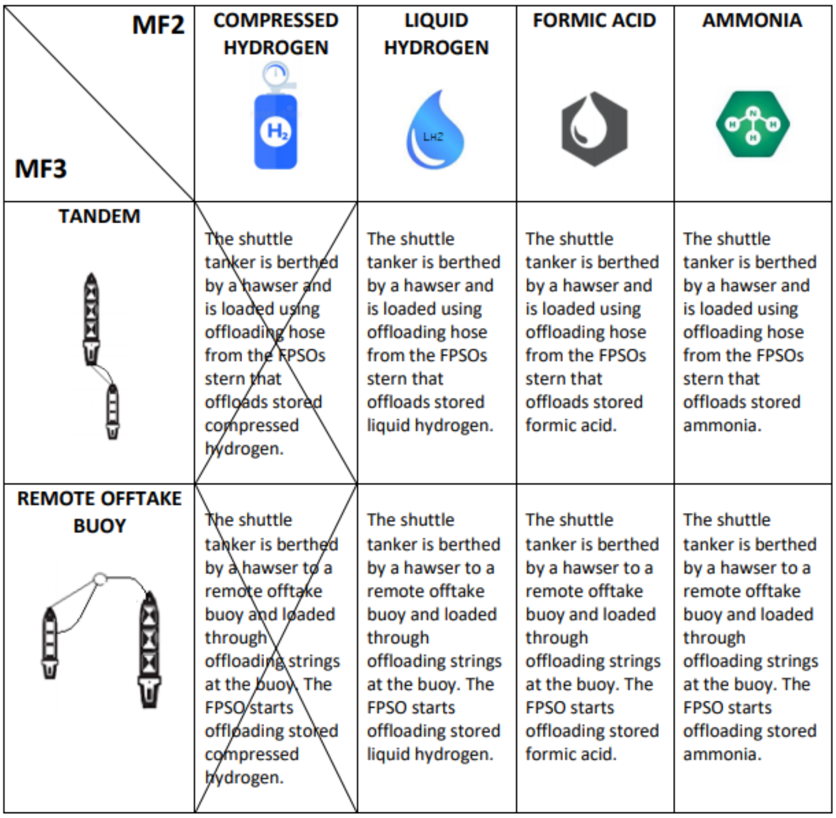
Starting with the production function and storing function, the compatibility matrix between them is shown in figure 5.5.1. As shown, the compatibility between MF1 and MF2 is a bit complicated. In theory, all of the interactions between the different principles in MF1 and MF2 are compatible with each other. The reason that the production methods such as natural gas, biomass, and photoelectrochemical water splitting are highlighted this was is due to the complexity of the solution in terms of the overall function. From now on, the only production method that will be considered for MF1 will be through electrolysis.

MF1 / MF2	ELECTROLYSIS	NATURAL GAS	BIOMASS	PHOTOELECTROCHEMICAL WATER SPLITTING
COMPRESSED HYDROGEN	Hydrogen is produced using electrolysis and stored in a compressed chemical state.	Hydrogen is produced using natural gas and stored in a compressed chemical state.	Hydrogen is produced using biomass and stored in a compressed chemical state.	Hydrogen is produced using photoelectrochemical water splitting and stored in a compressed chemical state.
LIQUID HYDROGEN	Hydrogen is produced using electrolysis and stored in a liquid chemical state.	Hydrogen is produced using natural gas and stored in a liquid chemical state.	Hydrogen is produced using biomass and stored in a liquid chemical state.	Hydrogen is produced using photoelectrochemical water splitting and stored in a liquid chemical state.
FORMIC ACID	Hydrogen is produced using electrolysis and stored as formic acid.	Hydrogen is produced using natural gas and stored as formic acid.	Hydrogen is produced using biomass and stored as formic acid.	Hydrogen is produced using photoelectrochemical water splitting and stored as formic acid.
AMMONIA	Hydrogen is produced using electrolysis and stored as ammonia.	Hydrogen is produced using natural gas and stored as ammonia.	Hydrogen is produced using biomass and stored as ammonia.	Hydrogen is produced using photoelectrochemical water splitting and stored as ammonia.

Figure 5.5.1: Compatiblity between MF1 and MF2

Compatibility between MF2 and MF3

The interaction between MF2 and MF3 is more complicated. Figure 5.5.2 shows the compatibility between them. The only difference between them is the interaction between stored compressed hydrogen and the offloading methods. That interaction increases the complexity of the solution compared to the other solutions and makes the solution unnecessary. That is why it is assumed that the offloading of compressed hydrogen will happen through pipelines, which is considered a type of carrier. The three other storing methods are compatible with the offloading principles.

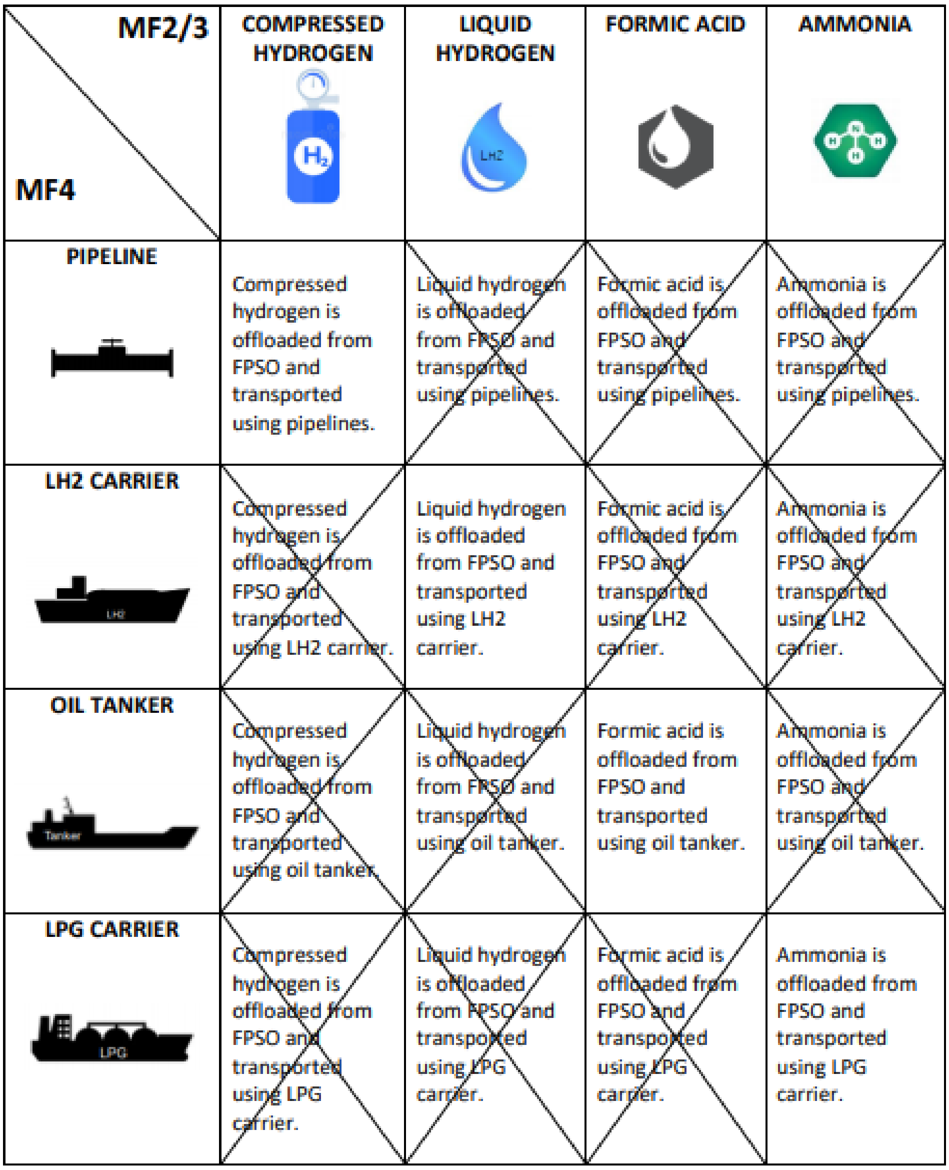


MF2 / MF3	COMPRESSED HYDROGEN	LIQUID HYDROGEN	FORMIC ACID	AMMONIA
TANDEM	The shuttle tanker is berthed by a hawser and is loaded using offloading hose from the FPSOs stern that offloads stored compressed hydrogen.	The shuttle tanker is berthed by a hawser and is loaded using offloading hose from the FPSOs stern that offloads stored liquid hydrogen.	The shuttle tanker is berthed by a hawser and is loaded using offloading hose from the FPSOs stern that offloads stored formic acid.	The shuttle tanker is berthed by a hawser and is loaded using offloading hose from the FPSOs stern that offloads stored ammonia.
REMOTE OFFTAKE BUOY	The shuttle tanker is berthed by a hawser to a remote offtake buoy and loaded through offloading strings at the buoy. The FPSO starts offloading stored compressed hydrogen.	The shuttle tanker is berthed by a hawser to a remote offtake buoy and loaded through offloading strings at the buoy. The FPSO starts offloading stored liquid hydrogen.	The shuttle tanker is berthed by a hawser to a remote offtake buoy and loaded through offloading strings at the buoy. The FPSO starts offloading stored formic acid.	The shuttle tanker is berthed by a hawser to a remote offtake buoy and loaded through offloading strings at the buoy. The FPSO starts offloading stored ammonia.

Figure 5.5.2: Compatiblity between MF2 and MF3

Compatibility between MF2/3 and MF4

This compatibility matrix is more complex than the others. The interaction between MF3 and MF4 is dependent on the chemical state of the hydrogen - MF2. That means that the transportation principle is dependent on how the hydrogen is being stored and in which chemical form. For instance, it is not possible to transport liquid hydrogen using an oil tanker. From the 8x8 compatibility matrix, there are only 4 solutions. It is assumed that all of the solutions will use either of the three compatible mooring systems as shown in figure 5.4.4.



MF4 \ MF2/3	COMPRESSED HYDROGEN	LIQUID HYDROGEN	FORMIC ACID	AMMONIA
PIPELINE	Compressed hydrogen is offloaded from FPSO and transported using pipelines.	Liquid hydrogen is offloaded from FPSO and transported using pipelines.	Formic acid is offloaded from FPSO and transported using pipelines.	Ammonia is offloaded from FPSO and transported using pipelines.
LH2 CARRIER	Compressed hydrogen is offloaded from FPSO and transported using LH2 carrier.	Liquid hydrogen is offloaded from FPSO and transported using LH2 carrier.	Formic acid is offloaded from FPSO and transported using LH2 carrier.	Ammonia is offloaded from FPSO and transported using LH2 carrier.
OIL TANKER	Compressed hydrogen is offloaded from FPSO and transported using oil tanker.	Liquid hydrogen is offloaded from FPSO and transported using oil tanker.	Formic acid is offloaded from FPSO and transported using oil tanker.	Ammonia is offloaded from FPSO and transported using oil tanker.
LPG CARRIER	Compressed hydrogen is offloaded from FPSO and transported using LPG carrier.	Liquid hydrogen is offloaded from FPSO and transported using LPG carrier.	Formic acid is offloaded from FPSO and transported using LPG carrier.	Ammonia is offloaded from FPSO and transported using LPG carrier.

Figure 5.5.3: Compatiblity between MF2/3 and MF4

5.6 Selecting working structures

The compatibility between functions based on material flow and the interaction between them has been found. Based on these matrices, several overall solutions can be found. That means that every incompatible solution will be removed, and only the compatible solutions will be focused on. As mentioned before, the incompatible solutions are either too complex or too unreasonable to search for. Only compatible and favorable solutions will be pursued. The combinations can be seen in appendix 9.5. It is worth noticing that each of these solutions will have the same mooring system - either external/internal turret SPM or spread mooring. The system will depend on the environment and location of the case study that will be evaluated at a later stage.

Solution set 1

Using compressed hydrogen as a storage method makes hydrogen able to be stored in a smaller space while retaining its energy effectiveness. At a pressure of 700 bar - 5kg of hydrogen can be stored in a 125-liter tank, which is significant.

Using pipelines for transportation and distribution at sea is limited, but it is possible to blend hydrogen into natural gas using either export or transmission pipelines. As mentioned in chapter 3.3.1, there are several ongoing projects about safe pipelines for hydrogen transport today.

Solution set 2

By liquefying hydrogen, the energy density and content of hydrogen would increase significantly. It is achieved by cooling the hydrogen to a very low temperature, which means that energy is required to do so.

The world's first LH2 carrier, Suiso Frontier launched this fall. The launch heralds a new era for the bulk carrying of non-hydrocarbon gases. The Suiso Frontier will have a capacity of 1250 m^3 , which translates to roughly 75 tons of hydrogen.

Solution set 3

The method of storing hydrogen as liquid formic acid could be a significant step towards a cost-efficient high-scale hydrogen storage method. The use of formic acid could potentially improve energy density and efficiency. And compared to other chemical-based hydrides such as ammonia, formic acid have the lowest storage capacity.

Since formic acid has similar characteristics to oil products, it can be transported as a liquid without the need for cooling. This would make the transportation and distribution of formic acid easy as oil product tankers can be used.

Solution set 4

Its high volumetric hydrogen density, low storage pressure, and stability for long-term storage are some of the beneficial characteristics of ammonia. The infrastructure when it comes to production, transportation, and distribution is quite large for ammonia being the second most used chemical product in the world. Furthermore, ammonia can be stored at 25°C and around 10 bar in a standardized steel tank which is already used for LPG storage. This means that the transportation and distribution of ammonia can be done using LPG tankers. An LPG tanker with a fully refrigerated storage technique and with a capacity of 40 000m^3 can supply the demand of 30 000 households.

5.7 Evaluation using different criteria

The solutions have been established and further work would be to start the selection process. The evaluation of design concepts is a vital phase of the development process due to its influence concerning cost, quality, and performance of the end product. As mentioned in section 4.8, the different system performance criteria that will be used to evaluate the solutions against each other are:

- Cost
- Availability
- Flexibility
- Safety
- Feasibility
- Emission

The AHP method is one of many mathematical models that supports the decision theory. Its essence is to construct a matrix expressing the relative values of a set of attributes. It contains three parts: the ultimate goal or problem you're trying to solve, all of the possible solutions, called alternatives, and the criteria you will judge the alternatives on. Firstly, the performance criterias needs to be compared to each other in terms of level of importance. These judgments will be assigned a number using the table below(adapted from Saaty[67]):

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgmenet slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed.

Table 5.7.1: Importance table used for AHP

The judgments have been performed using experience and logic. The pairwise comparison matrix also called the Overall Preference Matrix(OPM) is shown below.

	Cost	Availability	Flexibility	Safety
Cost	1,00	3,00	3,00	0,20
Availability	0,30	1,00	1,00	0,20
Flexibility	0,33	1,00	1,00	0,20
Safety	5,00	5,00	5,00	1,00
Feasibility	3,00	3,00	3,00	0,20
Emission	3,00	3,00	3,00	0,20

Figure 5.7.1: The criteria ranked up against each other

Notice that safety is the main priority compared to the other criteria. Feasibility and emission are two criteria that play a major role in the concept evaluation. These concepts are all renewable, which means the focus on emission and feasibility should be high.

The next step is the calculation of a list of the relative weights or values of the criteria. This is a list of the eigenvectors for the criteria, also called Relative Value Vector (RVV).

Attribute	w
Cost	0,094
Availability	0,053
Flexibility	0,054
Safety	0,469
Feasability	0,135
Emission	0,195
Sum	1

Figure 5.7.2: Relative Value Vector showing the weight of the criteria

The third step is to make a pairwise comparison of the concepts concerning the criteria as shown in figure 5.7.3. As mentioned before, the judgments are based on research(section 3) and logic. For instance, looking at the flexibility criteria, concept 4 is considerably better than concept 1. Concept 4 can be used as a production and transportation system during the summer and switch to solely being used as a transportation carrier in the winter. While concept one containing pipelines doesn't have that flexibility.

Costs

	C.1	C.2	C.3	C.4
C.1	1	0,2	0,33	0,14
C.2	5	1	2	0,2
C.3	3	0,5	1	0,14
C.4	7	5	7	1

Safety

	C.1	C.2	C.3	C.4
C.1	1	2	2	2
C.2	0,5	1	0,5	0,5
C.3	0,5	1	1	1
C.4	0,5	2	2	1

Availability

	C.1	C.2	C.3	C.4
C.1	1	2	3	2
C.2	0,5	1	2	1
C.3	0,33	0,5	1	0,2
C.4	0,5	1	5	1

Feasibility

	C.1	C.2	C.3	C.4
C.1	1	2	4	0,33
C.2	0,5	1	2	0,33
C.3	0,25	0,5	1	0,143
C.4	3	3	7	1

Flexibility

	C.1	C.2	C.3	C.4
C.1	1	0,14	0,33	0,11
C.2	7	1	5	0,14
C.3	3	0,2	1	0,2
C.4	9	7	5	1

Emission

	C.1	C.2	C.3	C.4
C.1	1	2	2	2
C.2	0,5	1	2	0,5
C.3	0,5	0,5	1	0,33
C.4	0,5	2	3	1

Figure 5.7.3: Pairwise comparison of concepts with respect to criteria

The fourth stage is to calculate the Consistency Ratio to measure how consistent the judgments have been relative to large samples of random judgments. This means that if the CR is greater than 0.1, the judgments are untrustworthy due to being too random and the process is valueless and must be repeated. The CR for this case is all lower than 0.1. This can be seen in appendix 9.6 where a detailed calculation of these processes can be seen.

The fifth stage is to construct a matrix of the eigenvectors for the four different concepts. This matrix is called the Option Performance Matrix(OPM). The matrix is used to summarize the respective capability of the four concepts in terms of what the customer requirement is.

	Cost	Availability	Flexibility	Safety	Feasability	Emission
C.1	0,220	0,410	0,041	0,391	0,177	0,384
C.2	0,194	0,220	0,227	0,138	0,294	0,192
C.3	0,110	0,094	0,090	0,195	0,069	0,123
C.4	0,645	0,277	0,643	0,276	0,460	0,301

Figure 5.7.4: Option Performance Matrix

The matrix is useful when looking at how the different concepts are compared to each other concerning each criterion. For instance, safety, which is a critical criterion, shows that concept 1 is better compared to the other concepts. This makes sense since pipelines are slightly safer than offloading and transporting using vessels. While feasibility favors concepts 2 and 4, which is logical.

The final stage is to calculate the Value For Money(VFM) vector using the formula 5.7.1. The vector is used to yield a final value of the different concepts when taking all the criteria and their weight into consideration. The result shows which solution gives the most value for money. It can also be explained as VFM = performance · requirement.

$$VFM = OPM \cdot RVV \tag{5.7.1}$$

	Weighted ranking
C.1	0,33
C.2	0,19
C.3	0,14
C.4	0,36

Figure 5.7.5: Most Value For Money vector

Using the Analytical Hierarchy Process, concept 4 is shown as the best overall and most viable concept compared to the other concepts. This means that the concept that will be focused on in the next section will be producing hydrogen using electrolysis and storing that hydrogen as ammonia. It will be offloaded and transported using an LPG carrier. It is also worth mentioning that concept 4 is not twice as good as concept 3 even though the value of concept 4 is much higher. The VFM simply says that something is relatively better than others at meeting some objectives.

Strength and weakness of the AHP

The process is an effortless mathematical tool of problem-solving that is used in project management and decision-making. Although the process is a viable concept selection method, it does have its drawbacks.

Advantages	Disadvantages
- Has the ability to rank choices in the order of their effectiveness in meeting conflicting objectives. - Provides a simple and flexible model for a given problem. - Has a very wide range of usage spanning from planning to risk analysis. - The main focus of the problem can be evaluated from different aspects. - The use of computer software makes the process much faster and more precise.	- It is possible to manipulate judgments to get some predetermined results. - Only works if the matrices are all of the same mathematical forms. - Increased number of criteria and solutions leads to an increase in pair comparisons so that building the AHP model takes much more time and effort. - The process can't handle uncertainty

Table 5.7.2: Advantages and disadvantages of the AHP

To summarize, the process is a useful method for decision-making. It is effortless and the calculations are not complex even though it relies on complex mathematics. It should be noted though, that the process only shows the relative value for money.

Chapter 6

Concept development

6.1 Topside

The most important components for the production were found in section 5.4.1. In this subsection, a more detailed description of the electrolyzer will be given. Additionally, an overview of the interaction between the main components and the ammonia production will be presented.

Electrolyser

Using PEM technology is the most promising technology with its efficient production of hydrogen from renewable energy sources. NEL Hydrogen is a company that delivers solutions to produce, store and distribute hydrogen. One of those solutions is the M Series Electrolysers. The M5000 electrolyzer is a flexible and viable solution for high daily hydrogen production and can produce 5000 Nm^3/h or 10 798 kg/h[87]. The electrolyzer is flexible and scalable which means that the number of cell stacks and capacity can be increased depending on the demand. This makes the electrolyzer viable for usage for the topside of the vessel. A 3D illustration of the electrolyzer can be seen in figure 6.1.1, and an overview of its components can be seen in table 6.1.1.

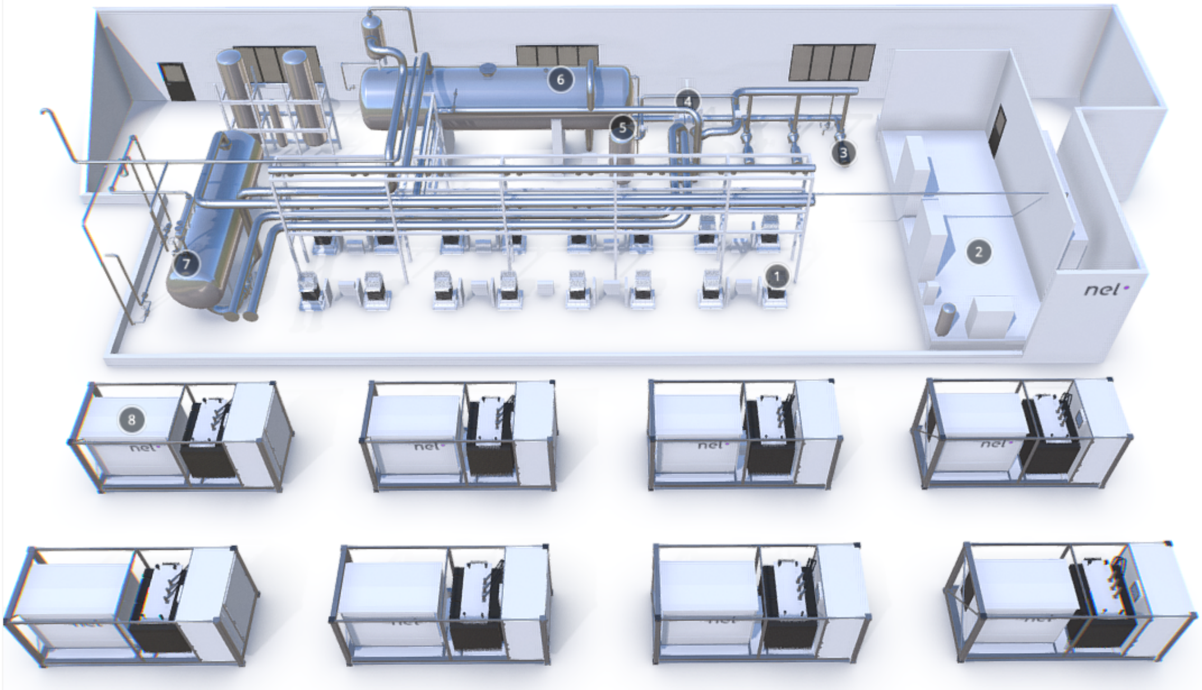


Figure 6.1.1: The M5000 electrolyser by NEL[87]

Number	Components	Description
(1)	Cell stacks	Generates hydrogen and oxygen from water using PEM technology.
(2)	Control room	Provides user interface to control and monitor the unit.
(3)	Circulation pumps	Circulates water through the system.
(4)	Heat exchanger	Removes excess heat from system to ensure proper operation.
(5)	Water polishing bed	Maintains the integrity of water prior to contact with the cell stacks.
(6)	Oxygen phase separator	Separates gaseous oxygen from water exiting the cell stack.
(7)	Hydrogen phase separator	Separates gaseous hydrogen from water exiting the cell stack.
(8)	DC transformers	Convert customer input to AC to DC power for PEM electrolysis and to a standard 240VAC for ancillary electrical components.

Table 6.1.1: Components used for the M5000 electrolyser[87]

Ammonia production

The electrolyzer and its components have been identified. The only thing missing is the components and the flow for the ammonia synthesis process. Figure 6.1.2 shows how ammonia will be produced from seawater. The process has been made using a prior model[89] as a basis.

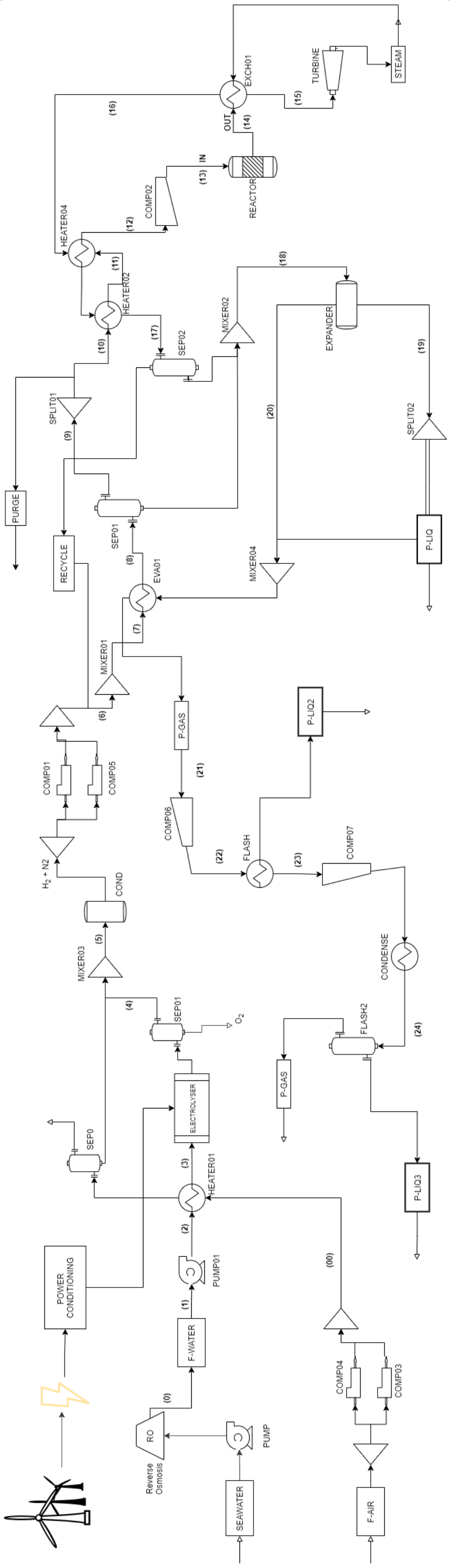


Figure 6.1.2: Set-up of liquid ammonia production system[89]

The components used in the system have been categorized into different sub-systems as shown in table 6.1.2.

Sub-System	Component
Reverse Osmosis	PUMP, RO and PUMP01
Air Separation Unit	COMP03, COMP04, SEP0
Electrolyser	ELECTROLYSER, SEP03
Ammonia Synthesis Loop	COMP05, COMP01, EVA01, SEP01, SEP02, HEATER02, HEATER04, COMP02, REACTOR, EXCH01, EXPANDER
Ammonia Storage	COMP06, COMP07, FLASH, CONDENSE, FLASH2, TURBINE

Table 6.1.2: Components used for the different sub-systems

A detailed system description that explains the different flows and the different principles between each component can be viewed in appendix 9.7. Figure 9.7.1 shows a simplified version of the ammonia synthesis process.

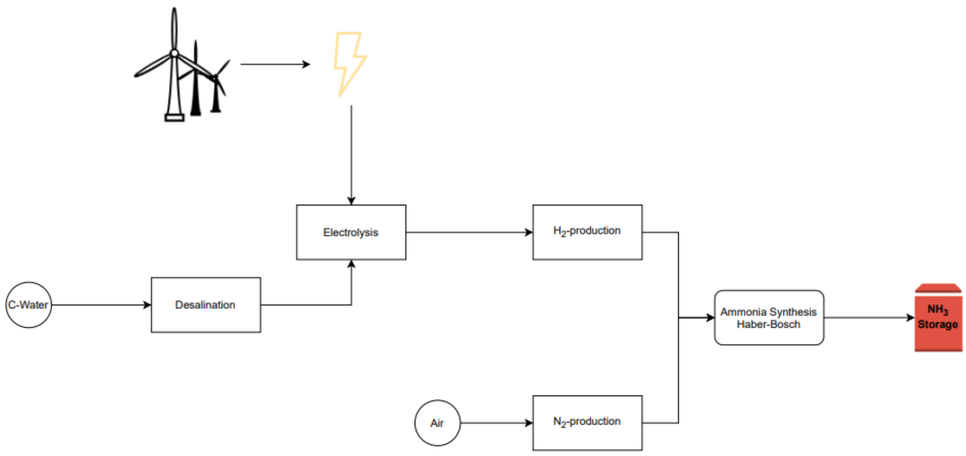


Figure 6.1.3: Simplified set-up of liquid ammonia production system

The diagram is based on the Haber-Bosch process mentioned in section 3.1. The main chemical principles behind the production is[88]:

1. Transport of the reactants from the gas phase through the boundary layer to the surface of the catalyst
2. Pore diffusion to the reaction center
3. Adsorption of reactants
4. Reaction
5. Desorption of product
6. Transport of the product through the pore system back to the surface
7. Transport of the product into the gas phase

6.2 Simulation

The purpose of the simulation is to simulate a roundtrip between the production facility and ports. The offshore wind farm that will produce ammonia is Hornsea P1[81], and it is assumed that all produced energy is utilized for ammonia production. The FPSO will have storage tanks for the produced ammonia. The ammonia will be offloaded to LPG carriers, and it is assumed that the carriers must fill up their capacity before leaving to the deposit's location. The location will be outside of Rotterdam. The simulation will not take anything else beyond this point into consideration. The simulation is set to a timestamp of 6 months, from 01.04 until 01.09 because of the low demand in this period. MathWorks Simevents was used to simulate the concept. An overview of the model can be seen in the figure below.

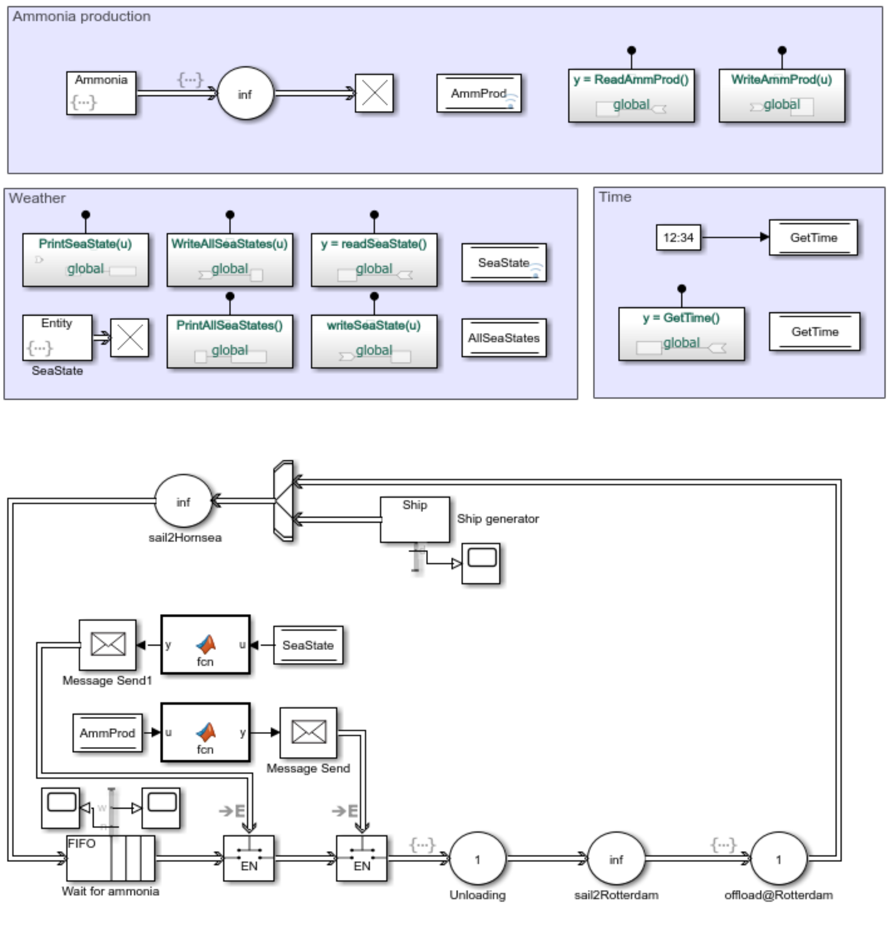


Figure 6.2.1: Overview of the simulation model

Production

The wind speed is estimated using weather forecasts from windfinder[82]. The average wind speed from April-September was between 8.5-13 m/s. Since the model will simulate over a long period of time, the average wind speed was set as an interval between 8-13 m/s. This means that the model will use a wind speed between that interval each hour and use the wind speed to estimate the amount of ammonia produced each hour. The power capacity for a turbine at a given wind speed was calculated using equation 6.2.1[83], where C_p is the power coefficient, ρ is the air density, A is the swept area of the turbine blades and V is the wind speed.

$$Power = \frac{1}{2} * C_p * \rho * A * V^3 \tag{6.2.1}$$

The rotor diameter of the turbines at Hornsea is 155 meters, and there is a total number of 174 turbines at the site[81]. The amount of produced ammonia per hour was calculated with the estimate of an energy loss of 60%. The energy density of ammonia is 3750 Wh/L, providing a total production rate between 79362 liters and 283915 liters per hour[84].

According to the Royal Academy of Engineering[84], it is normal to have two to four pumps per tank, with a pumping capacity of 1200-2000m^3/hr. Given that the ship will likely be of a smaller size, two pumps are assumed to be used in the offloading process at the site and Rotterdam. Assuming a capacity of 1500 m^3/hr each. 1500 m^3 is equivalent to 1500000 liters, meaning a total loading capacity of 3000000 liters per hour. One hour was added to the port time to account for berthing and unberthing of the carrier, as well as the preparations of offloading process[85].

Operational limit

The ammonia production facility is located close to Hornsea offshore wind park outside the west coast of the United Kingdom. The weather condition in the North Sea region can be extreme and is therefore essential in an operational investigation of ammonia production offshore. A loading operation is very weather sensitive and therefore an operational limit is required. Waves, wind, and currents are factors that will have a high influence if the operation will be performed or not. In this project, only the significant wave height will be considered for the operational limit as this is the most critical weather parameter.

The estimated weather forecast is based on historical data. Weather data from 2017 to 2019 of the Hornsea wind farm location are used to simulate weather calculations. The data file includes data measurements of every third hour over the three-year period and correlating significant wave height. With this and a modified Markov Chain file, a wave forecast can be made. The Markov Chain file is a stochastic model that describes a sequence of possible events, where the probability distribution of the next state depends only on the current state. The number of sea states from the historical data is then divided into a set. By doing this, the range of each sea state can be set and the occurrence of several sea states can be measured. Since wave was of interest in this project, the occurrence of the waves was calculated and the operational limit could be set.

The operational limit of the round trip will be the strictest at the unloading station at Hornsea. Any significant wave height above 4 meters is assumed to result in an unsafe loading operation. The ships travel to the Hornsea site, and will only be allowed to load ammonia if there is enough ammonia in the tank to do so and the wave height is acceptable

Capacity

As mentioned before, the time period that is simulated is 6 months. To have a high economical efficiency when it comes to leasing the carriers for offloading, it is assumed that the total number of offloading should be somewhere between 4-6 in this period. This means that the capacity for the LPG carrier should be between 20-25 million liters of ammonia(20-25 000 m^3). Handy Gas Carriers are LPG carriers that range between 15-25 000 cbm. It is a diverse segment that includes semi-refrigerated, fully-refrigerated, and some larger, pressurized ships that can carry ammonia[86]. For this particular case, the storage capacity for the LPG carrier is assumed to be 25 million liters of ammonia(25 000 cbm). The capacity of the production facility is assumed to be 20% higher - 30 000 cbm.

Results

With the ammonia production, weather constraints, and capacities set, the only things that are missing are to configure the sailing speed and sailing distance for the carrier. The speed is assumed to be 12 knots and the sailing distance from Hornsea P1 to Rotterdam is set to be 260 km.

Figure 6.2.2 shows the ammonia production and the offloading process. The total number of offloading, in this case, is 29 times and happens every 140-150 hours(around every 6-7 days). It is worth mentioning that this amount of ammonia produced is when the conditions are optimal. Parameters such as energy production, weather conditions, efficiency, and such need to be optimal to be able to produce this high amount of ammonia. The production facility will never be able to produce this much, but the simulation shows the interaction between the production and offloading processes.

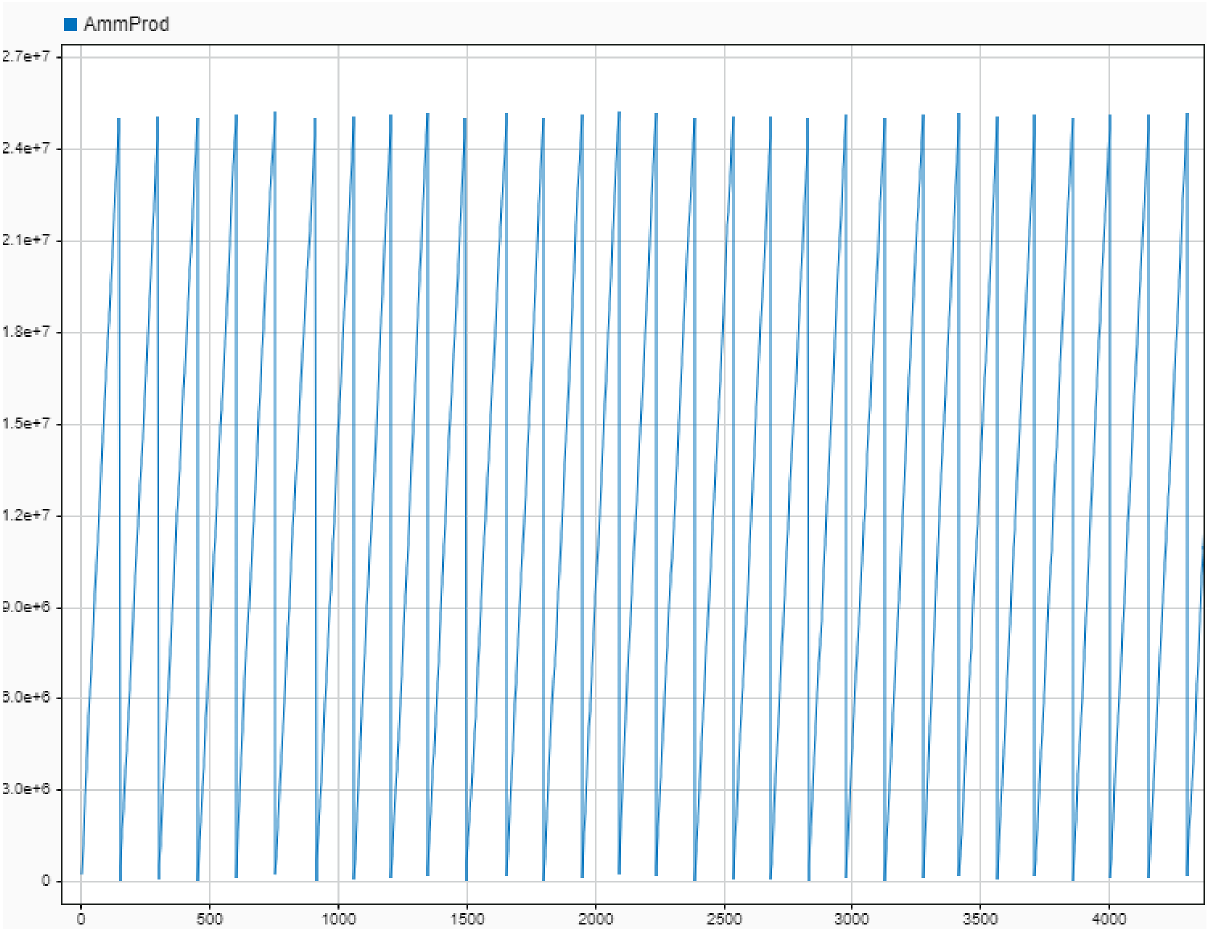


Figure 6.2.2: The correlation between production and offloading

Chapter 7

Discussion

With the increasing global population in the next couple of decades, the need for energy and electricity will be high. The question to be answered is if renewable energy can meet the demand and play a key role in the decarbonization of our energy system in the upcoming decades. offshore wind energy is the fastest-growing renewable power segment with an annual increase of 28%. Several forecast projects that the total global installed capacity will reach 300 GW in the next couple of years. Even though the levelized cost of energy is slightly high at the moment, the future of offshore wind energy will continue to develop regarding efficiency, power, technology, cost, and structure. With new changes and bigger investments, wind can become a leader within the renewable industry.

The wind doesn't always blow nor is it always optimal. By introducing hydrogen as the link used as a storage medium to supply energy during high demand the source becomes more viable. The same goes for using excess energy from wind farms to produce hydrogen. With the increased interest in renewables these past years and the declining costs for renewable electricity, interest in electrolytic hydrogen is growing. And in the maritime sector, that are aiming for a greener segment, hydrogen is receiving more attention than before. Long-haul transport requires a battery capacity that cannot be achieved with the current technology. Hydrogen is, therefore, highlights as one of the possibles to make the maritime sector emission-free.

After converting electricity to hydrogen, storing it, and shipping it, then converting back to electricity in a fuel cell, the energy output can be as low as 30% of what the initial energy input was. This makes hydrogen more ”expensive” than other energy storage methods. But with every new regulation, the economical aspect needs to be put aside. As long as CO2 emissions are valued, efficiency can be largely a matter of economics. This makes hydrogen a viable source towards a carbon-free world.

The aim is to produce green hydrogen and to achieve this, electrolysis is used to achieve a zero-emission production method. The electrolyzer that could be used have their advantages and disadvantages, but PEM(Polymer Electrolyte Membrane) is considered the most promising technology. Emitting only hydrogen as a byproduct and having high efficiency and pure production of hydrogen. This was used as the basis for the production method. The next big question that needed to be answered was in which chemical form should the hydrogen be stored as, and how should the product be transported from the production site to the deposit location. These were answered by developing a conceptual design for the problem based on methodology by Pahl et al. (2007, Chapter 6).

The methodology starts by identifying the stakeholders and finding the need or the potential of this case. The stakeholder analysis shows in this case that the shipowner/investor has the highest importance. The shipowner could be big energy companies like Equinor, Exxon, Shell, and so on. But it could also be big electricity companies like Statkraft, Enel, and E-on. These companies can be willing to invest in such a concept to achieve greener power generation. Furthermore, the companies could also use the electricity when the demand is low to produce hydrogen and use that as the link for storage to supply energy during high demand. Based on the analysis, system performance criteria were established. The criteria were established according to influence level.

When it comes to the potential there was a clear distinction when comparing the daily revenue plot from electricity and the daily revenue from hydrogen. Both assets are dependent on energy production, so one can make a case for OK predictability for both assets. The difference is that the revenue from electricity also depends on the spot prices. The spot prices vary a lot, and there is a significant difference when comparing prices in November - February with April-August. On the other hand, even though the daily revenue from hydrogen is significant, the cost of materials, production, storage, transportation, and systems will also be significant. It should be noted that these parameters have not been taken into consideration. The electricity spot prices with any surcharges have also not been taken into consideration. Even though this is a simplified analysis, such a system's clear use and potential are shown.

In section 5.5, compatibility and a morphological catalog were created to get an overview of the different parameters, principles, and functions. The morphological catalog can be seen in the appendix 9.4 and can be used to combine different solutions to create various solutions that are compatible with each other. In section 5.6, four various compatible solutions sets were gathered and selected using the morphological catalog. These were selected due to being the most compatible solution sets. Using the Analytical Hierarchy Process(AHP), the solutions were evaluated against each other using several criteria. Rank Order Centroids(ROC) is another concept selection method that can be used to turn preferences and rankings between attributes into numerical weight and scores. But the AHP method is a simple method of making complex decisions based on mathematics and psychology. Furthermore, the method has the ability to rank choices in the order of their effectiveness in meeting conflicting objectives, and using computer software such as EXCEL, makes the process much faster and more precise. On the other hand, it is possible to manipulate judgments to get some predetermined results which can be a major disadvantage. Using the Analytical Hierarchy Process, the best overall and most viable concept was shown as the concept of producing ammonia and using an LPG carrier to transport the product. This makes sense due to its feasibility and the established infrastructure mentioned in section 3.2.2. The drawback is first and foremost the production efficiency and the energy loss when converting the energy from hydrogen to ammonia. But, there is a huge potential to use ammonia without great environmental impact or technical obstacles. A proposed model of the production process was established in addition to descriptions of the chemical principles behind the sub-processes. This model should be modeled in Aspen HYSYS, a chemical process simulator to simulate and optimize the design as a possible start for further work.

Chapter 8

Conclusion

The main objective of this thesis was to develop a conceptual design of floating hydrogen production, storage, and offloading facility. A floating hydrogen production and storage system is fairly new and there are several limitations regarding the design and feasibility. Findings from the market analysis of wind energy and hydrogen were promising. Both industries are highly rated and hydrogen demand will grow as the installed capacity of wind farms will increase. Furthermore, the stakeholder and need analysis showed that there is a potential in using excess energy from offshore wind farms between May-August where the demand is significantly lower than the winter period. Utilizing the excess energy during this period is a promising solution. Additionally, for passenger cars, electric-powered vehicles appear to be the preferred technology, but in heavy-duty vehicles and the maritime sector, hydrogen and ammonia are more viable options for achieving emission-free transport. It takes a long time to charge a lithium-ion battery of several hundred kilowatt-hours while refueling a hydrogen or ammonia tank can be done in minutes. Furthermore, long-haul transport requires a battery capacity that cannot be achieved with the current technology. One of the major advantages of storing hydrogen via ammonia is that it can be stored in a liquid state at 25°C and around 10bar in standard steel tanks which are used for liquified petroleum gas(LPG). This means that the potential to use ammonia without great environmental impact or technical obstacles is promising.

There are several ways to design and develop this kind of system. While the production method and technology are fairly new, it is safe to say that using electrolysis will be the most robust when it comes to producing green hydrogen as free of emission as possible. The storage and distribution methods differ more. Final solution variants were obtained using the morphological catalog and were selected using the Analytical Hierarchy Method. The resulting solution variant for this case was found to be:

- A floating facility that utilizes renewables to produce hydrogen. The produced hydrogen will be stored as ammonia and transported using LPG carriers.

The solution contains technical and design parameters that fulfill the functions and requirements set at the beginning of this thesis.

Further work

The next natural step for further work is embodiment design. This means taking the concept into the embodiment design phase, where layout, auxiliary functions, arrangements, and such are found. But another possible route is to model the process in HYSYS and perform a simulation to evaluate the energy equilibrium and to get an overview and compare how much energy is produced compared to the amount of energy used in the system. When the model is simulated and all the necessary components are found, then the top side of the FPSO is basically done and a comprehensive and structured systems facility has been designed. The next step would then be to perform a life cycle cost analysis to estimate the overall costs of the project and the system. Additionally, the analysis can be used to select the design that ensures the facility will provide the lowest overall cost.

Chapter 9

Appendix

9.1 Characteristics of electrolyser summarised

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
Operating pressure (bar)	1–30			30–80			1		
Operating temperature (°C)	60–80			50–80			650 – 1 000		
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000	60 000 – 90 000	100 000 – 150 000	10 000 – 30 000	40 000 – 60 000	75 000 – 100 00
Load range (%, relative to nominal load)	10–110			0–160			20–100		
Plant footprint (m^2/kW_e)	0.095			0.048					
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
CAPEX (USD/kW_e)	500 – 1400	400 – 850	200 – 700	1 100 – 1 800	650 – 1 500	200 – 900	2 800 – 5 600	800 – 2 800	500 – 1 000

Figure 9.1.1: Characteristics of PEM, AE and SOE[24]

9.2 Properties of hydrogen and other energy carriers

	Boiling point (°C 1 bar)	***Density (kg/m³)***	***Specific energy LHV (MJ/kg)***	***Specific energy LHV (kWh/kg)***	***Energy density (MJ/m³)***	***Storage temp/pressure***	***Chemical comp.***
Hydrogen	-253	0,089	120	33,3	10,8		H_2
Hydrogen compressed		23 (350 bar)	120	33,3	5 040	Ambient 200-1000 bar	
Hydrogen liquid		71	120	33,3	8 500	Cryogenic Atm./Low pressure	
MGO	175-650	890	42,7	11,97	38 000	Ambient atmospheric	Hydro-carbon
LNG	-162	440	50	12,50	22 000	Cryogenic Atm./Low pressure	Mainly CH_4
LPG	-42	490	46,4	12,90	22 740	Amb. or Cryogenic/ Atm.	C_3H_8
Liquid ammonia	-33,3	653,1	18,6	5,17	14 100	Ambient High/Atm. pressure	NH_3
Methanol	65	780	20	5,56	36 700	Ambient Atm.	CH_3OH
Biodiesel	>130	875	37,27	11,80	32 375	Ambient Atm.	

Figure 9.2.1: Properties of hydrogen and other energy carriers[58]

9.3 Selected properties between LH2 and ammonia

		Liquid hydrogen	Ammonia
Process and technology maturity*	Conversion	Small scale: High Large scale: Low	High
	Tank storage	High	High
	Transport	Ship: Low Pipeline: High Truck: High	Ship: High Pipeline: High Truck: High
	Reconversion	High	Medium
	Supply chain integration	Medium/high	High

	Liquid hydrogen	Ammonia
Hazards**	Flammable; no smell or flame visibility	Flammable; acute toxicity; precursor to air pollution; corrosive
Conversion and reconversion energy required***	Current: 25–35% Potential: 18%	Conversion: 7–18% Reconversion: < 20%
Technology improvements and scale-up needs	Production plant efficiency; boil-off management	Integration with flexible electrolysers; improved conversion efficiency; H_2 purification

Figure 9.3.1: Properties of LH2 and ammonia[24]

9.4 Morphological catalogue

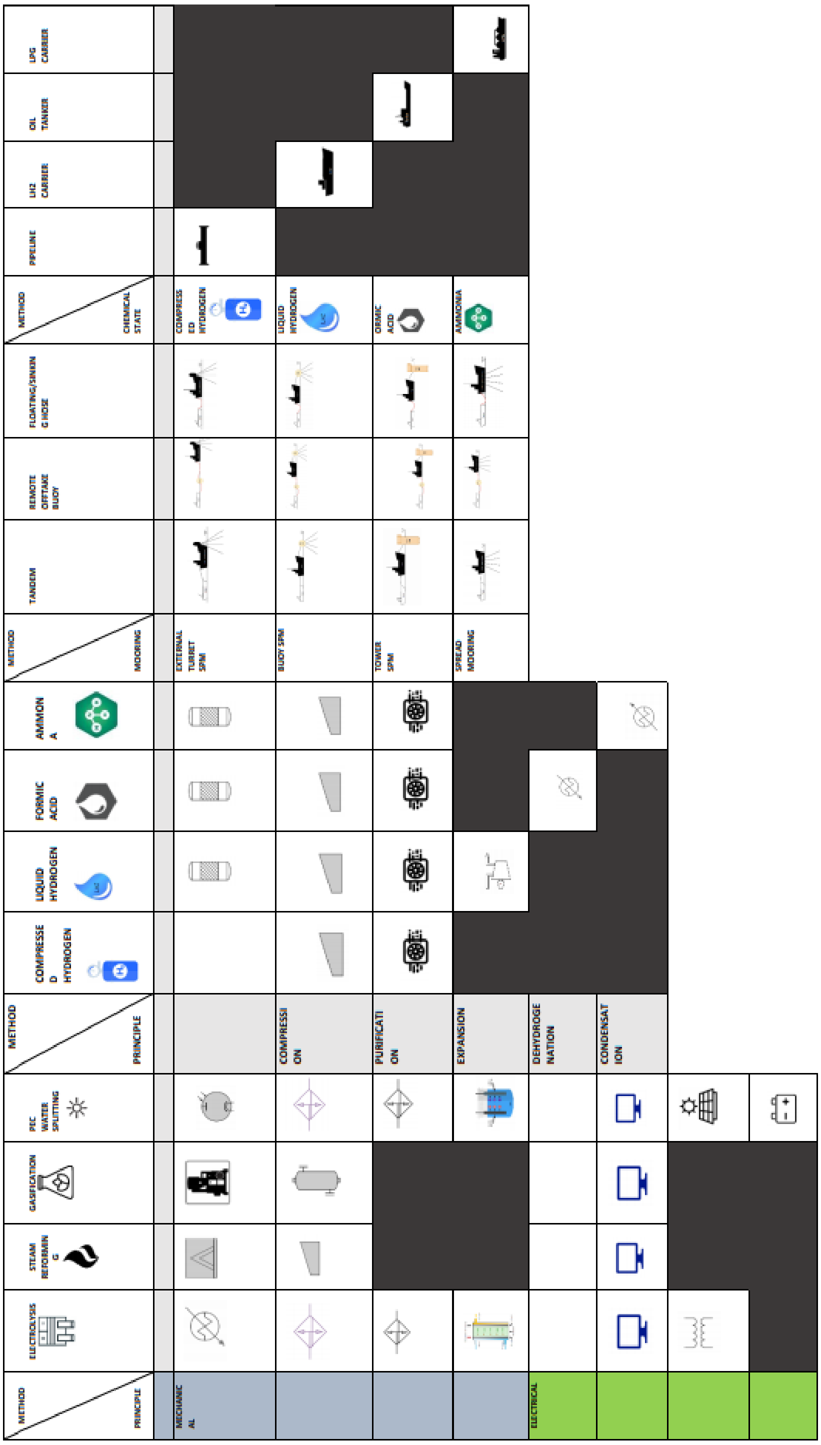


Figure 9.4.1: Morphological catalogue

9.5 Solution set

SOLUTION SET \ MF	PRODUCTION	STORAGE	OFFLOADING	TRANSPORTATION
1	Hydrogen will be produced using electrolysis as production method.	The produced hydrogen will be stored as compressed hydrogen using high pressure tanks.	The compressed hydrogen will directly be offloaded to pipelines before transportation.	The compressed hydrogen will be transported using pipelines.
2	Hydrogen will be produced using electrolysis as production method.	The produced hydrogen will be stored as liquid hydrogen using specialized hydrogen tank.	The liquid hydrogen will be offloaded to LH2 carrier using the floating/sinking hose method. The FPSO will be moored using either external/internal turret SPM or spread mooring depending on the location.	The liquid hydrogen will be transported to the deposit's location using a LH2 carrier.
3	Hydrogen will be produced using electrolysis as production method.	The produced hydrogen will be stored as formic acid using storage tanks for oil.	The formic acid will be offloaded to oil tanker using the floating/sinking hose method. The FPSO will be moored using either external/internal turret SPM or spread mooring depending on the location.	The formic acid will be transported to the deposit's location using an oil tanker.
4	Hydrogen will be produced using electrolysis as production method.	The produced hydrogen will be stored as ammonia using LPG tanks.	The ammonia will be offloaded to LPG carrier using the floating/sinking hose method. The FPSO will be moored using either external/internal turret SPM or spread mooring depending on the location.	The ammonia will be transported to the deposit's location using an LPG carrier.

Figure 9.5.1: Solution set that fulfills the overall function

9.6 AHP

Costs						nth root	w		row	λmax	CI	CR	CR < 0,1
	C.1	C.2	C.3	C.4		0,31004019	0,050556772		0,216087	4,274153	0,058446	0,06494	OK
C.1	1	0,2	0,33	0,14		1,18920712	0,193918321		0,796503	4,107415			
C.2	5	1	2	0,2		0,67694724	0,110386551		0,449335	4,070563			
C.3	3	0,5	1	0,14		3,956321	0,645138356		2,741333	4,249218			
C.4	7	5	7	1	sum	6,13251555	1,000000000	mean		4,175337			

Availability						nth root	w		row	λmax	CI	CR	CR < 0,1
	C.1	C.2	C.3	C.4		1,8612097	0,409519892		1,68426	4,112766	0,048966	0,054406	OK
C.1	1	2	3	2		1,0000000	0,220028881		0,88902	4,040468			
C.2	0,5	1	2	1		0,4262148	0,093779557		0,39427	4,20422			
C.3	0,33	0,5	1	0,2		1,2574334	0,276671671		1,170358	4,230134			
C.4	0,5	1	5	1	sum	4,54485791	1,000000000	mean		4,146897			

Flexibility						nth root	w		row	λmax	CI	CR	CR < 0,1
	C.1	C.2	C.3	C.4		0,2669984	0,040724282		0,172802	4,243226	0,159409	0,177122	OK
C.1	1	0,14	0,33	0,11		1,4878153	0,226930981		1,05082	4,630572			
C.2	7	1	5	0,14		0,58856619	0,089771831		0,385845	4,298068			
C.3	3	0,2	1	0,2		4,21286593	0,642572906		3,046467	4,741046			
C.4	9	7	5	1	sum	6,55624582	1,000000000	mean		4,478228			

Safety						nth root	w		row	λmax	CI	CR	CR < 0,1
	C.1	C.2	C.3	C.4		1,68179283	0,390524292		1,609476	4,12132	0,04044	0,044933	OK
C.1	1	2	2	2		0,59460356	0,138071187		0,569036	4,12132			
C.2	0,5	1	0,5	0,5		0,84089642	0,195262146		0,804738	4,12132			
C.3	0,5	1	1	1		1,18920712	0,276142375		1,138071	4,12132			
C.4	0,5	2	2	1	sum	4,30649992	1,000000000	mean		4,12132			

Feasibility						nth root	w		row	λmax	CI	CR	CR < 0,1
	C.1	C.2	C.3	C.4		1,27467944	0,24439896		0,993724	4,065992	0,015089	0,016766	OK
C.1	1	2	4	0,33		0,75792893	0,145320491		0,585991	4,032403			
C.2	0,5	1	2	0,33		0,36564658	0,070106758		0,281112	4,009765			
C.3	0,25	0,5	1	0,143		2,81731325	0,540173791		2,200079	4,07291			
C.4	3	3	7	1	sum	5,2155682	1,000000000	mean		4,045268			

Emission						nth root	w		row	λmax	CI	CR	CR < 0,1
	C.1	C.2	C.3	C.4		1,68179283	0,384436156		1,615564	4,202424	0,046837	0,052041	OK
C.1	1	2	2	2		0,84089642	0,192218078		0,779871	4,057222			
C.2	0,5	1	2	0,5		0,53593669	0,122508216		0,510112	4,163898			
C.3	0,5	0,5	1	0,33		1,31607401	0,30083755		1,245016	4,138501			
C.4	0,5	2	3	1	sum	4,37469995	1,000000000	mean		4,140511			

Figure 9.6.1: Overview of the AHP method and the Consistency Ratio(CR)

9.7 Ammonia production description

Number	Description
(00)	The cryogenic distilliation unit is two reciprocating compressors rated at 85% efficiency.
(0)	Seawater is used to make fresh water using reverse osmosis.
(1)	Water is compressed in a centrifugal pump rated to 72% efficiency.
(2)	The water is heated in a heat exchanger to 30 bar and 80°C.
(3)	The water is used to produce hydrogen utilizing the electrolyser.
(4)	The hydrogen and nitrogen gas are mixed adiabatically.
(5)	The gases are flashed at 30 bar and 20°C to remove traces of water.
(6)	The produced gases are compressed in two multistage inter-cooled compressors rated at 83% efficiency and 250 bar.
(7)	The compressed gas is adiabatically mixed.
(8)	To remove residual ammonia from the reactor, the gases are fed into a heat exchanger and fed into a separator.
(9)	Part of the residual ammonia liquefies at 0°C and is separated from the gases.
(10)	The reactant gas is preheated to 550°C using hot product gas from the reactor using heat exchangers in series.
(11)	The reactant gas is preheated to 550°C using hot product gas from the reactor using heat exchangers in series.
(12)	The gas stream is compressed back to 250 bar.
(13)	The reactor is considered to be at equilibrium under the conditions of 550°C and a pressure of 250 bar.
(14)	During the conditions of the reactor, heat fluxes are generated and is captured by the heat exchanger to generate steam.
(15)	The produced steam is used to run a steam turbine at 90% polytropic efficiency.
(16)	The reactant gas is preheated to 550°C using hot product gas from the reactor using heat exchangers in series.
(17)	The cooled products are separated at 250 bar.
(18)	The liquid streams from SEP02 and SEP01 are mixed and fed to an adiabatic flash drum operating at atm pressure.
(19)	The liquid is directed into a storage tank.
(20)	The gases are mixed with a small amount of liquid ammonia to make up a cold gas inlet stream for the heat exchanger.
(21)	The hot outlet gas is compressed to a pressure of 3 bars.
(22)	The gas flows into a flash tank where it is cooled. An amount of liquid ammonia is stored to the storage tank.
(23)	A second compressor compresses the gas to 13 bars to allow for cooling in a downstream air-cooled condenser.
(24)	The condensed ammonia expands upon entry and separates into a liquid and a vapor.

Table 9.7.1: Description of the process of ammonia production[89]

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