Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Green Ammonia Production for Maritime Transport

Grønn Ammoniakkproduksjon for Maritim Transport

Bachelor's thesis in Engineering, Renewable Energy
Supervisor: Kristian Myklebust Lien
Co-supervisor: Zohreh Jalili, NTE
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Preface

This thesis acts as the final assignment for the bachelor's program: Bachelor in Engineering, Renewable Energy, under the Department of Energy and Process Engineering at Norwegian University of Science and Technology (NTNU). This thesis is a work made complete through the cooperation of its authors and the Norwegian company Nord-Trøndelag Elektrisitetsverk (NTE).

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Abstract

Ammonia has gained interest as an alternative carbon-free fuel to use in the maritime sector, as a result of the worldwide commitment to reduce greenhouse gas emissions. This thesis aims to assert the technological and economic aspects of green ammonia production. The objective of this thesis is also to investigate whether green ammonia is a suitable marine fuel, both in regard to sustainability and from a business perspective.

Different technologies and solutions linked to green ammonia production are presented theoretically before different aspects of ammonia as a fuel are discussed. Key facets include main challenges like its toxicity and safety considerations. The promising prospect ammonia holds in regard to infrastructure is assessed. Ways to upscale and incorporate ammonia as a green fuel into the maritime market are also evaluated.

To concretize green ammonia production, a case study is performed. This is limited to an envisioned production plant located in Nærøysund in Norway, where the plant is scaled on the basis of a hydrogen production of 8.3 tonnes per day. Of the currently available technology, an alkaline electrolyzer, a PSA unit, a Haber-Bosch unit, and a refrigerated storage system were found to be the optimal components for the production facility.

Calculations of NPV and LCOA were done to investigate the economic feasibility of the production plant. Through a defined baseline scenario, the case study was found to make a small profit at the end of its 15-year lifetime. If the current price level of ammonia proves to be maintained, larger profits are expected.

Sensitivity analyses were carried out to illustrate a broader scope of the economic case since several of the key factors are hard to predict. The price of ammonia, price of energy, and number of operational days proved to be very decisive for the final outcome. A very high ammonia price would result in a great profit, however, this is most likely not sustainable for the market. The LCOA benefits from a lower price of renewable energy, which luckily is available at the production plant.

The thesis concludes that green ammonia is a viable alternative as a carbon-free marine fuel, provided that the main challenges are overcome. Furthermore, green production at small-scale is both feasible and sustainable.

Sammendrag

På grunn av den verdensomspennende forpliktelsen om å redusere klimagassutslipp har ammoniakk fått oppmerksomhet som et karbonfritt drivstoff til bruk i maritim sektor. Denne oppgaven har som formål å ta for seg ammoniakkproduksjon fra et teknologisk- og økonomisk perspektiv. Hensikten med oppgaven er videre å undersøke om grønn ammoniakk er passende som et drivstoff både med hensyn på bærekraft og fra et forretningsperspektiv.

Forskjellige teknologier og løsninger knyttet til grønn ammoniakkproduksjon er presentert teoretisk før forskjellige aspekter med ammoniakk som et drivstoff diskuteres. Hovedpoenger inkluderer større utfordringer som dets giftighet og sikkerhetshensyn. Det lovende potensialet ammoniakk har med tanke på infrastruktur er evaluert. I tillegg er måter å oppskalere og innlemme ammoniakk som et grønt drivstoff i det maritime markedet gjort rede for.

For å konkretisere grønn ammoniakkproduksjon, er det gjennomført en situasjonsspesifikk studie om et forestilt produksjonsanlegg i Nærøysund. Dette anlegget er skalert med et utgangspunkt om hydrogenproduksjon på 8.3 tonn per dag. Med dagens tilgjengelige teknologi, ble det kommet fram til at optimale komponenter for anlegget innebærer en alkalisk elektrolysør, en PSA, Haber-Bosch-prosess, og nedkjølte lagertanker som lagringssystem.

Beregninger av NNV (netto nåverdi) og LCOA ble gjort for å undersøke den økonomiske gjennomførbarheten til produksjonsanlegget. Gjennom et definert basis-scenario hadde anlegget en liten profitt etter anleggets levetid på 15 år. Dersom dagens prisnivå på ammoniakk opprettholdes, er det derimot forventet større profitt.

Sensitivitetsanalyser ble gjennomført for å gi et bredere omfang av den økonomiske analysen. Dette ble gjort med bakgrunn av at flere viktige faktorer kan være vanskelige å forutse, slik som ammoniakkpris, energipris og antall produksjonsdager, som alle viste seg å være veldig avgjørende for lønnsomheten. En veldig høy ammoniakkpris vil resultere i god fortjeneste, men dette er sannsynligvis ikke bærekraftig for markedet. LCOA-verdien synker i tråd med synkende grønn energipris, noe som heldigvis er tilgjengelig i området til produksjonsanlegget.

Oppgaven konkluderer med at grønn ammoniakk er levedyktig som et karbonfritt alternativt drivstoff for maritim sektor, forutsatt at hovedutfordringene løses. Videre så er grønn småskala-produksjon både gjennomførbart og bærekraftig.

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Abbreviations

AEC - Alkaline electrolysis cell

ASU - Air separation unit

CAPEX - Capital expenditure

CMS - Carbon molecular sieve

EUR - Euro

GHG - Greenhouse gases

GWP - Global warming potential

IDLH - Immediately dangerous to life or health

IMO - International maritime organization

LCOA - Levelized cost of ammonia

LNG - Liquefied natural gas

MEA - Membrane electrode assembly

MNOK - Million Norwegian krone

NOK - Norwegian krone

NPV - Net present value

OPEX - Operating expense

PEM - Proton exchange membrane

PEMEC - Proton exchange membrane electrolysis cell

ppm - parts per million

PSA - Pressure swing adsorption

SCR - Selective catalytic reduction

SOEC - Solid oxide electrolysis cell

USD - United States dollar

VBA - Visual basic for applications

VPSA - Vacuum pressure swing adsorption

VSA - Vacuum swing adsorption

Chemical formulas

CH_4 - Methane

CO_2 - Carbon dioxide

KOH - Potassium hydroxide

N_2O - Nitrous oxide

NaOH - Sodium hydroxide

NH_3 - Ammonia

NO - Nitric oxide

NO_2 - Nitrogen dioxide

NO_x - Nitrogen oxides

O_3 - Ozone

Glossary of terms

Ammonia slip - Unreacted ammonia passing through a combustion engine

Baseline scenario - The scenario that serves as a reference for the calculations of the case study. This acts as the basis for the sensitivity analyses

Bond dissociation - The bond dissociation is the measurement of the strength binding a chemical bond

Bunkering - The act of supplying fuel to ships

Cracking - Decomposition of larger molecules into smaller molecules

Cryogenic - Operating value pertaining to a very low temperature

Emission Control Areas - Sea areas with stricter emission regulations. The areas are defined by the MARPOL Annex VI convention

Exothermic reaction - A reaction where the change of enthalpy is negative. Releases energy to its surroundings

Global Warming Potential - Measurement of the impact a gas has on global warming, in relation to 1 tonne of CO_2

High sea ships - Large ships traveling across international waters

Industrial symbiosis - When a byproduct from one industry can be used by another industry

Inert gas - A gas that does not react

MARPOL - International Convention for the Prevention of Pollution from Ships

Material margin - A margin between revenue and the raw material cost

Permeable - Being of a porous nature, such that liquid or gas may penetrate it

Symbols

A_t - Total ammonia produced for a given year, t

i - Discount rate

I_t - Investment for a given year, t

n - The total period of the calculation

O_t - Operational cost for a given year, t

R_t - Total cash flow for a given year, t

Software

Software	**Version**	**Use**
Excel	16.0.2204	Calculations and data visualization
MATLAB	9.6.0.1472908	Data visualization
Microsoft VBA	7.1.1119	Calculations
Python	3.10.4	Calculations

1 Introduction

There has been an unprecedented interest in green and climate-friendly solutions in the last decades. World-encompassing rules governing emissions and climate measures have been born from the Kyoto protocol and later the Paris agreement. It is clear that every individual and every business will need to conform if they wish to stay relevant when the green transition comes into full force. This is true for the maritime sector as well. [1, 2]

The International Maritime Organization (IMO) is a United Nations specialized agency responsible for setting the rules and regulations governing pollution from ships (MARPOL), as well as the safety and security of shipping. In 2020, the IMO enacted regulations to reduce ship pollution, which were targeted towards sulfur emissions but not greenhouse gases (GHG) as a whole [3]. This is set to change in the coming years as new regulations limiting all GHG emissions emerge. Alternative green fuel options are therefore imperative if the maritime transport sector is to achieve sustainable development. [4]

1.1 A brief overview of ammonia

Ammonia (NH_3) is one of the world's most produced chemical compounds. It is primarily used as a fertilizer, either directly or as the foundation for fertilizer synthesis. The first commercialized ammonia production method was the Haber-Bosch method. Although it was discovered over a century ago, the Haber-Bosch method continues to be used for the vast majority of ammonia production. 45% of global food production today relies on ammonia fertilizers, so the conception of the Haber-Bosch method can easily be said to be one of the world's greatest inventions. Approximately 85% of all manufactured ammonia is used for fertilizers. The rest is used in a wide array of applications, such as water treatment, cooling agents, explosives, and cleaning products, to name a few. [5, 6, 7]

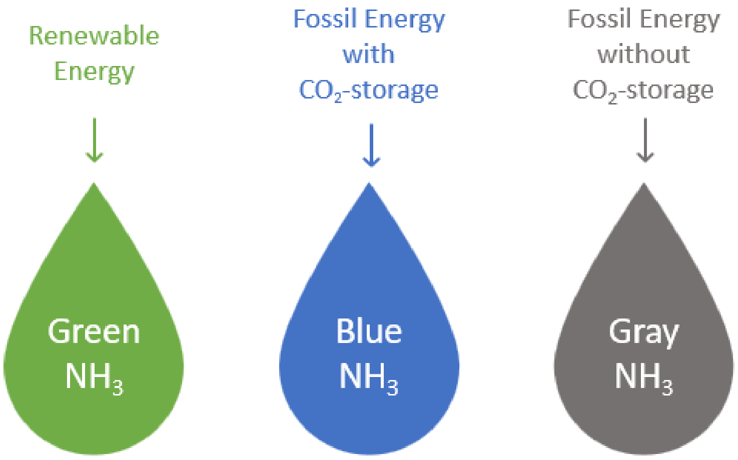

Figure 1.1: The different colour terms of ammonia

Most ammonia produced today is gray ammonia rather than its carbon-free counterpart, green ammonia. As shown in Figure 1.1, the type of ammonia being synthesized depends on the nature of the feedstock utilized for the production. Green ammonia is in this thesis termed by a basis in renewable energy. Gray ammonia on the other hand, is used as a generic term for ammonia based on fossil fuels like natural gas and coal. However, if the CO_2-emissions from fossil-based ammonia are captured and stored, it is labeled blue ammonia. [8]

About 67% of the hydrogen used for ammonia production is derived from natural gas. The remaining 33% stems from coal and oil, while a disproportionate amount, only 0.001%, is produced from renewable electricity, see Figure 1.2. There is currently no blue ammonia being produced other than in small lab-scales. [9]

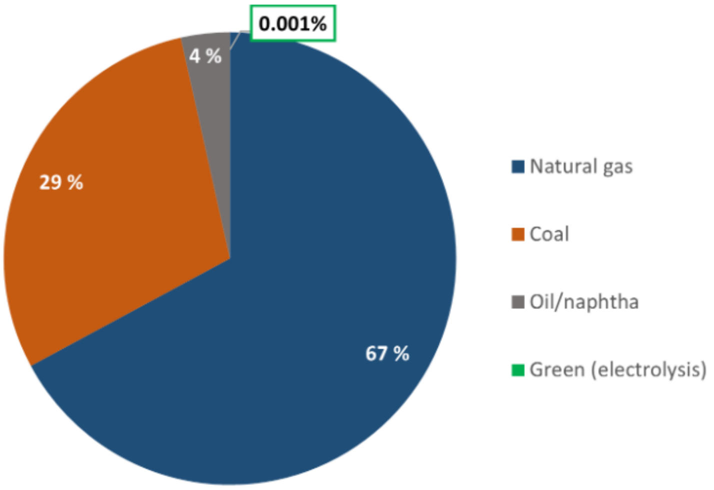

Figure 1.2: Percentages of different feed-stocks used in ammonia production [9]

Ammonia has gained great interest as of late, not as a fertilizer but as an energy carrier. In fact, ammonia is 17.8% hydrogen by weight. Liquid ammonia at 20°C and 8.6 bar reaches a hydrogen density of 108 H_2/m^3, which is 50% higher than that of compressed or liquefied hydrogen. Ammonia is also easier to store than hydrogen. The overall energy density of ammonia is lower than that of conventional carbon-based fuels, as seen in Figure 1.3. However, ammonia has a higher volumetric density than both pressurized and cryogenic hydrogen. The higher volumetric energy makes ammonia more suitable for ships with restrictions on space. Therefore, green ammonia has great potential as an alternative fuel in maritime transport, especially for large ships traveling for months at a time. [10]

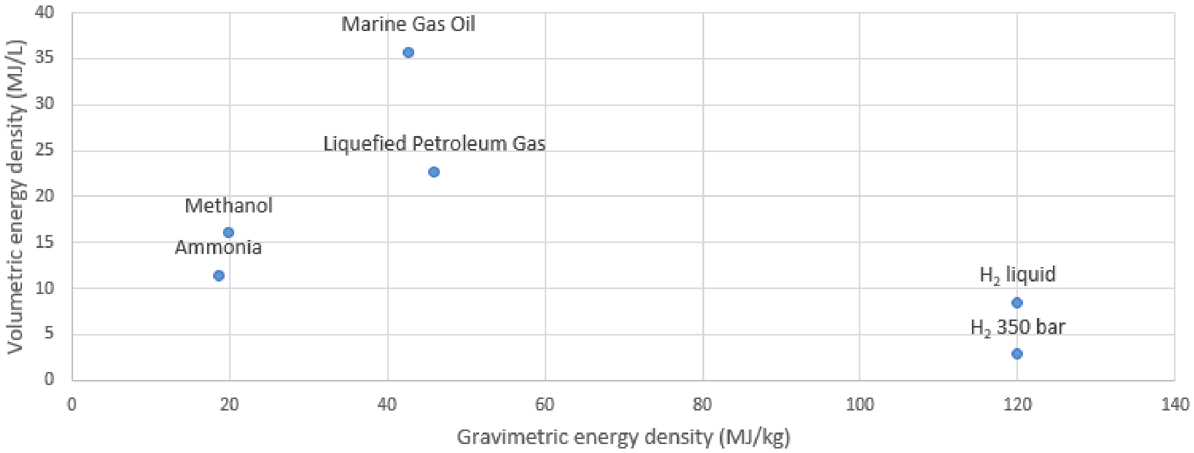

Figure 1.3: Gravimetric and volumetric energy densities of different marine fuel alternatives [11]

It should be noted that the values presented in Figure 1.3 do not consider the mass and space necessary for containment. If the values were to consider these factors, the total picture would show a reduced energy density. This is especially so for hydrogen, as it requires a comprehensive insulation system. [11]

Popular alternatives to the use of ammonia as a propulsion fuel are combustion engines. These types of engines can either be built new or retrofitted from existing engines [8]. Ammonia as a combustion fuel is a research topic that has stayed relevant for several decades. It has, however, not gained much traction until now. This is reflected in the fact that few engines are being produced and sold at the present time [12]. Another option is ammonia fuel cells. However, these lack the required power to be used for large vessels. [13]

1.2 Objective

The main objective of this thesis is to investigate the feasibility of producing green ammonia, including technological and economic aspects as well as safety considerations. The thesis also intends to assert whether ammonia is viable as an alternative green fuel for the maritime sector. This is performed through literary review and a case study.

1.3 Case study

The case will study the possibilities of green ammonia production in Nærøysund, Norway. NTE and partners are already in the building phase of a pilot hydrogen facility at the same location, and as such the case was built upon this pilot and its constraints. Nærøysund was chosen due to its apt location along the Norwegian coastline, making it a suitable port for larger vessels to bunker.

The case study was performed by investigating current and future technologies linked to the production of ammonia. These findings served as the basis for all major equipment choices made. Furthermore, the economic aspects of the production plant were analyzed. This was done by calculating net present values (NPV) and levelized cost of ammonia (LCOA) for the plant, as well as performing sensitivity analyses. Lastly, safety details and other challenges are discussed. The final outlook of the study aims to be a complete review of the technical and economic viability of the production facility.

1.4 Structure of the thesis

Chapter 2 introduces the theoretical background needed to understand the different production routes of green ammonia, from energy to storage. Every major step and the technologies pertaining to them are presented. Chapter 3 will indulge in additional theory linked to the safety and challenges of ammonia as a fuel.

Chapter 4 encompasses discussions on a few different subject matters concerning ammonia as a fuel; a general discussion of the usage, comparisons and the future outlook. Chapter 5 presents a case study for a small-scale green production facility. The focus of this case are technology choices, production simulations and economic calculations. Lastly, recommendations for further work are showcased in Chapter 6.

2 Production process of green ammonia

Green ammonia has its roots in renewable energy, which is used to run an electrolyzer and a separation unit. These units produce hydrogen and nitrogen, respectively. The gases are then run through the Haber-Bosch process, which forms ammonia. These production steps are visually presented in Figure 2.1. Through this chapter, different technologies linked with green ammonia production, including storage, are presented. [14]

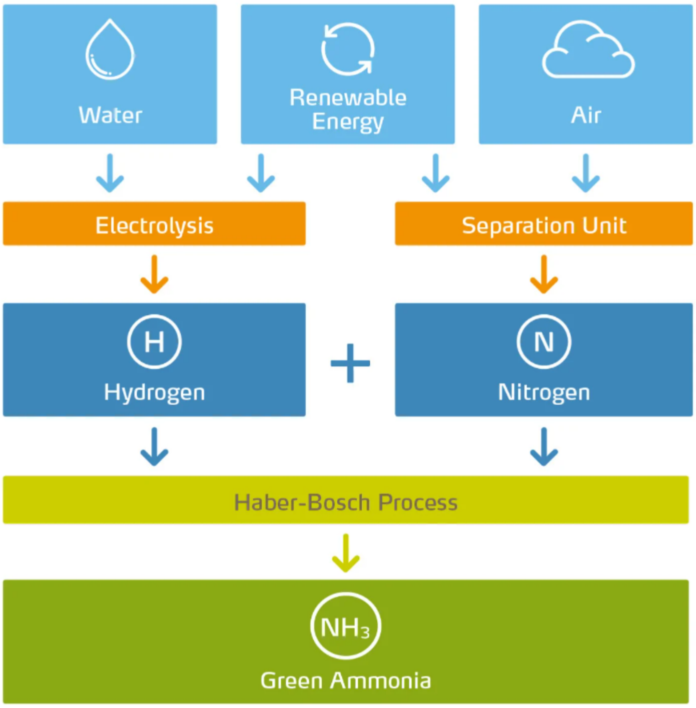

Figure 2.1: Visual presentation of a production route to green ammonia [14]

2.1 Electrolysis

Electrolysis is a non-spontaneous chemical reaction driven by an electric current. This process is commonly used to break down substances into other more desirable substances [15]. In the context of green ammonia production, water electrolysis is essential. Here, water is split into hydrogen and oxygen, as shown in Equation 2.1, and hydrogen plays an important part in ammonia synthesis.

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{2.1}$$

An electrolyzer consists of multiple cells stacked together, usually in series. The most used and known technologies for water electrolysis are alkaline-, proton exchange membrane- and solid oxide electrolyzers. [16]

The efficiency of an electrolyzer is usually defined by the ratio between the electric work put into the process and the work available from the produced hydrogen. [17]

2.1.1 Alkaline Electrolysis Cell

Alkaline electrolysis has been used in commercial production of hydrogen for a long time and is considered a mature technology with a highly consistent hydrogen production rate. The alkaline electrolysis cell (AEC) consists of a diaphragm and two electrodes submerged in a liquid electrolyte, often either NaOH or KOH. The diaphragm separates the two electrodes, as shown in Figure 2.2. [16, 18]

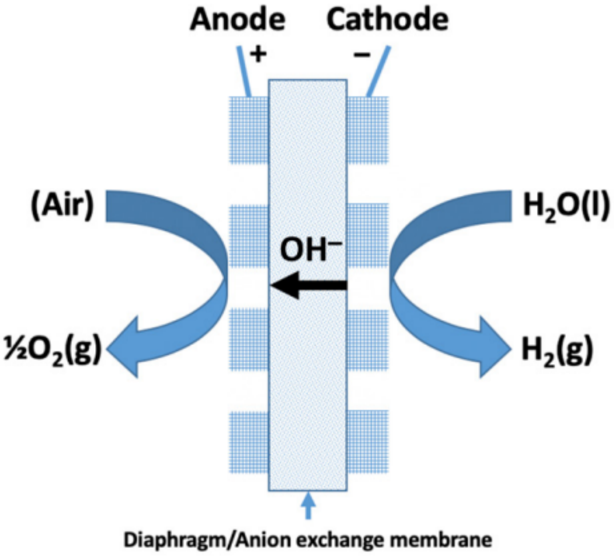

Figure 2.2: Visual description of an alkaline electrolysis cell [16]

The electrodes are usually grids made out of steel, and the diaphragm can be made out of polymer-based composites [19]. The chemical reactions happening at the anode and cathode in an AEC are presented in Equation 2.2.

$$Anode : 2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \quad , \quad Cathode : 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{2.2}$$

At the cathode in Equation 2.2, one can see that water is reduced, and hydrogen is formed. The hydrogen produced can reach a purity of around 99.9% [16]. To prevent the spontaneous recombination of hydrogen and oxygen, a diaphragm is added, which makes sure that only hydroxide passes through to the anode. Normal operating temperatures for an AEC are between 60 and 80°C.

There are many advantages when it comes to the AEC. As it is a mature technology, the operational costs are well documented and therefore predictable. At the same time, the installation costs are relatively low, as the materials needed are quite cheap. [16]

The efficiency of an alkaline electrolyzer is heavily dependent on the current density, which directly effects the ohmic potential loss. At lower current densities, it can reach an efficiency of up to 80% [20]. However, at higher production rates this is drastically reduced. [17]

2.1.2 Proton Exchange Membrane Electrolysis Cell

Proton exchange membrane (PEM) water electrolysis is considered a safe and efficient way of producing hydrogen from water. The proton exchange membrane electrolysis cell (PEMEC) consists of two thin and porous electrodes containing the catalysts, which are layered on each side of a membrane. This is called the membrane electrode assembly (MEA). The MEA is submerged in pure water, which gives the PEMEC as shown in Figure 2.3. [17, 21]

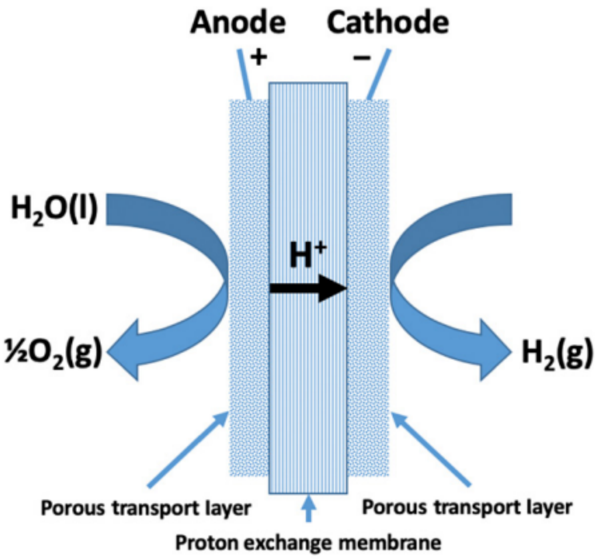

Figure 2.3: Visual description of a proton exchange membrane electrolysis cell [16]

The catalysts in a PEMEC need to be noble metals in order to sustain the acidity levels at the anode and cathode. Platinum group metals are most commonly used. The current collector is made of porous titanium. The most used membrane is Nafion, which is made of perfluorinated phosphonic acid copolymers. This has a structure that allows protons to pass through. The chemical reactions happening at the anode and cathode in a PEMEC are presented in Equation 2.3. [16]

$$Anode: H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \quad , \quad Cathode: 2H^+ + 2e^- \rightarrow H_2 \tag{2.3}$$

It is evident from Equation 2.3 that on the anode, water separates into oxygen and hydrogen-ions. The ions go through the membrane, and hydrogen is generated at the cathode. This process has an operating temperature between 50 and 80°C and the hydrogen produced can reach a purity of up to 99.99%. [16, 21]

PEMEC is an expensive technology, as rare materials are used, especially the catalyst materials. High purity water is another requirement of this technology. However, it is possible to operate the cells with high current densities and high efficiencies. They can reach an efficiency of around 80-90% at low current densities [21], and will not go much lower than 60% at higher current densities. [16, 17]

2.1.3 Solid Oxide Electrolysis Cell

The solid oxide electrolysis cell (SOEC) is considered a promising technology for hydrogen production. However, it is not yet ready for commercial use. The Danish company Haldor Topsoe is planning to have an operational SOEC facility with a capacity of 500MW in 2023 [22]. Figure 2.4 shows the composition of a SOEC. [16]

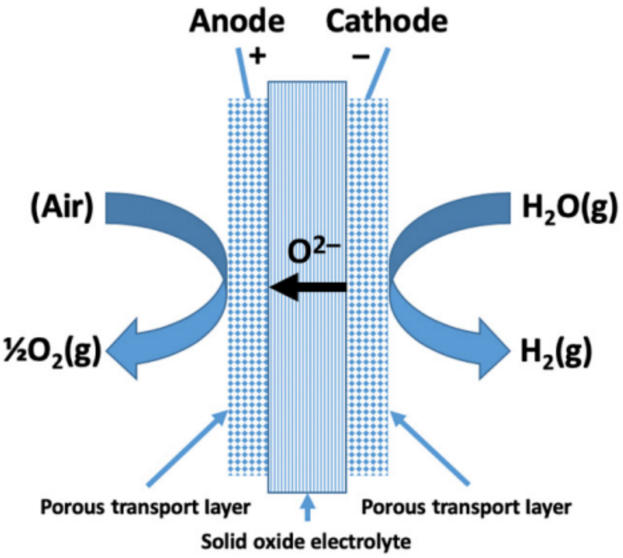

Figure 2.4: Visual description of a solid oxide electrolysis cell [16]

Both the cell separator and the solid electrolyte use oxide-ion conducting ceramics, and the electrolyte is usually zirconia doped with yttrium and scandium oxides. The electrode material at the cathode is typically either nickel or platinum, and the anode usually consists of nickel oxide mixed with the membrane material. The chemical reactions happening in the SOEC are shown in Equation 2.4. [16, 17]

$$Anode : O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^- \quad , \quad Cathode : H_2O + 2e^- \rightarrow H_2 + O^{2-} \tag{2.4}$$

At the cathode, water is reduced and hydrogen is produced. Oxygen ions cross the membrane to the anode, where pure oxygen is produced. This happens at an operating temperature between 600 and 900°C. Therefore, both the reactants and products are in a gaseous phase. The temperature is a big challenge when it comes to materials used, as they have to be able to tolerate both high temperatures and fluctuations in temperature from turning the SOEC on and off. [16, 17, 21]

If the energy efficiency of a SOEC is calculated by only considering the electric work put into the process, it is possible to achieve an efficiency above 100%. This is because one has to consider the heat input in addition to electric work. When doing so, the SOEC can still reach an efficiency of 94%. [17, 21]

2.1.4 Alternative hydrogen production

An alternative way to produce green hydrogen for ammonia synthesis is through thermochemical water decomposition. This is generally achieved by heat from solar towers, or by waste heat from nuclear power plants. The high heat derived from the respective sources is the driving force used to split water into hydrogen and oxygen. [23, 24]

There are, however, underlying issues linked to solar energy and nuclear power. Solar towers are heavily reliant on geography, have a high investment cost, and are arduous to start up and shut down. The biggest problem with nuclear power is the social stigma it bears, making it very troublesome to construct new plants, with the exception of some countries. [25, 26]

2.2 Air separation

Atmospheric air contains three main gases; Nitrogen (N_2), oxygen (O_2), and argon. In dry, clean air, nitrogen-gas takes up about 78.08% of the volume, while oxygen-gas and argon account for 20.95% and 0.94% respectively. There also exists small, but not insignificant amounts of trace gases in the atmosphere; Greenhouse gases of importance include carbon dioxide (CO_2), ozone (O_3), methane (CH_4), and nitrous oxide (N_2O). It is prudent to stop the increase of greenhouse gas concentrations with climate considerations in mind. Today, atmospheric CO_2 has reached a peak value of near 420 ppm, but this is further increasing, at a rapid rate of about 3-9 ppm per year. [27, 28]

In reality, all the mentioned measures will be slightly lower due to the fact that atmospheric air contains humidity. Water vapor is also considered a greenhouse gas, but the concentration varies strongly with the climate. It ranges from close to zero in the coldest parts of the atmosphere, up to 5% by volume in very hot and humid air masses. [29]

As shown in Figure 2.5 other noble gases such as neon, helium, krypton, and xenon exist in very low concentrations.

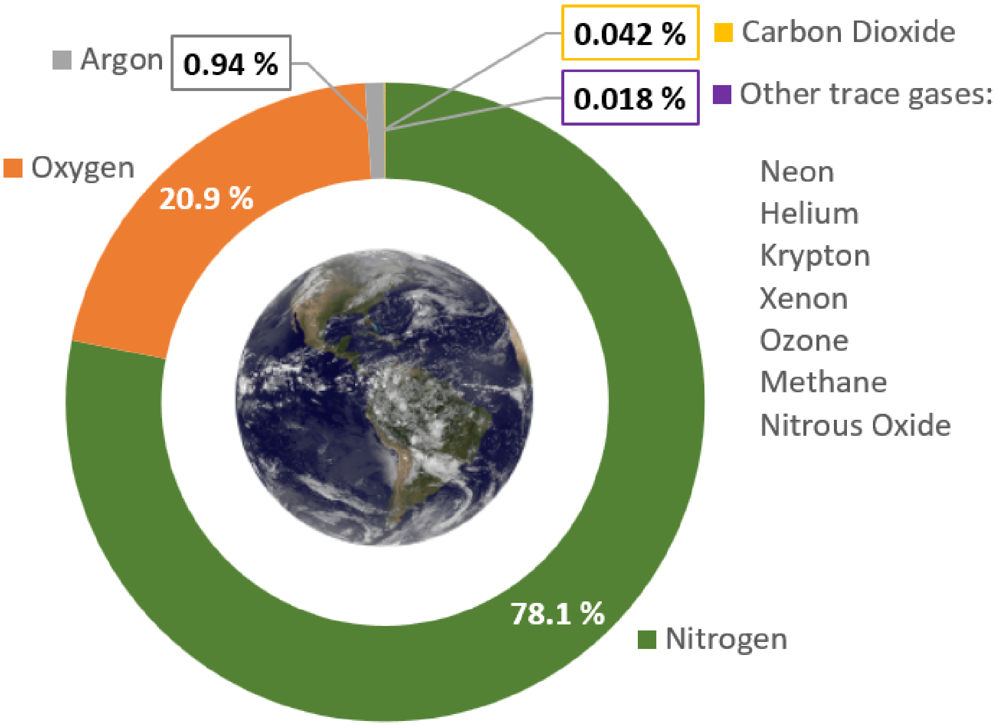

Figure 2.5: Composition of dry atmospheric air [27, 28]

The color- and odor-free nitrogen gas is in other words available in rich amounts. In fact, no other element exists naturally in such large amounts as nitrogen in free state [30]. This is a great advantage for ammonia as an energy carrier. Although it exists in plenitude, separating nitrogen from air can be energy-intensive.

2.2.1 Cryogenic distillation

The most conventional air separation technology is a cryogenic air separation unit, often just referred to as a cryogenic ASU. This unit utilizes the different boiling points that the various gases in air possess. Nitrogen gas condenses and liquefies at 77.4 K or about -195.8°C, while for oxygen the boiling point (condensation point) is 90.2 K or about -183.0°C [31]. The difference of 12.8 K is enough to separate the elements with high purity. The process is called fractional distillation. Cryogenic air separation units designed to produce nitrogen and oxygen will co-produce argon, as its boiling point lies between the two former at 87.3 K. Very large ASUs may also distill small amounts of the rare noble gases in air, but this would require a lot of energy. In fact, producing high purity nitrogen by using ASUs at cryogenic temperatures is also relatively energy-intensive. However, it is capable of handling high flowrate, and thus this technology is most suitable for large-scale production. [32, 33]

2.2.2 Pressure Swing Adsorption

Pressure Swing Adsorption (PSA) is a non-cryogenic technology which separates gases of a mixture. It uses relatively high pressure and chemical affinity to trap selected gases onto solid surfaces, thus the name *adsorption*. *Swing* refers to the utilization of at least two separate vessels; one high-pressure and one low-pressure column alternating back and forth. This concept results in significant energy savings as it effectively recycles the high pressure. For smaller and intermediate-scale plants, PSA can provide relatively low cost nitrogen compared to cryogenic air separation. [34]

To physically separate the nitrogen from air, PSA makes use of an adsorbent material that acts as a molecular sieve. There are different techniques for this matter, but especially two materials are used when separating nitrogen and oxygen. The first one is exploiting equilibrium selectivity by a zeolite which adsorbs N_2 over O_2 by a factor of 3 or more. This makes nitrogen the “heavy” product that stays in the column base, while oxygen is the light and volatile gas.

The other commercialized PSA cycle utilizes a carbon molecular sieve (CMS), which provides differentiation in adsorption kinetics for the two elements. Because the O_2-molecules are slightly smaller than the N_2-molecules, O_2 will diffuse 20-40 times faster than N_2 in CMS adsorbents. In this process, nitrogen acts as the "light" product and will therefore be accessible in a continuous flow through an outlet when pairing columns. [35]

The typical basis of a PSA process consists of a four-step cycle with the mentioned double-columns. This technology was first patented by C.W. Skarstrom in 1960 [36], and the Skarstrom cycle is shown schematic in Figure 2.6.

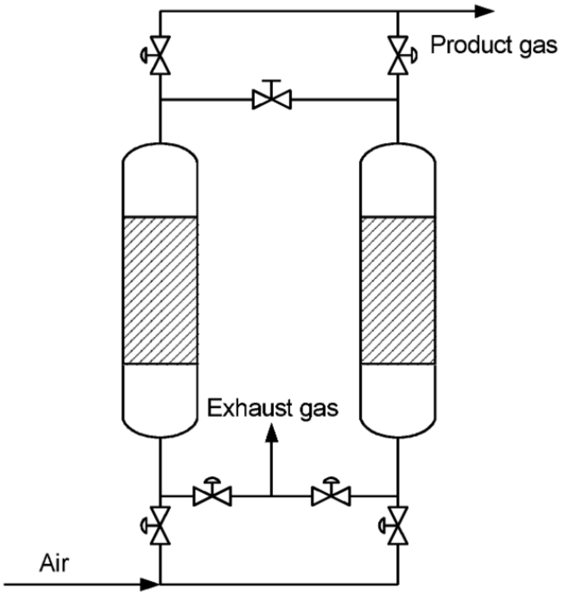

Figure 2.6: Schematic design of a two-column four-step Skarstrom cycle [37]

The four steps in the Skarstrom cycle consist of pressurization, adsorption, blowdown, and purge. Studying the cycle with carbon molecular sieves in the columns which gives nitrogen as the product gas: Dry air is pressurized, typically above 5 bar, and fed into the first column, which produces nitrogen gas as the volatile gas towards the column ceiling. When the adsorbent is saturated and cannot adsorb more oxygen, the valve between the two columns is opened, and the co-product oxygen is released through an exhaust valve. This also allows for natural pressure equalization, thus saving energy for the pressure swing. Subsequently, the flow direction is reversed by a countercurrent blowdown in the first column to further reduce the pressure. The air feed is now directed towards the second column to pressurize and make the second column produce nitrogen. To additionally remove oxygen from the first column, a purge step consisting of recycled parts of the other column is used. All these steps complete a cycle, and then the process is repeated under electronic control systems in order to produce high purity nitrogen continuously. [38, 39]

Although simple in concept, today's practical PSA technology can be fairly complex with several modifications to increase performance and purity. With the inclusion of a multicolumn design using a series of sequential steps, one would be able to control the desired gas purity. This makes PSA a very versatile gas separation technology, which could meet a wide range of purity and flow requirements. However, both the CAPEX and OPEX are directly correlated to the production purity, and the costs rise rapidly at very high purities. A modern PSA-unit with modifications is shown schematically in Figure 2.7. [40]

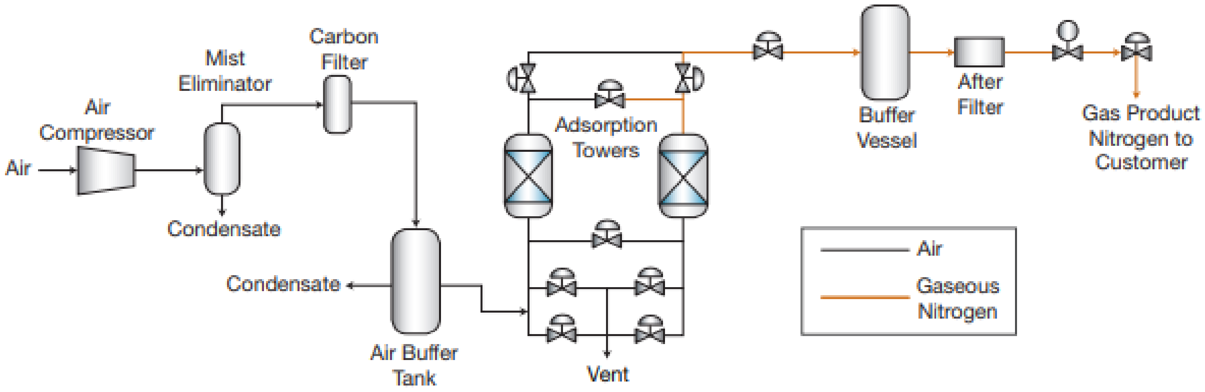

Figure 2.7: A modern PSA-unit that produces close to pure nitrogen [41]

Technologies applying vacuum instead of pressure have also been developed, labeled vacuum swing adsorption (VSA). While this will increase the CAPEX, it may decrease the OPEX by reducing the need for energy-demanding high pressurizing. A vacuum pressure swing adsorption (VPSA) utilizes both vacuum and pressure, and will lead to an even bigger investment, but the efficiency of the unit may be greatly improved if applied correctly. [38]

As a side note, hydrogen production and especially purification is also possible through PSA-technology, due to the element's low polarity and high volatility. However, with today's technology this is not reaching state-of-the-art efficiency as up to 20% of the hydrogen may be lost in the tail gas. [42]

2.2.3 Membrane separation and future technologies

Polymer membranes for gas separation is another emerging non-cryogenic technology for producing nitrogen. This technology utilizes several semi-permeable modules that are more permeable for the air compounds to be eliminated (O_2, H_2O, CO_2), thus leaving a purified steam of N_2 [43, 44]. An air blower can work as the compressor as it supplies enough pressure for the separation, and therefore a membrane process is possible at near ambient conditions [45]. This will lower the energy costs, which is an advantage with this method. A detailed schematic of such a gas permeation system is shown in Figure 2.8.

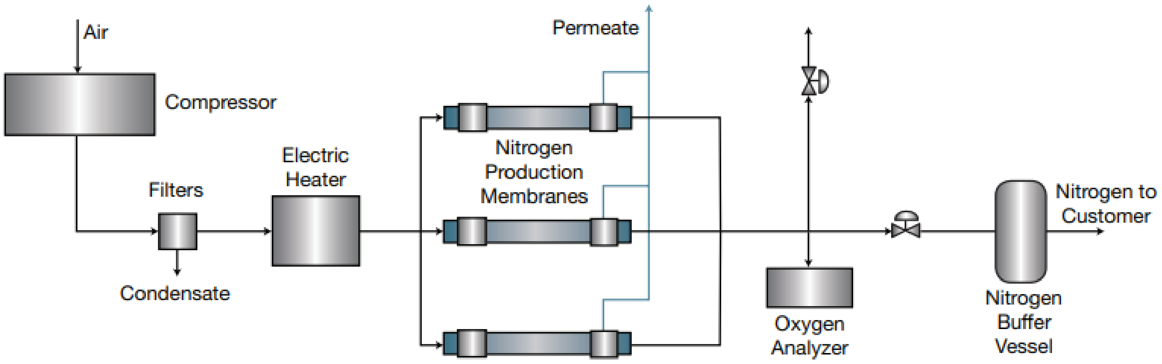

Figure 2.8: Membrane separation process to generate nitrogen gas [41]

Other specific advantages of this technology include ease of operation, compactness, and low maintenance requirements. In addition, a membrane process neither causes waste nor involves chemicals, and can be driven continuously without any regeneration steps. However, the current technology does not generally offer the same high gas purity as its competitors, and the economic viability is limited to lower volume production. [45, 46]

The simplicity of polymer membranes makes them an attractive alternative for small-scale production where very high nitrogen purity is not required. Also, it is the newest mentioned technology for air separation, and the aforementioned advantages have encouraged much interest from industries and academics to speed up the commercial viability of the nitrogen/oxygen-separation via membrane technology. [47]

2.3 Haber-Bosch

The most common way to synthesize ammonia is through Haber-Bosch synthesis. There are other methods to synthesize ammonia, which will be discussed later in this thesis. The biggest concern with the Haber-Bosch method is the sourcing of the feed, namely hydrogen and nitrogen. Currently, ammonia production relies mainly on natural gas, oil, and coal as its feedstock, which can be seen at the top of the power to ammonia map in Figure 2.9. This results in an end product rooted in pollution. [48, 49, 50]

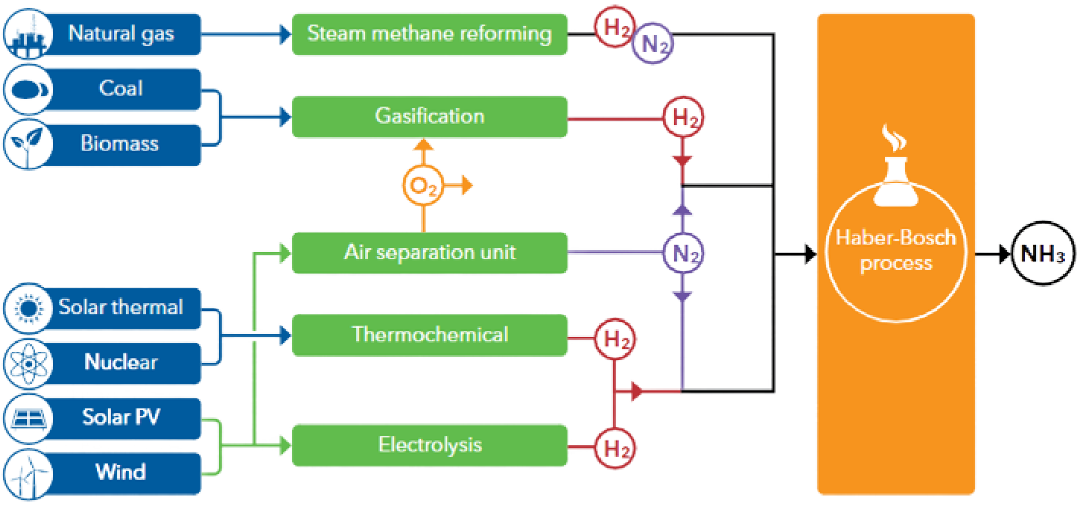

Figure 2.9: Map of some power to ammonia routes [8]

An alternative green energy vector would be to use an electrolyzer and air separation unit powered by renewable energy to source hydrogen and nitrogen, as is showcased in the lower part of the power to ammonia map in Figure 2.9. This thesis focuses primarily on this green option. However, the sourcing of the feed matters little to the Haber-Bosch process itself, as it works more or less in the same way regardless of its feedstock. [49]

Ammonia synthesis is achieved by an exothermic reaction between hydrogen and nitrogen, shown in Equation 2.5. While its intuitive to believe that the reaction is spontaneous, this is not the case. The main reasons for this are the reactants in the formation of ammonia, more specifically the nitrogen molecules. A comparatively large energy input is needed for the nitrogen molecules to reach their activation state, which is apparent when comparing the bond dissociation values of nitrogen and hydrogen, which are 941 kJ/mol and 104 kJ/mol, respectively. [51, 52]

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g), \qquad \Delta H = -92.44kJ/mol \tag{2.5}$$

With purely thermal energy as an input, the temperatures needed to achieve useful reaction rates would lie in the range of 800-1200 K. A catalyst is therefore crucial to lower the total energy required by the system. With the addition of an iron-based catalyst, the activation energy decreases to 103 kJ/mol, and consequently the operational temperature reduces to 250-400°C [51]. Furthermore, the temperature of the system will have a direct link to the outlet ammonia concentration, as is seen in Figure 2.10. [53, 54]

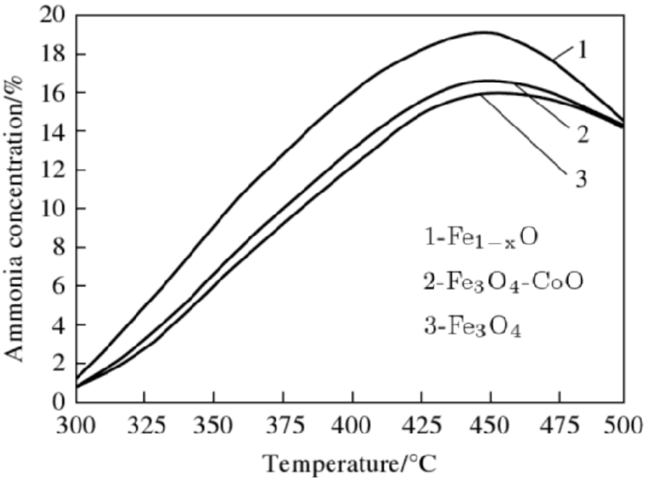

Figure 2.10: Effect of temperature on three iron-based catalysts [55]

Temperature is not the only operational point that should be considered; the pressure of the system is equally important. There will be an immediate increase in the conversion rate with a rise in pressure. This is due to the increase in pressure creating a more preferable ammonia equilibrium and an elevated reaction rate. The effect of pressure in conjunction with an iron-based catalyst can be seen in Figure 2.11. [53, 54]

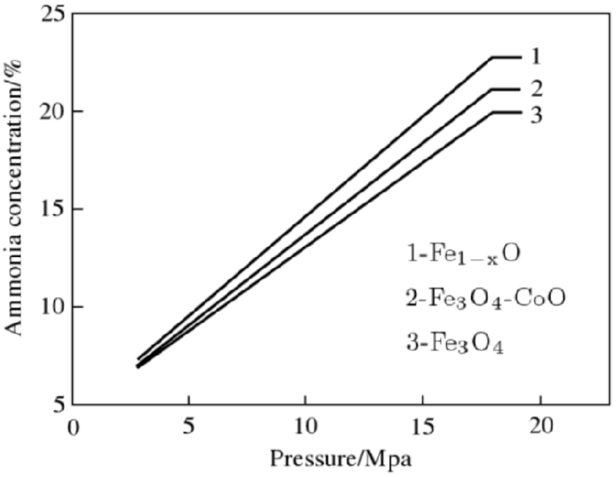

Figure 2.11: Effect of pressure on three iron-based catalysts [55]

Finding the best combination of temperature and pressure to optimize ammonia production is therefore extremely important when designing an ammonia production plant. The general operational range for ammonia synthesis lies at about 350-500°C and 150-300 bar. Safety aspects and practical limitations might, however, limit the final choice for a given production plant. [56, 57, 58]

There are several other factors that can be taken into account when finding the optimal operation points, such as space velocity and catalyst particle size. However, these will not be further addressed as an in-depth analysis on the variable effects in ammonia synthesis lies beyond the scope of this thesis. [59]

2.3.1 Ammonia synthesis loop

A schematic of the ammonia synthesis loop is presented in Figure 2.12. In this case, hydrogen is produced by an electrolyzer while nitrogen is produced by a PSA unit. The hydrogen and nitrogen gases are then mixed and compressed in a compression unit before being fed into the Haber-Bosch reactor. Additionally, the loop consists of a trail of transport pipes, a gas separator (the condenser), a purge outlet, a refrigeration compressor, and a recycle compressor. [49]

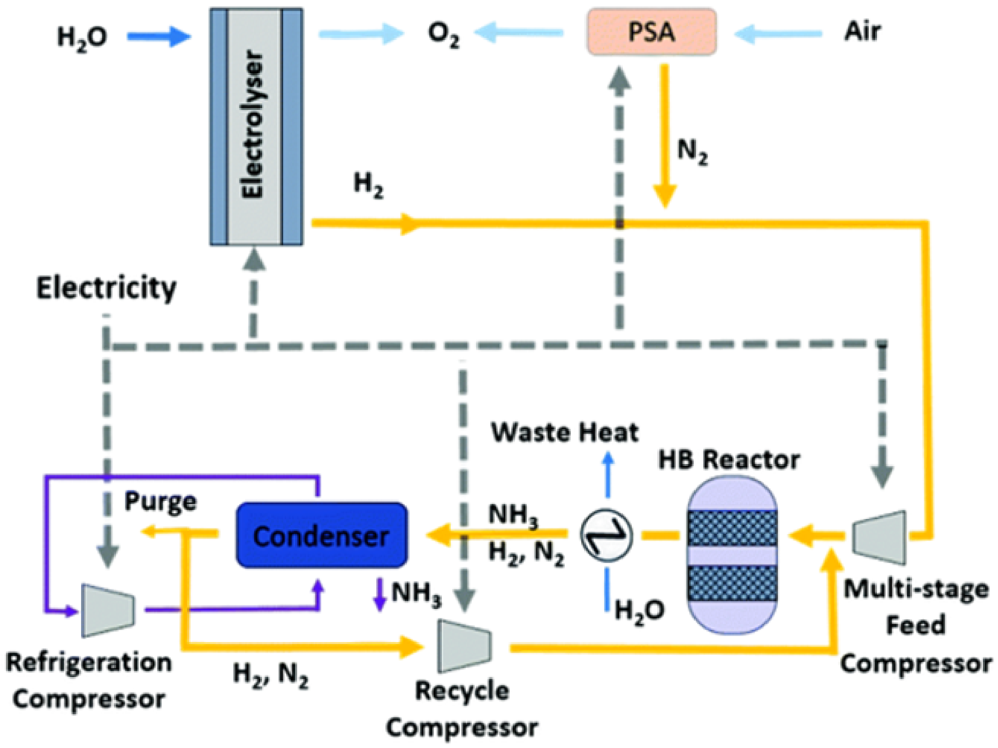

Figure 2.12: Schematic of a Haber-Bosch process with green hydrogen feed [49]

Ammonia is recovered after the feed gases have undergone synthesis in the Haber-Bosch reactor. Here, the resultant synthesis gas is cooled and the ammonia is condensed and separated at synthesis pressure, while the remaining gas is either purged or recycled within the synthesis loop. The pressure of the end product is then lowered by a let-down system to about 20 bar or possibly down to atmospheric pressure for storage in cold tanks, all depending on the plant's desired bunkering specifications. [51]

A main component of the synthesis loop is a recycle compressor. The need for this compressor stems from the low single pass conversion rate of the Haber-Bosch process at about 10-15%. The ammonia that is produced is filtered by condensation, and the remaining hydrogen and nitrogen are recycled to effectively utilize the feed gas. This leads to a final conversion rate of 97-99% [60].

Generally, the feed gas is not pure hydrogen and nitrogen. A small portion of the feed mix will contain inert gases. The main component of these is argon, which has been brought along from the processed air. Initially, the small amounts of argon will not result in any adverse effects, but the total amount accumulates with each recycling loop. This build-up reduces the conversion rate of the system and lowers the overall efficiency. A system for purging the gases is therefore a necessary design implementation. [61, 62]

Removal of the inert gases in the ammonia synthesis loop is achieved by purging a small portion of the recycle stream. The adverse effect of this is the loss of hydrogen, nitrogen, and ammonia, which is the main reason that the final conversion rate of the system does not reach 100%. There are several ways to handle this problem, the first and most obvious one being to pretreat the feed gases before mixing and compression. [49]

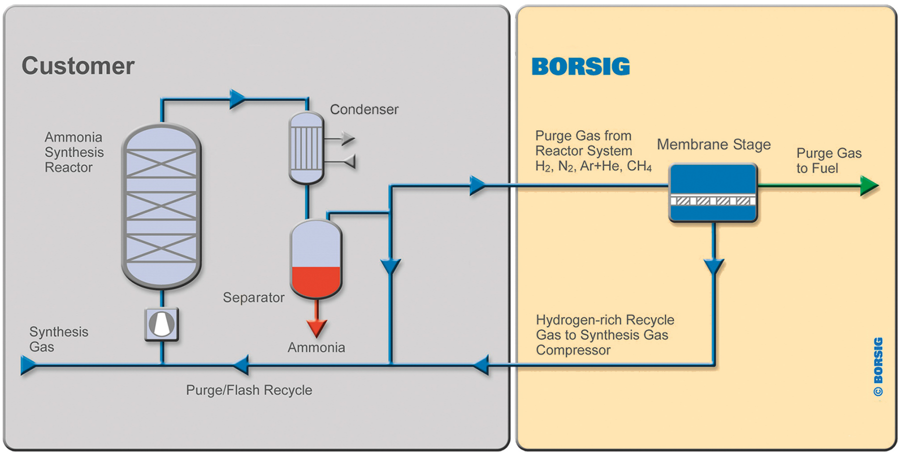

Figure 2.13: Hydrogen separation schematic developed by BORSIG [63]

Alternatively, one could also recover these purge gases and make use of them. A practical example of this is the German company BORSIG. They engage in industrial symbiosis in which they treat the purge gases from a partnering ammonia production plant, as shown in Figure 2.13. On the other hand, the utilization of alternative synthesis routes rather than Haber-Bosch would make the need to remove inert gases completely redundant. [49, 64]

There are two components within the synthesis loop that produce a significant amount of heat, namely the exothermic ammonia synthesis reaction and the compressor cooling. With a synthesis based on electricity as its main energy drive, this heat is generally lost, as there is no way to integrate the waste heat into the process in a conventional production setup. [49]

A possible means of utilizing this waste heat would be to heat buildings in the proximity of the production plant. Another option would be to sell the waste heat to adjacent industries that might be in need of thermal energy at that quality level. [65]

2.3.2 Alternative ammonia synthesis routes

The Haber-Bosch process imposes a high temperature and pressure requirement to successfully synthesize ammonia. This, in addition to the low single pass conversion at the reaction stage, has prompted several researchers to develop less energy-intensive and less costly alternatives. The development of substitute synthesis routes has not seen much progress beyond that of research and small pilot applications. [60, 66]

The limited progress is due to a lack of incentives, owing much to the low costs and abundance of natural gas. Nevertheless, this outlook has changed in the recent decade as the focus on green energy has blossomed. [67]

One of the ammonia synthesis routes being researched the most extensively is direct electrochemical ammonia synthesis. Electrochemical synthesis depends on an external power source to deliver an electrical potential that enacts the synthesis of ammonia. The feedstock used is air and water. Whether nitrogen is separated from air or if the water is treated before the reaction takes place depends on the type of electrochemical synthesis being performed. The three main types are plasma-enabled ammonia synthesis, electrothermochemical looping and N_2 electrolysis. Figure 2.14 shows a schematic of the three technologies. [68, 69]

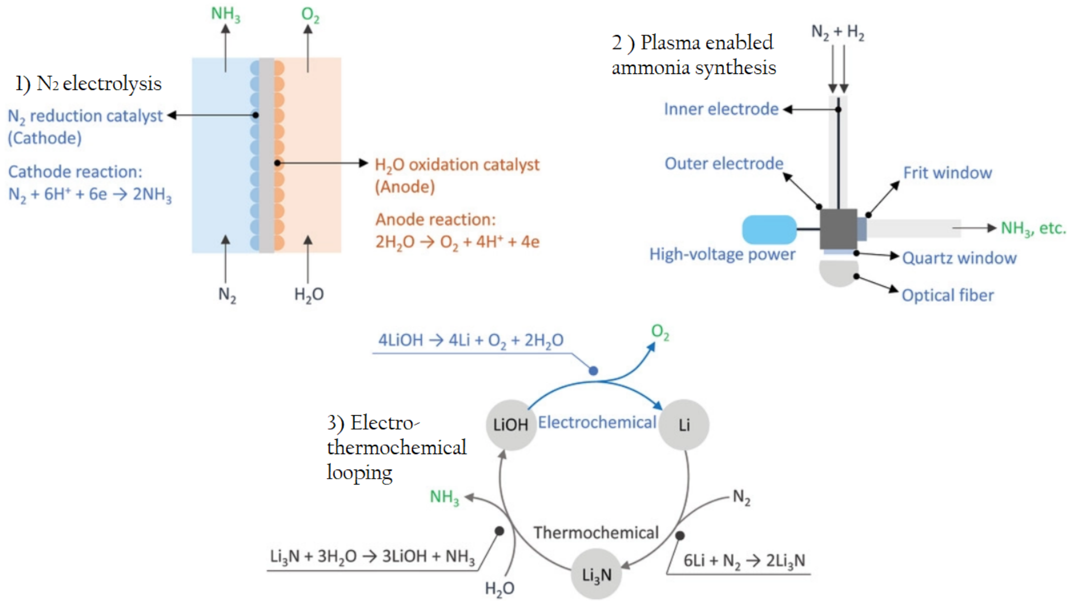

Figure 2.14: Schematic of three key types of electrochemical ammonia synthesis [68]

Electrochemical synthesis operates at a relatively low pressure, ranging from 50 bar to as low as ambient pressure. The temperatures required can be lower as well. For liquid and polymer electrolytes it is close to room temperature, while for solid electrolytes the temperature is about 400-800°C. Furthermore, it is estimated that when fully developed, electrochemical synthesis could see an energy reduction of 20% compared to conventional ammonia synthesis routes. [68, 70]

The preferable operational point of electrochemical synthesis, as well as the potential reduction of energy required by the synthesis, highlights the potential it has. The issue with the technology lies in its infancy. Electrochemical synthesis is very much in the research stage at the current standpoint, and further analyses and development are essential for its success. [70, 71]

Another researched synthesis route is photocatalytic ammonia synthesis. Photocatalytic synthesis utilizes solar energy as well as the readily available nitrogen gas found in air. During the reaction, light excites a semiconductor or a plasmonic material, which creates a potential that fixates nitrogen to ammonia. This reaction is completely green and quite flexible considering the feedstock, much alike the aforementioned synthesis technologies. [72]

The most limiting factor of photocatalytic synthesis is the catalyst, mainly due to the high bond dissociation of nitrogen gas. A catalyst and a semiconductor material combination able to compete with Haber-Bosch has yet to be found, and therefore photocatalytic synthesis remains a technology that is only used at a lab-scale. [73, 74]

There are a few more methods that have been omitted from this thesis, such as bio-electrochemical and electromagnetic ammonia synthesis. The plethora of synthesis routes highlights the growing interest in developing technologies capable of competing with or even beating Haber-Bosch. [75, 76]

2.4 Haber-Bosch in combination with SOEC

As the SOEC acts as an oxygen ion membrane, one approach is to use the electrolyzer to produce nitrogen as well as hydrogen. This technology is still under development, but if applied together with Haber-Bosch it has the potential to eliminate the need of an air separation unit. The concept is shown schematically in Figure 2.15. [77]

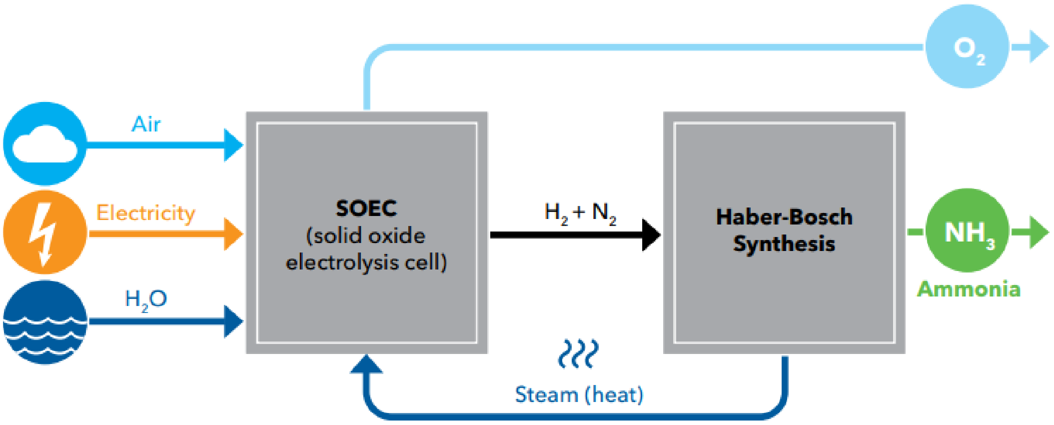

Figure 2.15: Ammonia production with SOEC as envisioned by Haldor Topsoe [8]

This technique also makes use of the large amount of waste heat from the Haber-Bosch process, as it can be applied directly to heat water steam fed into the SOEC. According to Haldor Topsoe, the concept could potentially amp up the total energy efficiency of ammonia production by 30% [78]. However, the first large-scale plant of this kind is not expected to be commissioned before 2024 [79], so the technology is yet to be commercialized.

2.5 Storage

Storage of ammonia is a practice that is well researched and documented, owing to its century-old use [80, 81, 82, 83, 84]. Equipment and storage tanks are commercially available, and experts capable of handling said equipment are manifold. Ammonia is traditionally stored as a liquid, see Figure 2.16. The temperature and pressure state of the liquid ammonia depend on the application of use and the magnitude of storage. [85]

Figure 2.16: Refrigerated liquid ammonia storage tanks [86]

A great benefit of ammonia is its high volumetric energy density compared to other carbon-free fuels. It is about three times larger than that of compressed hydrogen. Ammonia is also easy to keep in a liquid state. Little pressure is needed to store liquid ammonia, as it boils at -33.3°C at ambient pressure. Consequently, when the pressure goes above 8.6 bar the liquid ammonia can be stored at an ambient temperature of 20°C. [85]

There are currently three main ways of storing liquid ammonia. These are pressurized, refrigerated, and semi-refrigerated. The pressurized method holds liquid ammonia at about 10-15 bar and at an ambient temperature, while the refrigerated method typically stores the ammonia below -33.3°C and at an ambient pressure. The middle point between the two is the semi-refrigerated method, where ammonia is stored at 0°C and 3-5 bar. Semi-refrigerated storage is less used since it requires to be both refrigerated and pressurized. [87]

The pressurized storage method is limited to a couple hundred tonnes per tank. Refrigerated storage tanks, however, can store tens of thousands of tonnes. Ammonia in large quantities is typically stored in a refrigerated state, not only due to the convenience of storing all the liquid in one tank, but also because the capital cost is generally lower for refrigerated storage compared to pressurized. [8, 88]

2.5.1 On-board ammonia storage

There is generally no need for any additional energy to keep pressurized liquid ammonia stored. The energy heavy steps can all be performed on land. The same is more or less true for refrigerated ammonia storage. However, a continuous temperature might be difficult to sustain over longer voyages. A back-up system would therefore be necessary to maintain peak storage conditions. This would require additional equipment and energy costs. [8]

Retrofitting existing ships is a promising alternative for future ammonia-powered vessels. Ships that are already transporting ammonia would be good targets for retrofitting. They are already equipped with storage and safety devices necessary for the on-board handling of ammonia. In these cases, a refrigerated storage solution would be used due to the large volumes of ammonia. Liquid natural gas (LNG) ships are another ideal alternative for retrofitting. These ships would also employ refrigerated storage since it is the storage method most in line with the LNG storage tanks. [8, 89]

Bunkering of ammonia is a challenge that any production plant selling its ammonia on site must solve. The specific storage method chosen by the plant might not be the same as that employed by the ship. For example, the plant might have refrigerated ammonia stored while the ship handles pressurized ammonia. The plant should therefore hold the necessary equipment to supply the demands of the ships wanting to bunker. [11]

3 Safety considerations and main challenges

As with any energy carrier, ammonia comes with safety concerns. Using ammonia as a fuel comes with some underlying challenges. This chapter highlights both the safety concerns and challenges.

3.1 Safety concerns

Liquid ammonia will exhibit a corrosive effect on certain metals, such as zinc, copper, and copper alloys. It is therefore important to make sure that all tools used while working with ammonia are free from these metals. [8]

Liquid ammonia also has an increased risk of stress corrosion on nickel steel and carbon-manganese. High amounts of dissolved oxygen increase the risk of stress corrosion, which is why air needs to be properly purged from the ammonia system in advance. In addition, mercury has the potential to form explosive compounds with ammonia, so contact between the two should be avoided completely. [85]

An interesting facet of ammonia is the pungent smell it puts off, which promotes a reaction in humans to vacate the proximity. Even the smell from small concentrations of ammonia is noticeable. [90]

The most obvious safety concern linked to ammonia is the toxicity of the gas. Exposure to small concentrations at 50-250 ppm over a long period will result in bodily irritation and may lead to health issues. Higher concentrations at 700-1500 ppm will have immediate health consequences. If the concentrations rise above 2500 ppm, the gas becomes fatal. [91]

The toxic nature of the gas leads to certain safety requirements. A ship fueled by ammonia must be designed so that any large gas leaks can be contained and preferably mitigated fully. Furthermore, care must be taken when designing sectors visited by crew members, especially small spaces. The storage and handling area of the ammonia must be placed as far away as possible from the sleeping quarters of the crew. [11, 92]

A major worry regarding any flammable fuel is the likelihood of its self-ignition and the chance of an explosion occurring. Fortunately, this is less of an issue when handling ammonia since it is not flammable in air and has a relatively high self-ignition temperature (650°C). This allows for a more liberal ship design when employing ammonia, compared to other fuel options. The likelihood of its self-ignition and the chance of an explosion occurring for the different fuels can be seen in Table 3.1. [93]

Table 3.1: Physical properties and health risks of different energy carriers [93]

	Vapor pressure, p_i, at 293K/bar	**IDLH [ppm]**	**Apparent toxicity $p_{i,293K}$/IDLH**	**Flammability limits [in air]**	**Explosion limits [in air]**
Gasoline	0.047	750	63	1.4-7.6%	1.1-3.3%
Methanol	0.13	6000	21.6	6-36%	5.5-44%
Hydrogen	-	-	-	4-74%	18.3-59%
Natural gas	-	-	-	5.3-15%	5.7-14%
Liquid ammonia	8	300	$\sim 2.7 \cdot 10^4$	-	16-25%

While the apparent toxicity of ammonia trumps that of its contenders, the immediately dangerous to life or health (IDLH) remains low, see Table 3.1. This is mainly due to the lessened risk of flammability. This same aspect allows for a lower investment towards the handling of self-ignition and the explosion of ammonia. The increased cost linked to ensuring a safe design with regards to toxicity is therefore balanced out. [11, 92]

Figure 3.1: Location Specific Iso-Risk contour of an ammonia powered passenger vessel. Modified from [94]

The risk assessment linked to large ammonia leaks should not be overlooked. The first and most important risk is the proximity of people to the storage facility or production plant. It would be unwise to situate either in heavily populated areas, as accidents could lead to detrimental effects to human life. In 2021, DNV released a paper highlighting the risk connected to the bunkering of a passenger vessel in a populated area. The total risk area extends quite far away from the epicenter, as shown in Figure 3.1. [94]

The toxicity of ammonia does not only have adverse effects on humans, but also on aquatic life. Small concentrations of ammonia can be lethal to some aquatic organisms. Ammonia reacts with water to form both ammonium and hydroxide ions. As opposed to ammonia, ammonium is not toxic to aquatic life. The rate of toxicity varies depending on the temperature and pH levels of the water. [95, 96, 97]

Appropriate safety measures and a capable crew are essential to mitigate any chance of large leaks. This is, however, not a fail-safe solution, as accidents do happen. If a ship was significantly damaged in a collision, capsized or run aground, a substantial amount of ammonia might be released into the environment. A resulting large-scale leak would be almost impossible to control, comparable to that of oil spills caused by ships running aground, as seen in Figure 3.2. [98]

Figure 3.2: Oil spill caused by cargo ship run aground [98]

3.2 Main challenges of ammonia combustion

No CO_2 is generated from the combustion of ammonia. This is why it has potential to be a green maritime fuel, as previously mentioned. Nevertheless, the combustion of ammonia is not emission-free. Other chemical compounds, specifically nitrogen oxides (NOx) and nitrous oxide (N_2O), are formed as a result of the high temperatures found in the combustion engine. The consequential emissions are one of the biggest hurdles of ammonia as a fuel. [99]

NOx is a group name for a set of nitrogen oxides. When dealing with the combustion of ammonia, two compounds found in the NOx family are relevant, namely nitric oxide (NO) and nitrogen dioxide (NO_2). NOx emissions can result in the formation of smog, acid rain, and ground-level ozone. Heavy amounts of emissions will have direct effects on the quality of air and, consequently, the health of humans and the ecosystem. [100]

The handling of NOx is crucial not only from a moral perspective, but also from a legal standpoint. IMO ship pollution rules have set standards for NOx emission limits. Any ship running on ammonia would need to comply with these standards to be indiscriminately allowed to fare within IMO regulated oceans [101]. The current IMO regulations for NOx emissions can be seen in Table 3.2. It should be noted that a majority of cargo ships have a rated engine speed below 130 rpm, and that tier III restrictions are unique to “Emission Control Areas”. [102]

Table 3.2: IMO regulations for NOx emissions [101]

Tier	**Ship construction date**	**Cycle emission limit (g/kWh)**		
		rpm <130	*rpm 130-1999*	*rpm >1999*
I	1 January 2000	17.0	$45 \cdot rpm^{-0.2}$	9.8
II	1 January 2011	14.4	$44 \cdot rpm^{-0.23}$	7.7
III	1 January 2016	3.4	$9 \cdot rpm^{-0.2}$	2.0

There are some promising routes towards solving the issue of NOx emissions. Firstly, research has shown that further optimization of the combustion process can have a great impact on the amount of emission. One of the most effective methods is the selective catalytic reduction (SCR) method, in which the exhaust fumes are mixed with a water solution of urea and then passed through a catalyst reactor. This method greatly reduces NOx emissions while being slightly expensive. Alternatively, a scrubber could be used to capture the emissions. This option results in increased fuel consumption, and a subsequent increase in operational cost. [103]

In addition to NOx, N_2O emissions are produced from ammonia combustion. There are no current regulations aimed towards N_2O emissions, which decreases the incentive for ships to focus on N_2O emission mitigation. N_2O is a GHG with a global warming potential (GWP) of 298. [12, 104, 105]

Another issue is that conventional combustion engines will not burn the ammonia fuel completely. A small portion of ammonia gas escapes the combustion engine during operation. This unused gas is commonly referred to as ammonia slip. There are two main reasons for this; the gas might not ignite completely or the gas could get trapped behind the pistons of the engine. In both cases, the unignited gas escapes with the exhausted stream. The amount of ammonia slip varies depending on the type of combustion engine and the producer of the respective engines. [12]

Ammonia slip represents a loss of fuel, thus a loss of capital. Capturing the ammonia slip is therefore a very attractive venture. The issue lies in the high investment costs. Currently, the cost of equipment needed to capture the ammonia outweighs the gains. It is also beneficial from a green perspective to capture the ammonia slip, since it has a negative effect on the nearby ecology. [95, 106]

Finally, another equally pressing challenge is the flame stability of ammonia. Because it has a low laminar burning velocity, pure ammonia alone cannot be used in a combustion engine. A mixture of some kind is necessary for the initiation of ammonia combustion. An estimate of 20-30% of the total fuel would need to be an alternative fuel to ammonia. The most attractive method for combustion of two fuels at the time is through a duel-fuel combustion engine, as seen in Figure 3.3. A dual-fuel combustion engine would do fine running purely on carbon-based fuels. [11, 106, 107]

Cracking of ammonia back to hydrogen is an attractive solution, as hydrogen has a much higher laminar burning velocity and could be used to initiate combustion. The ship would in this case only need to carry ammonia. This would, however, require additional equipment on-board the ship, which increases the weight and incurs additional costs. [11]

Figure 3.3: A duel-fuel engine designed and produced by Wärtsilä [108]

4 Discussion of ammonia as a marine fuel

This chapter will look further into ammonia production and ammonia as a fuel. Firstly, the main issues linked to ammonia are analyzed, following that the green aspect of ammonia is discussed. The infrastructure and availability of ammonia are also examined, interluded by a comparison of hydrogen and ammonia, and finally, the future outlook of production technologies is evaluated.

4.1 Main concerns

Before ammonia as a fuel is able to succeed, its underlying concerns need to be solved. The toxicity of ammonia and its safe handling at the production level are thoroughly documented, owing to its long history. Likewise, its transport and use in the agricultural sector are both well established practices. The same cannot be said for the use of ammonia as a propulsion fuel, even though it is not a particularly new concept.

Toxicity of ammonia

A particularly clear challenge to ammonia as a fuel is its toxicity. Lives would be at risk if the equipment, storage tanks, pipes, and logistics were managed improperly. Thorough risk assessment and stringent regulations should be put forth for ammonia as a future marine fuel to succeed.

Utilizing toxic marine fuels is not an uncommon practice, nor is the transport of toxic chemicals. There are several operable ships capable of transporting ammonia. These ships have well trained crew members equipped with the knowledge and experience to handle the toxic chemicals. Retrofitting these ships would therefore serve as a quick route towards safe ammonia-ready vessels.

Human relations

Ammonia leakages can easily be discovered, even in small concentrations. This is due to its pungent smell, which makes it quite noticeable if a leak were to occur. Contrary, if one were to become accustomed to the odor, one might be oblivious to a leak. The smell is also a detriment to the passengers and crew of a ship. With ammonia slip the smell becomes very hard to escape, which could make ammonia less suitable for passenger ships.

There are considerable risks linked to the location of production plants and storage facilities. They should be kept distant from very populated areas, so as to keep the risk to human lives at a low. The risk associated with ammonia could also dissuade public opinion. Building new production facilities could be difficult if the local public opinion is strongly against it, similar to what has been seen with wind turbine installations.

Flame stability

The flame stability issue is another challenge for ammonia as a fuel. A separate fuel would be required for ammonia combustion to be successful. Which supplementary fuel to use is still an uncertainty, and so is the percentage of the fuel mix. There are many solutions for the fuel mix, and it is likely that there is no single answer. This issue could be circumvented fully if an ammonia fuel cell was used in place of a combustion engine. The problem lies in the inability of the fuel cell to supply sufficient power to large vessels. Ammonia fuel cells are redundant at the current standpoint, and more innovation would be necessary for them to compete with combustion engines.

4.2 The green aspect of ammonia

The name “green ammonia” comes from the fact that there is no CO_2 emissions from either the production or use. However, this does not guarantee that it is completely environmental friendly. If ammonia is used in combustion engines, there will be emissions of both NO_x and N_2O, which are harmful to the environment. Additionally, ammonia leakage would pose a threat to nature and its ecosystems.

NO_x and N_2O

Ammonia combustion-related emissions are easily overlooked upon learning that ammonia is carbon-free. Nonetheless, it is important to take into account when considering ammonia as a fuel. NO_x is the emission with the most focus, due to the regulations set by the IMO. There are some promising technologies for the mitigation of NO_x, but they are not 100% effective.

While NO_x emission mitigation has a few promising solutions, N_2O emissions are undermined, due to the lack of regulations. The amount of N_2O emitted from ammonia combustion is not expected to be extensive, although it is unclear how much as it is not yet a widely used fuel. Even though the emission level would be low, it is still important to consider and it should also be regulated. N_2O is a GHG with a GWP of 298, which means that even a small amount can have a big impact on global warming.

Ammonia slip and leakages

Ammonia slip and leakage are factors one has to think about. Ammonia is metabolized in nature, and does not affect global warming in the same way as CO_2. However, it is a poisonous substance, both to humans and animals. Therefore, nature and its ecosystems could be heavily affected if exposed to leakage. When ammonia is mixed with water it eventually turns into ammonium, which is not as harmful. It could therefore be argued that it is less of a problem at sea compared to on land. However, almost any fuel leakage is damaging, as energy itself is linked with some kind of risk.

CO_2 permits

As solving global warming and environmental problems has become a priority, it is expected that the price of CO_2-emissions will increase in the future. The fact that ammonia is carbon-free makes it very attractive to use and develop as a fuel. At the moment, fossil fuels combined with carbon permits are cheaper. However, with an increasing CO_2 permit price, ammonia might become more competitive in the future. There is also a possibility that there will be laws against the use of fossil fuels. Preemptively developing carbon-free alternatives such as ammonia would therefore serve as an investment for the future.

4.3 Ammonia infrastructure and availability

Considering that green ammonia used as a marine fuel is still in a piloting phase, it is usually difficult to make it very profitable due to a lack of an existing marked and infrastructure. This is usually the case for most pilot projects, nonetheless, they are vital for further expansion and innovation. When that is said, a great advantage with ammonia as a fuel compared to say hydrogen is that a well-functioning infrastructure is easier to accomplish. This is due to the possibility of retrofitting existing ships and ports used to handling ammonia, which provides an excellent starting point.

Creating a market for ammonia

One way of kick-starting the use of ammonia could possibly include gray fuel alternatives. The complementary fuel used alongside ammonia could just as well be a carbon-based fuel. These are already readily available for use in most of the world's ports. If no ammonia is available, a dual-fuel combustion engine would do fine running purely on carbon-based fuels. This could be a good solution in the starting phase of ammonia as a fuel since it would lessen the pressure on the ship owners.

It might also be worthwhile to utilize gray ammonia in the initial trial years. The IMO has yet to enact heavy regulations on carbon-based fuels, and it is likely that regulations like these would take a decade or two to come into full force. This period could be used to slowly initiate green fuel types. To begin with, the market could benefit from laws requiring green fuels to account for a few percent of the the total fuel consumption, and then gradually increase the demand. In this way, employing gray ammonia in addition to green would be a good way to kick-start the use of ammonia as a propulsion fuel.

There is a severe lack of green ammonia production at the present time. A ship would be hard pressed to find any bunkering options if it strictly adhered to green ammonia as its fuel. The scale of gray ammonia production serves as a stark contrast, although it is important to remember that it is mainly demanded by the agriculture sector today. Competition between the two applications could lead to increased rates of ammonia production. Alternatively, this might have negative effects should the maritime sector take away from the fertilizer industry. Anyhow, by facilitating the use of gray ammonia as fuel, more companies might be willing to invest in ammonia-powered vessels, as availability is less of a concern. This would again spur the investment in green ammonia production for the maritime sector.

Scalability

When scalability for green ammonia production plants is considered, it is indeed possible to expand further. There are several approaches, including building completely new plants, but also upgrading the many existing gray ammonia plants to hybrid plants that can produce both green and gray. The green ammonia could, in this case, be produced from the electricity purchased at the hours of the highest renewable energy influx, since it is cheaper at those hours.

A question of concern lies in whether or not enough renewable energy will be available for further expansion of green ammonia plants. Furthermore, the price of renewable energy might be too high in certain parts of the world today. It could therefore be helpful if the scale of renewable energy production were further developed, so as to meet the demand for ammonia production in the future.

If excess renewable energy is available, there might be an advantage with several outspread small-scaled plants compared to a few large production plants, to make use of the geographically spread green energy. However, this would certainly increase the CAPEX of green ammonia production. Another main challenge to make green ammonia succeed is that all the rivaling green technologies rely on this same clean energy.

4.4 Comparison of hydrogen and ammonia as a marine fuel

In the use as carbon-free marine fuels, ammonia and hydrogen can be seen as competitors. When it comes to production, ammonia is naturally more expensive. This is evident as one needs hydrogen to produce ammonia. For safety aspects they both have their downsides. While hydrogen is highly explosive, ammonia is toxic. Both require extensive safety measures to be used.

One edge hydrogen has over ammonia is that it can be used completely on its own, without any supplementary combustion fuels. Liquid hydrogen requires either very high pressure or cryogenic temperatures, whereas one of the main advantages of liquid ammonia is that storage is less energy-intensive. Ammonia also has a higher volumetric energy density than hydrogen, and thus is conceivably more suited for high sea shipping over long distances.

4.5 Future technology for ammonia production

There are a few technologies that could potentially help streamline ammonia production. Unfortunately, these technologies are yet to be commercialized.

Alternative ammonia synthesis development

Haber-Bosch is the most reasonable option for all commercial sized production plants. This is likely to be the case for the coming years as well. That is, unless some major innovative breakthroughs are made. The question is how much of an impact a cheaper and more efficient ammonia synthesis technology would have. A greater portion of the total CAPEX and OPEX of the plant goes toward hydrogen production, and not ammonia synthesis.

An increased ammonia synthesis efficiency would in other words not account for much when the total picture is analyzed. Any decrease in investment and operation costs is helpful, so the increased efficiency should not be completely undermined. The matter of fact is that the improvement of other investment facets might be more beneficial. A cheaper electrolyzer and cheaper electricity would help reduce the cost of ammonia production massively.

SOEC combined with Haber-Bosch

A very interesting concept for ammonia production, combining a SOEC and the Haber-Bosch process, was described in Section 2.4. This has the potential to reduce the energy consumption linked with both hydrogen and nitrogen, and thus ammonia production. The main reason for this is the synergy between the SOEC and the Haber-Bosch process, which makes the technology especially suited for ammonia production.

Firstly, the SOEC itself usually has a higher efficiency than both PEM and alkaline electrolyzers. As the process requires a very high temperature, one can utilize the otherwise wasted excess heat from the Haber-Bosch process directly to produce steam for the SOEC. In addition to this, all the extra energy required to separate nitrogen with a separate unit can be eliminated, as SOEC takes care of this with its oxygen-ion membrane. This is particularly interesting for small-scale production, because it would ensure a considerably lower capital cost.

The combination of all the aforementioned makes this next-generation ammonia synthesis plant very promising for the future outlook. It should be mentioned that Haldor Topsoe might be overly optimistic about their own patented technology, but if the concept matures well and manages to be commercialized, it could be great news for green ammonia as a fuel.

Unpredictability of new technology

While new technology might look good in theory, it can be difficult to accurately assess the working condition of said technology. Downtime linked to maintenance and repairs is an uncertainty. There is always a certain risk involved with new technology due to the fact that theory might apply differently in practice. If safety and predictability are a priority, one should consider opting for mature solutions with proven reliability.

5 Case Nærøysund

The following case study highlights the possibility of green ammonia production in Nærøysund. Nærøysund is a municipality in the north of Trøndelag county, situated along the Norwegian coast. The geographical location has made aquaculture the most important industry there and has also made it possible for two wind farms to arise. NTE and partners are already in the building phase of a pilot hydrogen facility at the same location. The main goal of this pilot facility will be to fuel small supply boats used by local businesses engaged in pisciculture.

This very same pilot project will serve as the foundation for this case study, in addition to being the background for many of the constraints and design choices. One such constraint is the production rate of ammonia. The pilot hydrogen production plant is expected to produce 8.3 tonnes of hydrogen per day, which equates to 46.7 tonnes of ammonia per day at a 100% conversion rate. The plant will source its electricity directly from the grid, which in Norway originates from renewable sources. The lifetime is set to 15 years.

The hourly, daily, weekly, and yearly rates of ammonia production, in addition to consumed hydrogen and nitrogen are presented in Table 5.1. Note that NTE has estimated a total of 360 operating days per year, hence 5 days for downtime and maintenance. For flexibility, these values were calculated in Python based on Equation 2.5 acting as a stoichiometric reaction, as shown in Appendix A. The presented production rates are used for the economic calculations of the case study.

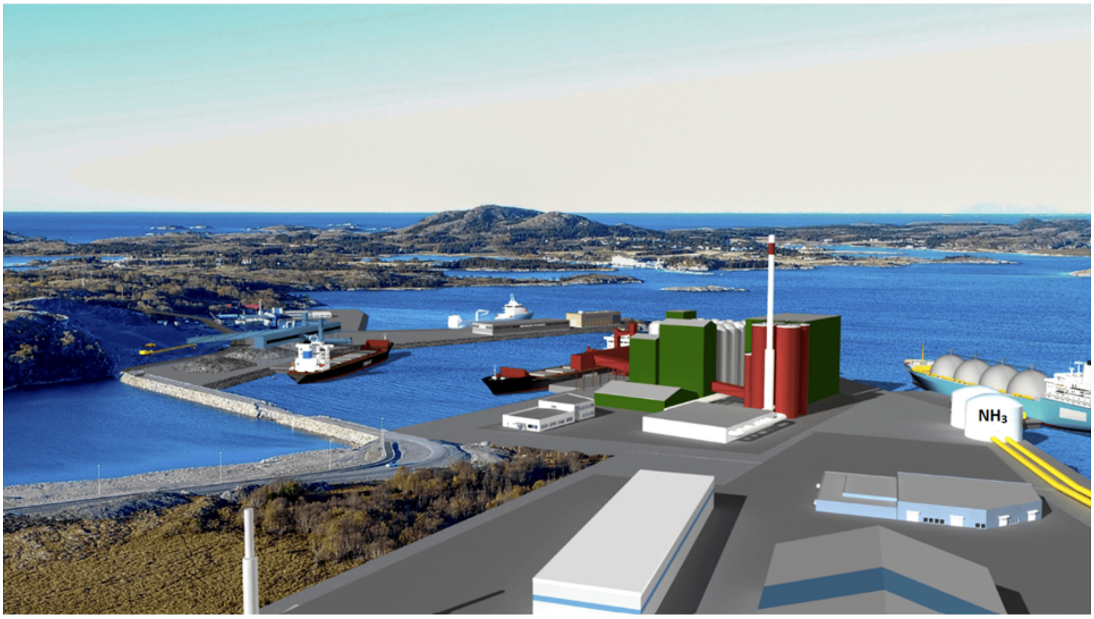

Figure 5.1: Illustration of the production site in Nærøysund. Modified from [109]

Nærøysund was chosen due to its apt location along the Norwegian coastline, making it a suitable port for larger vessels to bunker. Figure 5.1 illustrates the close proximity of the production plant to the port, which will shorten the production to bunkering route significantly. In this case study, there are no additional costs associated with the transport of ammonia since it will be produced, sold, and bunkered on-site.

Table 5.1: Maximum process consumption and production rates

	tonnes/hour	tonnes/day	tonnes/week	tonnes/year[a]
Hydrogen consumption (H_2)	0.346	8.3	58.1	2 988
Nitrogen consumption (N_2)	1.602	38.4	269.1	13 838
Ammonia production (NH_3)	1.948	46.7	327.2	16 827

[a] With an estimated 360 operating days

5.1 Technological choices and design discussion

The different technological solutions described in Chapter 2 are in this section reflected upon. Furthermore, a decision on what is most suited for the specific case study in Nærøysund is presented.

5.1.1 Electrolyzer

As far as hydrogen production is concerned, the choice falls mainly between the alkaline- and PEM electrolyzer. Thermochemical water decomposition is heavily dependent on geographic location with close proximity to a heat source such as solar towers or nuclear power plants. Neither of those are located near Nærøysund.

When considering a solid oxide electrolyzer, it seems very promising. It has a superior energy efficiency to the other electrolyzer technologies at the same time as it uses relatively cheap materials. Therefore, it has the potential to be a cost-efficient alternative. In the context of ammonia production, it can also be used to produce nitrogen, which removes the need for an air separation unit. As the ammonia synthesis has waste heat, utilizing a SOEC will give the ammonia production process a higher efficiency. This is achieved by using the waste heat to produce steam for the electrolysis. However, this technology is not yet ready for commercial use and therefore not applicable for this case study.

PEM electrolyzers fit perfectly with renewable energy, as the dynamic range is high. This means they can be turned on and off quickly, and therefore follow the inconsistency of energy production from renewable sources, which is dependent on factors such as weather. However, as the electrolyzer in this case study will use electricity directly from the grid, one can simply run it at a consistent production ratio. The price also weighs against the PEM electrolyzer, as it uses expensive catalyst materials. Should the production plant ever be connected to one of the two wind farms in Nærøysund, the PEM electrolyzer would be a good choice. When there is no use for the high dynamic range, the alkaline electrolyzer becomes more appealing.

Alkaline electrolyzers are a well-known and established technology, which means they will have a predictable life cycle. Therefore, unexpected problems and costs are far less likely to occur. It has high energy efficiency at lower current densities and is well suited for constant production with the grid as its electricity source. When it comes to price, it is the cheapest alternative as it uses inexpensive materials. As this case study is based on an already existing hydrogen pilot project, the feasible choice of an alkaline water electrolyzer was already made.

5.1.2 Air separation

Nitrogen production by air separation can be accomplished using a variety of approaches, as explained in Section 2.2. Choosing the right technology for a specific application may seem complex, but the two most significant decision factors are required nitrogen purity and flowrate. One of the world's largest suppliers of industrial gas projects, *Air Products* [110], provides a useful chart with an indication of the optimal technology, shown in Figure 5.2.

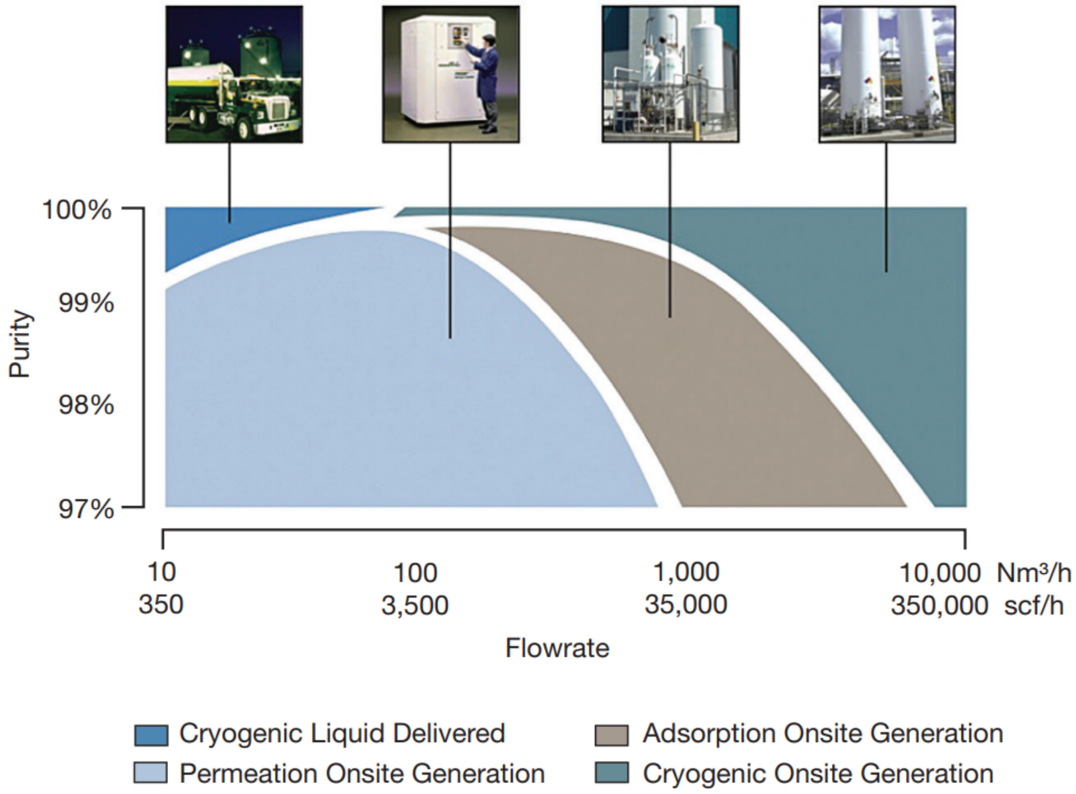

Figure 5.2: Optimal nitrogen production technology chart based on purity and flowrate [41]

The gravimetric flowrate of nitrogen necessary at the plant in Nærøysund equals about 1.602 tonnes/hour, as shown in Table 5.1. This converts to a volumetric flowrate of 1281 Nm^3/hour as calculated in Appendix A. By using this in combination with the desired gas purity of at least 99%, it becomes quite clear from Figure 5.2 that adsorption onsite generation is the most suitable solution.

PSAs equipped with carbon molecular sieves are a relatively simple technology that is particularly well suited for nitrogen production due to the significantly quicker oxygen adsorption rate. This, combined with a variety of process variables, provides the technology with flexibility, such as the possibility of being customized. However, heavily modified units can lead to a significant increase in CAPEX.

When flowrate is considered, it is also important to understand both the total hours of operation as well as the load profiles. The nitrogen flow pattern will matter for the air separation technology of choice. To maximize the energy-efficiency and thus economic benefits, a PSA nitrogen generator should operate at its full design capacity at all times. As this ammonia production plant is supposed to work at a steady and constant operation as opposed to periodic or erratic flow patterns, PSA is further cemented as an optimal solution.

Compared to cryogenic air distillation, PSA has the potential to reduce the impacts on the environment due to substantial energy savings. Cryogenic technology should in principle only be considered if extremely high purity is a must or if massive flowrates are regarded, as indicated in Figure 5.2. Nitrogen bought and delivered as a cryogenic liquid is also possible, but this further contributes to increased emissions through transportation.

Permeation gas generation by membranes was strongly considered for this case study. Membrane technology for commercial use has matured in the last decades, but as portrayed in Section 2.2.3 it still remains challenging to provide economic feasibility when both relatively high purity and flowrate are required. Membranes would have reduced the CAPEX, but have higher energy consumption because they need an even larger surplus of compressed air compared to PSA. This increases the OPEX and makes membranes less attractive in the long-term perspective.

An advantage of membrane technology over PSA is the low maintenance required and hence less downtime. The solution to increase the reliability of adsorption gas generation is to include two 50% sized PSA units instead of one big unit coping with all the production. In this way, the plant could continuously produce ammonia even when one unit is down for maintenance.

Utilizing vacuum in the process would further increase the CAPEX, so this case excludes this option as standard units without several modifications are preferred for the scale of this case study.

5.1.3 Ammonia synthesis

There are very few options when assessing different ammonia synthesis technologies. Most of them are limited to lab-scale and have a production cost that is unable to compete with the likes of Haber-Bosch. There are therefore only two practical options to choose between, either electrochemical or Haber-Bosch synthesis.

Electrochemical synthesis is a technology with great potential, and it is fairly cost-effective if the price of the electricity used to power the system is low. The technology is not very mature and has yet to find any success outside of small applications. Thus, direct electrochemical ammonia synthesis would be unfitting considering the scale of production envisioned for this case study.

The Haber-Bosch technology is mature and has widespread use across the whole world, which results in equipment and experts being widely available compared to the other technologies. The Haber-Bosch method would have no issue dealing with production rates of 46.7 tonnes of ammonia a day. This option is also the most cost-effective with respect to both investment and the final production costs. The clear choice is Haber-Bosch due to the aforementioned.

A few additional pieces of equipment are needed in combination with the Haber-Bosch system. These are a trail of transport pipes, a gas separator, a purge outlet, a refrigeration compressor, and a recycle compressor. All this equipment forms an ammonia synthesis loop, which is used for the economic calculations of the case study.

5.1.4 Storage

For this case study, it is assumed that the storage capacity of the plant should be large enough to handle one week's worth of production. This equals a total capacity of about 330 tonnes. Two technology types were assessed for the storage of ammonia, namely pressurized and refrigerated liquid ammonia storage tanks.

For pressurized liquid ammonia, several tanks would be required in order to reach a storage capacity of 330 tonnes. Refrigerated on the other hand, would only need one storage tank. This simplifies the operations and logistics of the plant. The capital cost is also lower for refrigerated storage compared to pressurized. Thus, a refrigerated storage system makes the most sense from the plant's perspective.

Pressurized storage tanks are beneficial for ships wanting to travel long distances. If the plant chooses to store liquid ammonia in refrigerated tanks, it would need additional equipment in order to bunker between refrigerated ammonia and pressurized. It might therefore be wise for the plant to utilize pressurized storage in order to meet the market demands. The economic benefits would have to be weighed to best draw a conclusion.

Retrofitted ships, on the other hand, would use refrigerated storage tanks, in view of the reasons described in Section 2.5. What is apparent is that the fuel demand of the ships bunkering in Nærøysund is not certain due to the lack of existing ammonia powered ships. However, if basis is taken in the discussed advantages with retrofitting existing ships, it is sensible to go for a refrigerated storage system. This is also more beneficial from an economic viewpoint of the production plant, and thus this technology was chosen for the case study.

5.2 Economic choices and constraints

To be able to do an economic analysis of NPV and LCOA, prices for different costs and expenses had to be found. This section will present and comment on the values that were found. Most of the values were either provided by NTE or found from different literature. For easier analysis, as different sources use different currencies, they are all converted to NOK. The exchange rates used are from 31.03.2022, where 1 USD equals 8.75 NOK and 1 EUR equals 9.71 NOK [111].

The prices highlighted in *italic* are the ones used directly in the calculations and form the foundation of the baseline scenario, together with the production rates in Table 5.1 and *360* days of operation. The baseline scenario serves as a reference for the calculations of the case study. This acts as the basis for the sensitivity analyses.

5.2.1 NPV and LCOA

The main calculations for the techno-economic analysis were performed in Excel and VBA, with Python and MATLAB serving as supporting tools. Net present values, see Equation 5.1, were calculated over a period of *15* years, n, with a discount value of *6%*, i, and an inflation rate of 0%. R_t is the total cash flow for a given year, t, in other words the income of the production plant minus the expenses.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{5.1}$$

The LCOA calculations, similarly to the NPV calculations, were calculated over a *15* year period, n, and the discount rate, i, was at *6%*. The LCOA was calculated by dividing the total costs over the total production, see Equation 5.2. Here, I_t and O_t represent the investment and operational cost of a given year, t. A_t is the total ammonia produced by the production plant for a given year.

$$LCOA = \frac{sum\ of\ cost\ over\ lifetime}{sum\ of\ ammonia\ produced\ over\ lifetime} = \frac{\sum_{t=0}^{n} \frac{I_t+O_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{A_t}{(1+i)^t}} \tag{5.2}$$

All economic calculations are done as seen in Appendix B and C.

5.2.2 Capital cost

The capital cost is a one-time expense to acquire the components needed and get them to an operable state. In this case, the cost of the electrolyzer, PSA unit, ammonia synthesis loop, buildings, and storage are taken into account.

Electrolyzer

A commercial alkaline electrolyzer costs between 100-140 MNOK, and as such the middle point of 120 MNOK was chosen. Furthermore, the total price for the transformer, compressor, and electric control systems is 35% of the electrolyzer's investment cost [112]. Thus, the final electrolyzer price ended at *162 MNOK*. After 10 years of operation, the electrolyzer needs a stack replacement, which literature estimates to cost 40% of the electrolyzer's investment cost [113]. The electrolyzer alone costs 120 MNOK, which gives a stack replacement price of *48 MNOK*.

Pressure swing adsorption unit

A price estimate for the selected air separation technology was found through direct contact with a manufacturer. *Air Products* provides a pertinent PSA unit with their specific production standards. The estimated price for a unit that covers 50% of the total required capacity is 3.0 MNOK . This results in a total price of *6.0 MNOK* for 2 smaller PSA units. Note that these estimates do not pretend to be exact, as they depend on various details. A heavily modified unit could increase the CAPEX by a factor of up to 4. [114]

A high-capacity compressor is required to feed the PSA with an over-proportional pressurized air demand. This is estimated to have a price of about *0.5 MNOK*. [115]

Ammonia synthesis

The price for the ammonia synthesis loop was found through literary research to be 3 000 EUR/kgNH_3 h [116]. This price covers the Haber-Bosch process, the compressor, and the pipes. With the production rates from Table 5.1, the total CAPEX for the ammonia synthesis loop is about *56.7 MNOK*. After 10 years, there is a need for a catalyst bed replacement. The cost of this replacement is estimated to be 30% of the initial investment cost for the ammonia synthesis [117]. This results in a price of around *17 MNOK*.

Buildings

Some additional costs for the production plant were the building and land costs. The price per square meter of area was assumed to be 4 000 EUR/m^2 [112]. This price accounts for both land and construction costs. The assumed area required for the production plant of the case study was found to be 4 460 m^2, see Equation 5.3.

$$13\ 000\ m^2 \cdot \left(\frac{16\ 827\ tNH_3}{100\ 000\ tNH_3}\right)^{0.6} \approx 4\ 460\ m^2 \tag{5.3}$$

The area was found by applying a scaling factor of 0.6 to a case study done by “Grønt Skipsfartsprogram” [118]. The ammonia plant in this case study was expected to produce 100 000 tNH_3 per year, and would occupy an area of 13 000 m^2. Thus, by multiplying the area by the cost per square meter and adjusting for the currency, the price of the buildings ended at around *173.2 MNOK*. [119]

Storage

NTE expects a storage capacity of 327.2 tonnes of ammonia. A refrigerated storage tank will be responsible for storing all the ammonia. A price of 0.9 EUR/kgNH_3 was found in literature [116], and with this the investment cost was found to be about *2.9 MNOK*.

Total capital cost

Table 5.2 gives an overview of all the capital costs, with a combined total of around *401.3 MNOK*.

Table 5.2: Capital costs for green ammonia production

Component/process step	**Price [NOK]**
Electrolyzer[a,b]	162 000 000
Air separation unit[a]	6 500 000
Synthesis loop	56 682 125
Buildings	173 226 400
Storage	2 859 401
Total capital cost	**401 267 926**
Stack replacement	48 000 000
Catalyst bed replacement	17 004 638

[a] Including compressor
[b] Including transformer

5.2.3 Annual expenses

The annual expenses for this case study were operating expenses, electricity- and water usage, and grid tariff.

Operating expense

The operating expense (OPEX) is the expense of operating the production plant. For a hydrogen production plant, the OPEX can be assumed to be 1% of the total investment cost [112]. However, through discussion with the internal supervisor, the OPEX was set to 3% of the investment cost [120]. This is because when expanding to ammonia production, one adds more production steps, components, and parts. Movable parts have a higher rate of deterioration and the cost of replacing these parts will give a higher OPEX. The total OPEX was calculated to be approximately *12.0 MNOK*.

Electricity- and water usage

The price of electricity was set to *300 NOK/MWh*, and the electrolyzer's energy consumption was assumed to be 55 kWh/kg [112]. Together with a production rate of 8 300 kg/day, the electricity for the electrolyzer will cost around 49.3 MNOK per year. When it comes to the rest of the production plant, the energy consumption is based on literature. At 738 kWh/tNH_3 one gets the power needed for air separation, compression, synthesis loop and storage [121]. For a year, this will cost about 3.7 MNOK. The total cost of electricity amounted to just over *53.0 MNOK*.

The electrolyzer demands water for the hydrogen production as well as for cooling. A price for water was given by NTE at 0.348 NOK/m^3. The electrolyzer has a consumption of process water at 9 L/kgH_2, and cooling water at 400 m^3/h [112]. Combining these values with those of the hydrogen production rate and the operation time gives a price for process water at 9 358 NOK and cooling water at 1 202 688 NOK per year. The total price for water consumption was set to the sum of these two values, at around *1.2 MNOK* per year.

Grid tariff

Norway has adopted a monopolistic approach to electricity grid ownership and operation. The distribution companies are, however, legally obliged to offer their services to everyone wanting to use the grid. They are also subject to an income limit. There are set values used to calculate the grid tariffs for customers wanting to connect to the grid. These values vary according to an array of situations. The final cost of the grid tariff will in the end depend on the amount of energy and the maximum power to be delivered. [122]

Estimating the yearly grid transmission tariff for the case study can thus be calculated with quite accurate precision. The total energy requirement for a year of production is 176 827 MWh. This was calculated by assuming an energy consumption of 55 kWh/kg for the hydrogen production and 738 kWh/tonne for ammonia. With this, a grid tariff estimate of approximately *11.5 MNOK* per year was found [112].

Total annual expense

Table 5.3 gives an overview of all the annual expenses taken into account in this case study, and the total annual expense of around *77.8 MNOK* per year.

Table 5.3: Annual expenses for green ammonia production

Expense	**Price/year [NOK]**
OPEX	12 038 037
Electrisity	53 024 177
Water	1 212 046
Grid tariff	11 479 958
Total annual expense	**77 754 218**

5.2.4 Ammonia pricing

The price at which one can sell ammonia is an important factor when calculating NPV, as this is the main source of income for this case study. Figure 5.3 shows the price development of natural gas and ammonia over the last 26 years. As explained in Section 1.1, a vast majority of ammonia produced today is gray, therefore the price development in Figure 5.3 is for gray ammonia.

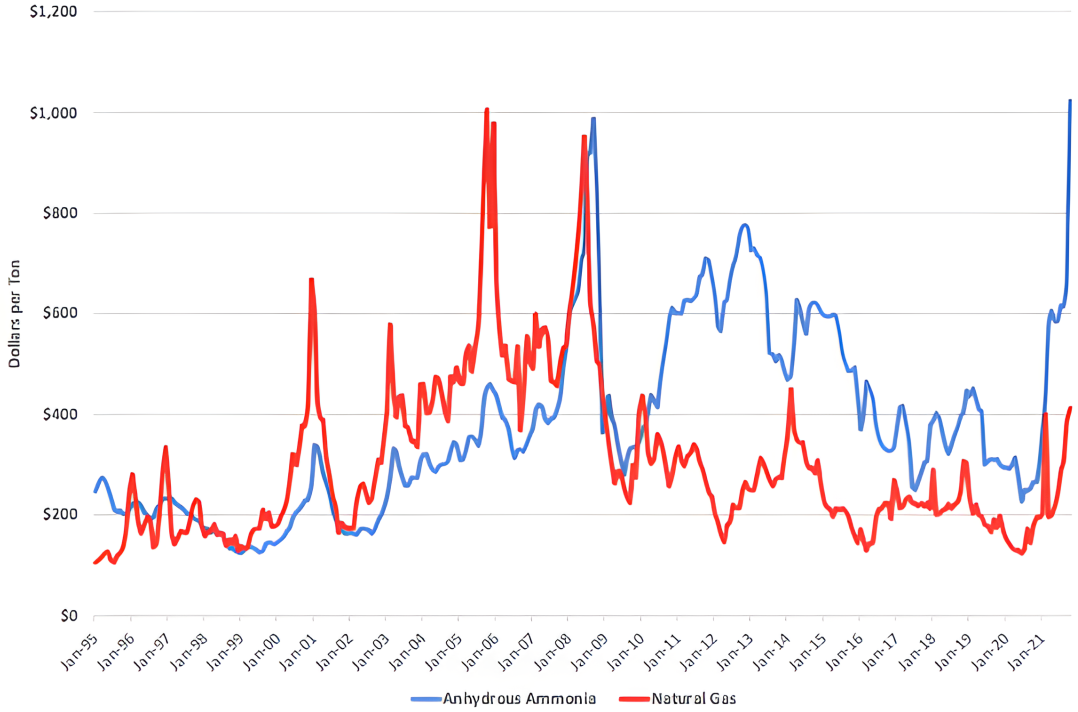

Figure 5.3: Price development of natural gas and ammonia from January 1995 until October 2021 [123]

As Figure 5.3 describes, the price of ammonia has not been stable over recent years. In the last two years, the price has seen a sharp increase. Therefore, predicting the future price will leave uncertainties, especially since this price will be used to simulate economic feasibility over a period of 15 years. One can see that the prices of natural gas and ammonia are connected, which is explained by the fact that natural gas is the most used resource to fuel ammonia production today.

The ammonia price as of 22.04.2022 is 1425 USD [124]. This high price is mainly because of an increase in the price of natural gas, which is amplified by the conflict in Ukraine, as Russia is the biggest exporter of natural gas to Europe [125]. As one can see, the price of ammonia has experienced a much higher increase than that of natural gas. This might be because of the recent hype around ammonia as a carbon-free fuel, and based on historical development, it will most likely see a reduction in price.

The price for the baseline scenario is set at 600 USD, which is based on the average value over the last ten years. The current price of ammonia is at a historic high, and a lower value was therefore chosen as it is expected to drop in the future. However, this price is for gray ammonia, and to simulate a price for green ammonia, the price for EU carbon permits is added. The price for these permits is 84.4 EUR per tonne [126]. Combined with the emission of 2.81 tonnes CO_2-equivalents per tonne of gray ammonia produced [127], a value of 237 EUR is added to the price. This gives a current price for green ammonia of 14 772 NOK, and a baseline price of *7 553 NOK*.

5.3 Economic results

This section presents the results of the economic analysis. The baseline scenario is covered, followed by a series of sensitivity analyses, in order to gain a broader view.

Material margin

An economic analysis is generally performed in order to investigate the profitability of a system. There are generally few incentives to engage in a business that has no feasible way to make money. An initial assessment can be easily made by comparing the cost of the feedstock with the income gained from selling a product. In the case of green ammonia production, the feed pertains to electricity and water, while ammonia is the product.

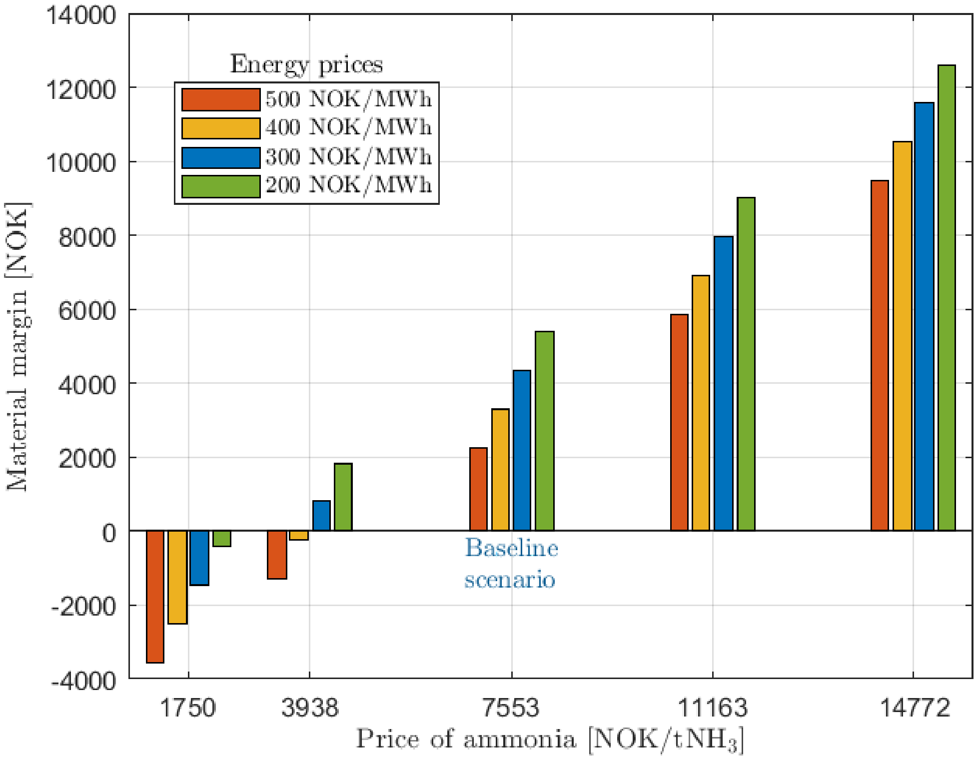

Figure 5.4: Material margin plots for different ammonia and energy prices

Figure 5.4 showcases a few different material margins as a function of the price of electricity and ammonia. The margins are found by subtracting the cost of the feed needed to produce one tonne of ammonia from the income gained from selling one tonne of ammonia. This has been done for five different ammonia price points, where the baseline scenario is the center-most plot.

Baseline scenario

Table 5.4 presents the results of NPV and LCOA for the baseline case, with estimated baseline values shown in the same table. The first row is for the estimated baseline price of ammonia, while the second is for the current price. For yearly NPV, see Appendix B.

Table 5.4: Results of NPV and LOCA

Electricity price	Ammonia price	Operating days	NPV	LCOA
300 NOK/MWh	7553 NOK/tNH_3	360	40 536 928 NOK	7 305 NOK/tNH_3
300 NOK/MWh	14 772 NOK/tNH_3	360	1 219 202 673 NOK	7 305 NOK/tNH_3

The NPV of about 40.5 MNOK means that the production plant will have generated this as a profit after 15 years. This is approximately a 10% return of the initial investment. It is not before the 14th year that the plant will start to generate a profit. With the current price of ammonia, one will start to generate a profit at the 3rd year, and get about a 304% return of the initial investment after 15 years.

The LCOA was calculated to be 7 305 NOK per tonne of ammonia. This is lower than both the estimated and current price of ammonia. Therefore, an indication that the production plant will yield a profit.

As these results are based on multiple assumptions and estimates, they leave uncertainties and inaccuracies, which are discussed in Section 5.4. For a more nuanced economic analysis, multiple sensitivity analyses are applied to the case study.

Sensitivity analysis of LCOA

A sensitivity analysis of the LCOA values, where the price of electricity acts as the variable, can be seen in Figure 5.5. The four graph lines represent different sets of operational scenarios. For the baseline scenario, it was assumed that electricity is bought for 300 NOK/MWh and that the plant operates for 360 days. At this price, the LCOA sits at 7 305 NOK. This value rises all the way to 9 407 NOK if the price of electricity reaches 500 NOK/MWh.

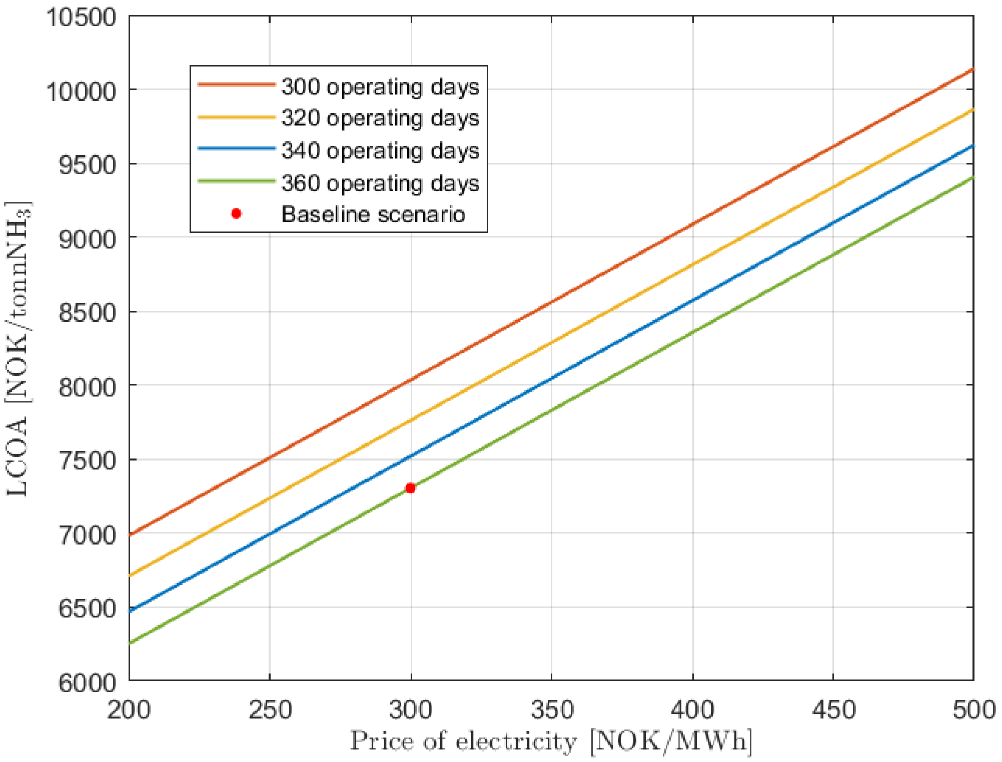

Figure 5.5: Plot of LCOA as a function of electricity price for different operation day scenarios

The graph line representing 360 running days gives the lowest LCOA values, independent of the price of electricity. The LCOA increases when the running days are decreased, and the different graph lines also have an equal slope. The highest LCOA value is found when the plant has 300 days of operation per year and when electricity is purchased at 500 NOK/MWh. The LCOA hits 10 140 NOK at this point. The lowest LCOA value of 6 253 NOK is consequently found at 360 running days and 200 NOK/MWh.

Sensitivity analysis of NPV

Figure 5.6 presents a sensitivity analysis projecting the years which the case study turns profitable. The factor that dictates if the project is profitable or not is a positive NPV, while the price of ammonia acts as the variable. A dip is seen at about 9 to 10 years, which is due to the increased cost incurred by the stack- and bed-replacement in the 10th year.

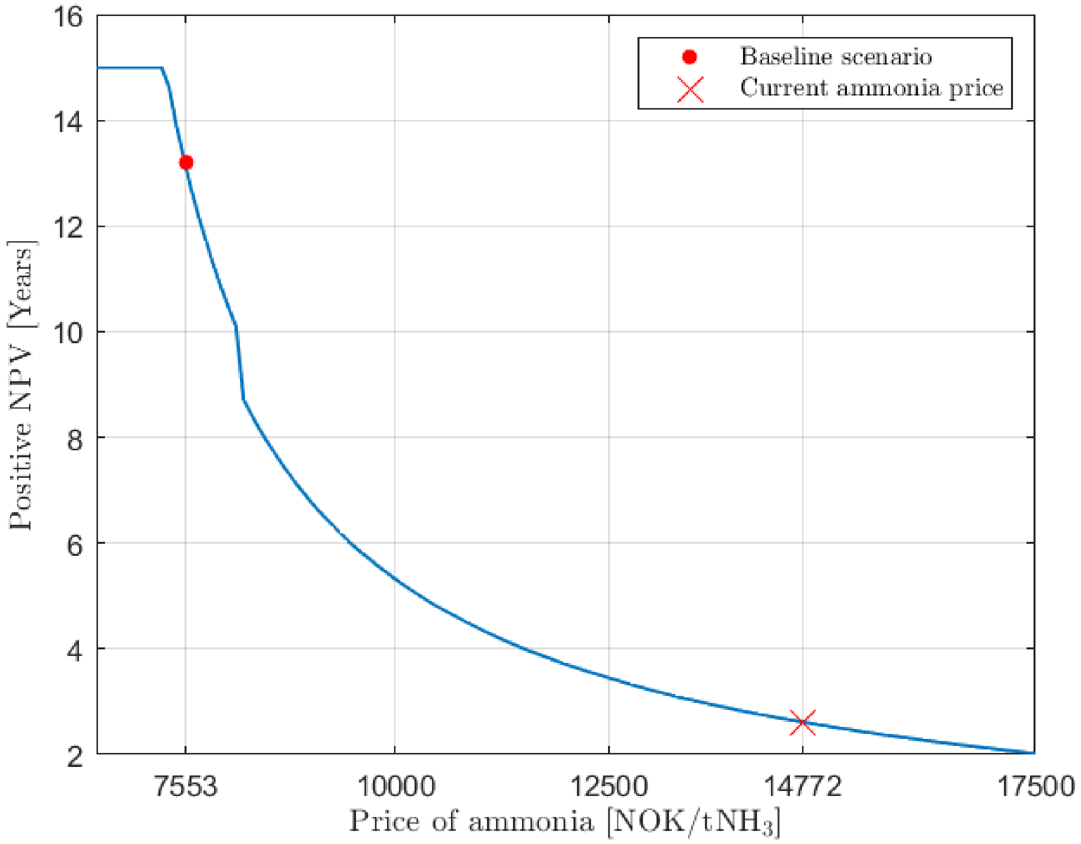

Figure 5.6: Plot of years it takes to achieve positive NPV for different ammonia prices

It takes more than 15 years to achieve a positive NPV when ammonia is sold for less than 7 305 NOK. This means that the project will never break even, considering that the project life-span is 15 years. The estimated price of ammonia for the baseline scenario is 7 553 NOK, which is a minimal difference from 7 305 NOK. Nonetheless, this price gives the project a positive return in 13.2 years. A relatively small increase in price will have a big effect, as is clear from the steep fall seen in Figure 5.6 from 7 305 NOK to about 9 000 NOK.

It would only take 2.6 years to reach a positive NPV if all the ammonia is sold for the present price of 14 772 NOK. The trend has mellowed out at this price range, such that a change in price does not affect the year of return that greatly.

A sensitivity analysis of the NPV at the end of the project's life-time was performed for different ammonia prices, seen in Figure 5.7. The different graph lines represent different days of running time. The baseline scenario assumes that the production plant has 360 days of operation every year. However, a few more scenarios were presented to gain a broader view.

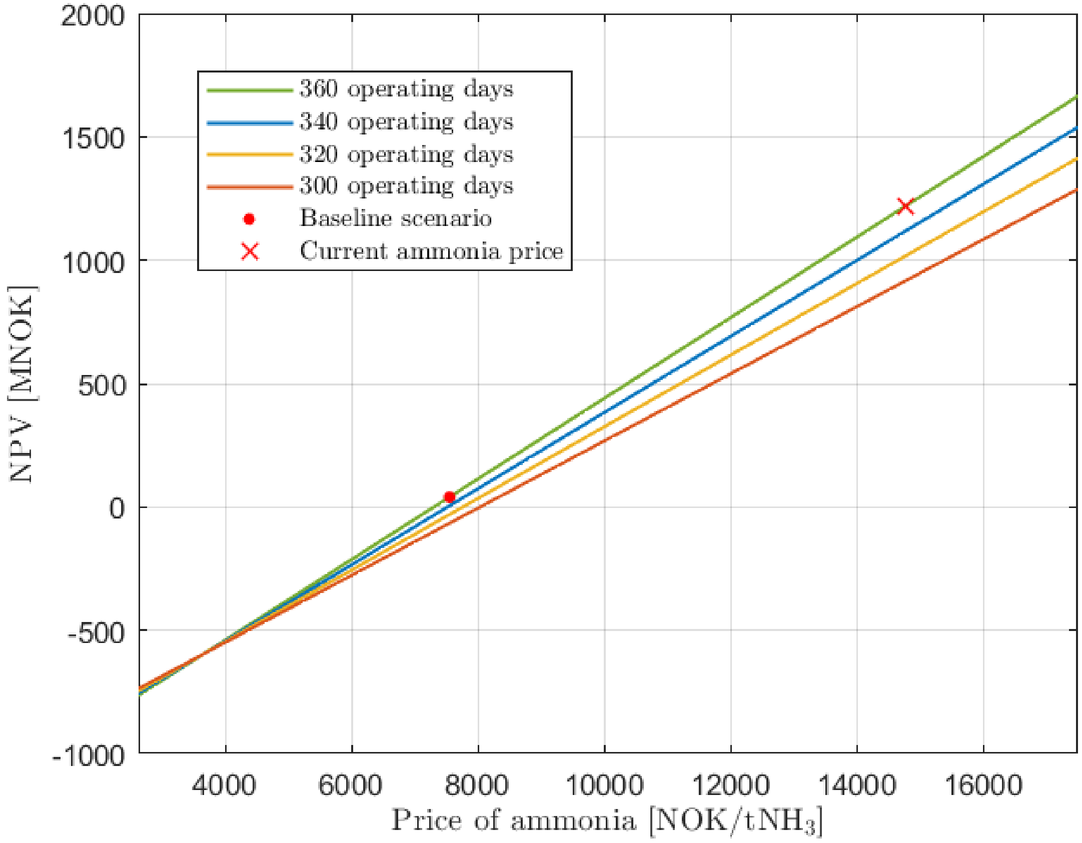

Figure 5.7: Plot of NPV as a function of ammonia price for different operation day scenarios

The graph lines converge when ammonia is sold for about 3 800 NOK. The slope of the graph representing 360 days of run time has a higher slope incline than that of the others. The NPV when ammonia is sold for the baseline estimate is approximately 40.5 MNOK. A stark contrast is seen when ammonia is sold for 14 772 NOK, which is the current price. The NPV at this price is around 1 219 MNOK. The NPV is 0 NOK when ammonia is sold for 7 305 NOK.

A change in production days has a heavy impact on the final NPV, as is more clear in Figure 5.8. This is essentially the same graph as in Figure 5.7, but focused around the baseline scenario to make it more clear. It is evident that a reduction from 360 to 300 operating days causes the NPV to drop from positive 40.5 MNOK to negative 65.7 MNOK.

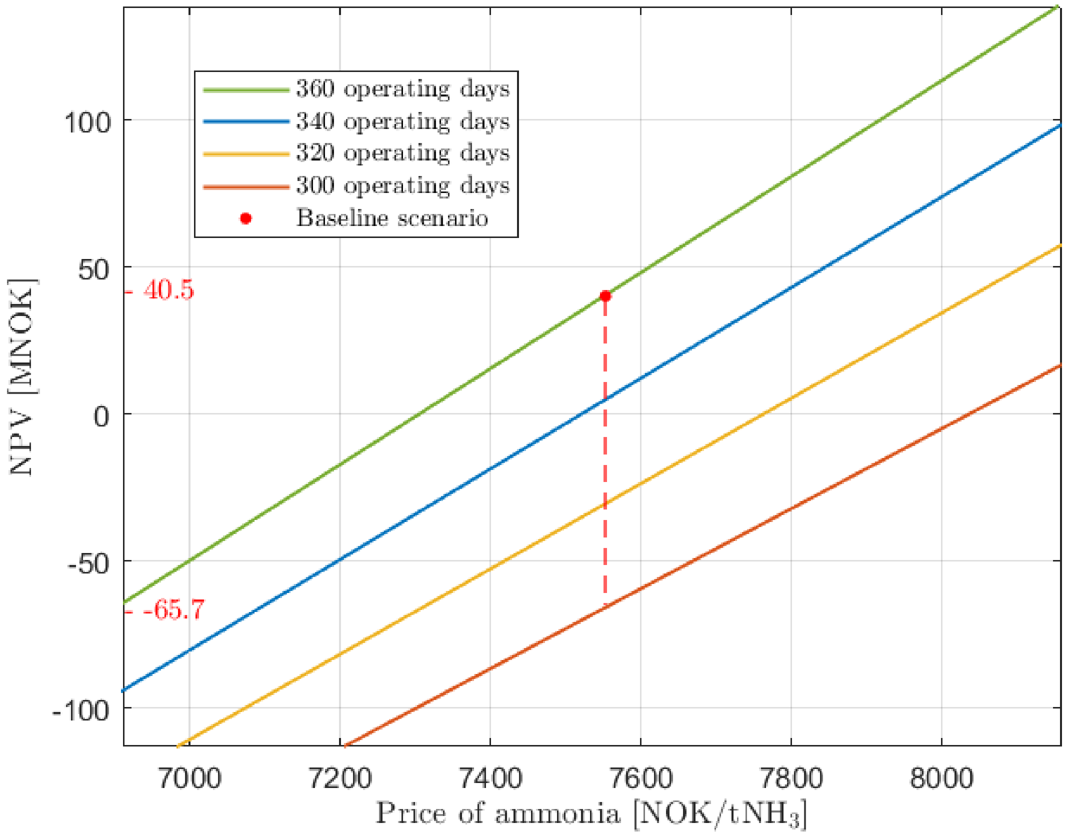

Figure 5.8: Focused version of Figure 5.7 around the baseline scenario

5.4 Review and discussion of the economic results

In this section, the economic results and factors are reviewed and discussed. Firstly, the material margin and the baseline scenario are discussed, before the LCOA and NPV sensitivity analyses are reviewed. Lastly, the importance of the ammonia price is analyzed before an extra source of income is evaluated.

Material margin

The material margins were presented in Figure 5.4. In the case of green ammonia production, the feed pertains to electricity and water, while ammonia is the product. It is clear from this initial assessment that the prices for both the feed and the ammonia would dictate the profitability of the case. The assessment also reflects the uncertainty of the case. If the price of ammonia stays at its present price, the production plant has a huge potential to profit from dealing with ammonia.

Ammonia production has great potential, given that the ammonia is sold at a high price. A more detailed techno-economic evaluation is needed to arrive at a more accurate price gauge, and a thorough risk assessment is imperative, considering the difficulty of estimating the future price trends of ammonia.

Baseline scenario uncertainties

The baseline scenario is carefully selected with the purpose of being the most accurate analysis possible. However, it should be strongly highlighted that there are several uncertainty factors included in this model. One could mention that such economic analyses of pilot projects are always somewhat of a guessing game, but the purpose is rather to get a rough estimate.

First and foremost, the prices of the components are mostly approximates. Conversions between different dynamic currencies make pricing inaccurate, as they are dependent on countless factors, including political and social concerns. Furthermore, many of the price estimates are based on literature that makes ambiguous assumptions or is imprecise about what is covered.

The selected price that ammonia is sold for is based on the historical price development. However, this assumption might be overly pessimistic if one considers the high price of today. On the other hand, it might have been optimistic to operate the production plant for 360 days. While this is not entirely impossible, it is a difficult target to achieve. A more conservative value might be in order.

It should also be noted that the case study assumes that the storage capacity is never reached and that all produced ammonia is sold. If the demand of ammonia from the maritime sector is very low, there might be possibilities to sell the ammonia to the agriculture sector instead. In this way, the assumption is more reasonable, nonetheless it still serves as an uncertainty.

A typical mistake when undertaking an economic analysis is to study every component separately, without considering the installation costs. There is a significant cost related to coordinating all the components, including control systems. While the main components have been accounted for in terms of the installation costs in this project, it is unlikely that every single component in the production facility is included. Unexpected complications may also lead to significant delays in the installation process and thus higher costs.

The economic analysis is also simplified due to the exclusion of both inflation and taxes. External supervisors advised against including such unpredictable factors, as it would overcomplicate the estimate. Inflation is the increase in prices and decline of purchasing power of a currency. Over the project's 15-year lifespan it is likely to have a notable impact.

Taxes are also indispensable for any business and would contribute to reducing potential profits. A reason to exclude taxes in NPV calculations is that the tax rates for a given business sector are not fixed. It is for instance not unlikely that renewable energy production might see a tax reduction to further motivate the development of sustainable solutions.

Moreover, pilot projects like the one in Nærøysund are subject to governing subsidies. Enova in Norway provides financial support for enterprises willing to invest in climate-friendly technology, particularly new and innovative solutions. Green ammonia is one such solution. As an example, the world's leading ammonia manufacturer, Yara, has received significant funds for a project including green ammonia at Herøya [128]. "Barents Blue" is another example; Horisont Energi together with Equinor and Haldor Topsoe among others, have projected to produce about 3 000 tonnes/day of ammonia, and have received almost half a billion NOK in financial support [129].

A small-scale production plant is often more likely to be affected by CAPEX rather than OPEX. This is reflected in the price of the electrolyzer and the building costs, which are the biggest cost contributors to the baseline scenario investment. Lowering these costs would decrease the final price of producing ammonia. This could be achieved by government subsidies or other forms of financial support, as mentioned previously.

The baseline scenario gave a NPV of about 40.5 MNOK, which equates to a 10% return on investment. This is quite a small profit when considering the lifetime of the venture. Nevertheless, this does not necessarily constitute as a failure. The expertise and knowledge gained from a pilot production facility in Nærøysund would be a greatly beneficial asset for NTE. These assets could act as a springboard for further expansion. It would also allow NTE to gain a foothold in the ammonia market.

LCOA - Levelized cost of ammonia

The price of electricity is crucial to the profitability of the baseline scenario, as is evident from the LCOA values. An increase in the electricity price will have a huge effect on the OPEX since a majority of the operational costs come from electricity. Cheap and readily available electricity will therefore decrease the LCOA and consequently increase the profit gained from ammonia production. Luckily, this happens to be the situation for the plant in Nærøysund, and as such the baseline scenario reflects quite a favorable energy price.

The LCOA benefits from an increase in operating days, in addition to cheap electricity. The two polar opposites presented in Figure 5.5 were LCOA values equal to 6 253 NOK and 10 140 NOK. The main contributor to this price difference is the price of electricity. However, the days of operation should not be overlooked. More operating days equals an increase in the production rate and energy consumption. With a higher production rate, the LCOA falls steadily, despite the elevated costs incurred by the additional energy consumption.

Year of positive NPV

A sensitivity analysis projecting the year in which NPV would return a positive value was presented in Figure 5.7. This helps highlight the importance of the ammonia price for the case study, unsurprisingly so, as it is the sole product of the production plant. A project such as this would see a net loss if the price is lower than 7 305 NOK, which is highly probable when factoring in the price of ammonia over the past decades.

The baseline scenario turns profitable after 13.2 years if the estimated price of 7 553 NOK is applied. This outlook might, however, not be sustainable for NTE or any other business for that matter, since the business would have to operate for 13 years without a profit. This could be very taxing on the company and its shareholders. This is of course dependent on the size and financial capability of the company.

There is also the likelihood of the company requiring a loan to facilitate the necessary capital for a project of this scale. This would incur additional costs due to interest rates, potentially leaving the project completely unprofitable at the estimated price.

NPV sensitivity analyses

The different graph lines in Figure 5.7 converge towards one NPV. This means that NPV is not affected by the number of operational days at this point. The deciding factor at this point is the price of ammonia, which is about 3 800 NOK. The convergence and trends share some resemblance to the marginal costs presented in Figure 5.4. The price that results in a net zero cost margin is just slightly above 3 800 NOK. It is therefore likely that the convergence happens, due to the production plant simply not making any money when ammonia is sold for 3 800 NOK.

If the selling price of ammonia falls below 3 800 NOK the plant might have to consider shutting down production for a while, as continuous production would only incur costs and not profits. Shutting down production might not be possible if the plant has any legal obligation to deliver ammonia, such as business contracts with a shipping company. If a deal like this were to take place, the plant should consider setting a fixed price for the ammonia so that the risk of selling ammonia at a loss is mitigated.

The NPV is 0 when ammonia is sold for 7 305 NOK at 360 operating days. The production plant will neither turn a profit nor a loss. 7 305 NOK is the exact same value as the LCOA for 360 operating days. This is a given, considering that the two values directly correlate with each other. The correlation can be seen in the two equations used to calculate the values, namely Equation 5.1 and Equation 5.2.

The fact that 360 operational days is used for the baseline scenario is a large uncertainty. Whether this is realistic or not is a complex inquiry, considering this pilot project is not yet realized. As shown in Figure 5.8, a reduction of 60 operational days turns the entire project unprofitable. More specifically, the reduction in NPV totals around 106.2 MNOK if all the other parameters stay unchanged. This further enlightens the importance of keeping the production plant operational at all times and, at the same time, how harmful unexpected downtime can be.

The Role of Ammonia Price

The price of ammonia is a large uncertainty factor for this case study. Accurately predicting the future price of the chemical compound is borderline impossible. The importance of the price can still be seen, even without an accurate price. It is evident that it needs to be high for the production plant to generate a profit. An increase in the ammonia price results in a higher NPV, so one might be inclined to think that an elevated ammonia price would be the best scenario.

Too high of a price could have detrimental effects. The profit margin would indeed be large, but the incentive for ships wanting to invest in ammonia as a fuel might not be there. The main goal of a ship is in most cases profit oriented. Using expensive fuel would therefore not be in their best interest. This would not be the case if ammonia has a monopoly over green alternative fuels, but this would be a highly unlikely instance.

There is little sense in operating a venture if no ships are in need of ammonia bunkering. A reasonable price would be necessary for an ammonia-based market to be successful and for the production in Nærøysund to be sustainable.

Industrial symbiosis through oxygen sales

Industrial symbiosis is when a byproduct from one industry can be used by another industry. Both the electrolyzer and air separation produce oxygen as a byproduct, as described in Chapter 2. In pisciculture, oxygen is needed to stimulate feeding behavior and breed healthy fish. As there are fish farms located in Nærøysund there is a possibility for industrial symbiosis between the two industries.

If one could sell oxygen to the pisciculture industry, it would add another source of income. This could increase the profit and make the production plant more desirable. As the oxygen is not used in the production process and would simply be thrown away, it seems like a foolproof way to increase the profit. However, it is important to remember that there will be some added costs as well. One would need to store, and transport the oxygen. Therefore, an analysis of potential income based on production capacity and oxygen demand versus extra costs, would be advised before taking any conclusions regarding the economics. From a sustainable, green perspective, utilizing so-called “waste” as a resource to reduce energy consumption is always favorable.

6 Recommendations for further work

In this chapter, recommendations for further work are presented. There were certain facets that were not extensively reviewed or unavailable at the time of this thesis. There were also uncertainties linked to the calculations performed in the case study. The underlying cause of this is a lack of time, expertise, or resources. It is advised that these details are accounted for if further work is to be made on the case study or similar studies.

More exact economic analysis

There were some economic aspects that could have been more precise throughout this thesis. Both inflation and taxes were excluded from the case study calculations. Employing these in the calculations would allow for more realistic results, and it is therefore encouraged to include them in further work.

Additionally, the prices of the components are mostly approximates. Many of the price estimates are based on literature that makes ambiguous assumptions or is imprecise about what is covered. By directly contacting manufacturers, a quote on all the machinery and necessary equipment costs could be found, and therefore make the calculations even more precise. A more exact OPEX can also be found from the manufacturer. This would make a location reliant case study increasingly valid.

Industrial symbiosis

The idea of industrial symbiosis from selling oxygen to local fish farms was briefly discussed earlier in this thesis. This is an interesting concept where one could accumulate extra profit from a byproduct which otherwise would go to waste. However, this was not included in the case study. A deeper analysis of this is recommended to discover whether it is a possible addition to the production plant. It has the potential to give both economic and sustainable benefits.

New technology

The SOEC has been covered in this thesis, and seems theoretically very suitable for green ammonia production. However, as it is not yet commercialized, it was not used in this case study. Haldor Topsoe is planning to have an operational production plant utilizing the SOEC by 2024. When this technology becomes available and proves to be effective, it is recommended to do a study where the SOEC is used in combination with the Haber-Bosch process. This is especially interesting for smaller scaled plants, as this concept has the potential to reduce the CAPEX significantly.

7 Conclusions

Ammonia is a carbon-free energy carrier that is considered green when produced by renewable energy. It is both easier and less energy-intensive to store than hydrogen. Additionally, it can be used in conventional combustion engines with little alterations needed. It is therefore suitable as an alternative marine fuel, especially for high sea ships.

However, gases that are harmful to the environment can be emitted through its combustion. If the emissions of N_2O and NO_x are extensive, a solution to neutralize them must be found if ammonia should be considered an environmental friendly fuel. Ammonia slip also has to be kept to a minimum.

One of the biggest drawbacks of ammonia as a fuel is its toxicity. Thorough risk assessment and stringent regulations need to be put forth for ammonia to succeed as a marine fuel. There are several operable ships capable of transporting ammonia. Retrofitting these ships would therefore serve as a foundation towards safe ammonia-ready vessels.

Stricter emission regulations will accelerate both the production and demand for green ammonia. The importance of such a market and an effective infrastructure is vital for a production facility like the one in Nærøysund to succeed.

From the case study it was found that an alkaline electrolyzer, PSA, and a Haber-Bosch unit were the optimal technology choices for a production plant in Nærøysund. The baseline scenario of the case study gave a small profit when considering the lifetime of the venture. The merit of the case study was rather found to be the expertise and knowledge gained from a pilot production facility. These assets could act as a springboard for further expansion. It would also allow NTE to gain a foothold in the ammonia market.

The results gained from the study show that the production plant is heavily reliant on the price of ammonia, price of energy, and number of operational days. If the current price level of ammonia proves to be maintained, larger profits are expected. A very high ammonia price would result in a great profit, however, this is most likely not sustainable for the market. The LCOA benefits from a lower price of renewable energy, which luckily is available at the production plant.

Considering all the aspects of green ammonia, it is viable as a carbon-free alternative marine fuel. Furthermore, green production at small-scale is both feasible and sustainable.

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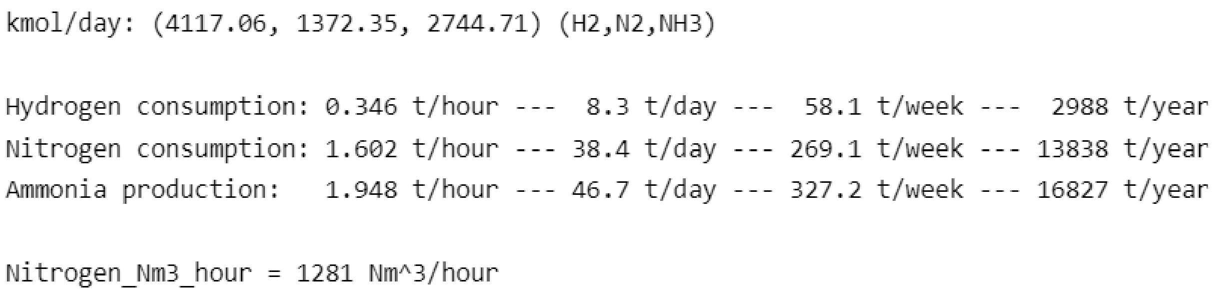
A Python script for stoichiometric calculations

```python
#Reaction equation:  N_2 + 3H_2 <=> 2NH_3
m_H2 = 8.300 #t/day

#molar mass [g/mol]:
M_H2 = 2.016
M_N2 = 28.01
M_NH3 = 17.03

#number of moles per tonnes per day:
n_H2 = (m_H2) / M_H2
n_N2 =  1/3 * n_H2
n_NH3 = 2/3 * n_H2
print(f'kmol/day: {round(n_H2*1000,2),round(n_N2*1000,2),round(n_NH3*1000,2)} (H2,N2,NH3)')
print()

#mass [t/day]:
m_H2 = m_H2
m_N2 = M_N2 * n_N2
m_NH3 = M_NH3 * n_NH3

#mass [t/hour]
m_H2_hour = m_H2/24
m_N2_hour = m_N2/24
m_NH3_hour = m_NH3/24

#mass [t/week] *for the instance of all running days
m_H2_week = m_H2*7
m_N2_week = m_N2*7
m_NH3_week = m_NH3*7

#mass [t/year] *with an estimated 360 running days
m_H2_year = m_H2*360
m_N2_year = m_N2*360
m_NH3_year = m_NH3*360

print(f'Hydrogen consumption: {round(m_H2_hour,3)} t/hour ---  {round(m_H2,1)} t/day ---  {round(m_H2_week,1)} t/week ---  {round(m_H2_year)} t/year')
print(f'Nitrogen consumption: {round(m_N2_hour,3)} t/hour --- {round(m_N2,1)} t/day --- {round(m_N2_week,1)} t/week --- {round(m_N2_year)} t/year')
print(f'Ammonia production:   {round(m_NH3_hour,3)} t/hour --- {round(
```

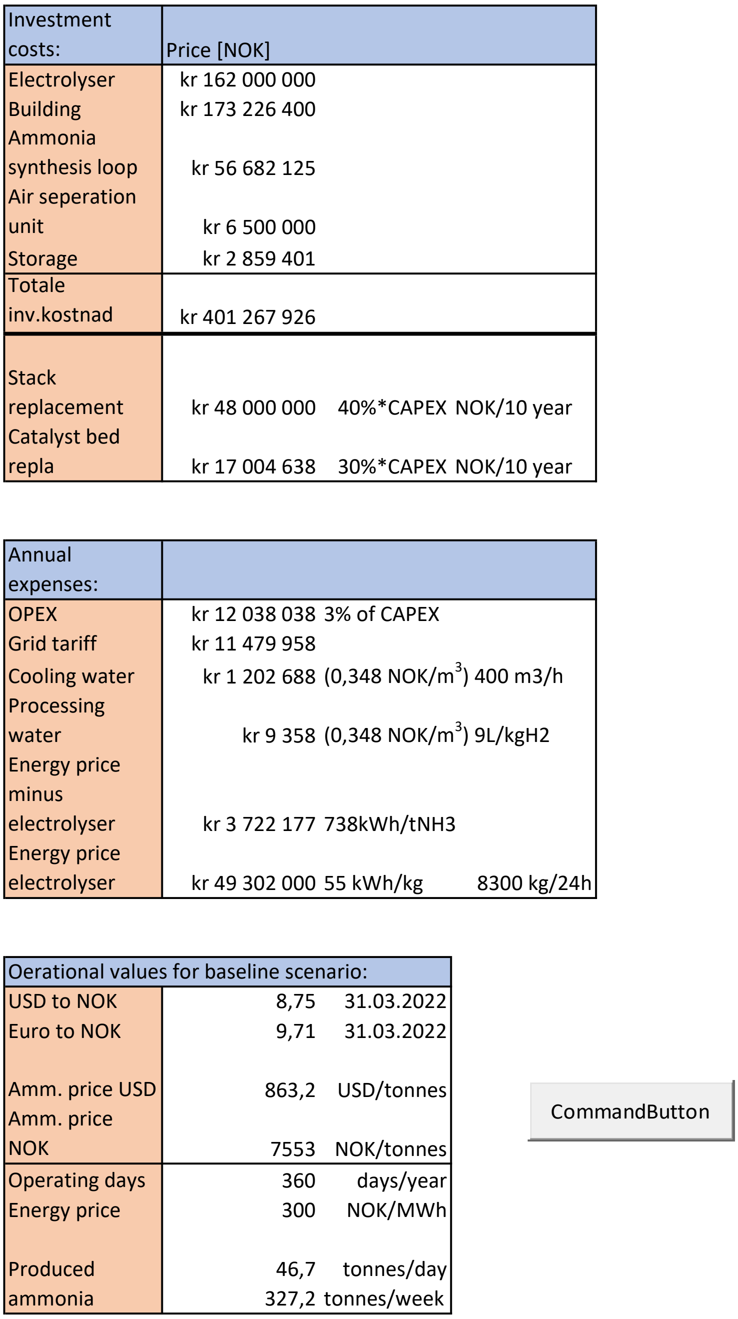
```python
m_NH3,1)} t/day --- {round(m_NH3_week,1)} t/week --- {round(m_NH3_year)} t/year')
print()

#Converting nitrogen flowrate to Nm3/hour, where 1kg Nitrogen (N_2) equals 0.7996 Nm3 gas at [1atm, 0 deg.Celcius]
print(f'Nitrogen_Nm3_hour = {round(m_N2_hour*1000*0.7996)} Nm^3/hour')
```

Output:



```
kmol/day: (4117.06, 1372.35, 2744.71) (H2,N2,NH3)

Hydrogen consumption: 0.346 t/hour ---  8.3 t/day ---  58.1 t/week ---  2988 t/year
Nitrogen consumption: 1.602 t/hour --- 38.4 t/day --- 269.1 t/week --- 13838 t/year
Ammonia production:   1.948 t/hour --- 46.7 t/day --- 327.2 t/week --- 16827 t/year

Nitrogen_Nm3_hour = 1281 Nm^3/hour
```

B Excel and VBA



Investment costs:	Price [NOK]		
Electrolyser	kr 162 000 000		
Building	kr 173 226 400		
Ammonia synthesis loop	kr 56 682 125		
Air seperation unit	kr 6 500 000		
Storage	kr 2 859 401		
Totale inv.kostnad	kr 401 267 926		
Stack replacement	kr 48 000 000	40%*CAPEX	NOK/10 year
Catalyst bed repla	kr 17 004 638	30%*CAPEX	NOK/10 year

Annual expenses:			
OPEX	kr 12 038 038	3% of CAPEX	
Grid tariff	kr 11 479 958		
Cooling water	kr 1 202 688	(0,348 NOK/m^3) 400 m3/h	
Processing water	kr 9 358	(0,348 NOK/m^3) 9L/kgH2	
Energy price minus electrolyser	kr 3 722 177	738kWh/tNH3	
Energy price electrolyser	kr 49 302 000	55 kWh/kg	8300 kg/24h

Oerational values for baseline scenario:		
USD to NOK	8,75	31.03.2022
Euro to NOK	9,71	31.03.2022
Amm. price USD	863,2	USD/tonnes
Amm. price NOK	7553	NOK/tonnes
Operating days	360	days/year
Energy price	300	NOK/MWh
Produced ammonia	46,7	tonnes/day
	327,2	tonnes/week

Net present value :

(kr = NOK)

Year:	0	1	2	3	4	5	6
Capex:	-kr 401 267 926						
Stack and catalyst bed replacment:							
OPEX:		-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038
Grid tariff:		-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958
Cooling water:		-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688
Processing water:		-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358
Energy price minus electrolyser:		-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177
Energy price electrolyser:		-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000
Profits from sales:		kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036
Sum:	-kr 401 267 926	kr 49 226 817	kr 49 226 817	kr 49 226 817	kr 49 226 817	kr 49 226 817	kr 49 226 817
NPV per year:	-kr 401 267 926	-kr 354 827 532	-kr 311 015 841	-kr 269 684 056	-kr 230 691 806	-kr 193 906 665	-kr 159 203 701

Discount rate:	6 %
NNV:	kr 40 536 928
LCOA:	kr 7 305

Ammonia produced inc. Discount rate							
NH3 tonnes/year:	0,00	15860,38	30823,00	44938,68	58255,36	70818,26	82670,06
Total costs:	-kr 401 267 926	-kr 474 620 963	-kr 543 821 941	-kr 609 105 882	-kr 670 694 506	-kr 728 796 982	-kr 783 610 638

7	8	9	10	11	12	13	14	15
			-kr 65 004 638					
-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038	-kr 12 038 038
-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958	-kr 11 479 958
-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688	-kr 1 202 688
-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358	-kr 9 358
-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177	-kr 3 722 177
-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000	-kr 49 302 000
kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036	kr 126 981 036
kr 49 226 817	kr 49 226 817	kr 49 226 817	-kr 15 777 820	kr 49 226 817	kr 49 226 817	kr 49 226 817	kr 49 226 817	kr 49 226 817
-kr 126 465 056	-kr 95 579 542	-kr 66 442 265	-kr 75 252 517	-kr 49 320 444	-kr 24 856 224	-kr 1 776 772	kr 19 996 297	kr 40 536 928

93851,00	104399,05	114350,05	123737,78	132594,14	140949,18	148831,31	156267,27	163282,33
-kr 835 321 635	-kr 884 105 594	-kr 930 128 196	-kr 1 009 843 996	-kr 1 050 803 949	-kr 1 089 445 414	-kr 1 125 899 626	-kr 1 160 290 392	-kr 1 192 734 511

```
VERSION 1.0 CLASS
BEGIN
  MultiUse = -1  'True
END
Attribute VB_Name = "Ark1"
Attribute VB_GlobalNameSpace = False
Attribute VB_Creatable = False
Attribute VB_PredeclaredId = True
Attribute VB_Exposed = True
Private Sub CommandButton_Click()

Dim i As Integer, y As Integer, x As Integer, temp As Integer
Dim intUpper As Integer, intLower As Integer
Dim result As Double

'The loop running 4 times is used to run the code for 360 , 340 , 320 and 300 operating days
For x = 1 To 4
    Cells(29, 4).Value = 300

    temp = 7 + (x * 2)
    Cells(28, 4).Value = 360 - (x - 1) * 20 'This value is set so that Ark1 is reset to the baseline scenario
    For i = 1 To 171
        'The following values print the cost of ammonia and the NPV
        Cells(26, 4).Value = 300 + (i - 1) * 10
        Cells(2 + i, 8).Value = (300 + (i - 1) * 10) * Worksheets("Ark1").Range("D24")
        Cells(2 + i, temp).Value = Worksheets("Ark2").Range("C19") * 10 ^ (-6)

        y = 1
        result = 0
        While y < 16    'This while - loop checks for what year the NPV turns positive
            intLower = Worksheets("Ark2").Cells(16, 2 + y) * 10 ^ (-6)
            intUpper = Worksheets("Ark2").Cells(16, 3 + y) * 10 ^ (-6)

            If intUpper > 0 Then
            result = (y - 1) + (1 / (intUpper - intLower)) * (-intLower)
            y = 20
            Else
            result = 15
            End If

```

```
            y = y + 1
        Wend

        Cells(2 + i, temp + 1).Value = result

    Next i


    For i = 1 To 61
        Cells(29, 4).Value = 200 + (i - 1) * 5
        Cells(2 + i, 17).Value = 200 + (i - 1) * 5
        Cells(2 + i, 17 + x).Value = -Worksheets("Ark2").Range("R24") / Worksheets("Ark2").Range("R23")
    Next i
Next x

'The following values are set so that the excel sheets default back to the baseline scenario
Cells(28, 4).Value = 360
Cells(29, 4).Value = 300
Cells(26, 4).Value = 863.2


End Sub
```

C MATLAB script for the result plots

```
close all; clear; clc

T = readtable('okoOversikt.xlsm');



%%%%%%%%%%360 dager%%%%%%%%%%
spotPrisAmmoniakk = [];
NNV = [];
yearOnReturn = [];
strompris = [];
LCOA = [];


for i = 1:(height(T)-33)
    newSpotPris = str2num(cell2mat(T{(33+i),1}));
    spotPrisAmmoniakk(i) = newSpotPris;

    newNNV = str2num(cell2mat(T{(33+i),2}));
    NNV(i) = newNNV;

    newYearOnReturn = str2num(cell2mat(T{(33+i),3}));
    yearOnReturn(i) = newYearOnReturn;


    if str2num(cell2mat(T{(33+i),7})) ~= 0
        newStrompris = str2num(cell2mat(T{(33+i),7}));
        strompris(i) = newStrompris;

        newLCOA = str2num(cell2mat(T{(33+i),8}));
        LCOA(i) = newLCOA;
    end
end


%%%%%%%%%%340 dager%%%%%%%%%%
NNV340 = [];
yearOnReturn340 = [];
LCOA340 = [];


for i = 1:(height(T)-33)
    newNNV = str2num(cell2mat(T{(33+i),10}));
```

```
    NNV340(i) = newNNV;

    newYearOnReturn = str2num(cell2mat(T{(33+i),11}));
    yearOnReturn340(i) = newYearOnReturn;


    if str2num(cell2mat(T{(33+i),7})) ~= 0
        newLCOA = str2num(cell2mat(T{(33+i),16}));
        LCOA340(i) = newLCOA;
    end
end


%%%%%%%%%%320 dager%%%%%%%%%%
NNV320 = [];
yearOnReturn320 = [];
LCOA320 = [];


for i = 1:(height(T)-33)
    newNNV = str2num(cell2mat(T{(33+i),12}));
    NNV320(i) = newNNV;

    newYearOnReturn = str2num(cell2mat(T{(33+i),13}));
    yearOnReturn320(i) = newYearOnReturn;


    if str2num(cell2mat(T{(33+i),7})) ~= 0
        newLCOA = str2num(cell2mat(T{(33+i),17}));
        LCOA320(i) = newLCOA;
    end
end


%%%%%%%%%%300 dager%%%%%%%%%%
NNV300 = [];
yearOnReturn300 = [];
LCOA300 = [];


for i = 1:(height(T)-33)
    newNNV = str2num(cell2mat(T{(33+i),14}));
    NNV300(i) = newNNV;

    newYearOnReturn = str2num(cell2mat(T{(33+i),15}));
```

```
    yearOnReturn300(i) = newYearOnReturn;


    if str2num(cell2mat(T{(33+i),7})) ~= 0
        newLCOA = str2num(cell2mat(T{(33+i),18}));
        LCOA300(i) = newLCOA;
    end
end




figure(1)
plot(spotPrisAmmoniakk,NNV, 'LineWidth', 1.25)
ax = gca;
ax.YAxis.Exponent = 0;
ax.XAxis.Exponent = 0;
hold on
plot(spotPrisAmmoniakk,NNV340, 'LineWidth', 1.25)
plot(spotPrisAmmoniakk,NNV320, 'LineWidth', 1.25)
plot(spotPrisAmmoniakk,NNV300, 'LineWidth', 1.25)
plot(7553,40.2,'ro')
plot(14772,1220,'ro')
ylim([-1000 2000])
xlim([spotPrisAmmoniakk(1) spotPrisAmmoniakk(end)])
grid on
ylabel('NPV [MNOK]','Interpreter','latex')
xlabel('Price at which ammonia is sold [NOK/mtonnNH$_{3}$]','Interpreter','latex')

%Grafen starter med de forste verdiene som ikke har return on investment,
%vil fjerne disse saa bruker denne lokken

%%%Funker ikke lenger, siden det som var et problem ikke er et problem
%%%lenger
i = 1;
xLimStart = 0;
while i < length(yearOnReturn)
    if yearOnReturn(i) < 15
        xLimStart = spotPrisAmmoniakk(i);
        i = length(yearOnReturn)+10;
    end
    i = i+1;
end
```

```
figure(2)
plot(spotPrisAmmoniakk,yearOnReturn, 'LineWidth', 1.25, 'HandleVisibility','off')
ax = gca;
ax.YAxis.Exponent = 0;
ax.XAxis.Exponent = 0;
hold on
plot(7553,13.2,'ro')
plot(14772,2.62,'rx')
xlim([6500 17500])
xticks([7553 10000 12500 14772 17500])
ylabel('Positive NPV [Years]','Interpreter','latex')
xlabel('Price of ammonia [NOK/tNH$_{3}$]','Interpreter','latex')
grid on

figure(3)
plot(strompris,LCOA300, 'LineWidth', 1.25)
hold on
plot(strompris,LCOA320, 'LineWidth', 1.25)
plot(strompris,LCOA340, 'LineWidth', 1.25)
plot(strompris,LCOA, 'LineWidth', 1.25)
plot(300,7304.7372,'ro')
ax = gca;
ax.YAxis.Exponent = 0;
ax.XAxis.Exponent = 0;
ylabel('LCOA [NOK/tonnNH$_{3}$]','Interpreter','latex')
xlabel('Price of electricity [NOK/MWh]','Interpreter','latex')
grid on



%55kWh/kg hydrogen, 738kWh/tNH3

energyPrTonneNH3 = (55*10^3*3/17+738)*10^(-3);    %[MWh/tNH3]
diff1750 = [];
diff3938 = [];
diff7553 = [];
diff11163 = [];
diff14772 = [];

for i = 1:4
    rawProductionCost = energyPrTonneNH3*(100+(5-i)*100)+72.1;  %72.1 = vannkostnad
    diff1750(i) = 1750-rawProductionCost;
    diff3938(i) = 4000-rawProductionCost;
```

```
    diff7553(i) = 7553-rawProductionCost;
    diff11163(i) = 11163-rawProductionCost;
    diff14772(i) = 14772-rawProductionCost;

end

figure(4)
bar([1750, 3938, 7553, 11163, 14772],[diff1750; diff3938; diff7553;
   diff11163; diff14772])
ax = gca;
ax.YAxis.Exponent = 0;
ax.XAxis.Exponent = 0;
ylabel('Material margin [NOK]','Interpreter','latex')
xlabel('Price of ammonia [NOK/mtonnNH$_{3}$]','Interpreter','latex')
grid on
```

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