Ammonia as fuel in maritime energy systems

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Bachelor's thesis in Energy Technology

Bergen, Norway 2021

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IMM 2021-M66

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Norsk tittel:	Ammoniakk som drivstoff i maritime energisystemer
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Study program:	Energy Technology
Date:	May 2021
Report number:	IMM 2021-M66
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Antall filer levert digitalt:	2

Preface

This report is a Bachelor of Science degree in the field of Energy technology. The bachelor is written on behalf of Western Norway's University of Applied Sciences (HVL), at the Department of Mechanical and Marine Engineering (IMM). The internal supervisor is associate professor Jonathan Økland Torstensen of HVL. The thesis was assigned by Ocean Hyway Cluster (OHC), and the external supervisor is Senior Advisor Renewable at OHC, Trond Strømgren.

We would like to thank our external supervisor Trond Strømgren for providing literature and guidance throughout the project, especially the access to OHC's database has been very helpful. We also want to thank our internal supervisor Jonathan Torstensen for his academic guidance and for providing relevant literature.

Abstract

The maritime sector is responsible for a significant portion of the globes CO_2 emissions. At the United Nations Climate Change Conference in 2015, the International Maritime Organization (IMO) set goals to reduce the CO_2 emissions from the maritime sector by 50% to avoid a irreversible and destructive change in the globes climate. As most of the emissions are caused by the combustion of fossil fuels, it is clear that more sustainable options are needed. Hydrogen is already used but has limitations. Ammonia (NH_3) has a higher volumetric energy density, hence it might be more feasible for deep-sea shipping. Ammonia does not have any CO_2 emission during combustion, and it can be produced with electricity from renewable energy sources. As of today, most ammonia is produced by cracking natural gas, which leads to CO_2 emissions, therefore the production needs to be rearranged to use electricity from renewable energy sources, which would also require an increase in renewable energy production, such as wind turbines and solar photovoltaics (PV).

This report reviews ammonias feasibility as a fuel in the maritime sector. Providing general information about its properties, barriers such as its toxic nature, production pathways, environmental advantages, risks and hazards, and different propulsion technologies. The report reviews ammonias efficiency in three different Fuel Cells (FC), Internal Combustion engine, and Gas Turbine, and compare the alternatives against each other from an economical perspective as well as the efficiencies. The development and status of the field is presented through reviews of relevant projects.

Sammendrag

Den maritime sektor er ansvarlig for store CO_2 utslipp årlig. På FNs klimaendringkonferanse(?) i 2015, satt IMO seg et mål om å halvere utslipp fra den maritime sektor innen 2050, for å unngå irreversible og destruktive klimaendringer. Siden mesteparten av utslippene kommer fra forbrenning av fossile drivstoffer, er behovet for et nullutslippsdrivstoff stort. Hydrogen er allerede testet og i bruk noen steder, men har tydelige begrensninger. Ammoniakk (NH_3) er en alternativ hydrogenbærer, og har høyere volumetrisk energitetthet i tillegg til at det er enklere å lagre/frakte. Dette gjør at ammoniakk kan være et godt alternativ spesielt i maritim sektor. Ammoniakk slipper ikke ut CO_2 ved forbrenning, og det kan produseres med elektrisitet fra fornybar energi. Foreløpig produseres mesteparten av ammoniakk ved å "cracke" naturgass, som fører til CO_2 utslipp, derfor må produksjonen legges om til å baseres på fornybar energi om ammoniakk skal brukes som et bærekraftig drivsstoff. Det vil også kreve en økning i produksjon av fornybar energi som solceller og vindturbiner.

Oppgaven gjennomgår ammoniakks gjennomførbarhet som drivstoff i maritim sektor. Det blir gitt generell informasjon om ammoniakks fysiske egenskaper, barrierene, som dens giftige natur, produksjonsveier, miljøgevinster, risikoer og farer, og forkjellige fremdriftsteknologier. Rapporten går gjennom ammoniakks forveentede virkningsgrad i tre forskjellige brenselceller, intern forbrenningsmotor, og gassturbin. Utviklingen og statusen i feltet er presenter ved gjennomgang av relevante pågående prosjekter.

Table of contents

Abbreviations

AB - After Burner

ADR - Ammonia Decomposition Reaction

AFC - Alkaline Fuel Cell

AHE - Ammonia Heat Exchanger

AIST - Advanced Industrial Science Technology

Atm – Atmosphere (pressure measurement)

Bn - Billions

CCS - Carbon Capture and Storage

CHE - Cathodic Heat Exchanger

CHP - Combined Heat and Power system

CI – Compression Ignition

CO - Carbon Monoxide

CO_2 – Carbon Dioxide

DPF – Diesel Particulate Filter

EJ - Exajoule (10^{18}J)

FC – Fuel Cell

GE - General Electric

GHG - Green House Gasses

GJ - Gigajoules

GWP - Global Warming Potential

GW - Gigawatt (10^9)

H_2 - Hydrogen

H_2O - Water

HAZID - Hazard Identification

HB - Process - The Haber - Bosch Process

HFO - Heavy Fuel Oil

HT - High Temperature

IGF Code - The international Code of safety for ships using gasses or other low flashpoint fuels

IMO - International Maritime Organization

ICE - Internal Combustion Engine

K - Kelvin (Absolute temperature)

Kg - Kilograms

KOH – Potassium Hydroxide

kW - Kilowatt (10^3 Watt)

LCA - Life Cycle Assessment

LHV – Lower Heating Value

LNG – Liquid Natural Gas

LOHC - Liquid Organic Hydrogen Carriers

LPG - Liquified Petroleum Gas

LSHFO – Low-Sulphur Heavy Fuel Oil

LT – Low Temperature

MDO - Marine Diesel Oil

Mg - Milligrams

MGO - Marine Gas Oil

MJ - Megajoules

N_2 - Nitrogen

N_2O – Nitrous Oxide

NH_3 - Chemical name for Ammonia

NO_x - Nitrogen Oxides

O_2 - Oxygen

OHC - Ocean Hyway Cluster

PEMFC - Proton Exchange Membrane Fuel Cell

PPM – Parts Per Million

PV – Photovoltaics (solar cells)

R & D - Research and development

SCR – Selective Catalytic Reduction

SI – Spark Ignition

SOEC - Solide Oxide Electrolysis Cell

SOFC - Solide Oxide Fuel Cell

SO_x – Sulphur Oxides

STP - Standard Temperature and Pressure

t - Tonnes

TWh - Terawatt hour (tera = 10^{12})

UN - United Nations

USD – US Dollars

1. Introduction

Deep-sea shipping is the most cost- and fuel-efficient method for transportation for large quantity goods. Heavy fuel oil (HFO) is and has been the industry standard since the 1950’s due to low cost and high availability. [1] The emission of greenhouse gases (GHG) into the atmosphere caused by human activity (e.g. combustion of fossil fuels) is proven to have a negative effect on the climate of the globe. [2]

At the United Nations (UN) Climate Change Conference in 2015, the International Maritime Organization (IMO) declared a progressive aim to reduce greenhouse gas emissions in the shipping sector by 50% within 2050, compared to 2008. This measure is part of the plan to keep the global average temperature increase below 2°C above pre-industrial levels.[3] To reach the target set by IMO in 2015 there must be a transition to carbon-neutral energy sources in the shipping sector.

There is plenty of technology available to produce renewable energy instead of burning petroleum. Solar-, and wind-power are both regarded as renewable energy and has had significant growth in recent years. An issue for these is weather-based production. Therefore, it is necessary to store the energy for it to be as transportable and applicable as petroleum. Lithium-ion battery technology has made it easier to use renewable energy in small mobile and remote applications (e.g. cars), but it is not feasible for the sizes of heavy transport ships due to a large weight to energy ratio. Due to the need of clean energy, hydrogen and other hydrogen derivatives such as ammonia (NH_3) has gained interest as fuel alternatives in maritime energy systems.

Ammonia (NH3) is a carbon- and sulfur-free molecule. Hence, if the ammonia is clean, there is no CO_2 or SO_x emission when burned, although there is some NO_x emission. Ammonia is now mainly produced by cracking natural gas, which means there is currently CO_2 emission in the production phase. Although ammonia has gained traction as a fuel alternative it is not without challenges, such as toxicity and difficult combustion properties are some of the challenges.

This report is a bachelor thesis in the study program energy technology at Western Norway University of applied sciences. The project is an initiative by Ocean Hyway Cluster, Norway’s leading network for maritime hydrogen.

1.1 Aim and objectives

Ammonia as fuel is in the research and development (R&D) stage. To determine ammonias feasibility as deep-sea fuel, there are several questions that needs answering.

The aim of this report has three main points:

- Give a general description of ammonia
- Compare ammonias energy efficiency when used in fuel cells, internal combustion engines, and turbines in large ships
- Specific descriptions of different ammonia projects involving deep-sea shipping to show examples of R&D activities

To answer these aims tidily and thoroughly, they are broken down into objectives, as following.
The report investigates ammonias efficiency as fuel in maritime energy systems, more specifically in internal combustion engines (ICE), turbines, and fuel cells in large ships. The three technologies are compared regarding efficiency and other relevant factors such as maturity, cost, and harmful emissions. The efficiency results are also compared with traditional carbon-based fuel. Ammonias current situation as a fuel in the R&D state is presented by reviewing several ammonia projects. Based on the findings, an outlook of how ammonias infrastructure and role in the maritime energy market might look in the future. An environmental assessment is done, comparing ammonias environmental footprint to traditional fuels. The barriers to the use of ammonia as fuel in maritime energy systems are investigated, including health and environmental risks, and economic feasibility.

All objectives are discussed in a context of a maritime application.

1.2 Methodology

1.2.1 Literature study

A literature study is conducted to gather information and data on the subject. This is done by collecting information from relevant literature, including scientific reports, research papers and articles. The data collected is used to determine ammonias feasibility and efficiency as a marine fuel. Data collection is also a fundamental part to enable further calculations on the efficiency of ammonia as fuel in large ships, which is the main part in this report.

To gather information, Google, Google Scholar, Science Direct, Web of Science and Oria has been used as search engines. In addition to these, Trond Strømgren granted access to Ocean Hyway Cluster's database which contained several relevant reports. Both Trond Strømgren and Jonathan Torstensen, the external and internal supervisors respectively assisted with relevant literature. The validity of the sources used have been considered and investigated to maintain a neutral and fact-based report. Key words for the research are "ammonia" combined with "fuel", "fuel cell", "combustion engine", "turbine", "efficiency", "energy carrier" and "sustainable fuel".

1.2.2 Sources of error

Ammonia as a fuel is in the research & development (R&D) state, and it has yet to be commercialized. Therefore, the numbers used in the efficiency chapter are either theoretical or from the laboratory and might differ from how ammonia will perform in a real marine application. In addition, the efficiencies differ from engine to engine, so to determine the system efficiencies is impossible, hence the efficiencies found are a pointer to what can be expected with current technologies. The technology concerning ammonia in fuel cells as well as the combustion of ammonia is currently being development by major companies in the energy sector, and due to competition, a lot of information is kept secret.

2. Background

2.1 A brief history of ammonia as fuel

Ammonia gained traction as fuel during the second world war. The interest came due to a shortage of diesel fuel for buses in Belgium, 1942, which led to a search for alternative fuels. After an intensive investigation of alternatives, they tried using ammonia, which had been patented as fuel as far back as 1905, in combination with coal gas due to ammonias ignition difficulties. This resulted in 6 buses successfully running 100.000 km on ammonia between April 1943 and May 1945, without any accidents or spills. When the war ended in 1945, Belgium again had access to diesel and gasoline, and the use of ammonia as fuel stopped. [4]

In 1962 ammonia was used as rocket fuel in the fastest aircraft ever built, the X-15, and there has been several small-scale projects converting vehicles to run on ammonia, for instance in Canada in 1981 and in 2008 the NH_3 fuel association converted a 2008 Ford Crown Victoria and a 2007 Ford Truck. [5]

Ammonia was researched quite a bit in the 1960's but as petroleum was widely available and cheap, it was deemed not to be feasible as long as petroleum fuels were available. [6] It was reports on the subject to some extent throughout the 70's, 80's and 90's but as the need to decarbonize didn't have the traction it has today it never led to any major projects.

2.2 Hydrogen

Hydrogen is a promising alternative as an energy carrier and as a fuel, in a future energy market based on renewable energy sources. H_2 is a very small molecule and will therefore leak easier than other substances. Hydrogen can be in both compressed and liquid state.

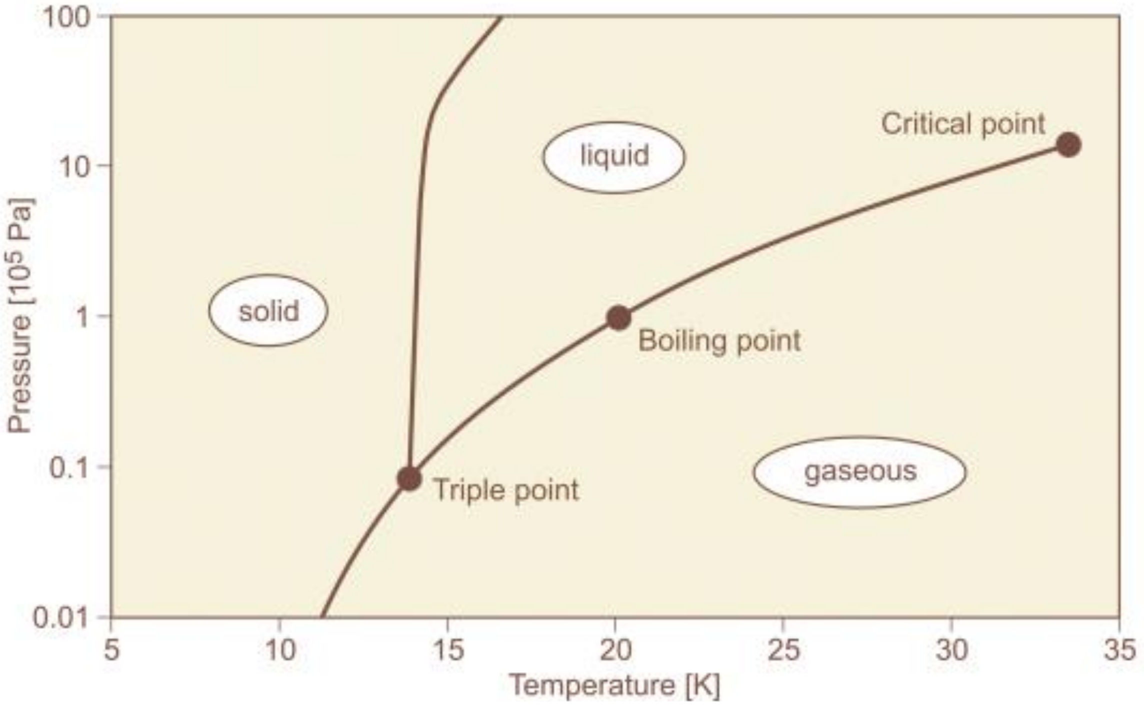


Figure 1; Phase diagram for Hydrogen. [54]

In figure 1, the phase diagram illustrates how hydrogen behaves in specific temperatures and pressures. The triple point indicates that for one specific temperature and pressure, hydrogen can be in all the different states at the same time. The temperatures are measured in Kelvin and 20 Kelvin equals -253,15 °C. (0 Kelvin = -273,15 °C).

There are advantages and disadvantages for liquid- and compressed hydrogen. One important difference is that liquid hydrogen requires a temperature at -253 °C at 1 atm. Therefore, the technology and transportation are a lot more advanced and complicated for the liquid hydrogen. There is required 25-35% more energy to produce liquid than compressed hydrogen. [7] The liquid hydrogen has a higher volumetric energy density than in hydrogen in compressed form. This leads to fewer tanks for compressed when it comes to shipping and transport and leads to less CO_2 emissions from transportation from the liquid hydrogen. Hydrogen can be stored in three different main methods: compressed, liquid and chemically bound.

Before hydrogen can be stored regardless of what method, it needs to be cleaned. There are different compounds that hydrogen might be stored chemically in, such as: ammonia, methanol, natural gas, metal hydrides and LOHC. LOHC stands for liquid Organic Hydrogen Carriers are oils in liquid form that can store hydrogen under ambient conditions at high storage densities.

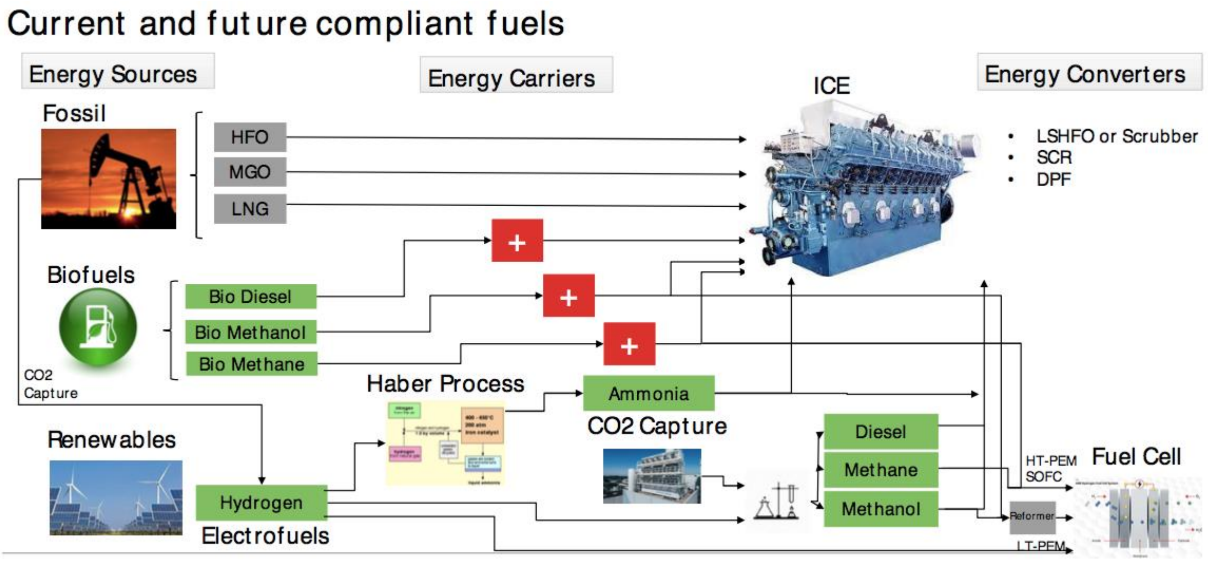


Figure 2; This figure shows the current standard (grey) and the possible future standard for energy- sources, carriers, and converters. [55]

Hydrogen does not come without risk. It mixes good with air; therefore, explosive mixtures can be formed. There is a chance of an explosion when hydrogen is in concentrations of 15-75% of oxygen. It is also important to know that hydrogen is flammable in 4 %- 94% concentrations in oxygen. Figure 2 illustrates the current and future compliant fuels, with the energy sources, the energy carriers, and the energy converters like the Internal Combustion Engine (ICE) and a Fuel Cell (FC).

2.3 Ammonia

An alternative to pure hydrogen, is hydrogen stored chemically bound in ammonia. The major advantage for ammonia is that it is much easier to store as a liquid, compared to hydrogen. There are many ways to convert ammonia to useful energy, or to use it as a hydrogen carrier. Ammonia can also be used directly, for example in an internal combustion engine (ICE), fuel cell (FC) or a gas turbine. [8] Ammonia is viewed as a good alternative in deep-sea shipping, as volume is more valuable than weight in large ships.

Ammonia (NH_3) is a colorless gas and has a lower density than air under STP (standard temperature and pressure, 1 atm, 25°C) conditions. It has a boiling point of -33.3°C at STP. Ammonia is a liquid at pressures over 8.6 bar at 20°C. Ammonia has the density of 680 kg/m^3 when liquid. [8] Table 2 compares ammonias energetic properties with MGO, LPG, compressed and liquid hydrogen.

Table 1; Comparison of relevant properties for ammonia, liquid hydrogen, compressed hydrogen, liquified petroleum gas, and marine gas oil. [9]

	MGO (Marine Gas Oil)	LPG (Liquified Petroleum Gas)	Compressed H_2 (350 bar)	H_2 liquid	Ammonia
Density (kg/m^3)	835	490	23	71	610
Lower Heating Values (MJ/kg)	42.7	46	120	120	18.6
GJ/m^3	35.7	22.6	2.80	8.52	11.4
Volume (m^3/GJ) normalized	1	1.58	12.75	4.18	3.14

The Haber Bosch Process made ammonia accessible, and feasible for use. This is a chemical process where you combine nitrogen and hydrogen under high pressure and temperature and with help from a catalyst, ammonia is produced. 96% of ammonia is produced with the Haber Bosch process. [9] The reaction is carried out at temperatures ranging between 400º-650º C and pressure between 200-400 atm. The process uses a catalyst made of mostly iron, if not the temperatures would have to be significantly higher. [10] Formula 1 shows the basic chemical reaction in the Haber Bosch Process.

The Haber-Bosch process

$$N_2(g) + 3H_2(g) \leftrightarrow 2NH_3\,(g) \quad (\Delta H = -92.4\, kJ * mol^{-1}) \qquad (1)$$

Ammonia is relatively expensive, toxic and smells bad. Another problem with ammonia is that its highly corrosive. Even though ammonia has been used for over a century, there are still a lot of challenges.

2.4 Alternative hydrogen derivatives

Ammonia is among one of the substances we can store hydrogen in. Ammonia and methanol have a few things in common. They can be used both as temporary energy carriers or directly into energy converters such as Internal Combustion Engine (ICE) or turbines. They are both toxic, and they can be stored in room temperature (25º C). Both ammonia and methanol can be stored and transported at much less difficult conditions than pure hydrogen, which saves time and money. It is also possible to store hydrogen chemically in metal hybrids. Since hydrogen only has one electron in the outer shell it can react with most metals. There are advantages and disadvantages with the use of metal hydrides. Advantages are that large volumes of hydrogen can be stored under low pressure, since the hydrogen is chemically bounded to a metal hydride, the probability of a leakage is small, both factors lower the risk. Disadvantages are that the weight of the metal powder is high, and therefore it is mostly used in stationary applications where weight does not matter, like trains. The technology is also immature and in development.

Table 2; Advantages and disadvantages of alternative hydrogen carriers, excluding ammonia.

Alternatives to ammonia	**Advantages**	**Disadvantages**
Methane	Known technology, can be stored at room temperature and atmospheric pressure. [11]	Toxic substance and temporary energy carrier, must be converted back to pure hydrogen. [11]
Metal hybrids	Large volumes of hydrogen can be stored at low pressure and the hydrogen is chemically bounded to the metal powder and therefore the risk of leakage is low. In most cases it does not require compression. [11]	The metal powder has a high weight and the technology is immature. The high weight is the reason that it should be used for stationary applications where weight does not matter, like a train. [11]
LOHC	Can be stored at room temperature and atmospheric pressure. It is required or should be required to use a catalyst. [11]	Temporary energy carrier must release the hydrogen again before use. Requires energy to release the hydrogen. Known technology, can be transported as other chemicals. Ideal for long term storage and in big volumes. [11]

2.5 Infrastructure

Historically ammonia has been used primarily as fertilizer in the agriculture industry and therefore it already has major production and transportation infrastructure set up. The most cost-efficient way to establish infrastructure for ammonia as fuel will therefore be to develop and scale up the already existing facilities. [12]

2.5.1 Production

The ammonia production worldwide was 176 million tons in 2014, and approximately 400.000 tons are produced yearly in Norway by Yara. [13] More than 80% of the ammonia is used as fertilizer, and fertilizer production is responsible for approximately 1% of the global climate emissions. [14] The shipping industry is responsible for 2% of the climate emissions, where deep-sea shipping carries 80% of that load. [14]

There are primarily three different methods used for production of ammonia. The ammonia is categorized into different colors, based on how the hydrogen is produced; grey, blue, and green. Grey ammonia is the most common method in present time and uses natural gas to collect the hydrogen by steam reforming. In this process CO_2 is released. If the CO_2 is captured, the ammonia qualifies as blue. For the ammonia to qualify as green, renewable energy must be used to extract the hydrogen. This can be done by electrolysis of water, while using electricity generated from a renewable source. [15]

Even though grey, blue, and green ammonia are the most used categories for ammonia, there is also a type called hybrid green ammonia. The hybrid ammonia is produced in hybrid plants that is fueled with both renewable electricity and fossil fuels. This can potentially be used in a transition from grey to green production, as renewable energy is not accessible everywhere yet.

The Danish company Haldor Topsoe has announced an opening of a new manufacturing facility using a new technology for hydrogen production called solid oxide electrolysis cell (SOEC). They claim that this process is significantly more efficient than existing technology, as they claim that "more than 90% of the renewable electricity that enters the electrolyzer is preserved in the green hydrogen it produces." [16] Current electrolysis technology has an efficiency of up to 70%. [16] It must be stated that a production efficiency of 90% seems unlikely and is yet to realize. Figure 4 shows different ammonia production pathways.

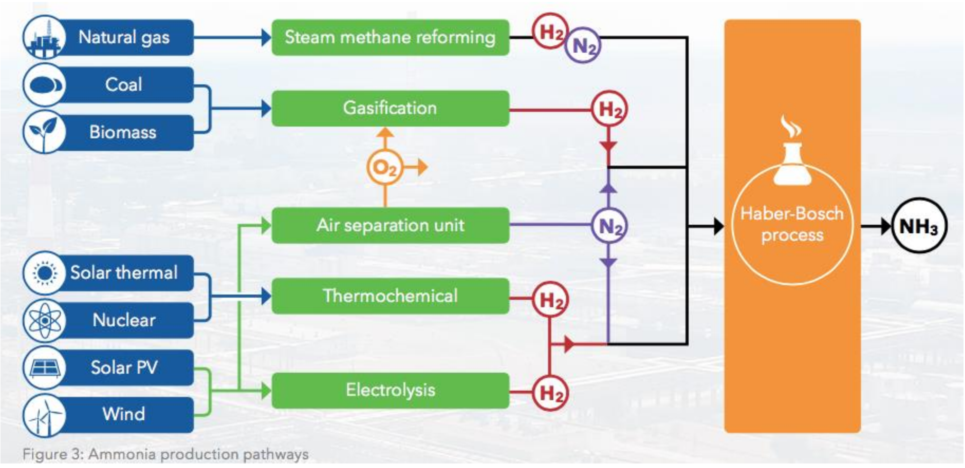


Figure 4; Ammonia/hydrogen production pathways. [8]

Yara has announced that their production facility on Herøya, the only ammonia production facility in Norway, will change its production from grey to green ammonia, a reorganization that will remove 800.000 tons of yearly greenhouse gas emissions. [14] In Spain there is currently a project being planned to produce emission free green ammonia for fertilizers. This is part of a plan to reduce the natural gas use in Spain by over 10 %. Another project is by Eneus Energy that plans to build a green ammonia production plant in Orkney, Scotland. This project is expected to produce 11 ton of ammonia per day, and the plant will be powered by two wind turbines. [17]

A problem with the ammonia as a maritime fuel is the difference between the global shipping fuel consumption and the global ammonia production. If all deep-sea shipping were to run on ammonia it would correspond to 5-600 million tons ammonia yearly, which is 3-4 times the amount produced yearly, according to Yara. [18] Figure 5 illustrates the gap. For the transition to ammonia as marine fuel, rather than petroleum, to have any positive environmental effect it must be based on green and blue ammonia. As earlier mentioned, most of the ammonia is made from natural gas without CCS and therefore increasing in volume means increasing CO_2

emissions. The volume of ammonia needs to grow, but in order to grow in volume and reduce the CO_2 emissions, green ammonia is required and therefore a growth in renewable energy is also required. [18]

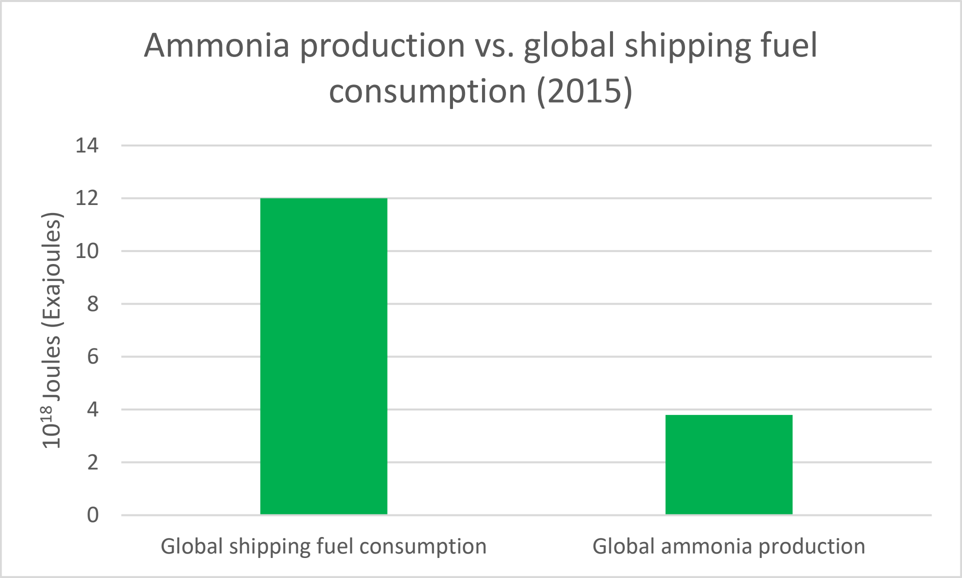


Figure 5; Global ammonia production vs. Global shipping fuel consumption. [18]

2.5.2 Transportation and bunkering

Ammonia is stored as a liquid at -33 °C, at pressures above 8.6 bar in at 25ºC or at ambient pressure. The capital cost for this refrigerated storage is around 700 $ /ton ammonia. Ammonia bunkering can be done in different ways, such as from bunkering ships, trucks, or terminals onshore. The current bunkering with loading and unloading from terminals to the ships carrying ammonia are handled with safety and specialized training. In areas with large amounts of people or animals nearby, even more care and safety should be taken. Since a ship has a specific range and pressure for the fuel it can use, ammonia can sometimes not be available for a ship. Therefore, the ship that is going to be bunkered and the bunkering vessel is required to have the necessary installations and equipment to bunker safely. In the DNV report "Ammonia as a marine fuel", there are mentioned 4 different bunkering vessels combinations and two of them are pressurized- and semi-refrigerated tanks. [8]

Ammonia is transported all over the globe in large quantities by public roads, pipelines, railways, and ships. Ammonia is classified as dangerous goods and is therefore handled accordingly. There are some accidents reported that have been reported involving transportation of ammonia, but none of them have been fatal. [19] The fact that ammonia is transported as such a large scale without major challenges already suggests that transportation will not be a significant issue as production is upscaled.

3. Energy conversion technology for ammonia

3.1 Fuel cell

3.1.1 General Information Fuel Cells (FC)

A fuel cell is an electrochemical cell that converts the chemical energy of the fuel into electrical energy through the electrochemical reaction of fuel and oxygen or another oxidant. The process involves both electricity and chemical reactions. Under combustion, electrons are passed between oxygen and hydrogen resulting in energy release in the form of heat. For any chemical reaction where energy is released, only a part of it can be converted into electricity. An FC requires a continuous source of oxygen and fuel so the chemical reaction can sustain, it also needs an electrolyte and an electron conductor. The electrolyte is one key component for all the types of fuel cells. An electrolyte is carrying electrical charges from one of the electrodes to the other one. Every fuel cell also has a catalyst which is speeding up the reaction that is happening at the electrodes.

When hydrogen is used in a FC and oxygen as oxidant, water is produced. Ammonia can be used either directly in a SOFC fuel or as a hydrogen carrier in AFC and PEMFC, which is cracked before entering the fuel cell.

We can use Life Cycle Assessment (LCA) to see how green the FCs really are during their whole life cycle. There are a lot of projects going on and planned worldwide, including several projects in Norway. Some ammonia fuel projects are further discussed in chapter 6.

According to the Zion marked research the FC marked globally will only continue to rise over the years. The countries that are currently the most successful with the most installed FC are Japan, South Korea, China, and Germany. There are different types of fuel cells and this report investigates the three most used. Fuel cells are categorized by how they operate and the type of fuel they use. It is not known for sure which one of them that will have the biggest impact in the future, but PEMFC and SOFC have been identified as most promising by both general market studies and a fuel cell marine application study done by DNV-GL. [8]

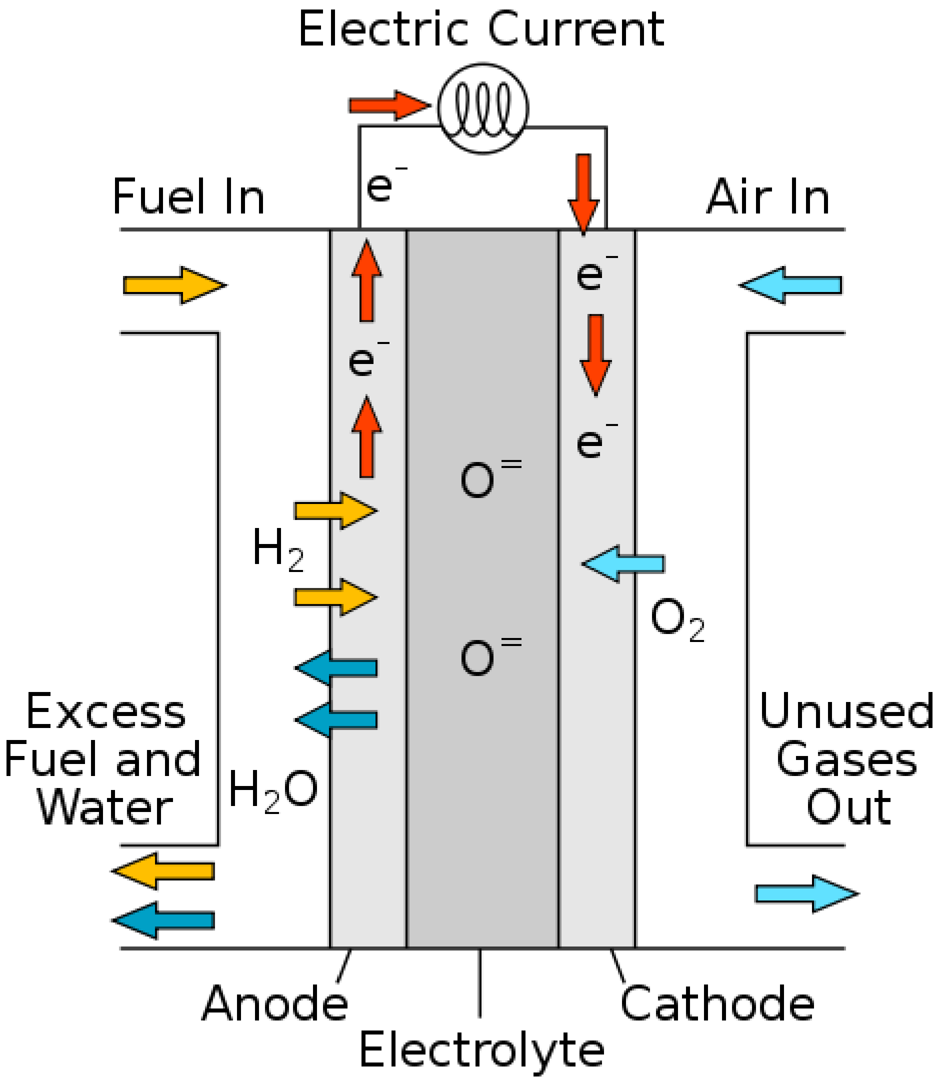


Figure 6; Solid Oxide Fuel Cell. [56]

Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC) and Alkaline Fuel Cells (AFC) are the three types of fuel cells covered in this report. The most common way to visualize the performance of a fuel cell (FC), either for a fuel cell stack or a single fuel cell is by polarization curves. Below is an example of a polarization of a fuel cell. Below is an example of polarization curve for a fuel cell (FC).

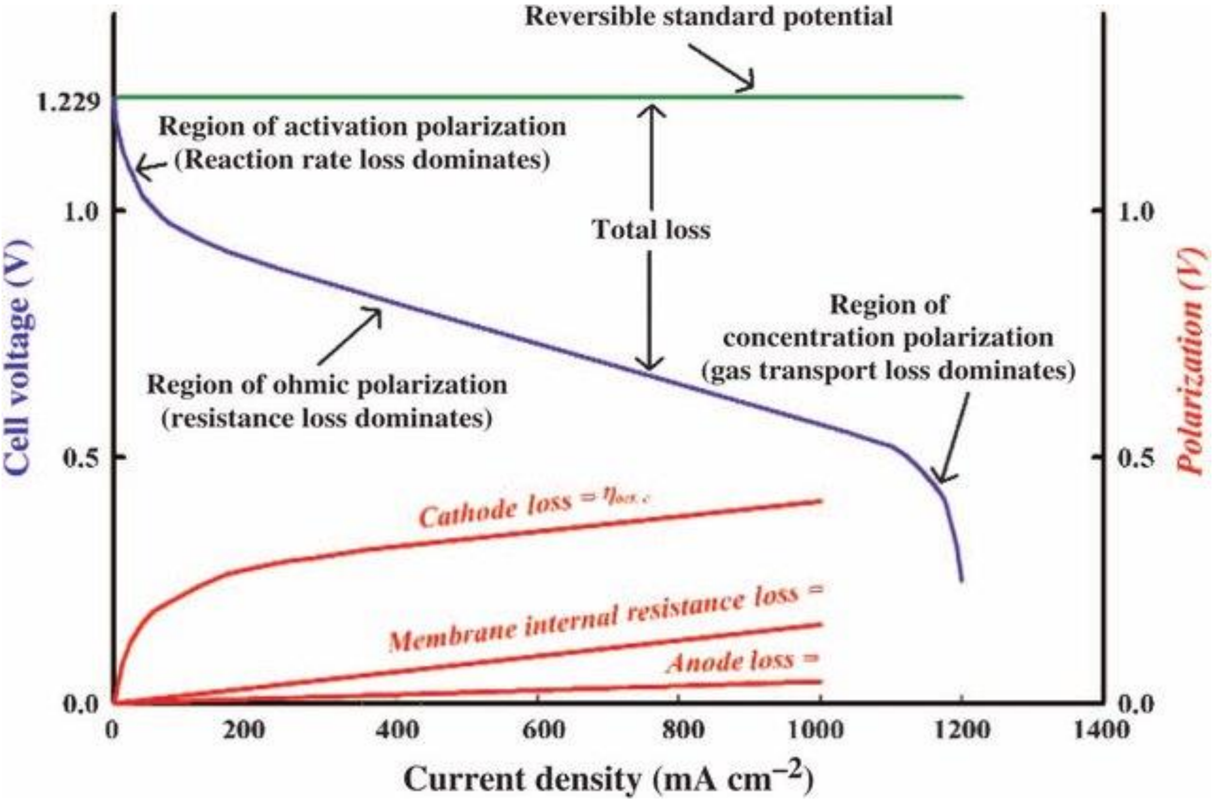


Figure 7; Polarization curve for a typical PEMFC. [20]

The polarization curve is a diagram of the Cell voltage (V) versus the current density (i) for a specific electrode- electrolyte combination. For any electrochemical reaction, this curve is the basic kinetic law and makes it easy to compare different online published polarization curves. The polarization curves shape is caused by voltage, which is various energy losses that take place on electrodes of the fuel cell (FC) and in the FC electrolyte when the current of FC is increased.

This table below is made to compare the three types of fuel cells (FCs) mentioned in this report, with operation conditions, advantages, and disadvantages.

Table 3; Advantages and disadvantages of the three fuel cells discussed.

Type of fuel cell (FC)	Operating temperature	Advantages	Disadvantages
AFC	Up to 230 °C	Can use several different fuels that are relatively cheap to produce. AFC are capable of being used in cars, such as the Silver Volt. [21] AFC energy plans to use ammonia crackers that are already existing and therefore does not need any further research. [22] The only bi products from an alkaline fuel cell is heat and water, and both have commercial use. [22] AFC does not have NO_x emissions. [23]	Highly sensitive to CO2 poisoning and therefore air treatment in the form of CO2 scrubbing is required. Ammonia as a fuel for the maritime industry, it can be found that AFC is the most expensive of the three types to install. Can only use hydrogen as a fuel. [23] Requires clean hydrogen
SOFC	800-100 °C	High efficiency and high modularity. Combination of environmental friendly power generation and fuel flexibility. [21] SOFC also produces a large amount of exhaust heat, which can be used for additional power generation or in combined heat and power systems. SOFC is less sensitive to impurities, can handle salty air, accelerations and can use different types of fuel. [23] Compared to the AFC and the PEMFC, the SOFC is less sensitive to impurities. [23]	Efficiencies are very dependent on temperature variations and SOFC has a loss of exergy. Even though SOFC might be the most promising FC for ammonia, it is far away from commercializing. [18] Lan and Tao are suggesting that there are NOx emissions related to the use of ammonia in SOFC. [18]
PEMFC	50-100 °C	Does not produce any NOx emissions. [23] The burner is assumed to combust ammonia continuously under optimal conditions; therefore, the NOx emissions are negligible low. PEMFCs has shown that it is capable of handling forces from accelerations, like cars and busses. Small concentrations of ammonia as low as 13 ppm can cause damage to the PEM Fuel Cells acidic polymer membrane. [24]	Cannot use ammonia directly as a fuel, but instead it needs a high purity hydrogen. Requires a clean hydrogen source. Can only use hydrogen as a fuel. PEMFC is sensitive to different types of contamination, such as salty air and other air pollutants, which could over timer educe the performance. [23]

3.1.2 PEMFC

Proton Exchange Membrane Fuel Cells (PEMFC) cannot use ammonia directly and therefore requires a clean hydrogen source. PEMFC can be purchased from many manufacturers and has been used in different transportation methods such as cars, buses, and light trains. The reaction rate and generated electric power may be increased by increasing temperature, using a catalyst, and increasing the electrode area.

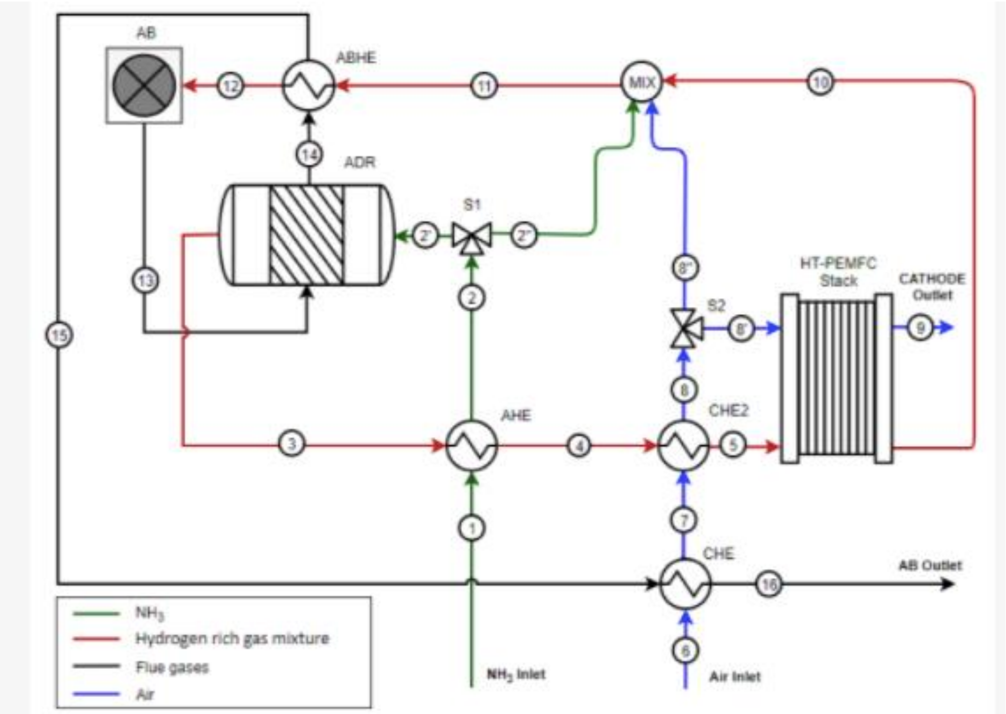


Figure 8; Conceptual schematic of the integrated ammonia decomposition reactor-HT-PEMFC system. [57]. ADR - Ammonia Decomposition reaction, AHE - Ammonia Heat Exchanger, AB - Afterburner, CHE(2) - cathodic heat exchanger

Figure 8 demonstrates a schematic of the integrated ammonia decomposition reactor with High Temperature PEM Fuel Cell (HT - PEMFC). Ammonia decomposition requires additional heat to maintain the chosen operation temperatures, because the decomposition of ammonia is an endothermic reaction. The number 1 - 16 are the different gas flow pipes. Before ammonia enters the ammonia decomposition reaction (ADR) it is pre- heated in the ammonia heat exchanger (AHE). A splitter separates parts of the ammonia and vie the mixer it sends it to the afterburner (AB). Since ammonia has high resistance to auto - ignition and has a low flammability which leads to ignition times, it is often mixed with other fuels for combustion.

In the ammonia heat exchanger (AHE) ammonia is cooled down to the temperature of the fuel cell (FC) and this heat is recovered and used to pre - heat the inlet of ammonia to 30 °C below the ADR operating temperature to secure the heat recovery.
Before the decomposed ammonia reaches the fuel cell inlet, the decomposed mixture enters a second heat exchanger, which is called cathodic heat exchanger (CHE2). Here is the remaining heat used to pre- heat the inlet cathodic air up to the fuel cell temperature. The afterburner (AB) and the HT - PEMFC requires oxygen in the air.

The market for PEMFCs can be divided into three major groups: transportation, portable power, and stationary power. The PEMFCs can be divided into two main categories, which is low temperature PEMFCs and High temperature PEMFCs (HT – PEMFCs). According to the University of Perugia, ammonia used in high temperature PEMFCs has been ignored, and therefore they decided to create the first study of an HT-PEMFC stack with decomposition of ammonia. [25] The decomposition of ammonia is an endothermic reaction, which means it requires external heat to be able to maintain the chosen temperature. An after burner (AB) is used to supply the needed heat to the reaction. Below is a picture of the High temperature PEMFC (HT- PEMFC) integrated ammonia decomposition reactor.

3.1.3 AFC

The alkaline fuel cell (AFC) uses an alkaline liquid as the electrolyte, which in the AFC in known as KOH (potassium hydroxide). Energy is extracted when the presence of KOH ions transits across the electrolyte which makes a circuit. [22] An AFC may only use hydrogen as fuel, just as the PEMFC. The difference is that SOFC requires pure hydrogen, AFC does not. AFC Energy was the first to successfully create integration of alkaline fuel cells (AFC) with cracking of ammonia. [22] GenCell has developed an AFC with a cracker which can use ammonia as a fuel, which was commercialized and provided to its first customer in July 2018. [22]

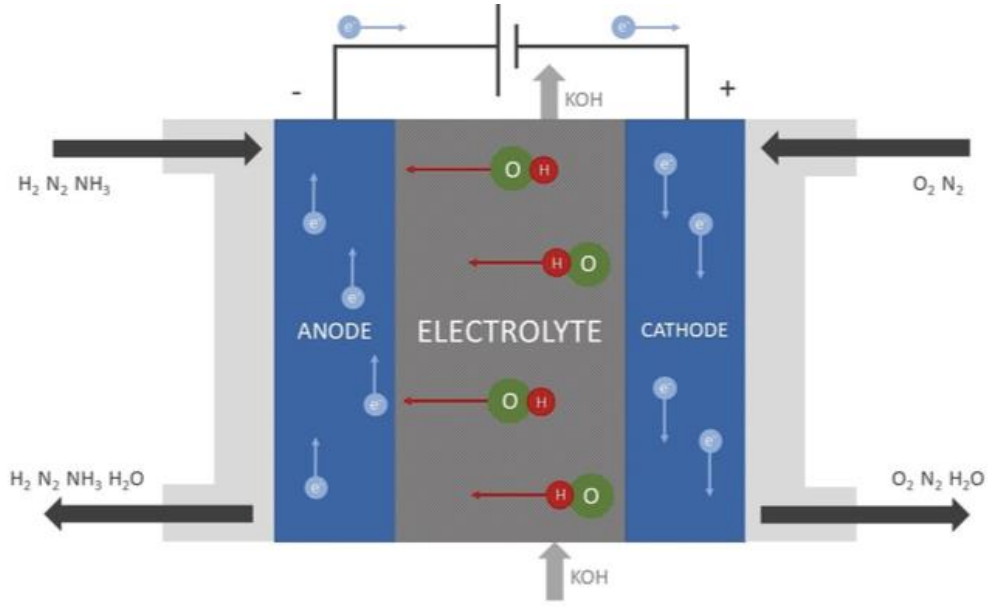


Figure 9; This picture demonstrates an alkaline fuel cell is fueled with hydrogen, which is derived from ammonia and a circulating electrolyte. [24]

The AFC has been developed and investigated since the 1950s. Even though this FC has achieved some big milestones in the FC industry, it has been overtaken by other FC types like the PEMFC. The PEMFC has not made a wide market yet, mainly because the technology is far away from competing with established energy conversion technology. The delays and issues in finding answers to the PEMFC have fueled the interest in AFC again. The AFC is the cheapest FC type to produce. The main reason is because the catalyst required in the AFC, can be chosen from several different materials that are relatively inexpensive to produce. [21] ZBT (Zentrum für BrennstoffzellenTechnik) also successfully developed and tested an ammonia fueled system using a nonelectrical cracker and an AFC with their project ALKAMMONIA. [21]

3.1.4 SOFC

SOFC are using ceramic materials as electrolyte and therefore it requires a higher temperature than PEM and Alkali. AFC operates at temperatures up to 230 °C, the PEM operates at 60-80°C and the SOFC operates at 800-1000°C. The SOFC can in general use many different types as fuel, such as methane, carbon monoxide (CO), methanol and ammonia. One other difference compared to the two other FCs is that SOFC only have two phases: gas and solid, which makes it an easier system. Ammonia is cracked at temperatures from 500 - 1000 °C, which are elevated. The main advantage of these elevated temperatures is that the electricity generation and the cracking of ammonia can be combined and merged. Therefore, the ammonia can be fed directly into the SOFC. SOFC produces a relatively large amount of exhausted heat, that can be used for additional power generation or in combined heat and power system (CHP). There are two different types of ammonia SOFC; SOFC-H and SOFC-O, where SOFC-H have greater efficiencies than SOFC-O. [21]

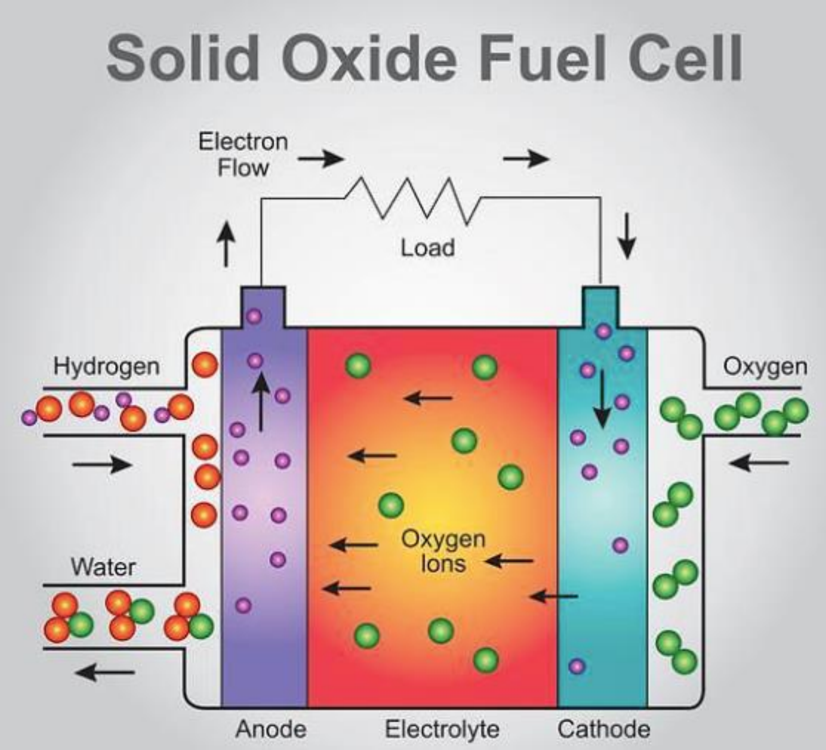


Figure 10; Solid Oxide Fuel Cell. [24]

With the high temperature there comes advantages and disadvantages. For example, the high temperature causes fast reactions, but it also causes higher demands on material selection and sealing. SOFC can use ammonia directly, unlike to PEM and AFC. This leads to preventing the need for purification and cracking. Ammonia fueled SOFCs are available, but currently only used for lab experiments. Research done by University of Perugia has found that successful operation with high efficiencies and no NO_x formation can be achieved. [21] In 2017 the Kyoto University announced it attained 1000 hours of continuous operation of an SOFC fueled by ammonia. [21]

SOFCs may use a variety of electroceramics that are used as electrolytes, cathodes, and anodes. This can be used for either home-scale powerplants or large-scale-powerplants as well was emergency power generators. There are researchers all over the world that are making efforts within the improvements of reasonable ceramic structures and materials. In fact, the ceramic structures and materials are the technical key challenges that the SOFC are facing. If the researchers can develop a simple ceramic process so the thin-film electrolyte that is decreasing the cell resistance can be used, the improvements can double the power output and reduce the costs of SOFC significantly. We can lower the size, cost of fuel cell systems and the weight by getting higher power density. Another important factor with the SOFCs is to reach the cost goal of 1000$/kW. If the price comes down to this, the SOFCs are close to be used for small-scale residential market applications. [21]

3.2 Internal combustion engine

Internal combustion engines (ICE) are the most common form of heat engines. They are used in vehicles, ships, aircrafts, and trains. The ICE is a heat engine where the combustion of the fuel occurs with an oxidizing part, usually air. This leads to an expansion of the high-temperature high-pressure gases which applies force to a component, in this case a piston. When the force moves the piston, or turbine which will be discussed further on in the report, the chemical energy is transformed to mechanical energy, in other words useful work.

ICE’s are generally divided in two groups: the spark ignition and the compression ignition (CI). The SI is used for gasoline, where the ignition is done by a spark into the compressed fuel-air mixture. The CI is used for diesel, and it happens by spraying fuel into compressed air, due to diesels high flammability. [26]

Figure 11 illustrates a spark ignition (SI) internal combustion engine. The camshaft is a rotating metal device that pushes the rocker arm to convert the circular motion into a reciprocal motion. This reciprocal motion is used to open and close the intake valve. From the intake valve the fuel-air mixture is injected to the combustion chamber where the mixture is ignited. The expansion of the fuel-air mixture proceeds to push the piston down, and the piston makes the crankshaft move. The exhaust from the combustion is removed through the exhaust valve and the process can continue.

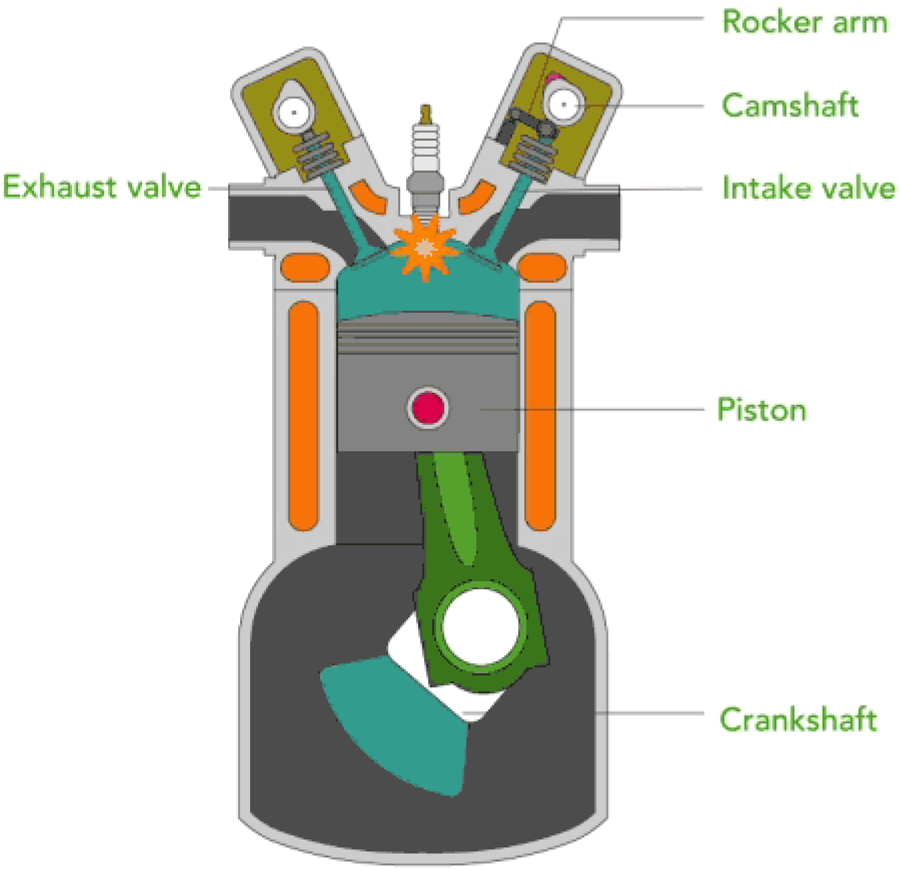


Figure 11; Illustration of an internal combustion engine. [26]

3.3 Turbine

When talking about turbine engines, there are two types which are generally considered: steam turbine and gas turbine. This report will only address the gas turbine, due to its higher power density and efficiency compared with the steam turbine.

The gas turbine works by taking atmospheric air flows through a compressor, fuel is then sprayed into the compressed air and the mix is ignited. The combustion generates a high-pressure high-temperature gas flow which applies force to the turbine and generates mechanical energy.

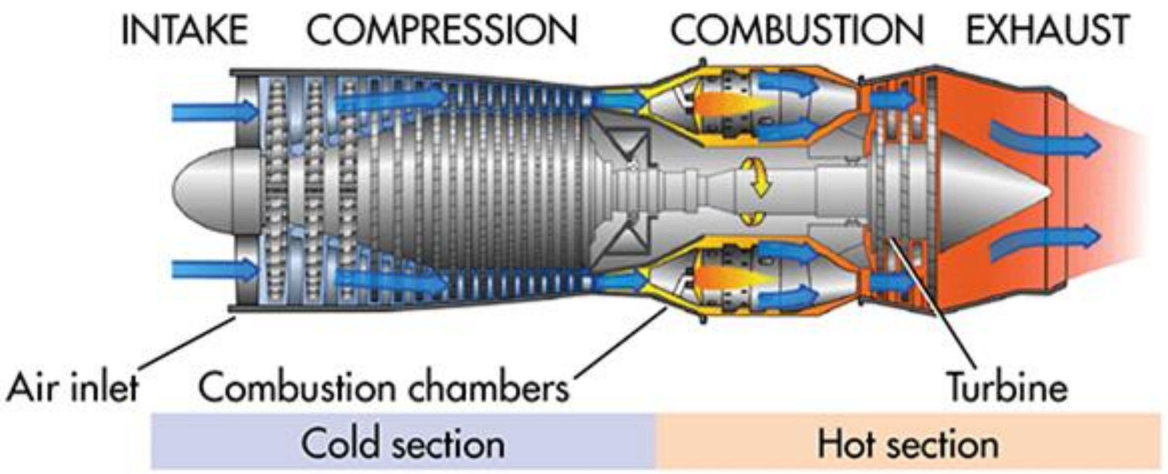


Figure 12; Illustration of a gas turbine. [27]

4. Ammonia's efficiency in marine energy systems

Efficiency for a system is defined as the percentage ratio of the energy output compared to the energy input. Higher efficiency equals less fuel demand, and less money spent. For a FC there are different ways to improve the efficiency, such as higher pressure and humidification. Waste heat recovery systems can improve the efficiency of a FC, ICE, and turbine, by using the waste heat energy for other purposes the total efficiency for fuel cell systems can be improved. For the different fuel cells, and the ICE, system efficiency is as the basis of comparison in this report. For the gas turbine, thermal efficiency is used, due to data availability. Thermal efficiency is the percentage of heat energy from the combusted fuel which generates mechanical energy. System efficiency also includes the mechanical efficiency.

4.1 Fuel cells

There are several companies that study ammonia fed fuel cells (FC) around the world. The competition worldwide, is probably one of the reasons to lack of information about the efficiencies for FCs using ammonia. [28]

Ing. De Vries report "safe and effective application of ammonia as fuel" states that SOFC is the only one of the three FC types without a big issue. The PEMFC requires air treatment with filtration and AFC requires air treatment with CO_2 scrubbing. [28] SOFC has several disadvantages as well, such as long waiting time for heat up and cool down cycles, to minimize structural stress due to the high operating temperatures. In addition, there are several requirements for the ceramic materials used, such as thermal expansion compatibility of various components and the stability in oxidizing and reducing conditions. [29]

4.1.1 SOFC

The SOFC might be the most promising fuel cell for ammonia use, but as mentioned above there are still several problems, such as the fact that the efficiency is very dependent on temperature variations. University of Perugia conducted a study using diluted ammonia fed into a SOFC system and found the efficiency of the system to be 50%. [25] E. Baniasadi and I. Dicer's report "energy and exergy analyses of a combined ammonia-fed solid oxide fuel cell system for vehicular applications" found that the solid oxide fuel cell fueled by ammonia reached efficiencies of approximately 50 %. [30]

C-Job, Enviu, and Proton Ventures report "Ammonia as a fuel for the maritime industry" ran a simulation of both SOFC and PEMFC running on ammonia. The simulation software used was COCO, a simulation software for chemical and thermodynamic processes. The simulation was of a 18 000- ton ship, with an 8 MW energy output, and was run on full load, under steady state operations and without start up analysis. These limitations may have inflated the numbers compared to what an actual marine SOFC would perform. The simulation resulted in a system efficiency of 53% for the SOFC ran on ammonia. [23]. Based on the reports mentioned above, the efficiency of an ammonia fed SOFC will be approximately 50%.

4.1.2 PEMFC

PEMFC is a mature technology itself but has a way to go with ammonia as fuel. The efficiency of the PEMFC is approximately 50- 60% if fueled by hydrogen. [23] For it to run on ammonia, several additional pieces of equipment are needed to prepare ammonia into suitable fuel for the FC. The biggest drawback is the steam purification process necessary to reach the hydrogen purity needed. The technology for this process is in the early stages, and therefore it will lower the system efficiency. Ing. De Vries report "Safe and effective application of ammonia as a marine fuel" calculated a theoretical system efficiency of 44.5% for the PEMFC. [28] The simulation described in 4.1.1. done by C-Job, Proton, and Enviu resulted in an efficiency of 28% for ammonia in a PEMFC. [23] The low efficiency in the simulation is due to the purification process of the hydrogen. The technology surrounding this will likely improve a lot if the PEMFC will be used with ammonia. As mentioned, the efficiency with hydrogen is 50-60%.

4.1.3 AFC

Ing. De Vries calculated in his report “Safe and effective application of ammonia as a marine fuel” that an AFC run on ammonia can have an efficiency of 44.8%, including the cracking of ammonia to hydrogen. [28]

4.2 Combustion

The main challenge for use of ammonia in combustion engines and turbines are its combustion properties. The auto-ignition temperature is at 651° C, it has a low flame speed, narrow flammability limits and high heat of vaporization, these are all challenges that major engine manufacturers are working to solve. Because of these properties, ammonia is often researched in different mixtures as well as pure ammonia, for example ammonia mixed with hydrogen. Ammonia-hydrogen mixes can be obtained by cracking some of the ammonia before the combustion process begins, this way ammonia is still the only fuel that needs to be supplied. Formula 1 represents the basic reaction of ammonia combustion. Considering that air is used instead of pure oxygen for the combustion in most cases, formula 2 shows ammonias combustion with air. Nitrogen and oxygen cover 99% of the air mass combined, therefore all other gases are neglected for simplification purposes. [28] Formula 2 and 3 are the final combustion of ammonia, considering Gibbs’ Law. NO_x will be a biproduct of the combustion if temperatures high. NO_x can be a health threat to people, in addition to several other undesirable effects. There are several methods to reducing NO_x formation, such as Selective Catalyst Reduction. For ammonia to be acceptable as a fuel NO_x formation has to be on an acceptable limit. [31]

Basic ammonia combustion with oxygen:

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \qquad (2)$$

Ammonia combustion with air:

$$4NH_3 + 11N_2 + 3O_2 \rightarrow 13N_2 + 6H_2O \qquad (3)$$

4.2.1 Internal combustion engine

The slow speed 2-stroke internal combustion engine (ICE) is the most common ICE in deep-sea shipping. The 4-stroke ICE is not investigated in this report, because the slow 2-stroke is more efficient, and efficiency is the focus point of this report. As mentioned in chapter 4.2 the ignition and combustion of ammonia is main challenge for the use of ammonia in ICE. Even though there are several large engine manufacturers currently developing ICE for ammonia use, e.g. Wärtsilä, there is not much published reports on specifications yet.

The companies Enviu, Proton, and C-JOB has published a report called “Ammonia as fuel for the maritime industry” in which they simulated the use of ammonia in an ICE, and different fuel cells. The software used to run the models were COCO, a simulation software for chemical and thermodynamic processes. The simulation was done on a 18 000- ton ship, with an 8 MW energy output, and it was run on full load, under stead state operations and without start up analysis. The ammonia conversion rate is set to 100%, in other words the combustion efficiency in the simulation is set to 100%, which is highly unlikely due to ammonia slip and NO_x formation. Due to these limitations the efficiency results are probably inflated compared what an actual marine ICE will perform. [23]

The result for the ICE in the simulation was a system efficiency of 43%. [23]

4.2.2 Gas turbines

The largest supplier of gas turbines for marine propulsion are General Electric (GE). They have a market share of nearly half (43%) in the marine gas turbine market. [32] Considering their position as market leaders, their 25 MW turbine “GE LM2500” is being used as a reference for technical specifications for a turbine. Although thermal efficiencies for gas turbines breaking 60% have been reached in testing, the efficiency for gas turbines in marine energy systems are generally between 30%-40%. [32] Gas turbines are known to be less efficient than internal combustion engines and fuel cells [33], but can be preferred for large ships due to higher power density. For GE LM2500 the marked efficiency is 36%. [34] The turbine is used with both natural gas, fuel oil, and a combination of both in a dual-fuel capacity. As mentioned in chapter 4.2 the challenge for ammonia in regard to efficiency is the combustion efficiency, which is what can potentially lower the thermal efficiency of the turbine when combusting ammonia.

Combustion efficiency for ammonia

Research Institute for Energy Conservation and Natural Institute of Advanced Industrial Science Technology (AIST) published the research paper "Performances and emission characteristics of NH_3-air and NH_3-CH_4-air combustion gas-turbine power generations" in 2016. This was the first successful NH_3-air combustion power generation, which they managed to do on a 50 kW-gas-turbine as described in 3.1.4. The ignition process is illustrated in figure 13. As shown in the figure, the ignition began with kerosene firing until stable combustion was achieved, thereafter ammonia was gradually added. As seen in the last stage of figure 13, kerosene supply was stopped at approximately half power. When ammonia was the only fuel injected, along with air, the power was gradually increased to full load. With this they reached a combustion efficiency ranging from 89% to 96%, and an average. [35] For comparison diesel usually has a very high combustion efficiency at 98% or more, while for natural gas and gasoline it is usually around 96%. [36]

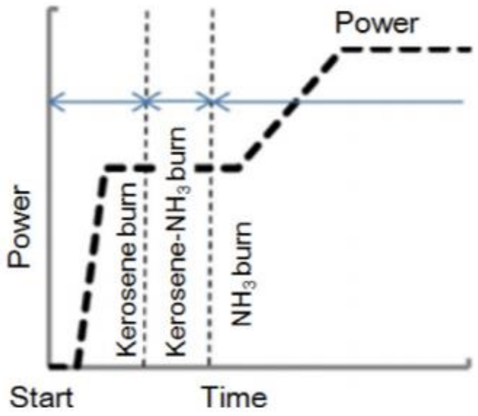


Figure 13; A schematic showing how the kerosine assisted ammonia ignition was completed. [35]

Thermal efficiency

As the thermal efficiency of the microturbine is not stated in the report [35], the combustion efficiency in combination with the mark efficiency of the GE LM2500 is used to draw a conclusion for the turbines system efficiency. Assuming an average combustion efficiency of 96% for the mark efficiency, the thermal efficiency for the GE LM2500 gas turbine running on ammonia, would be approximately the same as the mark efficiency of 36% as the combustion efficiency attained in the project is similar to the one of natural gas. Considering that the combustion efficiencies ranged from 88-96% the thermal efficiency would range from a little less than 36% to 36%.

It must be specified that the thermal efficiency is not the same as system efficiency. The system efficiency is the product of the thermal and the mechanical efficiencies. This report has used system efficiency as the comparative part for the internal combustion engine and the fuel cells.

For the chosen GE turbine neither the system nor the mechanical efficiency have been found online, but as the turbines mechanics do not change by using a different fuel it can be assumed that the mechanical efficiency is the same when using ammonia as when using other fuels.

4.3 Efficiency comparison

When renewable ammonia is produced from electricity, there is required an electricity input that is 3-4 times the actual work propelling the ship. The picture consists of two different systems: system A – Ice Propulsion and system B – SOFC propulsion. The chain consists of four stages, and the interesting thing about this picture is how much energy that is lost between these different stages. In system A (ICE) it drops from almost 4 down to 2,1 between stage one and two and ends up down to 1 in stage four. System B (SOFC) drops from 3,0 down to 1,9 between stage one and two and ends up 1 in stage four. The "energy lost" at the different stages are heat losses and can be converted to useful energy in heat recovery systems. The endpoint for the energy in figure 14 is propulsion of a ship, and heat recovery systems are not considered.

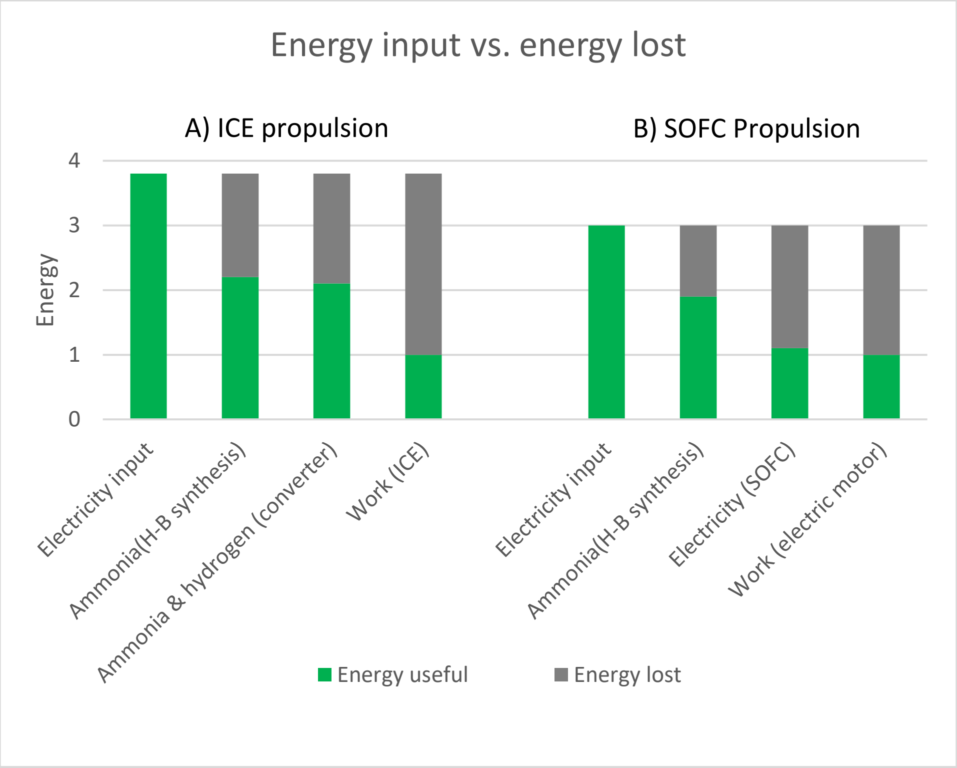


Figure 14; A comparison of energy input vs. energy output for ammonias life cycle when used in a SOFC- and ICE propulsion system. [18]

Table 4; Efficiency comparison of ICE, FC, and gas turbines in marine applications, with advantages and disadvantages of the different technologies. *-calculation, **-simulation, ***-assumption

	System efficiency with ammonia	Efficiency with HFO	Advantages	Disadvantages
SOFC	53,0 %** [23]		High efficiency, does not need external cracker, operational temperature below the threshold for NOx formation. [23]	Frequent start/stop operations cause thermal stress, immature technology. [23]
PEMFC	28%** / 43%* [23]		Mature technology, available, negligible NOx emissions. [23]	Low efficiency with ammonia due to additional equipment needed to purify hydrogen. [23]
AFC	44,80 %* [23]		Negligible NOx emissions, no problems with acceleration, negligible ammonia slip. [23]	Highly sensitive, prone to CO2 poisoning, high cost. [23]
ICE	43,0 %** [23]	49 %** [23]	Well known and mature technology, quite efficient, already used in a lot of ships.	High NOx emissions and other emissions, challenging combustion properties. [23]
Gas turbine	(Thermal efficiency) ≤36%***	(Thermal efficiency) 36%	Well known and mature technology, high power density.	Low efficiency, NOx emissions, challenging combustion properties. [35]

In table 4 the efficiencies of the different energy conversion technologies using ammonia is compared. For the ICE and the gas turbine their efficiencies with HFO are also stated. Figure 15 illustrates the development of the efficiency in Wärtsilä's marine diesel engines. It shows that a big leap was taken in the mid 2010's with the launch of their Wärtsilä 31 engine, which holds the Guinness world record for the most efficient 4-stroke combustion engine with more than 50% fuel efficiency. [37] Diesel engines are generally much more efficient than gasoline engines but have more problems with NO_x and CO emissions. Diesel engines usually have a thermal efficiency of approximately 40%. [38]

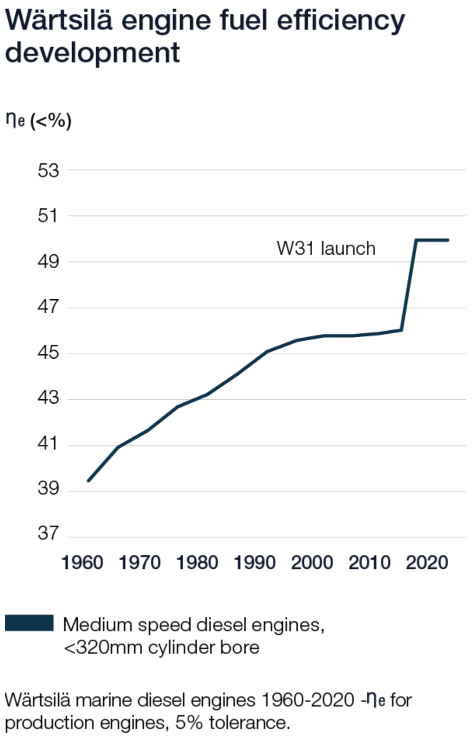


Figure 15; Wärtsilä marine diesel engine development, 1960-2020. [59]

5. Current ammonia projects

5.1 R&D state of ammonia in 2021

The idea of ammonia as fuel has gained some serious traction the last couple of years. This has resulted in several projects involving ammonia as fuel in maritime energy systems. Examples of such projects is Viking Energy, the technology group Wärtsilä who are currently testing ammonia in a marine four-stroke combustion engine, Japan tested ammonia in a 50 kW micro turbine in 2016, and the Japanese engineering firm Mitsubishi power is currently developing a 40 MW gas turbine fueled by ammonia.

5.1.1 Viking Energy

The cargo ship Viking Energy of the Norwegian shipping company Eidesvik offshore, has been a pioneer in maritime shipping regarding energy technology. In 2003 it was the first liquid natural gas (LNG) driven cargo vessel, in 2016 it was the first battery power hybrid, in 2018 it started using shore power while docked. [39] In cooperation with NCE Maritime Clean Tech and several other companies are currently working on an ammonia fueled fuel cell system which aims to be ready to use in 2024. The new energy system will be a SOFC delivered by prototech, with a 2 MW effect. The ammonia will be delivered by Yara, who through their pilot E-project will produce green ammonia. [40]

Figure 16; Picture of the cargo ship “Viking energy”. [41]

5.1.2 Wärtsilä combustion engine

The technology company Wärtsilä which are also involved with the Viking Energy project, are also, in close cooperation with Knutsen OAS Shipping AS, Repsol and the Sustainable Energy Catapult Centre, currently the in the process of the first long term full-scale testing of ammonia as fuel in a marine four-stroke combustion engine. [42]

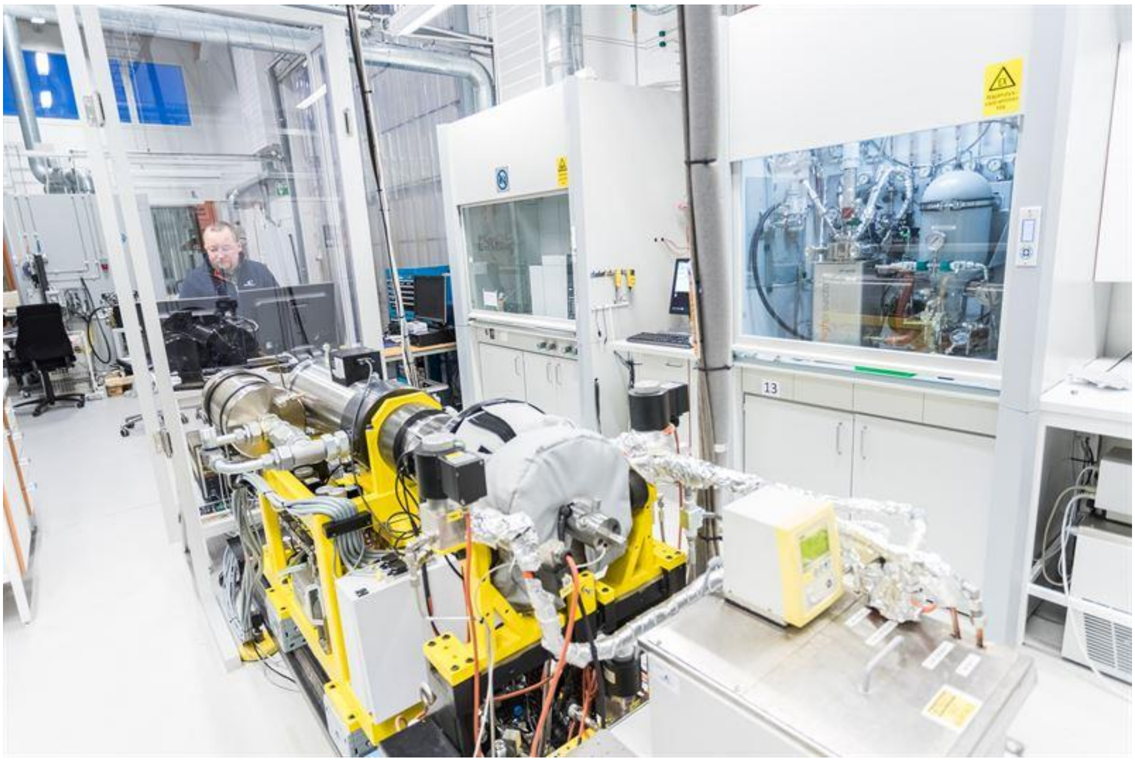


Figure 17; The four-stroke combustion engine Wärtsilä will fuel with ammonia. [43]

5.1.3 Mitsubishi turbine

Mitsubishi Power recently announced the initiation of the development of a 40 MW gas turbine fueled by 100% ammonia, which is by far the largest ammonia powered project currently. They have targeted commercialization in or around 2025. The project was announced on March 1. 2021.

Figure 18; Mitsubishi's H-25 Series gas turbine, intended for use with ammonia. [44]

5.1.4 Toyota micro turbine

The first successful ammonia fueled combustion power generation was realized in 2015/16 using a 50-kW gas turbine system at the National Institute of Advanced Industrial Science and Technology (AIST) in Japan. [35] Figure 19 illustrates the technical basics of the turbine. The swirler is used to generate recirculating flows that facilitate flame stabilization, and the fuel injector was tested on several angles to find out how it affects combustion efficiency and NO_x emissions.

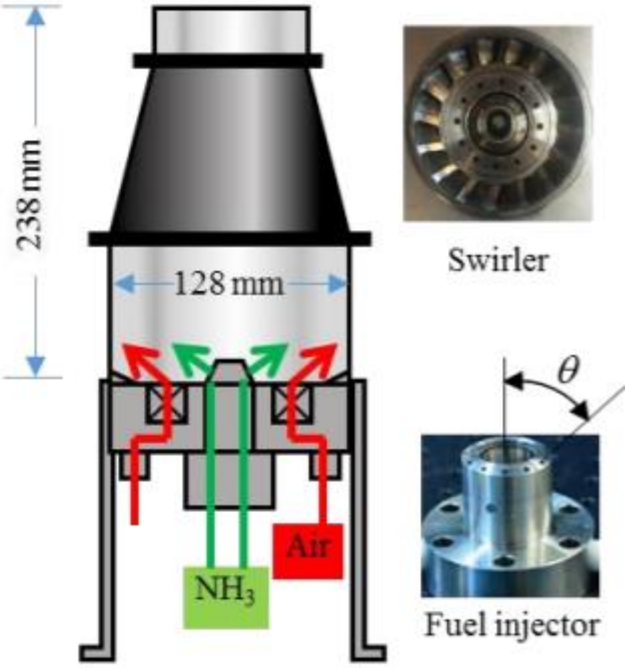


Figure 19; A schematic of the microturbine used in the project described above. [35]

6. Ammonias role as fuel in the future

Ammonia is viewed as a promising renewable alternative to traditional carbon-based fuel in the maritime sector. In 2018, the global production of ammonia was approximately 170 million tons, and the production is expected to grow by 6% by 2021. The shipping fuel demand is as well as the global production is set to increase even more. That is why the production of ammonia today will only cover a percent of the fuels in the marine sector.

If ammonia were to replace all fuel in the shipping sector, which accounts for about 300 million tons oil equivalents, around 650 million tons would be needed yearly, that is 3-4 times more than the yearly production today. While it is unrealistic for ammonia to take the whole fuel load in the shipping sector in any foreseeable future, it is likely to stand for a significant portion, if the current projects are successful. For this to happen there must be enormous investments into the infrastructure surrounding the use and production of maritime fuel. This includes production, transportation, storage, and bunkering. For ammonia to be sustainable the production has to be rearranged to blue and green.

6.1 Future demand for ammonia as fuel in Norwegian maritime sector

Ocean Hyway Cluster has with their project HyInfra attempted to map the future demand of ammonia in Norwegian maritime sector. For this it was made three scenarios for market penetration based on assumptions for replacement and upgrade possibilities by age and life expectancy for different vessel types. It is also assumed an unchanged fleet size and no energy efficiency improvements. [45] The market penetration scenarios they formed are shown in figure 20 below.

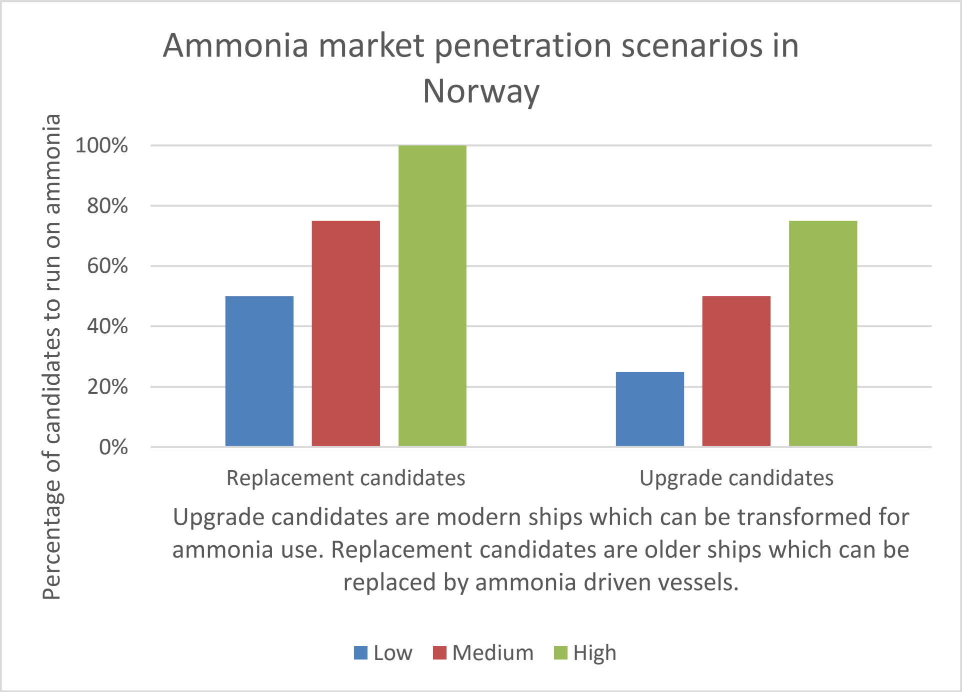


Figure 20; An overview of possible ammonia fueled vessels in 2030. Three scenarios for how many will be run on ammonia. [45]

Based on these three penetration scenarios they mapped the corresponding demand for ammonia. The results as shown in figure 21 below tells us that for the "high" scenario the demand will be almost 2 000 000 m^3 ammonia per year in 2030. A simple calculation shows us that this is almost 1 400 000 tons, which is almost three times Norway's yearly production of approximately 500 000 tons. For the low scenario, the number was approximately 750 000 m^3 which in mass is about 500 000 tons of ammonia. In figure 21 one can see that the demand starts in 2023, this is because there currently are not any vessels running on ammonia. Viking Energy is expected to run on ammonia from 2024. [45]

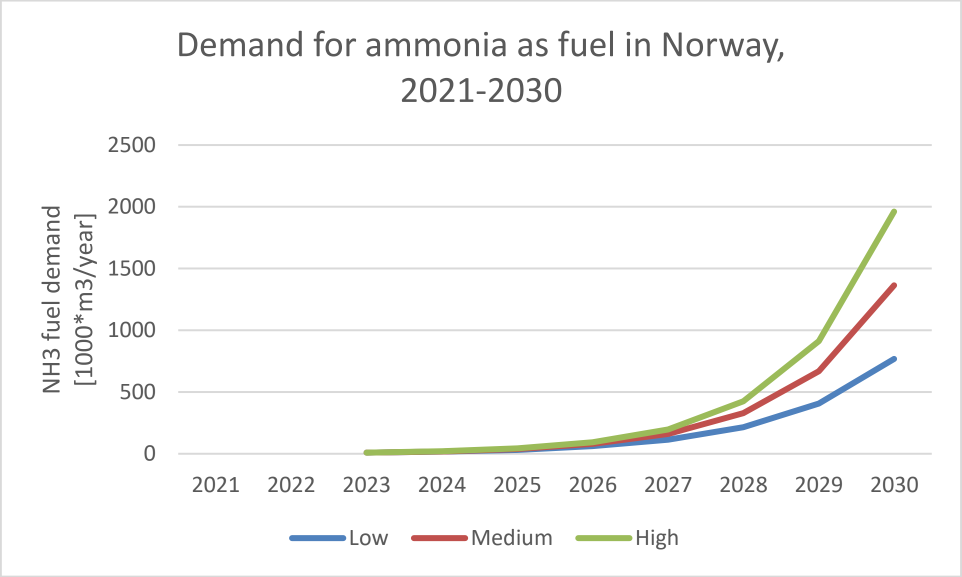


Figure 21; Possible development in demand for ammonia as fuel in Norway between 2021 and 2030. The aforementioned three scenarios. [45]

6.1.1 CO_2-emission reduction potential

The ammonia penetration scenarios also come with a potential CO_2-emission reduction as the ammonia will substitute carbon-based fuel. OHC also estimated this potential reduction as figure 22 below shows. By these estimations, the low scenario would cause a 700 000-ton reduction in CO_2-emissions and the high scenario would cause a 1 900 000-ton reduction in CO_2-emissions.

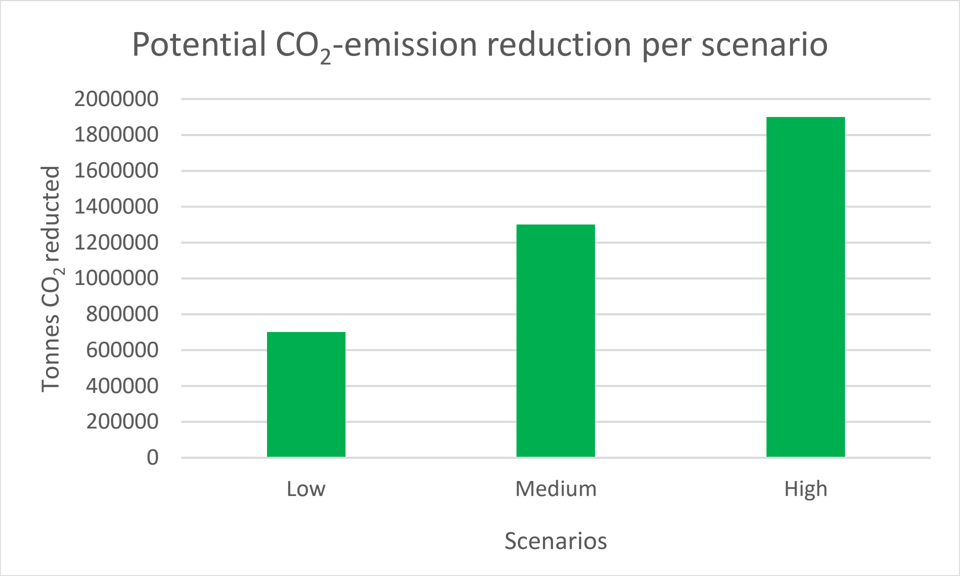


Figure 22; Potential reduction of CO_2-emission based on the three market penetration scenarios. [45]

7. Environmental aspects

Ammonia does not contain any carbon or sulfur emissions, and during combustion of ammonia it does not give any CO_2 emissions. Even though it does not contain any carbon, most of the ammonia production today is from natural gas, which leads to CO_2 emission. It is possible to produce green ammonia from electrolysis and the use of renewable energies. As mentioned, the world is dependent on a significant increase in renewable energies to produce larger volumes of green ammonia. Wind and solar energy as well as wave power are some of the renewable energy forms that needs upscaling.

Green ammonia has greenhouse gas (GHG) emissions close to zero in the production phase. Nonetheless there will be NO_x emissions depending on what engine technology used. There is also a risk of N_2O formation. N_2O has a high global warming potential (GWP) of 265 and it needs to be investigated if there are any N_2O slips from ammonia production. GWP is a comparison of the emissions of one ton carbon dioxide ($CO_{2)}$ with 1 ton of the different gasses. The higher GWP number, means that the given gas warms the earth more compared to how much warmth CO_2 gas gives to the atmosphere over a given time period, often 100 years. As a comparison methane has a GWP of 28, and N_2O has 265. [46]

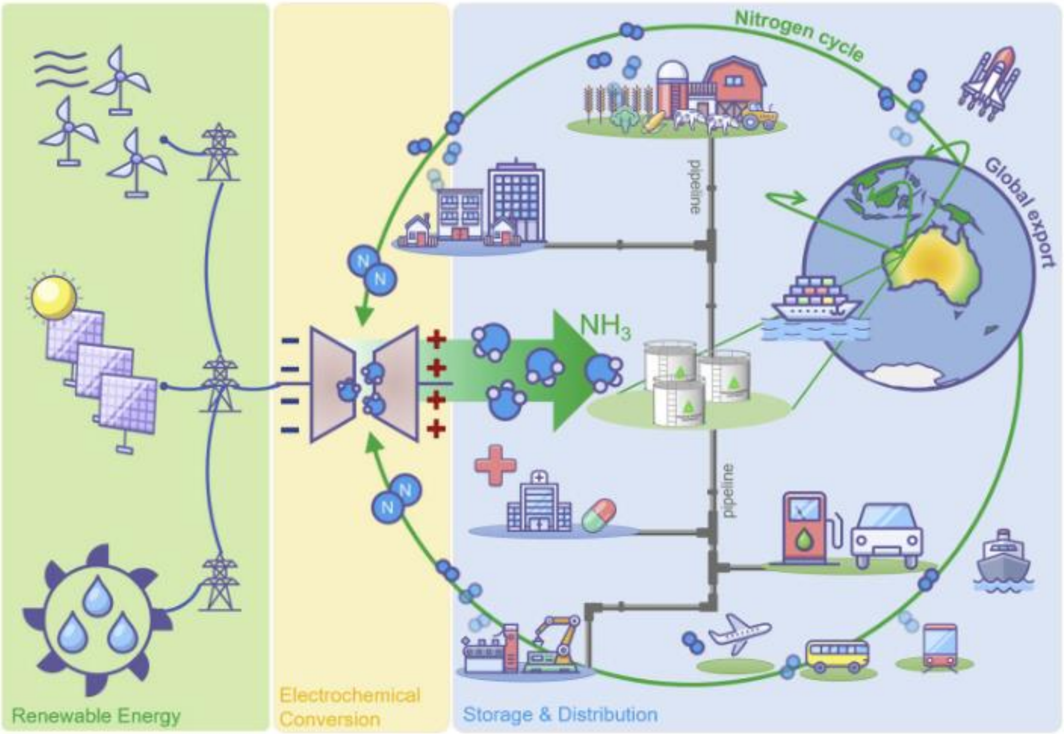


Figure 23; An illustration of an energy market based on renewable energy and ammonia. [58]

Combustion research on ammonia show problems with NO_X emissions. [31] NO_x is a chemical compound consisting of nitrogen and oxygen that is formed when reacting with each other at high temperatures for instance during combustion. NO_x can cause massive health damage to humans as well as causing respiratory diseases. NO_x can effortlessly react to organic compounds to form different types of harmful and toxic components. This is one of the reasons any system that is based on ammonia must undergo both health and safety impact analysis and a review of current legislation. [47] Ammonia slip is also a risk, as it in large concentrations in atmosphere can become a health risk.

When water reacts with ammonia, ammonium and hydroxide ions are formed. Both ammonia and ammonium are toxic to the aquatic life and organisms. There is an equilibrium in the water between the reaction of ammonium and the toxic ammonia. The equation is shown below. Aquatic life can be harmed if ammonia is spilled directly into the water surface even at low concentrations, such as 0.02 mg/L (48 hours) can be destructive to some sensitive freshwater fish. [48]

The reaction of ammonia and water.

$$NH_3(aq) + \ H_2O\ (l)\ \leftrightarrow NH_3 * \ H_2O\ (aq)\ \leftrightarrow\ NH_4^+(aq) + OH^-(aq) \qquad (6)$$

$$(ammonia\ in\ water) \leftrightarrow (ammonia + water) \leftrightarrow (Ammonia\ in\ water)$$

In consideration of the selected environmental impacts of ammonia production pathways with an LCA using non fossil energy sources for hydrogen and the Haber Bosch process shows the lowest GHG emissions are from hydropower compared to biomass and nuclear energy. [18]

8. Barriers for ammonia as fuel

In the report “Ammonia for power” by A. Valera-Medina, H. Xiao, M. Owen Jones, W.I.F. David and P.J. Bowen, it was stated that for a reliable energy system based on ammonia there are four major barriers, as following. [21]

1. **Carbon free synthesis of ammonia.**
2. **Economic viability for assimilation of green production of ammonia and technologies.**
3. **Appropriate community engagement and public acceptance of Ammonia through safe regulations.**
4. **Upscaling from small power generation to utility scale power generation.**

- **Carbon free synthesis of ammonia:** Even though ammonia does not contain CO_2, the production of ammonia is a long way from being carbon free. Ammonia is produced mostly from natural gas which leads to CO_2 being a biproduct of the production of ammonia.

  Many of the natural gas-based ammonia plants in the world are located in the countries with the lowest prices on natural gas, such as Russia, Middle East and North Africa. The newest ammonia plants are now being planned and built-in regions with good renewable resources, such as Australia with a lot of wind and solar power and Iceland with wind and geo-thermal energy.

  The issue with this barrier is that we need renewable energy to produce green ammonia, but the availability of these renewable energy sources fail to meet the need of demand.

The economy and how strict the rules in different countries are some of the main factors that needs to be solved to get the price of renewable energy sources down. This will lead to a bigger market growth worldwide for renewable energy sources, which will lead to a bigger interest in green ammonia as a maritime fuel, and this will eventually lead to less CO_2 emissions.

- **Economic viability for assimilation of green production of ammonia and technologies:** This barrier and the first barrier influence each other because they are both based on green ammonia (which is based on electrolysis made from renewable electricity from renewable energy sources). Something that most of the renewable energy sources has in common is if the price decreases, it will become more lucrative. The price must go down so it can start to compete with fossil fuels. For hydrogen energy, it also needs the market to grow, in addition to the prices go down. The big question is which comes first, demand or manufactures? Ammonia is a little different from hydrogen because the demand has been there a long time as well as the manufacturers because ammonia has been used as a fertilizer for a long time. Since ammonia is a potential hydrogen carrier and storage, it is likely that if the demand for hydrogen rises, so will the demand for ammonia.

- **Appropriate community engagement and public acceptance of ammonia**: this barrier is a little different from the rest. Public acceptance requires more studies, innovation as well as understanding. This barrier has played a crucial role in ammonias role in the world. Any potential system based on ammonia is required to have safety and health impact analyses, follow legislations as well as taking under consideration end-user tolerability and perceptions. More of public acceptance will come in chapter 6.2.2.

- **From small to utility scale power generations:** Most of the progress so far have been focusing on improving small and medium scale devices instead of utility scale power generation. The power output from these units using ammonia is typically around (0,1-1,0) MW. This leads to another huge problem, the reduction of unburned ammonia and NOx emissions.

Other major barriers are the toxicity of ammonia and the fact that ammonia has a bad smell. Even at low concentrations of ammonia, the smell is bad and hard to avoid. An important problem to address and understand is how the ammonia will be divided for use in the different sectors. Because ammonia is currently being used primarily for fertilizers, the marine sector may compete with ammonia that being used to produce food. [8]

8.1 Key barriers from Yara

Table 5; Barriers for ammonia as fuel.

	Barrier description	How to solve the problem?
Bunkering infrastructure	Security of supply and scalability of infrastructure. [49]	The starting point with 20 Mtn/year is decent for the global trade. The industry is required to gradually develop infrastructure to match the demand. [49]
Fuel Cost	Ammonia fuel will need long term high carbon price.	The key to bring fuel cost down will be to access low energy and/or large- scale development of CCS. [49]
Perception Safety	Safety risks can be a barrier for the uptake of NH_3 fuel.	Demonstration projects must be handled with big caution, building on global best competence and practice.
Regulatory	There are currently no rules for the use of ammonia as a fuel. [49]	Established first projects that are based on the IGF code for alternative design must be applied. [49]
Technology	There are still no proven technologies at the marine sector for large scale.	ICE and SOFC are both technologies that are being developed and should be demonstrated in 3-5 years. [49]

8.2 Public acceptance

Most people have in general no or little interest in unpopular products with a bad reputation. The public's view is important, especially for businesses and producers. Lack of information is a common problem when it comes to the public acceptance. For the use of ammonia in general and especially as maritime fuel the public acceptance is important as this will influence all factors (producers, users, policy makers). This will influence the public perception, development, and observants of safety regulations as well as the media. The media has such a massive influence on what people understand and believe and therefore it is important to get media on the right page with knowledge and potential around ammonia as a maritime fuel. Nowhere does information spread as fast as on the internet, so to improve the view of the public acceptance the internet should play a big role.

Ammonia is today currently used limited to farming communities and industrial applications. The question is: will broader use of ammonia be accepted by the public? There are several important factors, like the odor as well as the toxicity. The odor is noticeable for concentrations as low as 5 parts per million (PPM). [50] Small spills and leaks could cause the odor to spread to humans. Lack of information about ammonia in general and that a lot of the information about ammonia is negative to the public are issues that needs to be handled. To fix the issues about the view of ammonia, especially two things should be focused on: more general information about ammonia and address the issues with ammonia, such as the toxicity and the odor, and how it can be handled.

One final comment concerns the generally known fact that anhydrous ammonia, stolen from fertilizer nurse tanks, applicator hoses, etc., has found increasing application to the production of illegal methamphetamine in clandestine labs. This has become a common problem in the upper Midwest in USA farming regions where ammonia is readily available and has prompted the Minnesota Department of Agriculture, Agronomy and Plant Protection Division to issue a brief document20 describing the health hazards and spill response for first responders. [50]

Public acceptation study

Because of the importance of public acceptation, Cardiff University decided to make a study focused on the Yucatan Peninsula in Mexico. In this area of Mexico, they make big money on agriculture and are depending on ammonia as a fertilizer. An analysis was made for the government and general public. The results showed that the government in Mexico was currently not interested in ammonia because of the lack of development in other countries and the cost of ammonia. The overall results showed that the surveyed people had an interest in ammonia projects from clean energy sources. They were not concerned about the toxicity, instead they were concerned about the cost of introducing this technology. One problem to the public acceptance is the lack of information, especially information that benefits the ammonia.

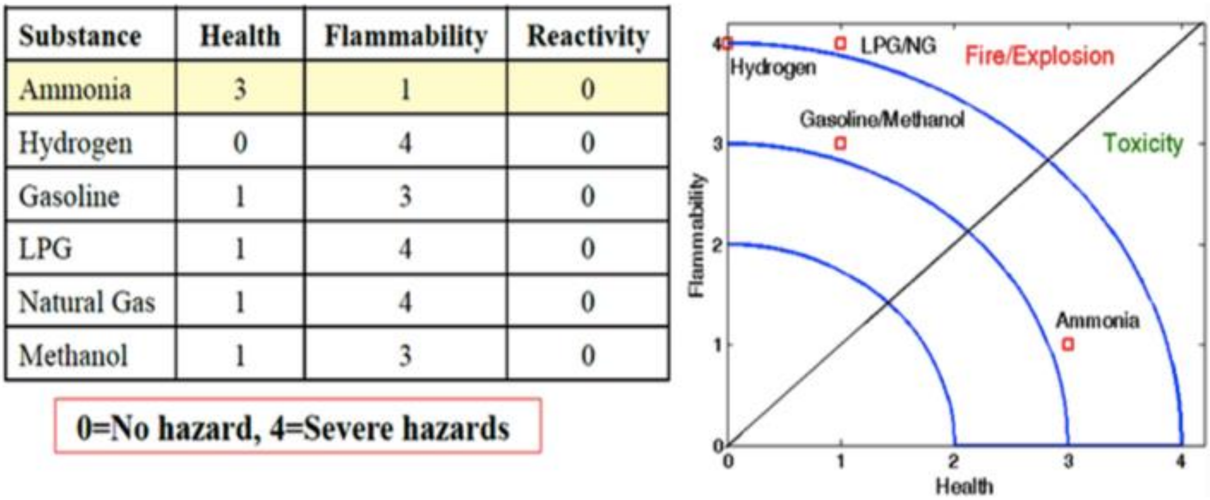
"The study applied a multi-methodological approach with a sample of 50 questionnaires and 7 interviews to people in the Mexican Government and people involved with cattle animals"

This study was based on the responses both before and after the surveys were given information about ammonia. Among the 76 % that had negative perceptive about ammonia, 96% of them changed their judgement when they were given technical information about ammonia and how to solve the main barriers. As a result, from this study, the researchers found that two main common barriers for ammonia was lack of information and that ammonia had the reputation to be a "dangerous gas". It is important to highlight that most of the people interviewed confirmed that they are willing to pass over the fear of using ammonia if the gas proves to be beneficial for the environment and proper health and safety systems are implemented. [51]

9. Health and safety

9.1 Health

The national fire protection association (USA) has ammonia classified as a substance that is toxic and therefore making it a health- and chemical risk. One important thing to be aware of is that ammonia has a low reactivity and therefore the hazards that are from combustions or accidental explosions are a lot lower than other liquids and gases. [21]



Substance	Health	Flammability	Reactivity
Ammonia	3	1	0
Hydrogen	0	4	0
Gasoline	1	3	0
LPG	1	4	0
Natural Gas	1	4	0
Methanol	1	3	0

0=No hazard, 4=Severe hazards

Figure 24; Comparison of ammonia and other relevant fuels on their risks. [21]

The picture to the right demonstrates a diagram that compares ammonia with methanol and hydrogen, relative to health (toxicity) and flammability (fire/explosion). The scale goes from 0 - 4, where 0 is no hazards and 4 is severe hazards. On the health scale ammonia has the value 1 because it has a low flammability, but on the health scale it has the value 3 because of the toxicity. The circular blue lines in the figure to the right illustrates the degree of hazard.

Table 6; Physical effects of exposure to ammonia at different levels of exposure. [19]

Concentration/time	Effect
10.000 ppm	Promptly lethal
5000-10.000 ppm	Rapidly fatal
700-1700 ppm	Tearing in the eyes and coughing
500 ppm for 30 min	Upper respiratory tract, irritation, tearing of eyes
134 ppm for 5 min	tearing of the eyes, eye irritation and chest irritation
140 ppm for 2 hours	severe irritation, need to leave the exposed area
100 ppm for 2 hours	Nuisance eye and throat irritation
50-80 ppm 2 hours	Perceptible eye and throat

Table 7; Physical effects of exposure to ammonia at different levels of exposure. [52]

Concentration	Effect
20 - 50 ppm	Readily detectable odor
50 - 100 ppm	No impairment of health for prolonged exposure
400 - 700 ppm	Severe irritation of eyes, ears and nose. (No lasting effect on short exposure)
2000 - 3000 ppm	Dangerous, less than 30 min of exposure can be fatal
5000 - 10.000 ppm	Serious odor, strangulation and rapidly fatal

The issue with the toxicity of ammonia needs new ways of handling gas release and a close consideration compared with traditional fuels. Hazard identification (HAZID) have been carried out by DNV GL along with several shipping companies and engine manufacturers to evaluate safety and especially the toxicity. [8] The HAZIDs have been covering for example the transportation of ammonia to engines and the transportation of ammonia from cargo to storage tanks. DNV GL has risk as the combination of consequence and likelihood. [8]

Potential leaks and spills will be hazardous for the environment and to the humans, and if the leakage is in water, it will be hazardous for the marine life. Over time periods ammonia is hazardous to inhale. The limits for ammonia for exposure of ammonia in Swedish workplaces are 20 ppm for 8 hours and 50 ppm for 5 minutes. Ing. Niels de Vries' report "safe and effective application of ammonia as a marine fuel" states that when exposed for 10 minutes, ammonia can be lethal for humans at 2700ppm [28], while the report "Ammonia for power" by Valera-

Medina and colleagues states that it may be fatal for humans if they are exposed to ammonia for less than half an hour at 2000-3000 parts per million (PPM). [21]

Being exposed to ammonia might be dangerous. It is classified as toxic and corrosive, and inhalation can result in irritation of nose and eyes, chest tightness, cough, sore throat, and confusion. Important factors that decide how dangerous the effects of ammonia might be, are the route of exposure, the dose, and the duration of exposure. Ammonia gas is lighter than air and therefore it does normally not settle in low-lying areas. Nonetheless ammonia can form vapors that are heavier than air if the climate is moisture. Ammonia might also be spread out to the circumstances because of the wind. This can lead to ammonia spread along the ground as well as low lying areas.

The report “ammonia as a marine fuel – a safety handbook” estimated 25-50 ppm of ammonia as the acceptable limit of exposure to humans and dangerous health effects if the exposure concentrations are above 300 ppm. Table 8 shows different levels of acute exposure guideline, with three different levels. **Level 1** is notable discomfort and irritation, **Level 2** is long lasting health effects and **Level 3** is life threatening health effects or death. [53]

Table 8; Shows how much different exposure levels, both time and quantity, affects physical health. [53]

	10 min	**30 min**	**60 min**	**4h**	**8h**
Level 1	**30 ppm**	**30 ppm**	**30 ppm**	**30 ppm**	**30 ppm**
Level 2	**220 ppm**	**220 ppm**	**160 ppm**	**110 ppm**	**110 ppm**
Level 3	**2700 ppm**	**1600 ppm**	**1100 ppm**	**550 ppm**	**390 ppm**

9.2 Safety

For a ship’s safety barriers, the choice of fuel is crucial. The toxicity is the main issue with ammonia as well as the flammability. The different types of fuels have different types of safety aspects. There are different tanks that are acceptable and can be used for transportation of ammonia, such as independent tanks type A, B, C, and membrane tanks. Only type A and C can be used in practice for ammonia. It is also possible to store ammonia in a refrigerated tank or a semi refrigerated tank, but it is required a backup system that is reliable to keep the temperature low. The placement of fuel pipes and tanks are anticipated to be close to the DNV GL requirements for LPG as a fuel. These requirements contain for example a distance that is minimum from ship bottom and sides to reduce the risk in case if a collision might happen. [8]

Klüssmann et al., (2019) proposed that it is possible to reduce safety issues with liquid ammonia stored on ships by storing ammonia in metal amine complexes or in mineral salts. [18] It was also said that ammonia has a flammability that is relatively low compared to other fuels, therefore it has a lower risk of fire, but can still create explosive mixtures with air. Compared to other fuels it is required a smaller amount for explosions to happen. The risk of fire still needs to be considered because hydrogen is achieved by cracking ammonia, and hydrogen is a very flammable gas. [28]

It is also important to know that ammonia is not new to shipping: it is typically transported as cargo and it is common practice to use ammonia onboard as a refrigerant. Most of the necessary practices for a safe ammonia handling onboard are already well-known in marine industries and accepted by crew and operators, including operational and safety procedures. The use of ammonia onboard are covered by international regulations and rules.

9.3 Risks and hazards

For ships, the level of risk and hazards are depending on the type of ship, operations, and the arrangement. Accidents like pipe rupture, venting of ammonia during an emergency shut down and uncontrolled venting of ammonia, are some of the events that might happen. A risk assessment that is required by the IGF Code has to be carried out and risk reducing solutions will be achieved. IGF code stands for the international code of safety for ships using gasses or other low - flashpoint fuels. For the ships that are using ammonia as a fuel, the crew is required to have special training (with ammonia). For potential cruise or passenger vessels, there will be different important factors relative to ammonia leakage, like the evacuation time and safe return to ports and the location of life saving equipment and medicine. [8]

“Ammonia as a marine fuel – safety handbook” by DNV GL, Green shipping program and Norwegian Maritime Authority states that the safety regulations for the use of ammonia as a maritime fuel on board ships are currently (2021) not established or in place. Before using ammonia as a maritime fuel, it is important to have all the different rules completed, for all the different types of scenarios and sizes of ships. [53] Even though the maritime industry has years of experience with usage and carrying of ammonia as a refrigerant and in carriers of gas, there are challenges. The challenges with ammonia as a fuel are associated with safety of ammonia supply, consumption and bunkering for different types of ships.

9.4 Flammability

Ammonia is hard to ignite, but it is still flammable. In general leaks of ammonia vapors will not produce a fire hazard. The risk of a potential ignition is higher indoors and if there are combustible materials like oil the probability of ignition is a lot higher.

Ammonia is flammable in the range of 15 to 28 % mixture in air. The minimum ignition energy for ammonia is 8 MJ energy, 30 times more than for methane (0.27 MJ), and 470 times more than for hydrogen (0.019 MJ). At temperatures 651 °C and higher, ammonia can self-ignite. [53]

10. Economical aspects

It is difficult to predict the global marked of ammonia because of the uncertainties around ammonia. Analysts claims that there are uncertainties regarding government regulatory frameworks and subsides and established storage technologies. [21]

Ammonia production has the potential to be increased quickly in volume for the global market. In general, the market for ammonia is estimated at $91–225bn per year. Several analysts have tried to estimate the worldwide energy storage marked size. Energy Research partnership have found the global market over the next 10-12 years to be worth around $600bn. Navigant Research have found the global investment between 2014-2024 to be estimated at $68bn in total over those 10 years. [8]

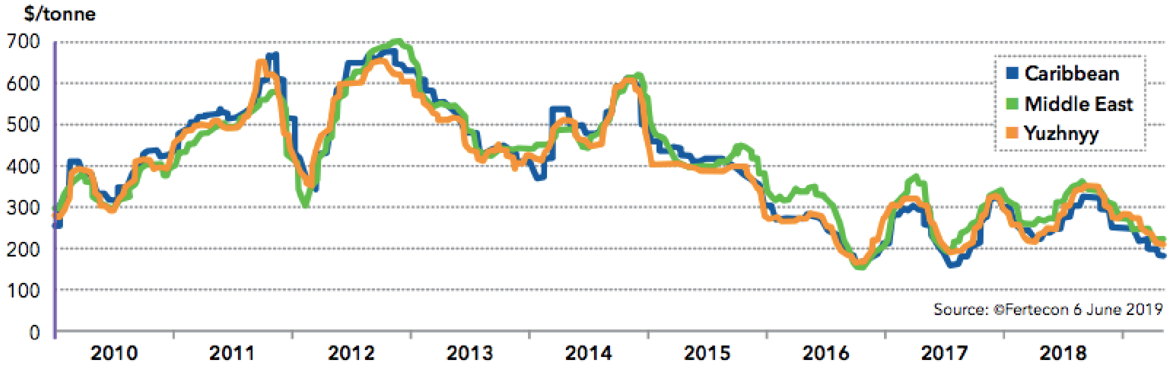


Figure 25; Shows the price development for ammonia, in US $/tonne, between 2010 and 2018 in relevant markets. [8]

The production route is deciding what the cost of ammonia production will be. For green ammonia, the electricity price is the largest contributor to the production cost. For ammonia based on natural gas it is the price on natural gas that is a major factor for the production route. The price on ammonia varies a lot over time and they are not the same in different geographic areas. In the last decades, the prices have been in the range of 200-700 $/ton. Because of the marked conditions for ammonia availability and for natural gas, the prices for ammonia has been lower than 400$/ton and normally around (200-300) $/ton since 2016. Most of the ammonia production is from fossil fuels (natural gas) and therefore the prices on ammonia are reliable on the prices on local natural gas. In the US, the ammonia production from natural gas is (70-85) % of the total production. As an example of the prices of local natural gas it was 100$/ton in the Middle east and more than 400$/ton in Western Europe is 2013. [8]

The cost of production of ammonia from coal is more expensive than from natural gas because of the increased capex and reduced efficiency. The cost of production from renewable energy is also more expensive than natural gas. The cost of ammonia production from renewable energy is near the compete with the cost of ammonia from coal. The cost of production of ammonia from renewable energy will be dependent on these two main factors: capital expenditure and the production of electricity. The cost of power for onshore wind is based on the capex and the capacity factor and the prices has been estimated at around 0.04-0.05$/kwh. [8]

10.1 Ammonia Prices in the future

The demand for an emission free fuel to solve the greenhouse gas (GHG) problems will only increase in for years to come. Ammonia still needs lower prices to compete with the fossil fuels. In 2020 the marine consumption was 250 million tons and therefore an expansion of renewable energy sources is needed. To replace 30% of the amount of the marine fuel consumption it is required 150 million tons of ammonia (because of the lower energy density), which requires 1500 TWh renewable electricity. In 2050 it is expected that 25-50% of the fuel consumption is replaced with ammonia. Below is a picture that shows how much Solar- and wind power required to produce the 1500 TWh electricity to cover 30% of the worlds marine fuel consumption in 2020. [19]

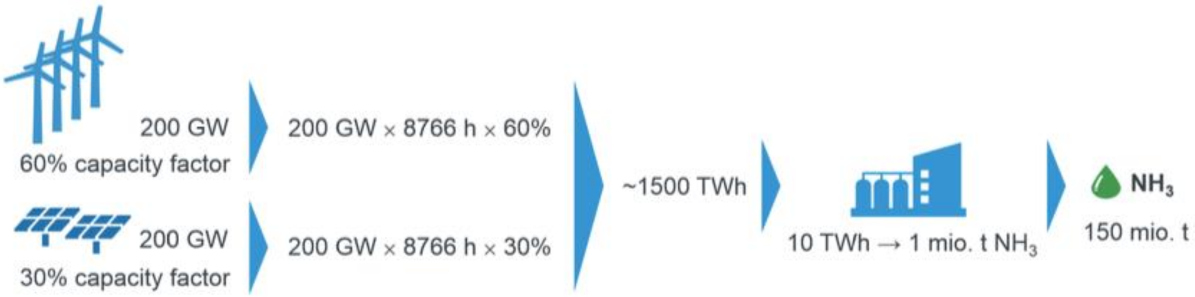


Figure 26; Shows how much installed wind- and solar -power is needed to produce enough ammonia to replace 30% of the world's fuel consumption (1500 TWh). [19]

Table 9; This table shows how much time it will take to install the required capacity, assuming same pace of installment as 2019. [19]

	Wind power	Solar PV
Cumulative installed capacity (2019)	**650 GW**	**636 GW**
Capacity installed (2019)	60 GW	124 GW
Time to install needed capacity	200 GW / 60 GW/year = 3.33 years	200 GW / 124 GW/year = 1.61 years

Figure 27 shows a prediction of production prices on ammonia in 2040, based on the production method, compared to the predicted price of electricity and hydrogen. Figure 27 suggests that grey ammonia, produced by steam reforming of natural gas and the H-B process, will be almost as cheap as electricity in 2040.

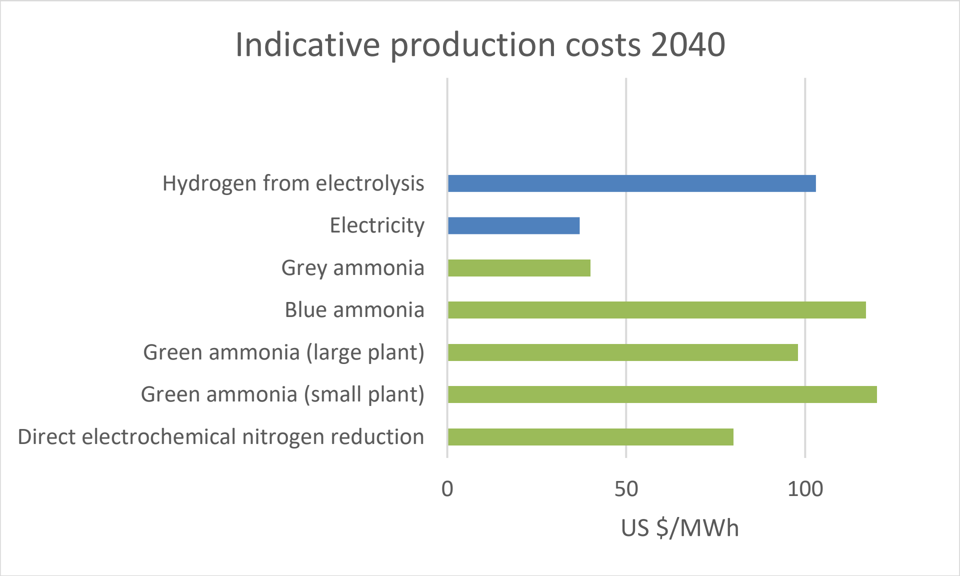


Figure 27; Predicted production cost for the different ammonia production methods, compared to the price of electricity and hydrogen. [18]

Below is a prediction from "Ammonfuel – an industrial view of ammonia as a marine fuel" made by Haldor Topsoe, Hafnia, Vestas, Alfa Laval, and Siemens Gamesa on the future ammonia prices. This is only a prediction and does not necessary show how the prices will be in 2025-2050. The table suggests that the price on conventional ammonia will not decrease from 2025-2050, and neither will blue ammonia, but green ammonia and hybrid ammonia will decrease.

Table 10; A prediction of future ammonia prices between 2025 and 2050, categorized into the different sustainability categories of ammonia. [19] LHV – Lower heating Value, GJ – GigaJoule, t – Tonnes, USD – US Dollars

	2025-2030	**2025-2030**	**2040-2050**	**2040-2050**
	30 EUR/MWh	30 EUR/MWh	20 EUR/MWh	20 EUR/MWh
	Price Per ton USD/t	**Price Per GJ LHV USD/GJ**	**Price Per ton USD/t**	**Price Per GJ LHV USD/GJ**
Grey ammonia	250	13,5	250	13,5
Blue ammonia	350-400	18,8-21,5	350-400	18,8-21,5
Green ammonia	400-850	21,5-45,7	275-450	14,8-24,1
Hybrid green ammonia	300-400	16,1-21,5	250	13,5

Conclusion

Ammonia has a huge potential as a maritime fuel for deep-sea shipping, with a high energy density in addition to that ammonia can be produced from electrolysis with CO_2 emissions that are close to zero. The public acceptance of ammonia requires more focus on the advantages ammonia has as a fuel, but also how to solve the problems, such as the toxicity and the transition from grey production based on natural gas to green ammonia from electrolysis. More studies around the public acceptation on ammonia should be created to see if there are any changes in the view of the public. It is also important to highlight that in order to produce green ammonia from renewable electricity, it is required a growth in renewable energy sources in the world. Even though ammonia does not contain any CO_2 in the compound, most of the ammonia today is created from natural gas which leads to CO_2 emissions, but other potential emissions like N_2O and NO_x requires further research.

The use of ammonia in ships has some key barriers and factors that needs to be in place before it is used as a fuel. Ammonia has a low flammability compared to other gases and therefore the toxicity is the main barrier. Even though ammonia has a low flammability, it can still ignite, and this also needs to be taken seriously. It was found from two different sources, that if the ammonia concentrations are 5000- 10.000 ppm (or higher), it is dangerous and can cause serious health damage.

When it comes to safety, there are rules that needs to be made for all the different scenarios and all the different types of ships that will use ammonia, especially for deep-sea shipping (over long distances), since contribute to significant CO_2 emissions for each vessel. It was mentioned that the safety can be reduced for liquid ammonia stored on ships, if stored in mineral salts or amine complexes.

There are currently many companies around the world who works with ammonia, either with Fuel Cells (FCs), Internal Combustion Engines (ICE) or Gas Turbines and therefore it is expected that the knowledge around ammonia in different technologies will develop. The results of the efficiencies for the different technologies using ammonia were: SOFC (53 %), PEMFC (28-43 %), AFC (43,0 %), ICE (43,0 %) and Gas Turbine (thermal efficiency, 35 %). The PEMFC scored very low in the simulation described in chapter 4, due to the cracking and purification process the ammonia has to go through for the hydrogen to be clean enough for use in the application. With hydrogen PEMFC have an efficiency between 50-60%. To put these efficiencies in perspective, marine diesel engines usually have a thermal efficiency of approximately 40%, while Wärtsilä’s world record holder W31 has a thermal efficiency of over 50%.

As of today, the market standard for fuel in the shipping sector is Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), Marine Diesel Oil (MDO), and Marine Fuel Oil. These fuels are usually used in ICE or turbines and have slightly better efficiencies compared to ammonia as shown in table 4. The reason for the difference in system/thermal efficiency is that these fuels have better combustion properties, and they also have a long history of usage and engines have been optimized for its use. Further development of ammonia combustion technology and optimalization of the engines for ammonia use can limit these differences. Heat recovery systems for engines are also a method for improving the overall energy efficiency, by using waste heat, or the heat that is not used for propulsion/electricity generation, for other purposes such as warming inside areas on a ship.

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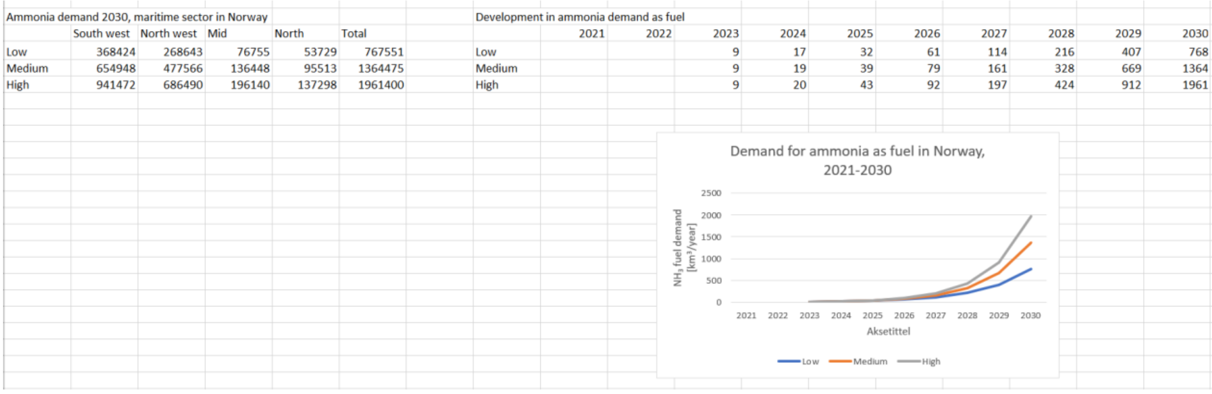
List of figures

List of tables

Attachments

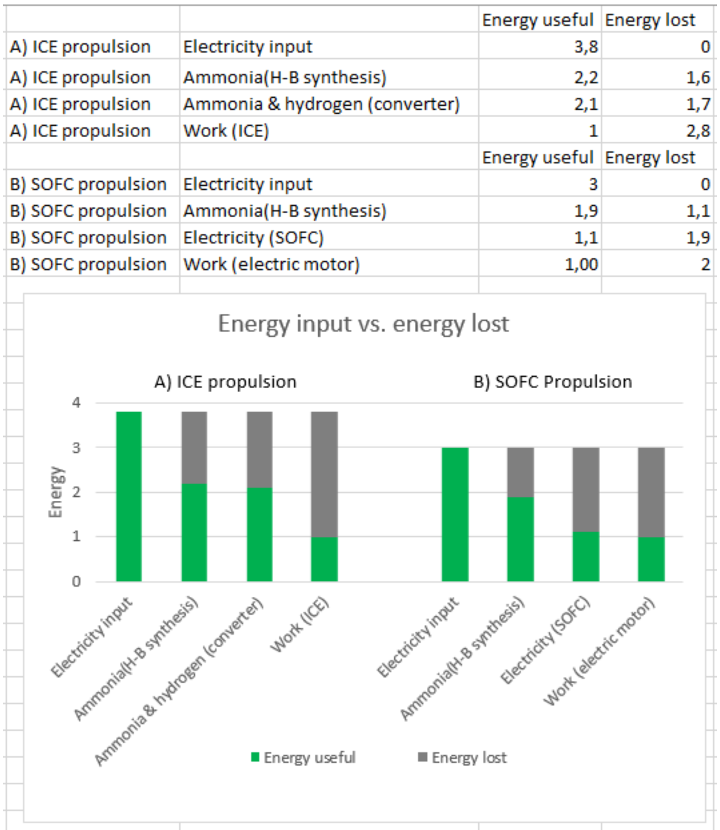


Ammonia demand 2030, maritime sector in Norway

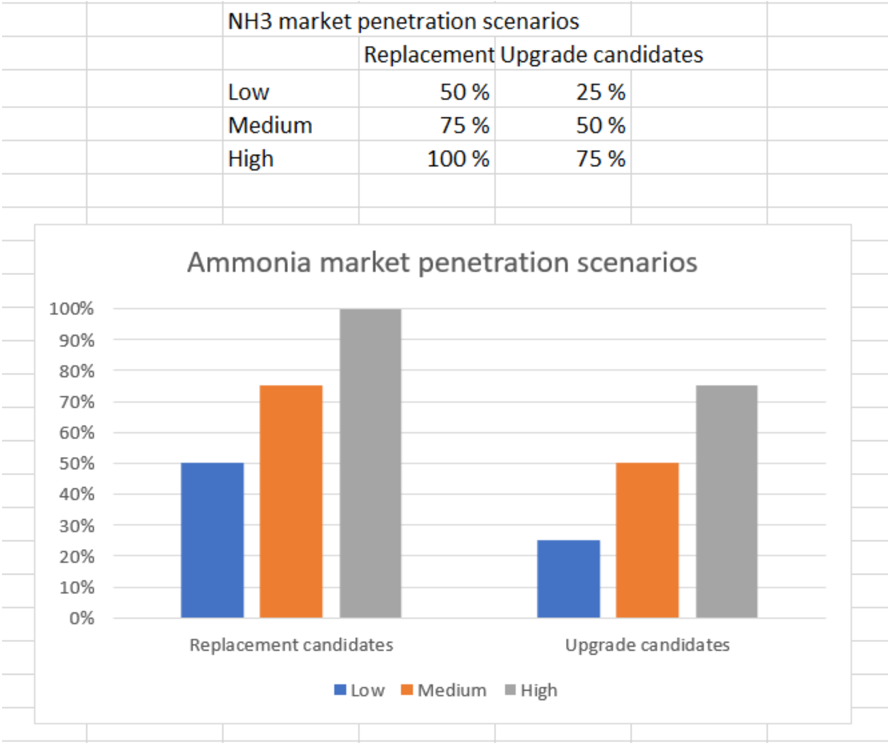
	South west	North west	Mid	North	Total
Low	368424	268643	76755	53729	767551
Medium	654948	477566	136448	95513	1364475
High	941472	686490	196140	137298	1961400

Development in ammonia demand as fuel

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low			9	17	32	61	114	216	407	768
Medium			9	19	39	79	161	328	669	1364
High			9	20	43	92	197	424	912	1961

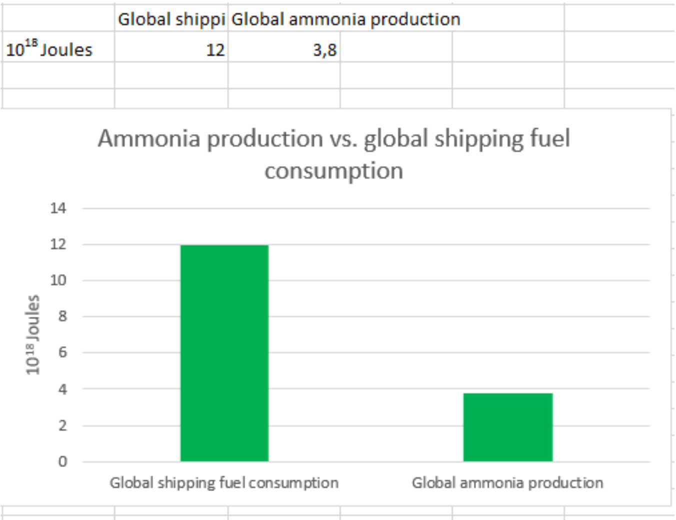


		Energy useful	Energy lost
A) ICE propulsion	Electricity input	3,8	0
A) ICE propulsion	Ammonia(H-B synthesis)	2,2	1,6
A) ICE propulsion	Ammonia & hydrogen (converter)	2,1	1,7
A) ICE propulsion	Work (ICE)	1	2,8
		Energy useful	Energy lost
B) SOFC propulsion	Electricity input	3	0
B) SOFC propulsion	Ammonia(H-B synthesis)	1,9	1,1
B) SOFC propulsion	Electricity (SOFC)	1,1	1,9
B) SOFC propulsion	Work (electric motor)	1,00	2

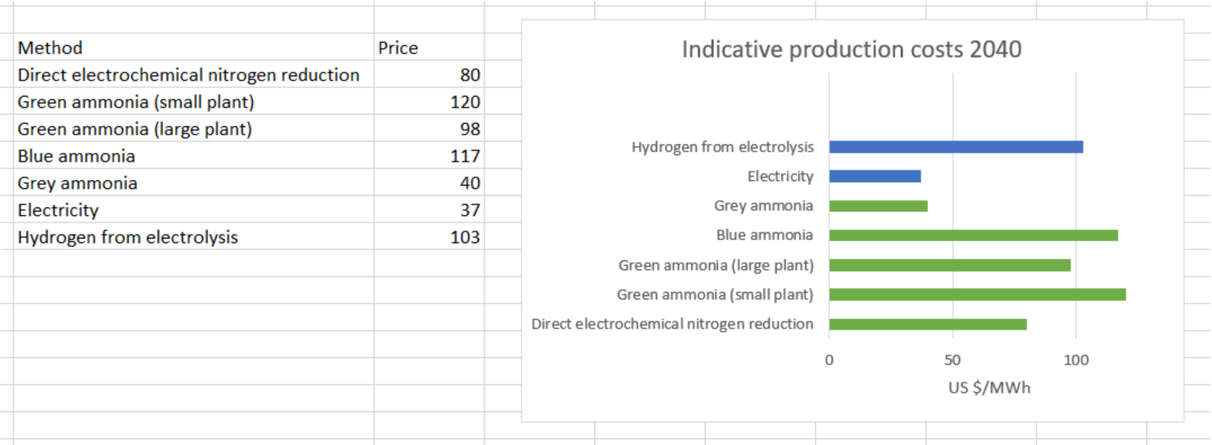


NH3 market penetration scenarios

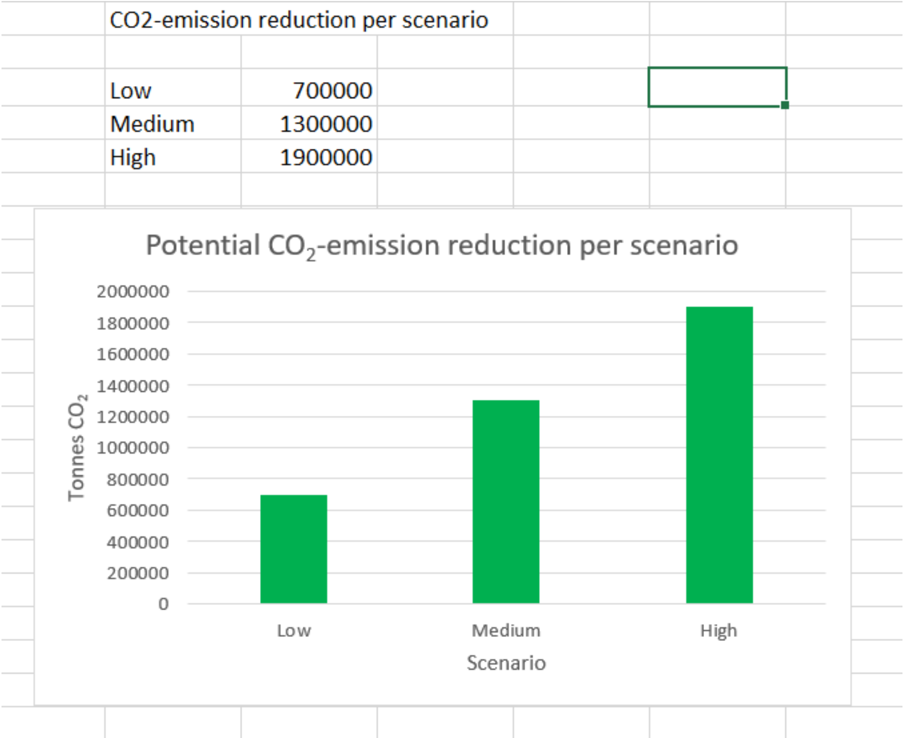
	Replacement	Upgrade candidates
Low	50 %	25 %
Medium	75 %	50 %
High	100 %	75 %



	Global shippi	Global ammonia production
10^{18} Joules	12	3,8



Method	Price
Direct electrochemical nitrogen reduction	80
Green ammonia (small plant)	120
Green ammonia (large plant)	98
Blue ammonia	117
Grey ammonia	40
Electricity	37
Hydrogen from electrolysis	103



CO2-emission reduction per scenario

Low	700000
Medium	1300000
High	1900000