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MASTER'S THESIS

What are the operational difficulties and risks related to use of new types of fuels for marine applications?

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Master in Maritime Operations: Maritime Technology and Management
Department of Maritime Studies
Supervisor: Jens Christian Lindaas
Submission Date: The 2nd of June 2023

Preface

This thesis is the concluding work of 2-year's masters programme in Maritime Operations at Western Norway University of Applied Sciences. This master is under the department of Maritime Studies. It is a joint master's programme with Hochschule Emden-Leer, whereas the second semester Is taken place in Germany. We chose the Haugesund programme, Maritime Technology and Management as specialization for the final year.

This topic for this thesis was chosen due to our background in ship upgrades, internal combustion engines and process design. Also, the subject Ship Propulsion, held in the second semester in Leer sparked a great interest for the both of us for further research. This subject was very interesting and challenging when it comes to technical solutions for converting existing ships. We wanted to expand this into our thesis and saw great potential with the research proposal from Kystverket.

In this regard we would like to extend a sincere thank you to our supervisor at HVL, Jens Christian Lindaas. Your follow up on our thesis was truly appreciated, we had some nice discussions together and your advice was great – also concerning when we needed a second opinion. We also thank you for the great constructive feedback you gave. We were very happy when you said yes when asked to be our supervisor.

We would also like to thank our external supervisors at Kystverket, Hans Morten Midtsand and Nora Helen Lund Lyngra. Thank you for the valuable input and discussions regarding the topic, as this contributed to the fundamentals in our thesis work. We would also like to extend a sincere thanks to Bjørnar Kleppe who assigned us this research proposal by Kystverket.

We also extend a sincere thank you to Jan Emblemsvåg, that was kind enough to supply us with his research articles, which gave us great motivation to write about Thorium Molten Salt Reactors. We truly hope that TMSR (thorium molten salt reactor) can be commercially available in the future, as we believe this is one of the key-factors that can contribute to Norway in reaching Its emission goals. Lastly, we would like to thank Hilde Sandhåland that has been a great support for us these last two years.

Abstract

As of recent IMO committed that the next big deadline is set to be in 2050 for the shipping industry, by this time all emissions must be halved. To meet the future emission demands which are set by the IMO; the shipping companies, class companies, maritime authorities, etc. must take action for facilitating that new carbon-neutral alternative fuels can be implemented. These alternative fuel types can be such as green ammonia, methanol, hydrogen, Thorium Molten Salt Reactor, and to some extent, LNG (liquefied natural gas). However, some challenges must be solved, to make the fuels a viable option.

For this reason, alternative fuels were further researched to broadly understand how the fuel can be implemented as a solution to reduce emissions. Through an extensive literature review, the technical and operational aspects such as its availability and infrastructure, emission, fuel consumption, economic feasibility, and technical storage capacity were investigated. Also, regarding the calculations and the operational aspect MS Nordlys from Hurtigruten was considered as the vessel to be opted for use for these alternative fuels, as it is today sailing regularly along the Norwegian coast. The alternative fuels were compared together with the base case Marine Diesel Oil. This fuel is regarded as the most common fuel in Norway, accompanied by LNG which is a more available environmentally friendly option as of today. LNG is considered a bridging fuel, which can in the short term reduce the emissions, but is still regarded as a fossil fuel that needs to be replaced with a more environmentally friendly option in the future. The risk of each fuel type was examined regarding the properties of the fuel itself, and how this constitutes a risk in an operational aspect.

It is seen in this context that for the new fuel types, several of them are not ready for the market as it is today. There is a lot of work that remains when it comes to further technological development and research before it can be ready for implementation as a usable operational solution that can help reduce fuel emissions. This also applies to developing infrastructure that can take care of the bunkering needs of coastal ships. The shipping companies might as of now hesitate to make a switch to more environmentally friendly options due to the vast competition in the shipping market when it comes to the current price level of acquisition for the alternative fuels. Onshore installations to produce these fuel types must also be developed before they can be considered a competitive option. With established infrastructure, this can also bring down the acquisition cost of the fuels in question. Although most of the alternative fuels investigated seems promising if it is further researched and developed, in this report, it was found that green methanol and thorium molten salt reactor seems even more interesting. Green methanol on the other hand has zero emissions if the CO2 is stored and re-used for the production of new methanol, accompanied by hydrogen from renewable sources such as wind- or solar power. As for the thorium molten salt reactor, the road is barely begun. With its vast energy density and very low thorium consumption for power generation it can operate for a very long time. It is undoubtedly something that should be prioritized for research and development, and it is also regarded a safe option.

Norway seems to be on a good path in research and development when it comes to the alternative fuels investigated. With the downside of thorium molten salt reactors not being researched. Furthermore, more funds must be allocated to reach the emissions goals as set by IMO.

Keywords: Ammonia, Hydrogen, Methanol, Liquefied Natural Gas, Marine Diesel Oil, Thorium Molten Salt Reactor, Emissions, Fuel Consumption, Energy Density, Storage Capacity, Economic Feasibility, Risk Analysis.

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Abbreviations

ABS – American Bureau of Shipping

AFI – Alternative fuels insights

Atm. – atmospheric pressure

CCS – Carbon capture and storage

CO – Carbon monoxide

CO_2 – Carbon dioxide

DNV – Det Norske Veritas

DWT – Deadweight tonnage

ECA – emission control area

EROI – Energy Return On Investment

GA – General Arrangement

GHG – Green-house gases

H_2 – Hydrogen

H_2S – Hydrogen Sulphide

HC – Hydrocarbon(s)

HFO – Heavy fuel oil

IMO – International Maritime Organization

ICE – Internal combustion engine

kWh – Kilo-watthours

LNG – Liquefied Natural Gas

Liq. – Liquid

LPG – Liquified Petroleum Gas

MCR – Maximum continuous rating

MDO – Marine Diesel Oil

MGO – Marine Gas Oil

MSR – Molten Salt Reactor(s)

NDT – Non-destructive testing

NOK – Norwegian Krone

nm – nautical miles

NO – Nitrogen monoxide

NO_x – Nitrogen oxides

N_2O – Nitrous oxide

NuProShip I – Nuclear Propulsion for merchant shipping I

NTNU – Norwegian University of Science and Technology

PM – Particulate matter

PPE – Personal protective equipment

Ppm – Parts per million (mass)

Ppmv – Parts per million volume

PWR – Pressurized Water Reactor

RPM – Revolutions per minute

R&D – Research and Development

SCR – Selective Catalytic Reduction

SFOC – Specific fuel oil consumption

SNG – Synthetic Natural Gas

SO_2 – Sulphur dioxide

SOx – Sulphur oxides

TMSR – Thorium molten salt reactor

USD – United States Dollar

1. Introduction

1.1 Research Question and objective

Research question: What are the operational difficulties and risks related to use of new types of fuels for marine applications?

Research objective: Research and assess different types of technological and operational aspects, and risks that are imposed with alternative types of fuels for vessels sailing along the Norwegian coast. Concerning operational aspects such as fuel consumption, storage capacity, emissions, and risks regarding handling, fire, explosion, and/or other types. The aspects of technological and operational data, together with identified risks are further compared to each other.

1.2 Research Methods

The approach that has been used to investigate and answer the research question as stated above is by means of conducting a literature study and communication with other subject experts.

1.2.1 Literature Study

A literature study (or review) is an approach in which one reviews literature for recorded work produced by scholars, practitioners or researchers, using the method in a systematic, explicit and reproducible way to synthesize the identified and evaluated text. The requirement for the research is that it is originally founded upon empirical research, and this is to be put systematically when reviewing it. One can argue that it is essential to carry out a good literature review in order to go through all available evidence, and this is structured as a systematic review of all existing literature. Reviewing this literature reveals all the evidence in such a way that it strives to find the full truth to the question or subject that is to be studied, and this is a fundamental scientific activity. This further allows the reviewer to use a reproducible method for several situations that are to be studied and also appraises the same level of quality as the method. The results of the studies are analysed and summarized as researched material/literature. The evidence that is gathered can be synthesized, which may reveal what we do not know and what we already know, enabling further research to reveal answers to the research subject. This illustrates the quality of the research and how strong it is, indicating confidence in the results. It reveals the consistency between multiple studies, or it may help reveal how well a technique, intervention, policy, or program work. Research synthesis highlights weaknesses and reveals areas that need to be further researched. Although a well-defined research synthesis may reveal a lot, they do not solve all problems – but they do offer decision-making and valuable aid for the researcher to reveal more information about the research topic or question. An easily rememberable way to set up a literature review can be set up as in "SALSA" elements: Search, AppraisaL, Synthesis, and Analysis.

The literature review can be from these particular contexts be showcased, it could be as a major component of a thesis, dissertation, or another academic deliverable. It could also be a peer-reviewing publication, that could be in a journal or a book chapter. It can also be used in commissioned research, consultancy or a report from a funded research project.

(Booth, Sutton, & Papaioannou, 2016, pp. 9-12)

So, what exactly is the purpose of a literature review?

- Structure the work in a context for how it contributes to the understanding of the subject which is reviewed.
- To highlight what is needed for further research.
- To identify the previous or original work within present literature (or literature which is under review).
- To consider how each work relates to each other and describe this.
- Shed light on gaps and in new ways interpret previous research which is carried out.
- To prevent duplicating some previous research that has already been covered and is not necessary to research any further.
- That from previous conducted research it resolves and identifies the conflicts which is in contradiction.

(Booth, Sutton, & Papaioannou, 2016, p. 14)

1.2.2 Correspondence and Communication

Another method which was extensively used was by means of communication and correspondence with subject experts. This includes our internal- and external supervisors, but also reaching out to companies and reaching out to key persons within the field of subject. This could for instance be further investigation of research articles, or in search for more information that was not available for the given research articles at present time. Reaching out to get technical information about engines and the ships technical drawings. It was further for good discussions regarding the subject, for instance discussions about weaknesses that was found.

Key persons and companies are:

- Western Norway University of Applied Sciences (internal supervisor, Jens Christian Lindaas)
- The Norwegian Coastal Administration (external supervisors, Nora Helen Lund Lyngra and Hans Morten Midtsand)
- Norwegian University of Science and Technology (Prof. Jan Emblemsvåg)
- DNV (Key person behind the study ‘Comparison of Alternative Marine Fuels’)
- Western Norway University of Applied Sciences, retired lecturer (Gisle Kleppe)
- Bergen Engines AS
- Hurtigruten AS
- Aibel AS (colleagues for good discussions)
- Odfjell Drilling AS (colleagues for good discussions)

This list is not exhaustive.

1.3 Background

A commitment made by IMO (International Maritime Organization), is that the big deadline in the shipping industry is in 2050 when it comes to halving the emissions. It is quite ambitious but is possible to do so if one implements some actions. To reach this goal, one needs to implement carbon neutral fuel types and/or alternative fuel types that gives off less emissions when consumed. As of today, some of these fuel types still have some challenges that needs to be solved. This is such as the toxicity of ammonia, and that it is produced from fossil natural gas. And as for LPG (liquefied petroleum gas) and LNG (liquefied natural gas) they are fossil fuels. If you take for instance biofuels, they have limited availability, is expensive and have challenges when it comes to sustainability. The alternative fuels may prove to have difficulties when it comes to transport/conversion of the value chain as this will require consumption of energy. Following this the alternative fuels introduces new aspects when it comes to bunkering and may require new technical infrastructure to facilitate the use, let alone be developed for commercial use. If one considers travel with fully electrical solutions, one has limited range, and if one considers long range travel with use of electricity this proves the need for bigger and more heavier batteries, which in turn will cause diminishing returns to go into negative returns for travel as it requires more energy to accelerate the vessel as heavier it gets. (DNV and partners, 2021, p. 12) One of Norway best-known shipping companies for cruise trafficking and cargo transport banned the use of heavy fuel oil in 2009. (Hurtigruten, 2023c) It is important to further investigate the alternative fuels in the maritime shipping industry. More specifically these fuels are ammonia, methanol, hydrogen, and thorium molten salt reactor. These are seen in relation to the base case marine diesel oil, and to some extent LNG. LNG can be considered a bridging fuel to reduce the emissions on a short term.

1.4 Limitations

The focus in this thesis will be on the ship traffic along the Norwegian coastline, and the availability there is for the various fuel types.

Focusing on ship types that typically operates along the Norwegian coastline, with a maximum length of 150m and maximum depth of 9m. For this thesis “MS Nordlys” was chosen as the vessel to be investigated with use of alternative fuel types, as this fits well within the above-mentioned specifications.

While looking at each fuels operational capacity in chapter 2, the calculations will only deal with the ships propulsion engines fuel consumption, and not considering auxiliary engines and systems. It is also considered using 100% of the described fuel type with no additional pilot fuel, even though engine technology has not developed that far yet for some of the fuel types. The sailing distance considered in the calculations is calculated for direct sailing time without stops.

To make the calculations in chapter 3 less complex, the energy density used is the pure energy density for that specific fuel type and does not consider storage- and fuel handling systems. If this was accounted for this would affect the energy density by decreasing Its value. This was one way to limit the extent of this thesis.

To calculate the cost of fuel consumed in chapter 3, the prices on the various fuel types was retrieved from different available sources online on April 15th, 2023.

Suggestions for tank location given for the alternative fuel types in chapter 3 are only shown as a simple illustration of various suggestions, and do not take into consideration additional systems or fuel preparation rooms which are also necessary for several of the fuel types.

In agreement with our internal supervisor, the risk related to collision or ground-breaking for the vessel was delimited due to the scope of the thesis. However, for marine diesel oil and thorium molten salt reactor it was considered very briefly.

2. Theoretical Background of Fuels

In the world shipping fleet today, heavy fuel oil (HFO) is still the most common marine fuel used, in addition to other low sulphur fuels like marine diesel oil and marine gas oil. (BOMIN, 2015a) On the way to meeting the future goals of the IMO for zero emissions in the shipping fleet, shipowners worldwide have begun to investigate other directions and options for emission-reducing measures and marine fuel to be used on their ships. Large tankers probably make up the majority of ships that are operated on heavy fuel oil today, but especially in Norway, the focus from shipowners has been of high priority for reducing its use. One of Norway’s best-known shipping companies, Hurtigruten AS, banned the use of HFO on their ships in 2009. (Hurtigruten, 2023c) More and more new ships are being operated on LNG or by a diesel-hybrid solution, where battery packs are installed on board to reduce the use of the internal combustion engines, which in turn reduces fuel consumption.

To establish a basis for comparison for the new types of marine fuel that are assessed in this thesis, the low sulphur fuel marine diesel oil (MDO) will be described as a base case, as it is one of the most commonly used marine fuels in the shipping fleet today, and especially along the Norwegian coast. Following this there will then be introduced alternative fuel types such as: LNG, ammonia, methanol, hydrogen, batteries and fuel cells, and lastly TMSR (thorium molten salt reactor). Batteries and fuel cells will only be presented for information and is delimited from this thesis when it comes to the operational study, risks and comparative study (discussion).

2.1 Base Case: Marine Diesel Oil

MDO consists of a mixture of middle distillates separated in a crude oil refining process, such as light gas oil, heavy gas oil, kerosene, etc. Compared to HFO, MDO is considered a cleaner fuel with higher quality as HFO consists of residual residues after the distillation process and the cracking process of crude oil, and is thus more polluted, which in turn leads to a more polluting emission during combustion. MDO also requires less energy than HFO as it does not need to be heated during storage or before being injected into an internal combustion engine. This is because it has a lower viscosity than HFO, but again has a higher viscosity than pure diesel. Today, MDO is usually produced with a sulphur content of less than 0.5%, which is significantly reduced compared to HFO, which has a sulphur content of up to 3.5%. (BOMIN, 2015a) In relation to CO_2 (Carbon dioxide) and NO_x (Nitrogen oxides) emissions, there is not much difference between the fuels, but the reduction in sulphur content makes MDO a far more attractive alternative, especially in ECA (emission control area) areas. (Spoof-Tuomi & Niemi, 2020, p. 36) Another common option is marine gas oil (MGO) which exclusively only consists of distillates. It has much the same qualities as MDO, but it has a slightly higher density and lower viscosity. (BOMIN, 2015c) It is often considered as a measurement unit for comparing bunkering prices. (Ship & Bunker News Team, 2021) Seen from an economic perspective, MDO is significantly more expensive than HFO, and it can be argued that this is the main reason why HFO is still the most used marine fuel in commercial shipping to this day. (BOMIN, 2015b)

2.1.1 Technical description

Property	**Value**
Volumetric energy density	36 MJ/l
Gravimetric energy density	42,7 MJ/kg
Density (at 15°C)	890 kg/m^3
Auto ignition temperature	210°C
Boiling point range	160 to 366 ˚C
Viscosity (at 40°C)	2-11 cSt
Flash point	< 60°C
Main Hazards	Fire Skin irritation Aspiration hazard Toxic to aquatic life with long lasting effects

Table 1 – Properties of MDO

(ExxonMobil, 2023) (Bottini fuel, 2018)

Marine diesel oil is a liq. (liquid) fossil fuel that can be stored at ambient conditions. It is a low flashpoint fuel, and it must be handled as a flammable liquid. (Bottini fuel, 2018) Marine diesel oil is sold in several varieties with different sulphur content, which depends on the mixing ratio between distillates and HFO. The more HFO the mixture contains, the higher the sulphur content. These different blending ratios also make MDO a fuel type that can be used in several various engine types. (BOMIN, 2015b)

When we look at the energy density of a fuel, it can be specified as energy content per volumetric unit or as energy content per mass unit. The advantage of a marine fuel that has a high energy density is that it has less mass, which means that it requires less storage space on board the ship, and the fuel “last longer”. The figure below shows that diesel has the highest volumetric energy density of the types of marine fuels considered. It requires the least space, but it is heavier than, for example, LNG and hydrogen. The figure basically only illustrates the fuel properties, but the arrows in the figure show how the storage system and associated necessary auxiliary systems for the specific fuel type affect the energy density, which changes the picture to a large extent for several of the fuel types. This applies in particular to fuels such as hydrogen and LNG that require refrigerated/cryogenic or pressurized storage.

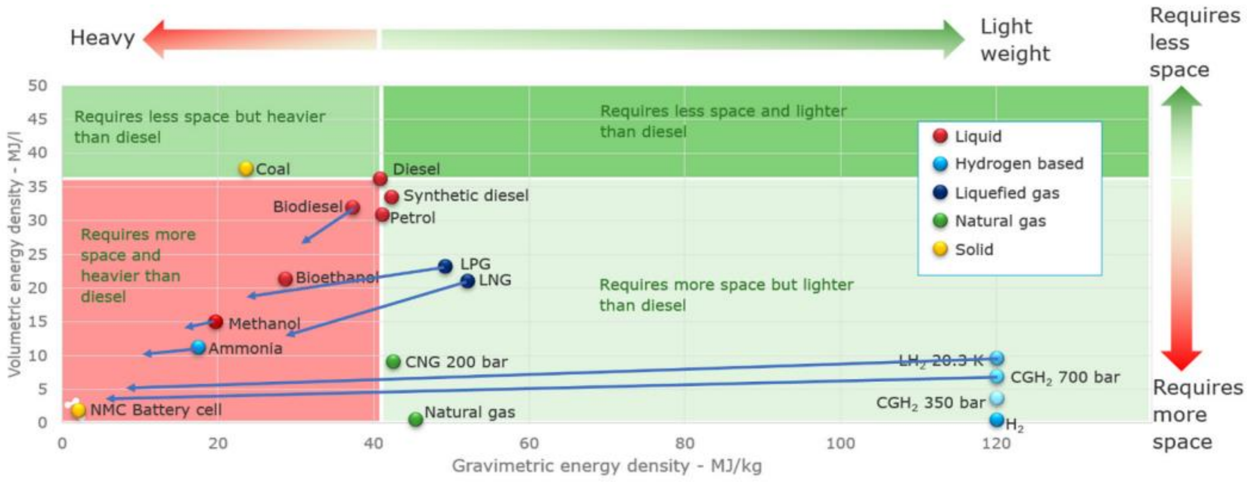

Figure 1 – Energy density of various marine fuels (DNV, 2019, p. 28)

The energy density is an important factor when looking at how applicable it is for given ship types operating in various areas, and especially regarding how often the ship must bunker fuel. The bunkering intervals can vary from months to hours between the different fuel types. For diesel, it can take weeks and months before it is necessary to bunker, which can be compared to liquid hydrogen where it can only take days before it becomes necessary to bunker again. (DNV, 2019, pp. 28,29)

2.1.2 Availability, infrastructure

As previously stated, marine diesel oil is one of the more common choices of marine fuels as of today, and it has been for a long time. Keeping this in mind, it goes without saying that the availability and infrastructure are well developed for the bunkering of MDO along the Norwegian coastline. Based on maps of bunkering stations retrieved from st1 and Googles Bunker Oil map, which is displayed in the figures below, it shows that the availability for MDO is in fact very good in most areas.

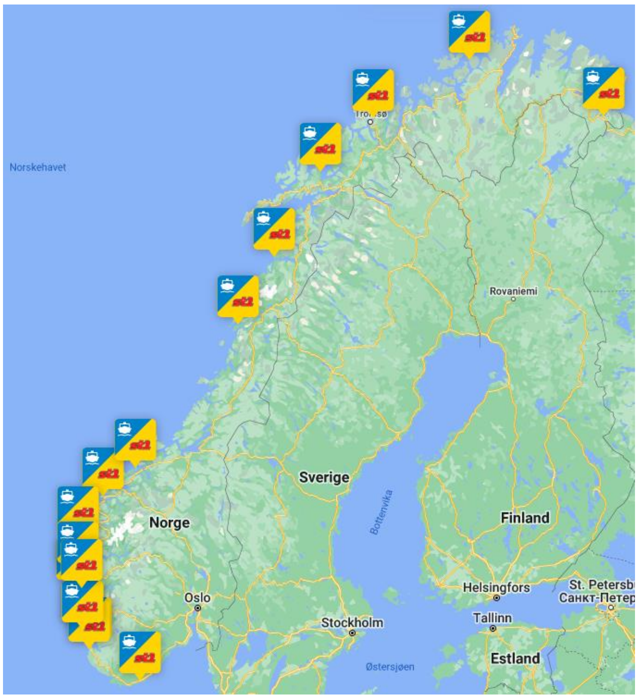

Figure 2 – Marine Diesel Oil bunkering stations along the Norwegian coast, St1 (St1 Marine, 2023)

Figure 3 – Bunkering locations for marine diesel oil along the Norwegian coast, Bunker Oil (Google, 2023)

Ships in short-haul shipping like passenger ferries or other types of vessels operating along the coastline, mainly receives supply of MDO from a fuel truck located on the quay or from a supply tanker. (DNV GL, 2014)

2.2 Liquified Natural Gas

LNG is short for liquefied natural gas. Consists of mainly methane, but also some trace amounts of ethane, other hydrocarbons and nitrogen. And is the most common alternative fuel which is in use today. LNG is introduced in the commercial fleet sailing today, the fuel tank solutions, the regulatory framework and engine technology is already developed, tried in operation and tested – so It's a readily option that can be implemented now when it comes to the alternative fuel types. Making natural gas a good solution to lower carbon solutions, more specific it helps to reduce the carbon intensity by 25% to 15 % in comparison to the main fuel types which is more discouraged to use due to Its higher pollution. The global supply is steadily being more secure as the bunkering infrastructure is developing fast and is expanding. (DNV, 2023c)

It is commonly used for power generation (35%), residential use (22%) and for manufacturing (17%). The LNG is transported and distributed via gas networks out to import terminals. Its usage is expanding every day in the transportation sector, whereas China currently has 300 000 busses and trucks running on LNG. LNG is also expanding in the maritime sector and there is currently 165 LNG powered ships worldwide (Remark, according to source from year 2019) and was on that time of writing confirmed to be constructed another 154 LNG powered ships. This implies that there currently may be 319 vessels in total fuelled by LNG. This is excluding LNG carriers, which amount to 500 carriers. Ships worldwide consume roughly 6.5 million tons of LNG and is 2% of all the marine consumption – from this 75 % is consumed by the LNG carriers transporting the LNG. (DNV, 2019, p. 43)

Further advantages of LNG are the competitive vessel design which ensures ten years longer compliance in comparison to conventional designs. Another great contribution LNG offers is the 80 % reduction of NO_x and almost eliminates the SO_x (sulphur oxides), with the particulate matter as well. 23 % of the greenhouse gas emissions can be reduced with the modern engine technology. Emissions can further be reduced if drop-in fuels are used as well in combination, this can for example be biogas – and will further reduce the carbon intensity the vessel gives off. (DNV, 2023b)

2.2.1 Technical description

Property	Value
Chemical formula	85-95% CH_4 (Methane) Few percentages of: C_2H_6 (Ethane) C_3H_8 (Propane) C_4H_{10} (Butane) N_2 (Nitrogen)
Volumetric energy density, fuel only (liq.)	21 MJ/l
Volumetric energy density with storage systems included (liq.)	13 MJ/l
Gravimetric energy density, fuel only (liq.)	50 MJ/kg
Gravimetric energy density with storage systems included (liq.)	25 MJ/kg
Characteristics	Odourless, colourless, non-corrosive, non-toxic
Density (liquid state -158°C)	430-478 kg/m^3
Flashpoint	-188°C
Boiling point (In atm. conditions)	-161.4 °C
Auto ignition temperature	537°C
Flammability range	5-15 % when mixed with air
Main hazards	Material embrittlement (exposed to materials not designed to withstand) Freeze burn. Hot vapour release from engines Toxic (Release of H_2S gas or ammonia for cryogenic cooling) Asphyxiation (NO, CO, CO_2, SO_2 in closed compartments)[1] Pool fire (accidental spill of LNG) Jet fire (pressurized gas release and ignite) Flash fire Vapor cloud explosion (Within flammability range)

Table 2 – Properties of LNG

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[1] CO – Carbon Monoxide, SO_2 – sulphur dioxide

(Hofstad, 2023), (CH-IV, 2023) (Bergen Engines AS, 2023b), (DNV, 2019, pp. 28,30), (U.S Department of Energy, 2005, p. 3), (Jørstad, 2021)

However, there are some challenges with LNG that needs to be solved in order to make it fully viable, those being:

- The tanks are large and expensive. The tanks are twice the size of a heavy fuel oil tank which in turn makes them require a lot more space and is in addition to this more expensive. This will further drive up the capital expenditure.
- Natural gas is not really a zero-carbon solution. It is categorized as a fossil fuel and is produced from an oil and gas production field. This implies that as of now and in the coming time, even natural gas will have to be replaced with a renewable version of LNG and LPG.
- There is known risks with methane slip, this is a risk that needs to be mitigated as methane which is escaped to atmosphere can be detrimental to the environment. Technology must be able to avoid this by production methods and engine technologies.

Despite the challenges LNG is still an important step in the journey for decarbonization of shipping. (DNV, 2023c)

2.2.2 Availability, infrastructure

According to the alternative fuel insight map provided by DNV (Det Norske Veritas), it can in Figure 4 be seen that the availability of LNG as fuel together with the infrastructure is well established along the Norwegian coast. There is 13 bunkering infrastructure that is established and in operation in Norway, and this is accompanied by 4 LNG bunkering vessels that can provide fuel for other vessels – However vessel such as “K. Lotus” does not operate in Norway alone, this vessel that operates mainly in Europe. As for providing fuel to other vessels, the bunkering vessel from Bergen Tankers, “Bergen LNG”, is retrofitted to provide LNG to Hurtigruten and Havila Kystruten as of Q4 2020. Hurtigruten is a vessel that is seen in a case study for this thesis, for the transportation of passengers from Bergen to Trondheim. Further developments of infrastructure when it comes to LNG along the Norwegian coast, it has been decided that Mongstad is to be established as an LNG bunkering location – the owner of this infrastructure is Gasnor AS. There are also discussions ongoing for 5 other locations to be established for LNG bunkering locations. These locations are Mosjøen, Karmsundet (Haugesund region), Lista, and Kristiansand. However, a decision has not been made if this is to be established. (DNV, 2023a)

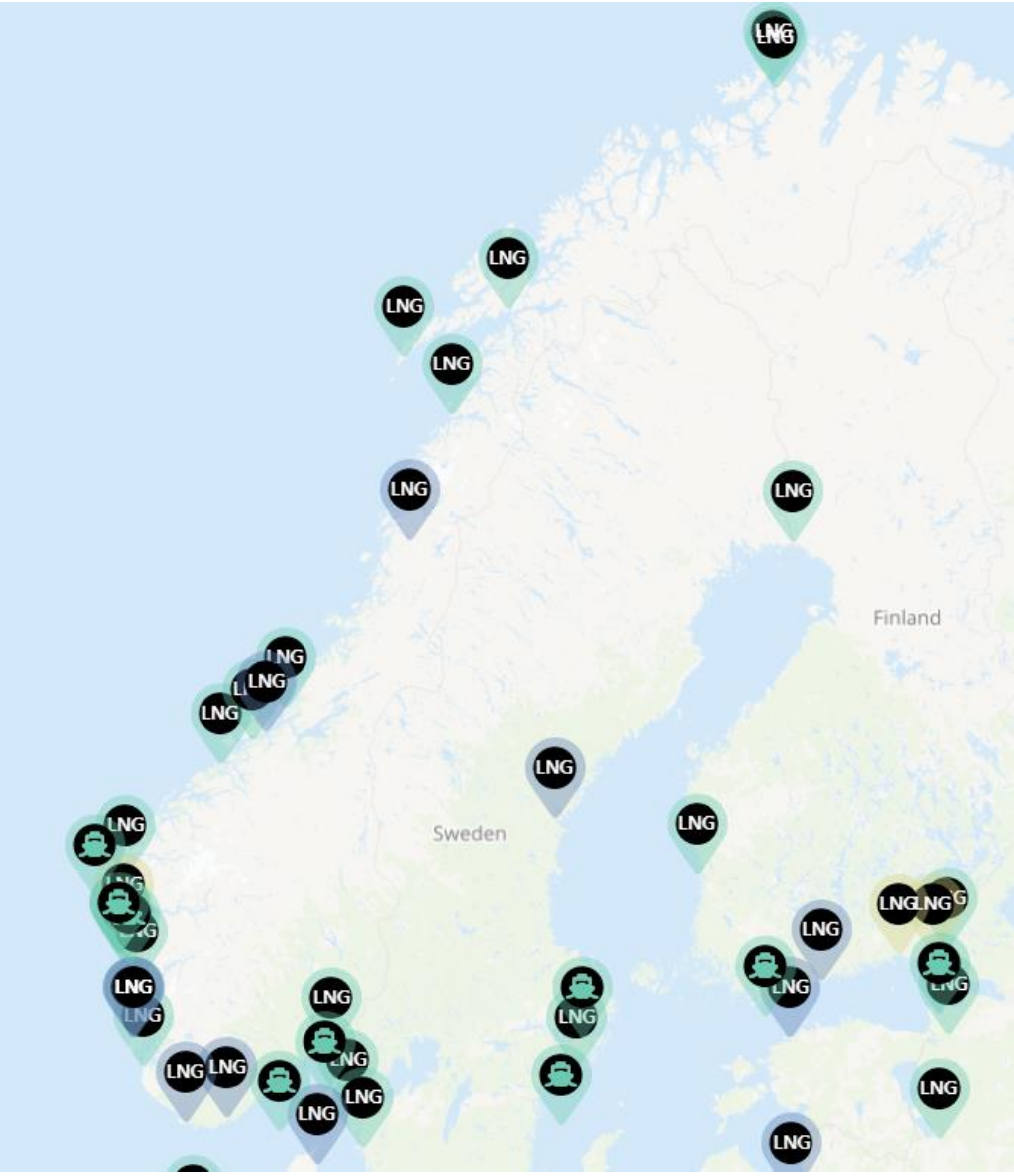

Figure 4 – LNG bunkering locations along the Norwegian coast (DNV, 2023a)

2.3 Ammonia

Ammonia is a colourless gas consisting of nitrogen and hydrogen, and it dissolves easily in water. As a marine fuel in combustion engines, ammonia is considered to be one of the most promising future fuels moving towards a carbon free maritime industry. However, it comes with challenges. It is highly toxic and an only a small amount of ammonia in the air can be fatal. Another issue is that the production of ammonia will have to increase significantly to meet the future demand as approximately 80 percent of the global ammonia supply today is used as fertilizer. Hendrik Brinks, Principal Researcher for Zero Carbon Fuels at DNV, states the following:

"In the context of decarbonization it's important to understand that when we talk about ammonia's great potential for shipping, we mean green ammonia. The fuel's sustainability credentials vary depending on how it is sourced." (DNV, 2022b)

Ammonia can be divided into three categories, each one with its own colour designation:

- **Grey (also known as brown) ammonia** makes up the majority of ammonia produced today, and it is produced from fossil sources. In this process, the nitrogen is separated directly from air and the hydrogen is produced mainly from natural gas being reformed into hydrogen gas (H_2) and carbon dioxide (CO_2). This method of producing ammonia is the most environmentally hostile method and one tonne of ammonia produces a CO2 emission of 1.6 tonnes.
- **Blue ammonia** is much the same as grey ammonia, but in this process, CO_2 is captured and stored, which results in a reduction of CO_2 emissions of up to 85-95%. It is not emission-free, but significantly reduced.
- **Green ammonia:** is produced in an electrolysis plant where water is split into hydrogen and oxygen using renewable electricity. This is the only option for production of ammonia that is completely emission-free. (Øystese, 2020, p. 9)

One of the main problems with green ammonia is that it is currently produced to a minimal extent worldwide. But ammonia producers are actively working with the framework to start production of green ammonia. (DNV, 2022b) Among the producers of ammonia in Norway is Yara, which in collaboration with Aker Clean Hydrogen and Statkraft has started the project

HEGRA, which aims to electrify and decarbonise the ammonia factory in Herøya in Porsgrunn. (YARA, 2022) Previously, ammonia was produced based on renewable energy in Norway, but that changed as it was not competitive against grey ammonia when there was greater access to cheap gas. In order for green ammonia to be competitive again, it requires a higher carbon price and sufficient access to affordable renewable electricity, as it requires large amounts of green energy to produce. Today, around 180 million tonnes of ammonia are produced worldwide, which is enough to replace around 20-30% of fossil fuel in shipping. If this were to be produced green, it would require around 1,800 TWh of electricity, which corresponds to more than 10 times Norway's total electricity production. (Øystese, 2020, pp. 10-12)

2.3.1 Technical description

Property	**Value**
Chemical formula	NH_3
Volumetric energy density, fuel only (liq.)	12,7 MJ/l
Volumetric energy density with storage systems included (liq.)	10,5 MJ/l
Gravimetric energy density, fuel only (liq.)	18,8 MJ/kg
Gravimetric energy density with storage systems included (liq.)	11 MJ/kg
Density at boiling temperature (liquid)	680 kg/m^3
Flashpoint	132°C
Vapour pressure	18 bar
Gas density	0,73 kg/m^3
Boiling point (1 bar)	-33°C
Auto ignition temperature	651°C
Flammability range	15-28%
Main Hazards	Highly toxic Asphyxiation Explosive Flammable Highly corrosive

Table 3 – Properties of Ammonia

(Green shipping program, 2021, p. 8) (ABS, 2020, p. 5) (DNV, 2019, pp. 28,30)

Compared to liquid fossil fuels like marine diesel oil, ammonia has a lower energy density. It weighs more and requires more space for equivalent operating capacity. In addition, there are several types of materials such as galvanized metals, zinc, brass and copper which quickly corrode when they come into contact with ammonia. (Øystese, 2020, pp. 8, 14) This means that the choice of material for an internal combustion engine that will be operated on ammonia must be carefully selected. Ammonia is lighter than air when it is in gaseous form. It is highly flammable, but it is difficult to ignite. Generally speaking, an outdoor release is not flammable, but if there is a high concentration of ammonia in the air indoors, it is far more flammable, especially if there are other combustible materials nearby. Ammonia is transported and stored in a liquid state. To get it into a liquid state, it must either be compressed or cooled down to -33°C at atmospheric pressure. (Green shipping program, 2021, p. 7)

Ammonia burns much more slowly than diesel oil because it has a very slow flame propagation. It also has a much higher auto-ignition temperature, which means that it will be much more challenging to maintain combustion in an engine compared to other types of fuel. The engine manufacturer MAN is researching the development of a dual-fuel ammonia-powered internal combustion engine. The engine is planned to operate on 95% ammonia and 5% of a pilot fuel such as marine gas oil. However, they are working to solve the biggest challenge, which is how to burn ammonia efficiently to extract maximum power from the engine, while maintaining a compact engine design. (DNV, 2022b) The use of ammonia in internal combustion engines can generate NOx emissions, but today there is a well-developed SCR (selective catalytic reduction) technology that is able to handle and reduce such emissions. In addition to NOx, burning ammonia could as well produce N_2O (nitrous oxide) emissions, which is a powerful greenhouse gas. If ammonia is to function as a zero-emission fuel in combustion engines, it is essential that engine manufacturers find a solution for handling N_2O. (Green shipping program, 2021, p. 10)

2.3.2 Availability, infrastructure

The availability and infrastructure for ammonia along the Norwegian coastline is until this day, extremely limited. Based on DNV's alternative fuel insight map (DNV, 2023a) it is displayed in the figure below that there are only two active locations in Norway who produces and supplies ammonia. The two areas marked green, shows the two established production facilities located in Porsgrunn and Glomfjord. The grey areas show possible future locations, which is still in the discussion phase.

Figure 5 – Ammonia bunkering locations along the Norwegian coast (DNV, 2023a)

As previously stated, it is no production of green ammonia in Norway at this point, which means the map only shows the availability of ammonia itself that is not produced emission-free. However, in 2022 it was announced that Yara International had pre-ordered 15 floating barge-based and land-based bunkering terminals, aiming at building a Scandinavian bunkers network, where ships will be able to bunker emission-free green ammonia. This network of bunkering terminals will be a great step moving towards a fossil-free shipping market. The two terminal designs will consist of storage tanks and processing facilities that are suitable for ammonia to be safely stored, handled and transferred, as well as efficient for loading and unloading to ships, and trucks. The first pilot terminal is barge-based and is under development, aiming for it to be completed and ready for operation by 2024. This means that green ammonia as a marine fuel can be available for ships operating in Scandinavia within a short time. (Maritimt magasin, 2022)

Figure 6 – Barge-based pilot terminal for green ammonia (Finansavisen, 2022)

2.4 Methanol

Methanol is a colourless, liquid fluid (at atmospheric pressure) which is highly toxic and flammable. It biodegrades quickly and easily dissolves in water. It is a biodegradable wood alcohol that has been used to produce everything from plastics to pharmaceuticals and is now seen as a promising and sustainable marine fuel. (Thurman, 2023)
There are various ways of producing methanol from different materials and with different processes. The sustainability of methanol as a marine fuel, especially in terms of greenhouse gas emissions, depends on how it is produced. We have four different types of methanol:

- **Brown methanol** which is produced from coal.
- **Grey methanol** which is produced by using natural gas.
- **Blue methanol** which is produced by using blue hydrogen and further combining it with use of carbon capture technology.
- **Green methanol** can either be bio-methanol that is produced from biomass, or it can be e-methanol, which is produced from green hydrogen, renewable electricity and captured CO_2. (Bureau Veritas, 2023)

All types of methanol can lead to a reduction in CO_2 emissions, but if you look at the whole picture from production to utilization, the CO_2 impact from grey and brown methanol is actually worse compared to diesel. Most of the methanol produced today is either grey or brown, and this is one of the challenges we face with maritime decarbonisation and implementing methanol as a greener alternative. In terms of emissions, blue methanol is a far better alternative as it significantly reduces CO_2 emissions. However, green methanol is the most environmentally friendly option, and the best option on the road to zero emissions as it has the potential to be carbon free. (Thurman, 2023) So, focusing on the best option on the road to zero emissions for methanol, the 'green methanol'. The key point here is that for production of methanol, it combines green hydrogen, which is produced from renewable sources by means of electrolysis. Electrolysis process separates the hydrogen from water by means of an electric current. With the use of renewable sources such as wind or solar power there is no CO_2 emitted to the atmosphere. If the green hydrogen is then synthesized with CO_2, methanol can be distilled. In order to make this the 'green methanol', this can be from a biomass power plant which utilize a pyrolysis process. (Iberdrola, 2023) By means of photosynthesis plants and trees use the energy from the sun to convert water (from soil) and carbon dioxide (from the atmosphere) to carbohydrates and oxygen. The chemical reaction for this is as follows (Norsk Landbrukssamvirke, 2019):

$$Energy + 6H_2O\ (water) + 6CO_2 \rightarrow C_6H_{12}O_6\ (sugar) + 6O_2$$

With the use of a sustainable biomass power plant this can potentially make green methanol a very promising option as the emissions cycle does not emit more CO_2 to the atmosphere. The full process for green methanol production is shown in Figure 7.

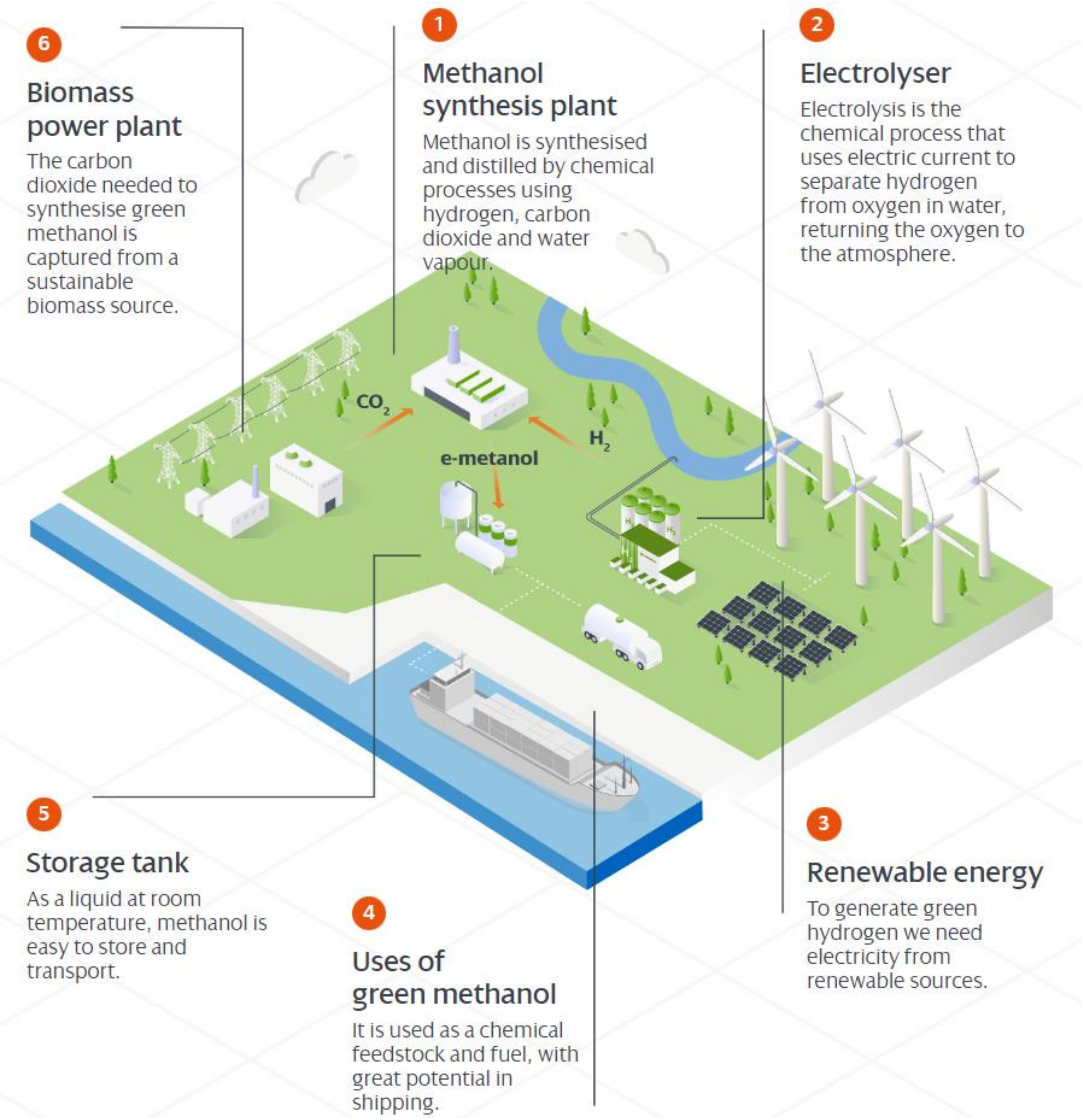

Figure 7 – From green hydrogen to green methanol, production process (Iberdrola, 2023)

2.4.1 Technical description

Property	Value
Chemical formula	CH_3OH
Volumetric energy density, fuel only	15 MJ/l
Volumetric energy density with storage systems included	14 MJ/l
Gravimetric energy density, fuel only	19,9 MJ/Kg
Gravimetric energy density with storage systems included	17 MJ/kg
Flash point	11-12°C
Auto ignition temperature	470°C
Boiling point	64,6°C
Vapour pressure (at 20°C)	12,8kPa
Density (at 20°C)	790kg/m^3
Main Hazards	Highly flammable Burns with nearly invisible flame, no smoke Toxic Corrosive Asphyxiation

Table 4 – Properties of Methanol

(DNV, 2019, pp. 28,30) (Boles & Cengel, 2011, p. 945) (Methanol Institute, 2023) (ABS, 2021b, pp. 6,7)

Methanol is in a liquid state between –93°C to +65°C, at atmospheric pressure. (DNV, 2019, p. 23) Compared to fuel types such as LNG and diesel, methanol has a much lower energy density, and to obtain a similar energy content to conventional fuels, methanol requires around 2.54 times more storage volume. On the other hand, it is easier to store and handle than other alternative fuel types such as hydrogen and ammonia, and there are fewer challenges in using it as marine fuel. However, methanol is corrosive to certain materials, which must be considered in terms of pipes, tank linings and the fuel handling system. It will probably also require some changes in the design of the internal combustion engine. Of the liquid fuels, methanol has the highest ratio between hydrogen and carbon, which in turn can potentially reduce CO_2 emissions from combustion. Methanol's clean burning properties lead to a significant reduction in SO_x and particle emissions, as the methanol molecule does not contain sulphur or carbon bonds that create particles. Compared to diesel, it also has a lower adiabatic flame temperature, which can potentially lead to limited NO_x formation during combustion due to reduced peak cylinder temperature.

Methanol burns at a low temperature and with flames that are almost invisible in daylight, which makes them particularly hazardous, as the flames can quickly spread before they are detected. The vapor of methanol is heavier than air and thus increases the risk of the crew on board inhaling it in the event of leaks. It typically accumulates at low points and the correct placement of ventilation and detection arrangements around leak-prone areas is very important. It must be handled with care as it is a toxic substance that can cause suffocation at excessively high vapor concentrations. Seen from an environmental perspective, methanol is easily biodegradable, and in the event of leaks or spills it will have a lesser impact on the marine environment. (ABS, 2021b, pp. 2,4,6)

2.4.2 Availability, infrastructure

The availability and infrastructure for methanol along the Norwegian coastline is today extremely limited, as it is for several of the new types of marine fuels. Based on DNV's alternative fuel insight map (DNV, 2023a) it is displayed in the figure below that there is only one active location in Norway where methanol is produced and supplied. The one area marked on the map is located at "Tjeldbergodden" and is operated by Equinor. (DNV, 2023a)

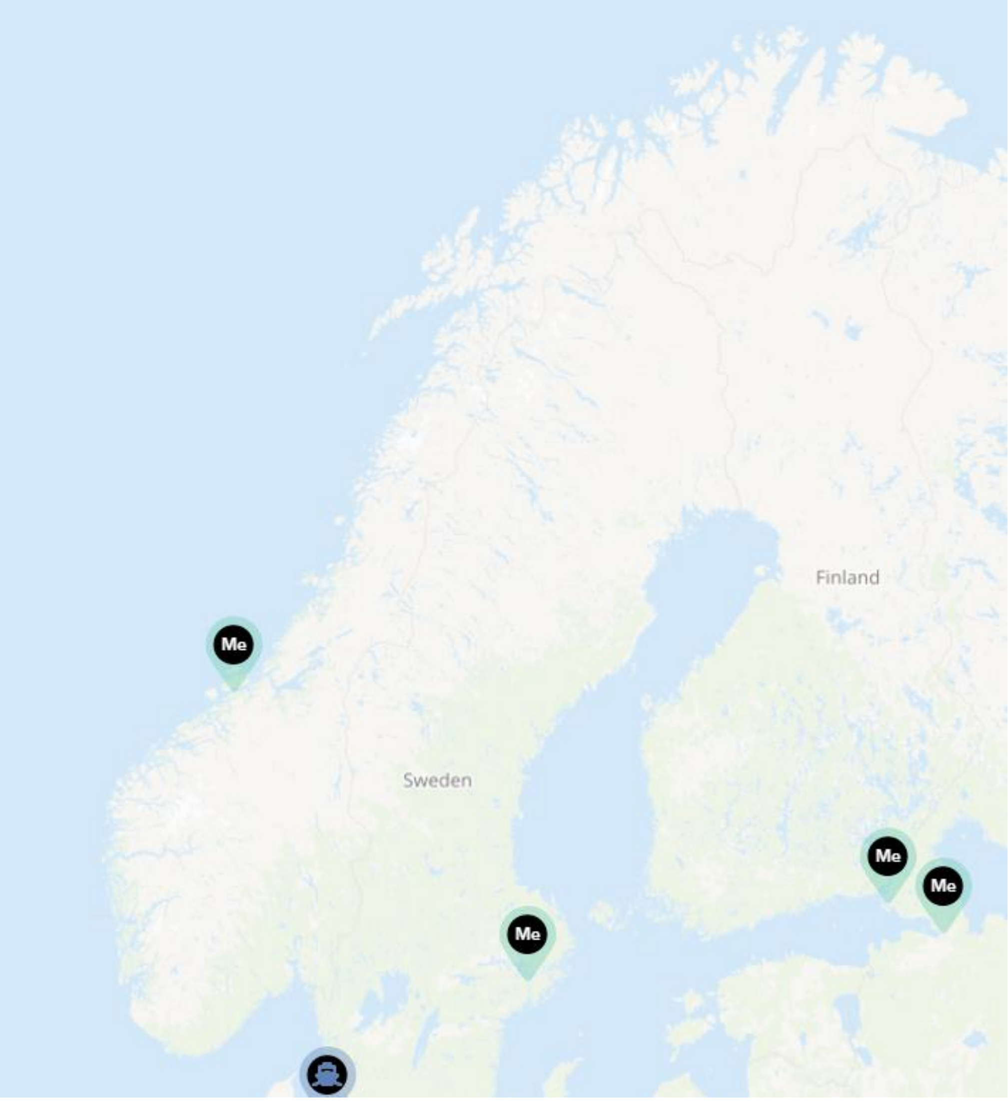

Figure 8 – Methanol bunkering locations along the Norwegian coast (DNV, 2023a)

As of today, Equinor is the biggest supplier of methanol to Europe, and the factory at "Tjeldbergodden" is the biggest in Europe. It is also among those factories with the lowest emissions of CO2 per produced tonnes. It is produced approximately 900,000 tons of methanol annually, and it is based on gas from the "Heidrun" field. The methanol gets transported to customers by ship. (Equinor, 2023)

2.5 Hydrogen

Hydrogen is in comparison to batteries (presented in section 2.6) much lighter in weight, whereas if there was a speedboat travelling from Trondheim to Kristiansund, the hydrogen storage would be one seventh of that same amount of energy needed with batteries. Hydrogen is distinguished between three types (Teknologirådet, 2022):

- **Green hydrogen:** Is produced with electricity from renewable energy sources by means of extracting the hydrogen from a water molecule by electric potential. This process is called an electrolysis (For hydrogen, hydrolysis) Norway sits today on vast resources when it comes to hydroelectric power – this can be used to produce green hydrogen. It is also adaptable for other renewable sources such as wind and solar power (Teknologirådet, 2022).
- **Blue hydrogen:** Is produced from natural gas – and it is essential that the CO_2 from this production process is extracted out and stored. In short this is called carbon capture and storage (CCS). As of now very small amounts of "blue" hydrogen is produced (Teknologirådet, 2022). The process for extracting the hydrogen is called steam reforming, which takes heated water (steam) and the natural gas and combine it to create hydrogen and CO_2. The process is named blue hydrogen as it is by means of CCS technology that the CO_2 is captured and stored, and this is essentially what makes the production process more environmentally friendly. (Nationalgrid, 2023)
- **Grey hydrogen:** Is considered the same as blue hydrogen, but without CCS. This implies that the grey hydrogen emits greenhouse gases when consumed. Grey hydrogen is created from natural gas, or methane, using steam methane reformation (Teknologirådet, 2022)**.**
- **Other types of hydrogen:** Black/brown hydrogen is hydrogen produced using coal or lignite for electricity generation for the electrolysis – brown hydrogen is also sometimes referred to as hydrogen from fossil fuels. Pink hydrogen is produced in electrolysis by means of nuclear power. Turquoise hydrogen is only at its early stages but is a process to create hydrogen and solid carbon by means of methane pyrolysis. Yellow hydrogen is referred to production by means of solar power. White hydrogen is naturally occurring hydrogen in underground deposits and is retrieved by means of

fracking – there are no active efforts in carrying out this method as of today. (Nationalgrid, 2023)

As previously mentioned in the chapter 1.3 background, there are some challenges that emerges when introducing alternative fuel types, and when making considerations to the fuels, many stakeholders see hydrogen as a potential solution for short-sea shipping and coastal shipping. It can in comparison to batteries store more energy onboard the vessel, proving to be a more flexible energy carrier. To consider hydrogen as an option, we might discard it from being produced from the less available biogas as it is not a very sustainable option. Instead, one should perhaps only consider hydrogen as in use in fuel cells as this can be proven to be a zero-emission alternative when combined with a renewable energy source for producing the hydrogen. This can also prove to be a good option when sailing in very environmentally friendly regions such as Norwegian Fjords or the Arctic. (DNV and partners, 2021, p. 12)

Hydrogen is a popular solution when it comes to being a potential alternative fuel type for the shipping sector. Industries are considering hydrogen for the future and are investing more in researching the technology; thus, hydrogen technology is growing. The hydrogen technology is for applications such as rail, heavy trucks, and maritime. (DNV and partners, 2021, p. 12)

As of today, when it comes to Hydrogen there are not present any satisfactory rules or/and requirements for ships when it comes to propulsion systems onboard with the use of Hydrogen as the fuel type. This is to be seen concerning the demanding approval process, which is also like the process for technology qualification developed by DNV. The demanding approval process is highlighted in the international rule base, which is issued and developed by IMO. It is referenced by the IGF code[2] (published 2016) and MSC.1/Circ 1455, chapter 6 (published 2013). It seeks to attain the same level of safety when Hydrogen is compared to conventional fuel types (I.e., Marine Diesel Oil, Heavy fuel oil, etc.). (DNV and partners, 2021, p. 12)

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[2] International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)

2.5.1 Technical description

Property	**Value**
Chemical formula	H_2
Volumetric energy density (liq.)	10 MJ/l
Volumetric energy density with storage systems included (liq.)	6 MJ/l
Gravimetric energy density (liq.)	120 MJ/kg
Gravimetric energy density with storage systems included (liq.)	9 MJ/kg
Gas density (NTP)	0,0827 kg/m^3
Density (Liquid, at boiling point)	0,07099 g/cm^3 (Also, 70,99 kg/m^3)
Flammability range (25 °C, 101,3 kPa)	4-75 vol%
Boiling point	-253 °C
Auto ignition temperature	585 °C
Adiabatic flame temperature	2 045 °C
Distinguishes	Almost colourless flame
Main Hazards	Fire Fire produces toxic gases in confined spaces (CO from combustible materials) Explosion Hydrogen induced stress cracking. Cold burns, serious skin damage
Storage options	Pressurized state or cryogenic liquid

Table 5 – Properties of Hydrogen

(DNV and partners, 2021, pp. 17-19) (DNV, 2019, p. 26) (Boles & Cengel, 2011, p. 945) (ABS, 2021a, pp. 7,8,10)

Hydrogen gas is highly explosive and flammable and when compared to other gas fuel types (i.e., natural gas). It has different properties and behaviour when it comes to the safety aspect – and cannot be for instance compared with natural gas as they are different from each other. Hydrogen is challenging due to its safety properties. For instance, when Hydrogen is to be stored onboard the vessel it needs to be stored at a very low temperature of -253 °C and with a slight overpressure of 1 to 10 bar, and at this temperature Hydrogen is in a liquid state. The other alternative when it comes to storage option is to pressurize the Hydrogen to very high pressure, in technical terms this could be from 250 to 700 bar. However, when hydrogen is in a gaseous state one must consider that the hydrogen molecules are the smallest of all the molecules there are, and the gas is hard to contain. The hydrogen may escape easily, and that is not favourable when the gas is highly flammable, ignites easily, and could also self-ignite. This means a great safety system to apprehend the risks of Hydrogen is a clear necessity. (DNV and partners, 2021, p. 13)

As mentioned before, it does not exist an established safety standard or approving bodies for the use of Hydrogen. DNV and its partners try to utilize the knowledge from all available sources for considering Hydrogen as a potential alternative fuel to cut emissions. However, as seen before the lack of safety standards and approving bodies may cause delays to the operation of the new technology. The process is illustrated in Figure 9. (DNV and partners, 2021, p. 13)

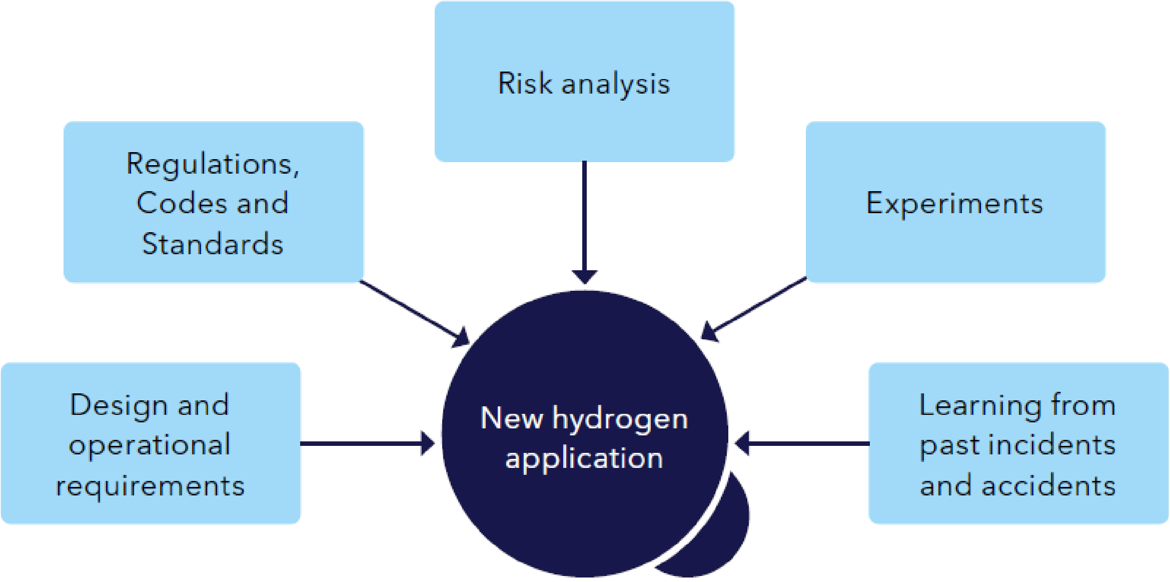

Figure 9 – Input of new technologies when lack of approving bodies and safety standards (DNV and partners, 2021, p. 13)

2.5.1.1 Operational standards

When constructing a facility for use of Hydrogen fuel, the following standards and maritime codes can be applicable when developing pipe systems for hydrogen as a medium. However, it is important to mention that there is still more work to be done when developing fully functional standards:

IMO Resolution MSC 420(97)	This resolution is for liquefied hydrogen carriage in bulk and lists interim recommendations.
IGF code	Is for ships that use low flashpoint fuels, typically gas, and is the international code of safety.
ISO/TR 15916	Hydrogen systems and the considerations that must be made when it comes to safety.
EN13480	Metallic piping standard when it comes to industry
ASME B31.3	Process piping
ASME B31.12	Hydrogen Pipelines and general piping
EN USI 5817	Welding standard for fusion welded joints (and beam welds). Applicable for titanium, nickel, steel and corresponding alloys.
ISO 10675	NDT[3] of welds – Radiographic testing and acceptance levels.
ISO 11666	NDT of welds – ultrasonic testing and acceptance levels.
EN 1779	NDT – leak testing – criteria for method and technique selection
EN 13184	NDT – Leak testing – pressure change method. (Testing joints in pipelines etc.)
EN ISO 20485	NDT – leak testing with use of tracer gas method.

As for classing of the vessel that is to use hydrogen as a fuel, the DNV classification RU-SHIP can be applicable, and the following parts and chapters are highly relevant:

- Part two Chapters one to four is for materials and welding.
- Part five in chapter seven, is used for liquefied gas tankers.

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[3] NDT – Non-destructive testing

- Part four in chapter six, is used for the piping systems.
- Part four in chapter seven, is used for pressure equipment.

Additionally, DNV-RP-D101 is highly relevant and is used for structural analysis of piping systems (DNV, 2017a) (DNV and partners, 2021, p. 55)

2.5.2 Availability, infrastructure

The availability and infrastructure for Hydrogen along the Norwegian coastline is until this day, extremely limited – or said in other words non-existent. Based on DNV's alternative fuel insight map (DNV, 2023a) it is displayed in Figure 10 below that there are no bunkering locations in Norway for Hydrogen at all. However, according to Teknologirådet, Norway was back in 2020 supporting schemes worth a 770 million NOK (Norwegian krone) on hydrogen projects, to make hydrogen a viable alternative fuel. Norway could become a leader in hydrogen technology if steps are taken accordingly before 2025 to develop hydrogen further and make it commercially viable. This implies production of green and blue hydrogen, transporting it, and lastly using it for the industry, transport on land and maritime sector. Germany is on the other hand investing a lot of resources into developing hydrogen technology, putting a vast 82 billion NOK (as of 2020) into research and development projects. (Teknologirådet, 2022)

Figure 10 – Hydrogen bunkering locations along the Norwegian coast (DNV, 2023a)

According to one source there is ongoing construction of a bunkering location for hydrogen at Viganes in Hjelmeland municipality. This bunkering location in Figure 11 will accommodate the need for the ferry, MF Hydra, has for operation between the locations Hjelmeland-Nesvik-Skipervik. The Norwegian Directorate for Civil Protection was present during construction of the facility to inform regarding the safety protocol as the safety restrictions for bunkering with Hydrogen is very strict. (Sivertsen, 2022)

Figure 11 – Bunkering location for Hydrogen at Viganes (Sivertsen, 2022)

According to another article from upstream, green hydrogen and ammonia will be used for marine fuel. Further ExxonMobil together with partners signed a memorandum to study and assess the potential for distribution of these fuels from Slagen terminal in Norway. They will also study the potential for production. (Klinge, 2022) Slagen terminal is located between Horten and Tønsberg and is a terminal for distribution of liquid fuels to all of Norway. (Esso Norge AS, 2023) Following this there was also planning and developments by a group of companies to build a hydrogen facility in Mongstad – just outside Bergen. The facility would have distributed liquid hydrogen to vessels that are sailing along the Norwegian coast. (FuelCellsWorks, 2020) Sadly, the project to build this facility was cancelled as of March 2022. (Bergens Tidende, 2022) It is still however, promising that the project at Slagen to study and consider building a hydrogen production facility is still ongoing (as of 30.06.2022) for introducing hydrogen as a viable alternative fuel to the maritime sector (GreenH, 2022), however having only one bunkering station limits the reach for the vessel that is sailing along the Norwegian coast.

Another report issued by SINTEF highlights that for maritime transport that many stakeholders see the true potential for hydrogen as an alternative fuel for the maritime sector, and there are production initiatives that are being studied – Especially for Kvinnherad, Jelsa and Tjeldbergodden. However, these activities for studying are just project-based. Further there must be developed technology and standards, and also qualification of these, as there is no procedure for design type of a vessel that use hydrogen as a fuel. As the bunkering facilities are not in place, the hydrogen potential in Norway as of now is still in its early stages. Shipping is also considered a conservative market; the shipowners are worried that a move to hydrogen propulsion ships will lock them to the first generation of ships that may not be very competitive. The ships often have a lifespan of 30-40 years, and today there is a surplus of ships. The fear of being locked to a new ship type that use hydrogen can also be seen in the framework conditions and how they change, in example how CO_2 taxes was implemented for vessels that use LNG as a fuel. There are also other fuel types that are being introduced to the market, such as ammonia, LOHC, batteries etc. which also raise the concern for being locked-in to a hydrogen vessel. (Damman, Sandberg, Rosenberg, Pisciella, & Johansen, 2020, pp. 48-49)

Another view of Hydrogen is to use it for partly as fuel for internal combustion engines, but it could also prove to be a feedstock for production of methanol, green ammonia and SNG (synthetic natural gas). Hydrogen can be adapted for ferries and coastal vessels. (MAN Energy Solutions, 2023a) However, as already mentioned there must be existing bunkering infrastructure along the Norwegian coast to allow this implementation. As for hydrogen itself, there already exists pipelines that is used for natural gas today, which can facilitate transportation. The hydrogen can in terms of this be compressed by already developed compressor technology for pipeline transportation or liquefaction plants. (MAN Energy Solutions, 2023a) In Norway the 8829 km pipeline network owned by Gassco will be readily to transport hydrogen in 2025. There are very small changes that needs to accommodate hydrogen transportation. It can either be transported as pure hydrogen, or together with natural gas. (Tallaksrud, 2021)

2.6 Electricity in form of batteries and from fuel cells – a general introduction

In 1839 the first ship with an electric propulsion system onboard was introduced, in that regard electrical propulsion is not a new invention by far. Electric powered ships had its golden age from year 1890 to 1920 and was at the end of this period surpassed by petrol-driven engines – then diesel driven engines in 1926. As of recent years, there have been great strides in the development of lithium-ion batteries. This proves to be a viable option for maritime applications, and for electric and hybrid solutions that can further contribute to large-scale grid systems. In that regard it is worth to mention that:

- Viking Lady was in 2013 installed with 500 kWh (kilowatt-hours) battery for hybrid use. This made it possible to carry out measurements with the system, which in turn provided valuable data in terms of efficiency and emissions - further documented for its benefits.
- Edda Ferd, a new built supply ship put in operation autumn 2013, was installed with a battery system.
- Viking Queen was the first offshore vessel with a commercial retrofit in having a battery energy storage system. This commercialization was joined by a R&D (research and development) project where they worked on this technology for five years.
- Several ferries have been equipped with battery systems. As an example, the vessels Prinsesse Benedicte, and its three sister ships.
- Nordled’s Ampere was the first large size all electrical battery powered car ferry that was introduced. It has a capacity of 350 passengers and 120 cars, and has batteries installed onboard with 1 MWh rated capacity. Allowing a quick charge of 10 minutes between the trips.

Following this with all new invitations of new ferries in Norway, the Norwegian parliament decided that they shall if possible be installed with low- or zero-emission technology. It can therefore be expected that in the upcoming years (from 2015) there will be a substantial number of ferry projects that either have a hybrid battery or an all-electric solution onboard the vessel that is being projected for. (DNV GL, 2015, pp. 8-9)

Batteries enable a broad range of energy sources to be used, such as wind or solar power being renewable energy sources that can be utilized for production/use and storage, also when it comes to use of hydrogen. (DNV GL, 2015, p. 37) A battery consists of electrode pair, anode and cathode, electrolyte, separator, and respectively positive and negative current collectors. In a lithium-Ion battery, the electrode pair consists of lithium. From the anode to the cathode the electrolyte transfers positive charged lithium ions, and also oppositely through the separator. This results in free electrons at the anode, and further produce a charge at the positive current collector. In the positive current collector, the current travel through the equipment, which is being powered up, for instance a propulsion engine, car, mobile phone etc., to the negative current collector. The flow of electrons inside the battery is blocked by the separator. Similarly, this process is reversed, when the battery is depleted and is recharging. (Minos, 2023) An illustration of a lithium-ion battery is shown in Figure 12.

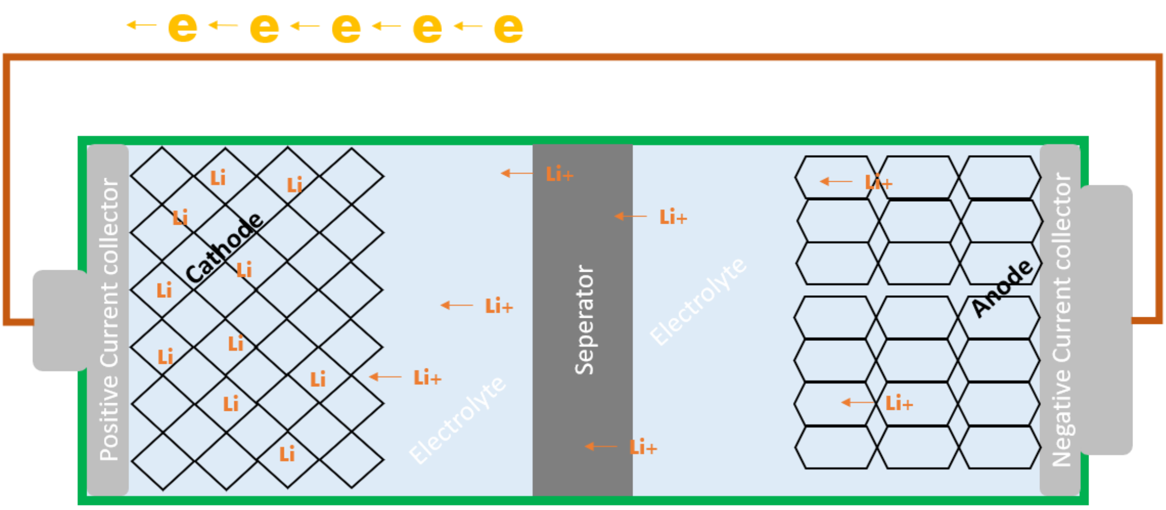

Figure 12 – Lithium-ion battery (source, Own production)

This can further be seen in relation to nuclear power. Such as the design proposed by Ulstein, the “ULSTEIN THOR”, a 149m replenishment, research and rescue vessel with a thorium molten reactor. The design concept has a cruise vessel sailing alongside it, THOR (vessel) could power SIF (battery driven cruise vessel). This idea gives the pairing vessels a mobile power/charging station when it comes to cruising in environmentally friendly areas and allows preservation of the surrounding nature. (ULSTEIN, 2022) The potential of nuclear power is further mentioned in section “2.7 Molten salt reactors” and is a nice alternative for long distance travelling for electrically driven systems.

When one talks about battery, one could also mention fuel cells as an energy provider. This is an electrochemical cell that generate electricity through spontaneous reactions on the electrodes. Arguably one can compare a fuel cell to a battery which is discharging, where in a fuel cell the reactants are instead continuously fed into the reaction. In Figure 13 a fuel cell with the use of hydrogen-fuel is shown. However, the fuel that is used for electricity production could also be other hydrocarbons or ammonia.

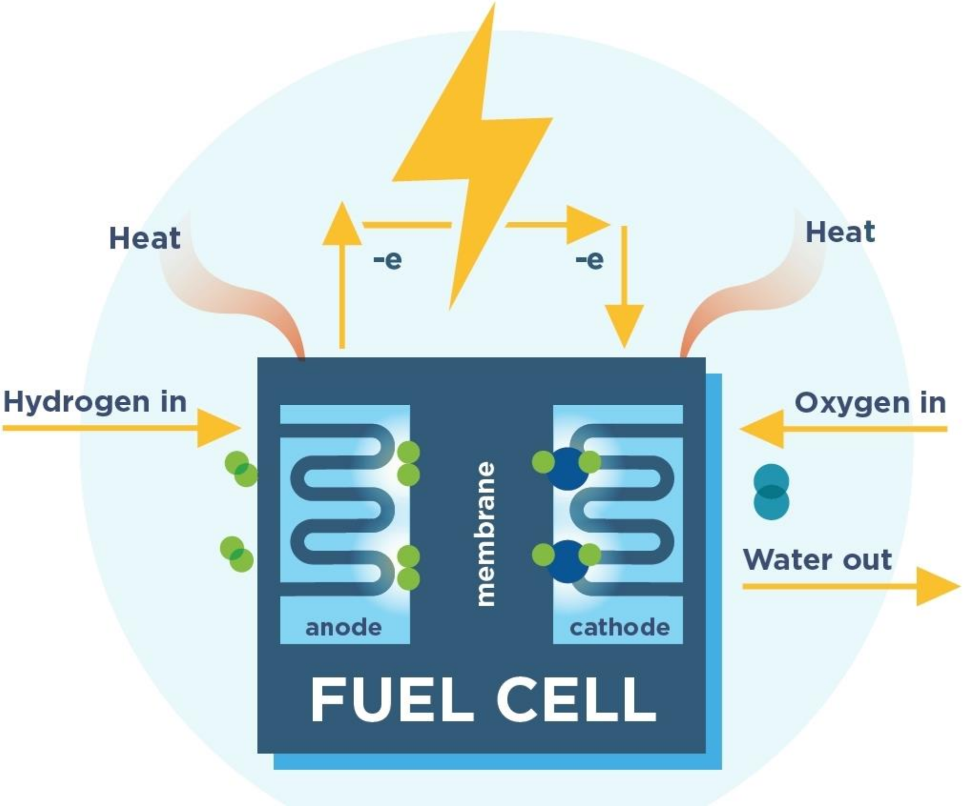

Figure 13 – Fuel cell, hydrogen fuel (Fuel Cell & Hydrogen Energy Association, 2019)

In the figure it is displayed two electrodes, this is the anode and the cathode, which is placed into an electrolyte. Sometimes separate electrolytes are used for each electrode and is separated by a membrane as shown in Figure 13, the membrane still allow charges between atoms to still be transferred through the membrane.

The reaction process at each electrode occurs as such with hydrogen as fuel:

Anode: the fuel is introduced into the fuel cell at the anode, could be hydrogen gas or in liquid state, and there will occur an oxidation reaction. This implies that electrons are lost. The result will be water molecules that is created with a release of energy.

$$\mathrm{H_2 + OH^- \rightarrow 2H_2O + 2e^-}$$

Cathode: At the cathode, which is the positive electrode, the other reactant is fed in, and it will occur a reduction reaction. This implies that electrons are gained.

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Energy efficiency of a typical fuel cell can range from 50 to 65 percent. Energy losses are typically from heat generation – and this heat is generated because of limitations of reaction speed and loss of voltage of the transferring current. (Holtebekk, Pedersen, & Haarberg, 2021) From Figure 14 it is displayed a well-establishes electrical grid when it comes to charging stations along the Norwegian coast. Having an electrically driven propulsion system onboard with batteries therefor is a nice concept as the infrastructure is already built. Green markers in the figure illustrates powering stations allowing to charge up the batteries, whereas yellow markers are stations that is decided to be built.

Figure 14 – Battery-charging locations along the Norwegian coast (DNV, 2023a)

As battery-systems and fuel cells for electrically driven propulsion systems is already well established both in technology and is commercially available, batteries and fuel cells are not further investigated due to its relevancy in the following chapters and the extent of this master thesis.

2.7 Molten salt reactors

These days old technologies and existing fuel types are challenged with new alternative fuels, to make a greater effort to lower the emissions together with realizing the potential of other energy sources. It's important to keep in mind that introducing new fuel types comes with Its limitations as well so It's important to act with care, so no wrong investments occur. Such as previously mentioned with the limited availability of green ammonia, even if the green ammonia proves to be technically viable as a fuel type. And arguably if all the HFO (heavy fuel oil) in the world is to be replaced, which is estimated to be 300 million tonnes, one would need twice the size of Europe's power-demand to produce the green ammonia which is needed. This is a very unrealistic starting point. Following this and what's important to keep in mind, is that the maritime transportation sector amount to 3 % of all fossil emissions – which is why It can be hard to reach the goals set in the Paris Agreement which states a 50 % reduction by year 2050. This urges the importance for thinking in new ways, as there are some challenges that needs to be solved. (Emblemsvåg, Fremtidens drivstoff – for den grønne omstillingen, 2023a)

An alternative fuel that can be introduced to face the challenges with reducing emissions in the shipping sector, is nuclear power. Nuclear power has the best EROI[4] (Energy Return on Investment) with a factor of 75 with the technology that is in use today. This factor can increase to 500 to 4000 if nuclear power technology is further researched together with reactor design. In comparison other fuel types such as renewable energy has a factor of 10, oil & gas a factor of 30 and hydroelectric power with a factor of 40. Nuclear power is not to a large-scale dependant on exotic materials other than uranium/thorium which exist in large amounts in our world. Just in the ocean alone, there is enough uranium/thorium at the earth to power the human existence for four billion years. Just this alone highlights why It's so important to research nuclear power technology. (Emblemsvåg, Fremtidens drivstoff – for den grønne omstillingen, 2023a)

Thorium is a radioactive element which is usually found in mountains and generally inside rocks. It is a so-called fertile element which means it does not split by itself and release

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[4] Ratio between amount of produced energy in relation to amount of energy spent to produce this energy through the full life cycle.

energy and is in this regard dependant on an external source to be activated for fission – this would be a neutron which needs to be bombarded into the thorium forcing the thorium to excite and split. The easiest and most cheap option to emit a neutron into thorium is by the use isotope uranium-235. Uranium-235 is highly radioactive and is the substance as of today which is common to use in nuclear reactors. To start the nuclear reaction with thorium using fission, the thorium is converted into Uran-233. (Brembo, 2022)

Thorium-232 has a half-life of 14,05 billion years – and is in this regard very stable. When thorium is excited into thorium-233 by a neutron it will have a half-life of just 22 minutes. This in turn causes the thorium-233 to decay into protactinium-233 with beta- and gamma radiation emitted by the reaction. Protactinium-233 has a longer half-life of 27 days to decay, and will eventually decay into uranium-233, which in contrast to thorium is fissile. This type of uranium isotope can be used in fission principally the same way uranium-235 is used today, and the total reaction from thorium-235 to uranium-233 is as follows:

$$ {}_{0}^{1}n + {}_{90}^{232}Th \rightarrow {}_{90}^{233}Th \rightarrow \frac{decay}{\beta^{-}} \rightarrow {}_{91}^{233}Pa \rightarrow \frac{decay}{\beta^{-}} \rightarrow {}_{92}^{233}U $$

Once the substance of uranium-233 is achieved this will further be bombarded with more neutrons, this in turn can free up two to three more neutrons as well as energy and two more products from the fission that can be used in a nuclear power plant. In this reaction this is the reaction which is most favourable and will occur in 94 % of the occasions. However, in 6 % of the occasions there is only gamma radiation emitted (unfavourable). The reactions are as follows:

$$ {}_{0}^{1}n + {}_{92}^{232}U \rightarrow {}_{92}^{234}U \rightarrow ({}_{54}^{137}Xe + {}_{38}^{94}Sr + 3{}_{0}^{1}n)\ \boldsymbol{OR}\ ({}_{92}^{234}U + \gamma) $$

Considering the nuclear reaction of thorium-232 to uranium-233 is that this reaction can be carried out by means of a proton-accelerator, this proton-accelerator will fire protons at a substance which will give off an equal number of neutrons which will be used for the decay of thorium to uranium-233. The benefit of this process is that the reaction can be prevented by stopping the proton-accelerator at any given time and this prevents the fission to run out of control. This also delimit the need for control rod in the reactor. Thorium is also very safe to use as the reaction does not produce plutonium as it does in a regular nuclear reaction with uranium, and plutonium is of course the substance which is used for nuclear warheads.

(UngEnergi, 2022)

As of now there is a research project between NTNU and Knutsen OAS shipping company, the project is named NuProShip I[5] and they are researching which type of generation IV reactor design is most viable to run the vessel with nuclear power. The reactor design they are studying is liquid lead reactor, helium cooled reactor and two to three molten salt reactors. They are expected to be finished in 2 years' time. The cons of using a Generation IV reactor design for nuclear power generation is:

- They are extremely safe.
- They require little to none amount of manual activities to keep in operation.
- They are highly efficient.
- They don't require a lot of space.
- They require small amounts of nuclear materials which in turn gives of small amounts of radioactive waste.

And the best generation IV reactors that are in use, produce 98 % less waste, whereas regulation states that 83 % of the nuclear waste needs to be stored for 10 years – the remaining waste is to be stored 300 years. (Emblemsvåg, 2023a) However, some state that there is still a long journey to go before commercializing molten salt reactors in Norway, the biggest argument is that most of the key-components is missing to operate reactors like this. There needs to be developed new materials that can withstand the molten salt over time. The molten salt, which is liquid also need to be stored somewhere, as of now there is no location for this. There are too many un-answered questions when it comes to safety and storing of waste-materials. However, reactors can be bought from other countries and competence withing this field can be developed, and further researched and developed. According to this, the debate on thorium power-generation must be brought back up again if Norway is to reach the climate goals. (Brembo, 2022)

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[5] Nuclear Propulsion for merchant shipping I

2.7.1 Technical description

Property	Value
Chemical formula	Th, also known as Thorium-232
Energy density	79 420 000 MJ/kg
Energy potential, produced power	2628000 kWh/kg[6] 3942000 kWh/kg[7]
Density	11,7 g/cm^3, also 11 700 kg/m^3
Relative atomic mass	232,038
Melting point	1750 °C
Boiling point	4785 °C
Main Hazards	Toxic if exposed (due to radioactivity) Radioactive waste Fuel meltdown (Not with TMSR)
Storage options	Reactor vessel with concrete or lead shielding Radioactive waste products – N/A (In Norway)

Table 6 – Properties of Thorium (and TMSR)

(National Center for Biotechnology Information, 2023), (Emblemsvåg, 2023a), (Royal Society of Chemistry, 2023), (Touran, 2023)

2.7.2 Availability, infrastructure

As previously mentioned, the NuProShip I project seeks to build up a network in Norway for nuclear power. They plan to further develop the technology, and the findings from their current project will be utilized further into a 10-year research plan. They hope that this can be a great contribution to maritime sector and increasing the availability for the technology, together with power generation for Norway, production of synthetic materials, process heating, hydrogen production and similar industries. (Emblemsvåg, 2023a)

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[6] Assuming to 900 TWy for 3 million tons of Thorium, according to (Emblemsvåg, 2022, p. 32)

[7] Assuming to 900 TWy for 2 million tons of Thorium, according to (Emblemsvåg, 2022, p. 32)

3. Operational study for alternative fuels

3.1 Base Case: Marine Diesel Oil– Operational efficiency

To be able to form a picture of the performance effect of diesel as a marine fuel to further form a basis for comparison for new types of fuel in this study, it was chosen to look at a given type of ship that typically operates along the Norwegian coastline, with its given type of engine power, which sails a certain distance. The ship chosen in this case is Hurtigruten's ship "MS Nordlys which sails a fixed route along the Norwegian coastline all year around. The operational distance examined is the route from Bergen to Trondheim, which is approximately 344 nautical miles (nm) or 637km. (Regjeringen, 2023)

Figure 15 – Baseline travel distance, Bergen – Trondheim (Hurtigruten, 2023a)

As the figure displays, there usually are several stops along the coastline, but for this particular case the calculations will be done by assuming sailing directly from Bergen to Trondheim without stops. MS Nordlys is equipped with two B33:45L propulsion engines and two KRG-8 auxiliary engines from the engine manufacturer Bergen Engines AS. (DNV, 2022a) Focusing on the ships fuel consumption for the given operational distance, the calculations will be aimed at the main propulsion engines' technical specifications and consumption. However, it must be taken into consideration that the auxiliary engines have a certain fuel consumption in addition for power production to the ship's interior, and other electrically driven components. Other components using diesel, like boilers, will also not be taken into consideration as it is not seen as relevant to the study.

With the main engines' technical data provided by the manufacturer where the engines are driven at 100% MCR (maximum continuous rating), (Bergen Engines AS, 2023a) the two engines fuel consumption per hour can be calculated:

$$F_{consumption} = SFOC * P_{engine} * 2 = 0{,}173\frac{kg}{kWh} * 3600kW * 2 = 1245{,}6\frac{kg}{h}$$

MS Nordlys operates with, what is assumed to be, a maximum speed of 18 knots. (Hurtigruten, 2023b) 1 knot is 1 nm per hour or 1852m/h, which means the vessel moves 18nm/h. Calculating the sailing time from Bergen – Trondheim at operational speed:

$$Sailing\ time = \frac{344nm}{18\frac{nm}{h}} = 19{,}1\ hours$$

Making the engines fuel consumption for the whole sailing distance:

$$Total\ F_{consumption} = 1245{,}6\frac{kg}{h} * 19{,}1h = 23790{,}96\ kg\ \approx 23{,}8tons$$

The two main engines on MS Nordlys will use 23,8 tons of MDO for sailing from Bergen to Trondheim. Considering the results of the calculations, it must be mentioned that the vessel would most likely not operate at a maximum speed, and the engines would probably not be driven at 100%MCR, which would further affect the calculations.

3.1.1 Storage options

Considering the minimum fuel tank capacity required for having a sufficient amount of fuel for the whole journey:

$$Minimum\ Tank\ Capacity = \frac{Fuel\ consumption, t}{Density, \frac{t}{m^3}} = \frac{23{,}8t}{0{,}89\,\frac{t}{m^3}} = 26{,}74m^3$$

The result of the calculations give that the minimum tank capacity required for the main propulsion engines to be operating at 100% MCR, sailing from Bergen – Trondheim is $26{,}74m^3$. By including some consumption from the auxiliary engines and other diesel consumers onboard, a minimum capacity of $35m^3$ should be considered. Technical information about the ship gives that MS Nordlys has a total bunkering capacity of 660t (Sundfær, 2017) which means that the vessel can operate with a much longer sailing distance and can go weeks before bunkering is required. Keeping this in mind, one can safely say that diesel is a suitable marine fuel when it comes to operational endurance and not least in terms of storage space.

Highlighted in the figure below some of the MDO storage tanks onboard MS Nordlys are displayed. They are integrated in the hull structure and the settling tanks named T33,34,35 is located right outside the engine room. (Assumed tank arrangement from "MS Kong Harald" is same as sister ship "MS Nordlys" retrieved from Appendix A. Technical Drawings, Tank Arrangement «MS Kong Harald»

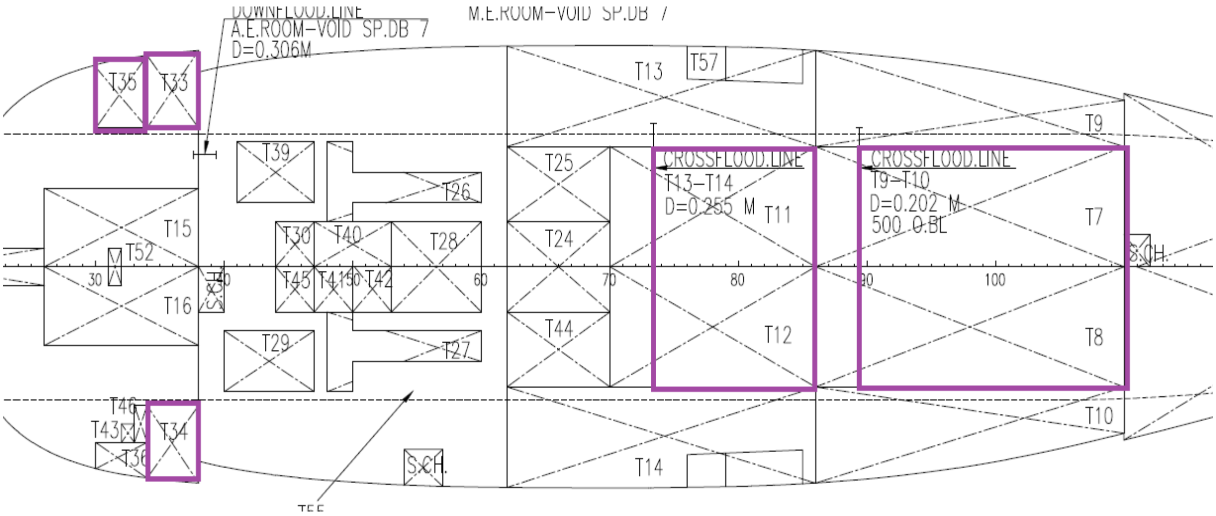


Figure 16 – MS Nordlys MDO storage tanks

3.1.2 Economic feasibility

Based on the calculations made regarding the ships total fuel consumption on the journey from Bergen to Trondheim, it is now interesting to see what the consumption costs, to further create a basis for comparison for looking at the cost-effectiveness of each of the marine fuel types discussed in this study.

As previously calculated, during the ship's journey of 19.1 hours from Bergen – Trondheim, it had a fuel consumption of 23.8t MDO. Retrieving the fuel price from "Global marine fuel prices" in Rotterdam (Thomson Reuters, 2023), the total cost of fuel for the whole journey can be calculated:

$$Cost_{fuel} = Fuel_{consumed} * Price_{MDO} = 23{,}8\,t * 568\frac{\$}{t} = 13518{,}4\$$$

As of April 15th, 2023, the 1 USD (United States Dollar) was equivalent to 10,31 NOK. (Norges bank, 2023a)
Calculating the cost of fuel in NOK:

$$Cost_{fuel,NOK} = Cost_{\$} * Exhange\ rate = 13518{,}4\$ * 10{,}31\frac{NOK}{\$} = 139374{,}7NOK$$

The cost of MDO consumed by MS Nordlys on the journey is 139374,7 NOK.

3.1.3 Emissions

For fossilized fuel the combustion reaction can be generalized as following:

Equation 1 general combustion reaction

$$C_XH_y + \left(x + \frac{y}{4}\right)O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O + energy$$

And diesel have a wide range in a carbon number from $C_{12}H_{24}$ to $C_{17}H_{36}$. Generalizing this and assuming that diesel with carbon number 15 can be used for emissions for MDO, this means the reaction would be like this (Also assuming full combustion, and without N2):

$$C_{15}H_{32} + \left(15 + \frac{32}{4}\right)O_2 \rightarrow 15CO_2 + \frac{32}{2}H_2O + energy$$

$$C_{15}H_{32} + 23O_2 \rightarrow 15CO_2 + 16H_2O + energy$$

(Bernodusson, 2018)

In terms of mass the following equation exists to convert to mass, whereas M_w is molar weight, m is mass and n is molecules (Pedersen, Gustavsen, Kaasa, & Olsen, 2013, p. 159):

Equation 2 Molar mass in relation fraction of mass and molecules

$$M_w = \frac{m}{n}$$

Molar weight for carbon, hydrogen and oxygen is respectively "12,01", "1,008" and "16,00" kg/kmol. (Pedersen, Gustavsen, Kaasa, & Olsen, 2013, p. 288) Converting the above reaction in terms of mass we get (assuming kilo-molecules to convert to kg):

$$212{,}406\ kg\ C_{15}H_{32} + 736\ kg\ O_2 \rightarrow 660{,}15\ kg\ CO_2 + 288{,}256\ kg\ H_2O + energy$$

$$1\ kg\ C_{15}H_{32} + 3{,}47\ kg\ O_2 \rightarrow 3{,}11\ kg\ CO_2 + 1{,}36\ kg\ H_2O + energy$$

So, for every kg of diesel (assuming $C_{15}H_{32}$) there is a emission of 3,11 kg of CO_2. And the fuel consumption for the voyage from Bergen to Trondheim with MS Nordlys was previously calculated to be 23,8 ton. The total amount of emission by CO_2 is therefor:

$$MDO_{Emissions_{CO_2}} = 23790{,}96\ kg * 3{,}11\ kg = 73\ 940{,}31\ kg \approx 73{,}9\ ton$$

The total amount of emissions by CO_2 is calculated to be 73,9 ton. However, the above combustion reaction does not amount for NO_x, SO_x, CO, and particulate matter (solid carbon particles). A more realistic reaction would be as such (Assuming <u>not</u> 100% full combustion):

$$C_{15}H_{32} + 23O_2 \rightarrow 15CO_2 + 16H_2O + energy + (SO_x + NO_x + C_s + CO)$$

For NO_x emissions, this will amount to 0,04 kg NO_x gas for every kg of diesel which is combusted. The products will mostly be NO and NO_2, NO_2 is harmful for the atmosphere as due to moisture it can form into HNO_3 this in turn can cause acidic rain. As for SO_x emissions produced, this is proportional to the sulphur content in the diesel. To avoid SO_x emissions, one can choose to use a diesel which have no sulphur content – however these fuels are very costly. SO_x can also produce acidic rain like NO_x. For every kg of sulphur in the fuel, this will in the combustion create a product of 2 kg SO_2. (Bernodusson, 2018, pp. 13-16) According to ISO8217 and table 1 specifying requirements for marine distillate fuels, a marine fuel of category DMB has a sulphur content of 2%. Although there exist regulations set by IMO to regulate sulphur limit to 1,5 %. (ISO 2005, p. 5) For calculations a sulphur content of 1,5% is assumed for the marine diesel fuel.

The calculation of NO_x emissions for the voyage from Bergen to Trondheim:

$$MDO_{Emissions_{NO_x}} = 0{,}04\ \frac{kg\ NO_x}{kg\ fuel} * 23790{,}96\ kg = 951{,}6\ kg \approx 0{,}95\ ton$$

For the calculation of SO_2 emissions for the voyage from Bergen to Trondheim, we first need the sulphur content in kg for the fuel:

$$S_{content} = 0{,}015 * 23790{,}96\ kg = 356{,}9\ kg$$

$$MDO_{Emissions_{SO_2}} = 356{,}9\ kg * 2 = 713{,}7\ kg\ \approx 0{,}71\ ton$$

Total emissions of combustion of 23,8 ton marine diesel oil can be seen in Table 7

CO_2	73,9 ton
NO_x	0,95 ton
SO_2	0,71 ton

Table 7 – MDO emissions

3.2 Liquified Natural Gas – Operational efficiency

For the vessel MS Nordlys it can be considered LNG engines instead of the current type they use B33:45L6 as previously mentioned in the chapter of the base case for Marine Diesel Oil. The new types of engines could then be a Bergen Engines B3645L6P with 6 cylinders with four-stroke cycle. These engines have a rated power of 3600 kW same as the base case. The RPM (revolutions per minute) with the new engines would then be 750 RPM. According to Bergen Engines technical description of B3645L6P it has a SFOC (specific fuel consumption) of 7 420 kJ/kWh, this is the specific fuel energy consumption needed to utilize the power of the engines. (Bergen Engines AS, 2023a) The new LNG engine is shown in Figure 17.

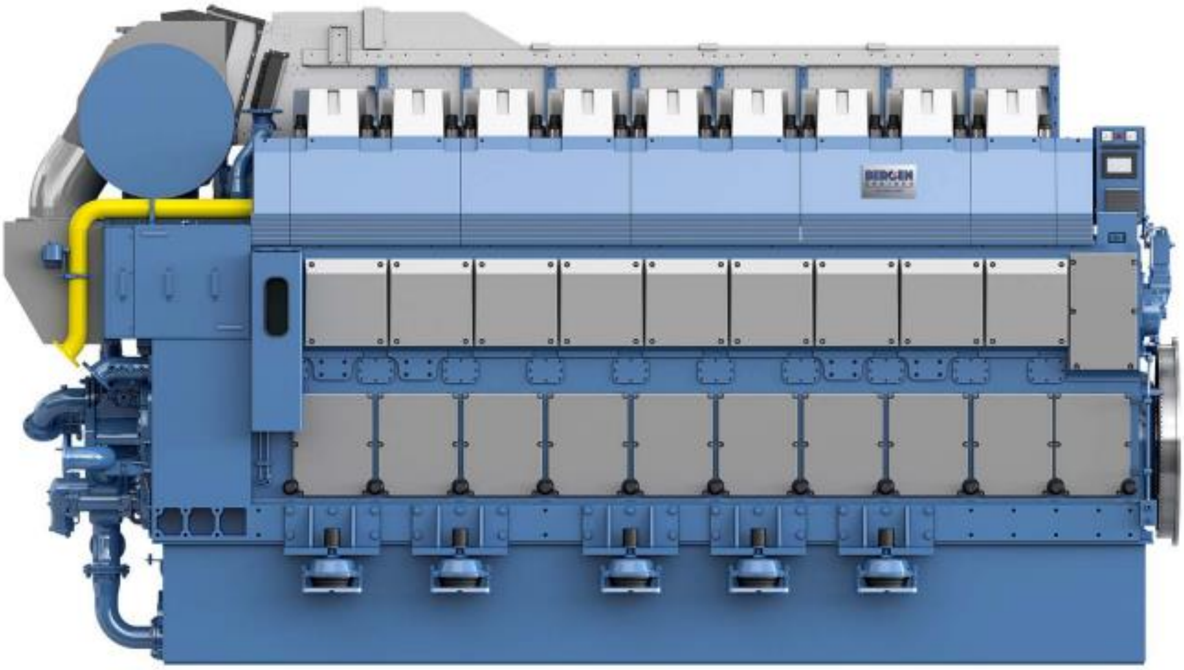


Figure 17 – B36:45L LNG Propulsion Engine (Bergen Engines AS, 2023a)

<u>LNG calculation without cooling systems:</u>

Gravimetric energy density: 50 000 kJ/kg (LNG, mainly methane) – this is without cooling systems.

In the calculations we take into the considerations of the new LNG engines is to be installed for MS Nordlys. This engine is also further used when calculating for the other alternative fuels such as Ammonia, Methanol and Hydrogen. It is assumed that this engine could in ways be retrofitted to accommodate the other fuel types.

The engine efficiency is not considered – this will presumably be different from each fuel type. The calculations are conducted as to make a comparison between the fuels on a general basis.

In order to complete the calculations, the gravimetric energy density is used, which for LNG is 50 MJ/kg without cooling systems.

Previously there has already been made calculations for how long the vessel is travelling from Bergen to Trondheim, this is in this case 19,1 hours with a speed of 18 knots. Calculating the full amount of energy needed for this journey this would be for one engine 68 760 kWh (engine power of 3600 kW multiplied with 19,1 hours), and for two engines the total energy would be 137 520 kWh. It can from this be calculated the specific fuel consumption, calculations as follows:

$$SFOC_{LNG} = \frac{Specific\ energy\ consumption}{Gravimetric\ energy\ density} = \frac{7420\ kJ/kWh}{50\ 000\ kJ/kg} = 0{,}1484\ kg/kWh$$

So, the specific fuel consumption in regard to the Bergen Engines engine is calculated to be 0,148 kg/kWh. As we know the full energy demand needed for the journey, the amount of fuel for each engine can be calculated, and then found for each hour.

$$SFOC_{LNG,h} = \frac{SFOC_{LNG} * Total\ energy}{Travel\ time}$$

$$SFOC_{LNG,h} = \frac{0{,}1484 \frac{kg}{kWh} * 68760\ kWh}{19{,}1\ hours} = 534{,}24\ kg/h$$

So, the specific fuel consumption for LNG is 534,24 kg each hour. This is the pure amount of LNG needed to give the required power output for one engine, however it does not display the actual need for also powering up the cooling systems to keep the LNG liquid in the storage tanks.

The total fuel consumption for the full journey if one considers ignoring the need to power up the cooling systems, this would be with two engines:

$$Total\ F_{consumption} = 2 * 534{,}24 \frac{kg}{h} * 19{,}1h = \ 20\ 408\ kg \approx 20{,}41\ tons$$

The total fuel consumption needed to complete this journey is 20,41 tons of LNG, from Bergen to Trondheim with MS Nordlys. However, it is important to remark that according to Figure 1, the gravimetric energy density will be more realistically at 25 MJ/kg if the cooling systems and other systems needed for the storage tanks is also included. The reduction in energy density comes from factors such as packaging factors for cylindrical tanks, transfer losses, boil-off gas and insulation and filling factors. (ABS, 2021b, p. 2) Another remark to be made is considering the results of the calculations the vessel would most likely not operate at a maximum speed, and the engines would probably not be run at 100%MCR, which would further affect the calculations. It is assumed in the calculations a 100% MCR, this is also considered for the other alternative fuel types in the following chapters.

3.2.1 Storage options

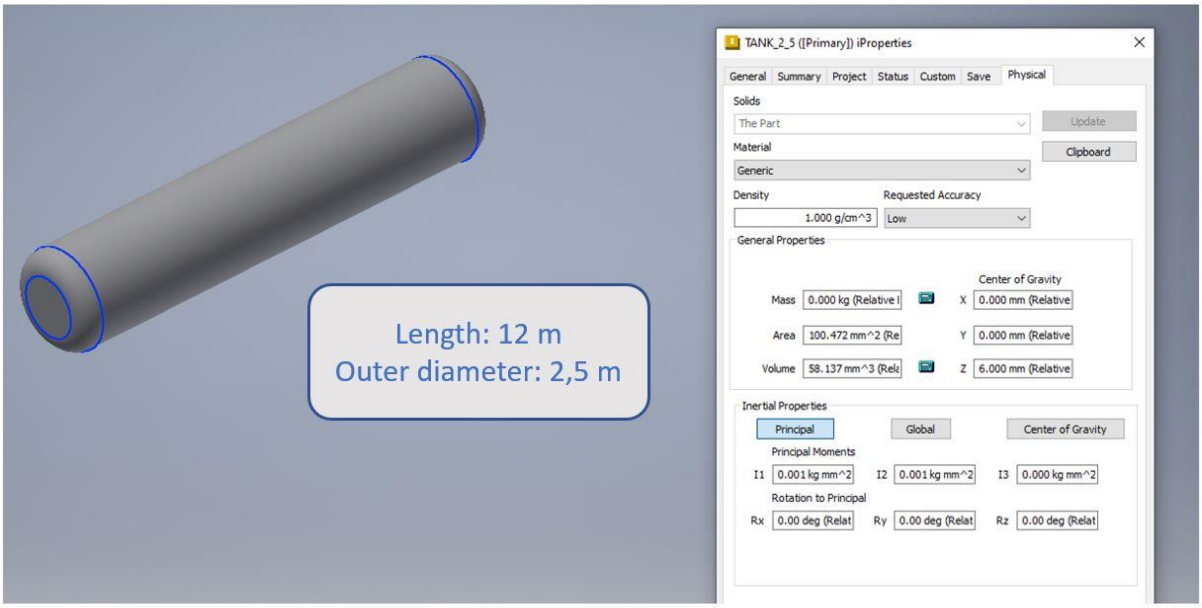
As the fuel needed for the voyage from Bergen to Trondheim was found in calculations above concerning the total fuel consumption, it can from this also be calculated the minimum storage capacity which is needed for MS Nordlys without powering up the cooling systems. In the following calculations there will be calculated the storage tanks needed to store the LNG. The density of LNG is from Table 2 – Properties of LNG and is as previously stated as 478 kg/m^3 in liquid state.

$$Storage_{LNG} = \frac{Total\ F_{consumption}}{Density_{LNG}} = \frac{20\ 408\ kg}{478\ kg/m3} \approx 42{,}69\ m^3$$

According to the above calculation MS Nordlys needs to be fitted with tanks with a storage capacity of at least 42,69 m^3.

As LNG has a low boiling point and is kept liquid at around -162°C at 1 bar pressure, it must be stored in insulated tanks for cryogenic use. (DNV, 2019, p. 19) Keeping LNG in liquid form instead of in gaseous state reduces the volume to around 1/600 of that. The heat penetration into the tanks leads to the formation of boil-off gas, and pressure regulation systems are required to handle this. Either the gas can be consumed by the engines, or it can be liquefied again by regulating the tank pressure within acceptable limits. There are several options for storage tanks for LNG, but for ships like MS Nordlys, the most common option is the IMO's Type C pressurized storage tank. These tanks also simplify the equipment required to handle boil-off gas due to their pressure accumulation capability. But, seen from another side, these tanks are not necessarily the most space-efficient option. (ABS, 2022) Classification companies like DNV have set rules and requirements for LNG storage tanks and associated systems, which are in accordance with design requirements set in various codes by IMO. The requirements deal with the safe placement of tanks regarding potential damage in the event of collision, fire and other operations that may cause damage to the storage tanks and surrounding systems. There are requirements for double barriers where a leak could potentially occur. This can be double piping, tank connection spaces, fuel preparation rooms, etc. In addition, leak detection systems such as gas detection and measurement of pressure and temperature changes are required. If something should go wrong with the fuel system and a leak occurs, it is required that there is a system for automatically shutting off the fuel supply and isolating leaks. (Green shipping program, 2021, p. 13)

In Figure 18, a simple LNG Type C storage tank design is presented. It was designed by using the "Autodesk Inventor" software. LNG storage tank design drawing retrieved from Appendix F. Technical Drawings, Tank Design.


Length: 12 m
Outer diameter: 2,5 m

TANK_2_5 ([Primary]) iProperties

Solids: The Part
Material: Generic
Density: 1.000 g/cm^3
Requested Accuracy: Low

General Properties
Mass: 0.000 kg (Relative
Area: 100.472 mm^2 (Re
Volume: 58.137 mm^3 (Rel
Center of Gravity
X: 0.000 mm (Relative
Y: 0.000 mm (Relative
Z: 6.000 mm (Relative

Inertial Properties
Principal Moments
I1: 0.001 kg mm^2
I2: 0.001 kg mm^2
I3: 0.000 kg mm^2
Rotation to Principal
Rx: 0.00 deg (Relat
Ry: 0.00 deg (Relat
Rz: 0.00 deg (Relat

Figure 18 – Proposal of LNG storage tank of 58m³ illustrated by Autodesk Inventor software.

The storage tanks designed and presented has a capacity of 58 m^3 each. The figure below shows a proposal drafted in the "General Arrangement" drawing by using the AutoCAD software, for the placement of the presented LNG storage tanks onboard MS Nordlys. These are located on tank top deck (the deck below the engine room), where storage space, freezer and cooling rooms are replaced with tank rooms. Modified GA (general arrangement) drawing is retrieved from Appendix B. Technical Drawings, LNG.

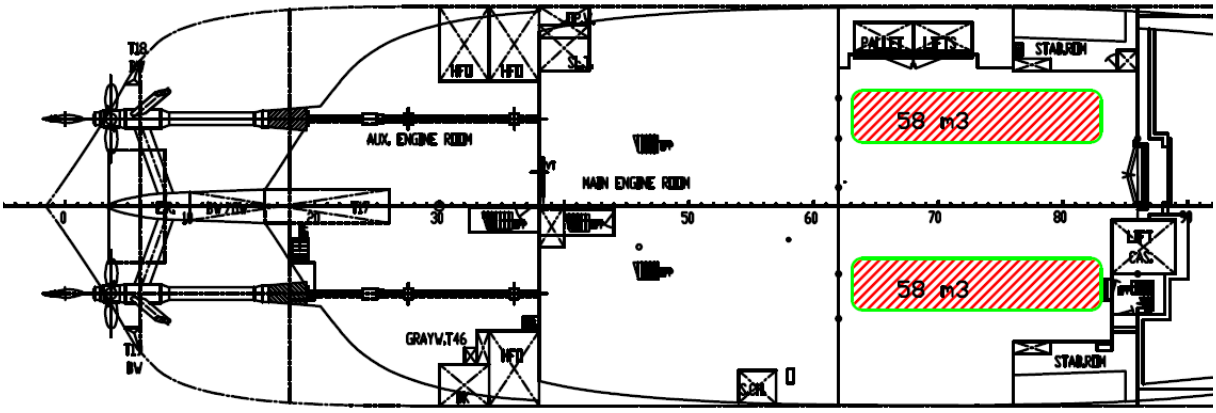


Figure 19 – Potential location for LNG storage tanks illustrated in GA drawing by AutoCAD software.

The solution that is presented makes a total storage capacity of LNG of:

$$Total\ storage\ capacity = 2 * 58m^3 = 116m^3$$

The previous calculations made regarding the minimum storage capacity of LNG that is required for journey from Bergen to Trondheim was 42,69 m^3, which means that this solution presented will be a good and sufficient tank capacity for MS Nordlys. It can even operate with longer sailing distances with this capacity, which is an advantage for this ship which often operates with shorter berth stays.

3.2.2 Economic feasibility

As the fuel consumption for sailing "MS Nordlys" from Bergen to Trondheim was previously found to be 20,41 ton – we can from this calculate the fuel cost. According to "Ship & Bunker" the bunker price for LNG in Rotterdam is 856 $/ton, retrieved April 15th, 2023. (Ship & Bunker, 2023) With the fuel price retrieved and by knowing the fuel consumption that is required to achieve the sailing from Bergen to Trondheim, the total cost of fuel for the whole journey can be calculated as follows:

$$Cost_{fuel} = Fuel_{consumed} * Price_{LNG} = \ 20{,}41t * 856\frac{\$}{t} = 17470{,}96\$$$

As of April 15th, 2023, the 1 USD was equivalent to 10,31 NOK. (Norges bank, 2023a) Calculating the cost of fuel in NOK:

$$Cost_{fuel,NOK} = Cost_{\$} * Exhange\ rate = 17470{,}96\$ * 10{,}31\frac{NOK}{\$} = 180125{,}6NOK$$

The total cost of LNG consumed by MS Nordlys on the journey is 180125,6 NOK.

3.2.3 Emissions

For the calculation of emissions produced when combusting LNG (natural gas) we assume that the composition is 90 % methane and 10 % ethane for simplicity. It is further assumed that this composition of methane and ethane correspond to the total volume calculated to be 42,69 m^3. Densities for methane and ethane is assumed to be 422,6 kg/m^3 (The Engineering Toolbox, 2023c) and 628,3 kg/m^3 (The Engineering Toolbox, 2023b) at -161,6 °C. It is further assumed that although the densities are for liquid state, the combustion will be in an evaporated form.

$$mass_{methane} = (0{,}90 * 42{,}69\ m^3) * 422{,}6\ kg/m^3 = 16\ 236{,}7\ kg$$

$$mass_{ethane} = (0{,}10 * 42{,}69\ m^3) * 628{,}3\ kg/m^3 = 2\ 682{,}2\ kg$$

The total mass is changed from 20,41 tons to 18,92 ton when using the volume of LNG in this example for just methane and ethane, this correspond to a relative change of -7,3% and is a deviation. The reason for the changed mass (total volume is unchanged) is that the LNG composition normally also include products such as propane, butane, and nitrogen. (U.S Department of Energy, 2005) The masses calculated can further be used when calculating the mass fractions of the fuel combustion reaction. The fuel reactions are as following (assuming 100 % combustion, with no nitrogen) and using Equation 1 as basis:

Methane:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + energy$$

Ethane:

$$4C_2H_6 + 14O_2 \rightarrow 8CO_2 + 12H_2O + energy$$

Respectively knowing the molar weight of carbon, hydrogen, and oxygen, we can show this in kg of fuel for combustion:

$$1kg\ CH_4 + 3{,}99\ kg\ O_2 \rightarrow 2{,}74\ kg\ CO_2 + 2{,}25\ kg\ H_2O + energy$$

$$1\ kg\ C_2H_6 + 3{,}72\ kg\ O_2 \rightarrow 2{,}93\ kg\ CO_2 + 1{,}8\ kg\ H_2O + energy$$

The amount of CO2 produced from these reactions is as following:

$$LNG_{CH4Emissions_{CO_2}} = 16\ 236{,}7\ kg * 2{,}74\ kg = 44\ 544{,}2\ kg \approx\ 44{,}54\ ton$$

$$LNG_{C2H6Emissions_{CO_2}} = 2\ 682{,}2\ kg * 2{,}93\ kg = 7851{,}8\ kg \approx\ 7{,}85\ ton$$

In total for CO_2 emissions this is then:

$$LNG_{Emissions_{CO_2}} = 52{,}39\ ton$$

Arguably if the LNG composition would have been calculated from the total mass of fuel, 20,41 tons, instead of the total volume, the CO_2 amount from the combustion would be 56,4 tons. The relative change from the volumetric calculation is in that case 5,3 %.

Important to mention with LNG engines, is that as methane is the main component in LNG, it can if not combusted end up in the atmosphere through the exhaust gas. This is known as “methane slip”. Methane in the atmosphere have a typical lifetime of 12 years, then the molecule will decompose to carbon dioxide and water vapor, however methane in comparison to carbon dioxide (which have a lifetime of 1000 years) have a global warming potential of 28 times greater than CO_2 when looking at a 100-year perspective. (Sachgau, 2023) As for “methane slip” and according to MAN Energy solutions, see Figure 20, the methane slip for gas mode for a four stroke otto-engine is typically between 2,4-4 g/kWh when the engine is at 100 % load. (MAN Energy Solutions, 2023b, p. 9)

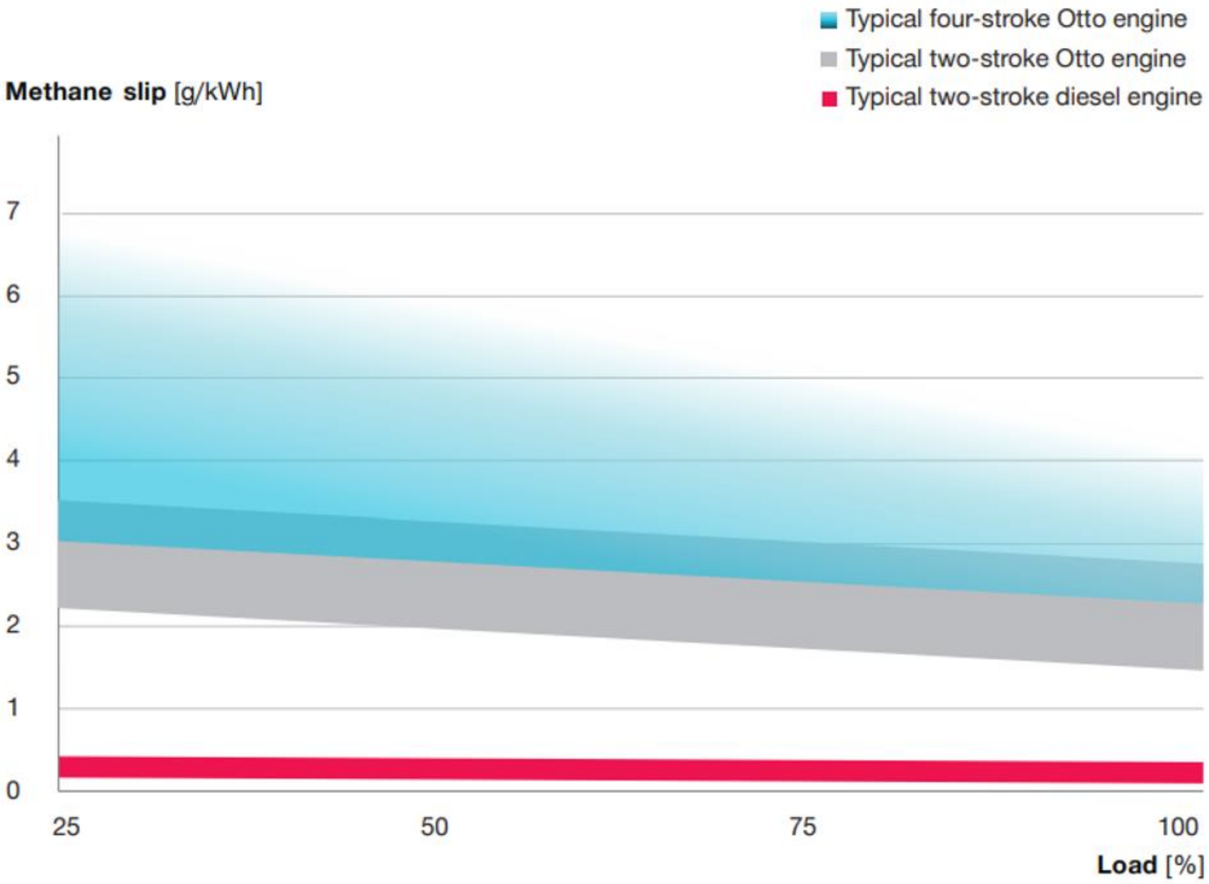


Figure 20 – Methane emissions in gas mode for two- and four stroke otto engines (MAN Energy Solutions, 2023b, p. 9)

As the exhaust gas data is limited for the B36:45 engine, we find a similar engine that the values for exhaust gas are available. We can in this case use the exhaust gas properties of natural gas engine B35:40 from Rolls Royce. In Table 8 following values for exhaust gas from combustion is retrieved:

NO_x	1,3 g/kWh
CO	1,4 g/kWh
CH_4	4,2 g/kWh
CO_2	431,6 g/kWh
GHG_c[8]	1,3 g/kWh

Table 8 – RR LBSI Engines, E3 Cycle – Engine type B35:40

(Stenersen & Thonstad, 2017, p. 21)

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[8] GHG – Green House Gases

Assuming that these values for emissions from engine B35:40 is similar to the emissions B36:45 engine will produce. Also remarking the emission of methane to be 4,2 g/kWh which is also in the same area as presented in Figure 20. And we have the previously calculated energy demand of the B36:45 engine to be 137 520 kWh when sailing from Bergen to Trondheim. The exhaust gas emissions are then:

$$LNG_{Emissions_{NO_x}} = 1{,}3 * 10^{-3} \frac{kg}{kWh} * 137\,520\; kWh = \; 178{,}8\; kg \approx 0{,}18\; ton$$

$$LNG_{Emissions_{CH_4}} = 4{,}2 * 10^{-3} \frac{kg}{kWh} * 137\,520\; kWh = 577{,}6\; kg \approx 0{,}58\; ton$$

So, the emissions for NO_x and methane slip (un-combusted methane) are assumed from these calculations to be 0,18 and 0,58 ton respectively. As we also have the CO_2 emissions for the B35:40 engine, we can calculate this for comparison:

$$LNG_{Emissions_{CO_2}} = 431{,}6 * 10^{-3} \frac{kg}{kWh} * 137\,520\; kWh = 59\,353{,}6\; kg \approx 59{,}4\; ton$$

The total CO_2 emission is calculated to be 59,4 ton, this is a deviation from the original calculated value by a relative change of 13,4 %.

The total emissions for LNG assuming we have methane slip and NO_x, and no CO is presented in Table 9:

CO_2	52,39 ton[9]
NO_X	0,18 ton
CH_4	0,58 ton

Table 9 – LNG total emissions

And if one accounts that methane slip to the atmosphere is 28 times greater than CO_2 when it comes to a global warming potential – this number is 16,24 tons if this was assumed to be CO_2 (In total this would be 68,6 ton, which is still lower than for the base case for marine diesel oil – which is at 73,9 ton).

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[9] See previous calculation from the combustion chemical reaction with LNG.

3.3 Ammonia – Operational efficiency

As of today, there are no ships in the world that operate on ammonia. (Øystese, 2020, p. 4) However, several engine manufacturers are actively working towards developing the engine technology and design that is required for operating on ammonia. Wärtsilä is one of the manufacturers that has come relatively far in testing and has achieved good results where the engine is operated with 50% ammonia and 50% diesel. They are working on increasing the content of ammonia over a long period of time to see how much they can mix in. As ammonia is highly toxic and corrosive, the engine compartment is closed during test driving. For an ammonia-powered engine to be able to operate on a ship, this is one of the challenges Wärtsilä must solve, as it must be possible to be present inside the engine room during operation. (Røli & Andersen, 2023) Based on this, it is currently challenging and speculative to say anything about how this will work operationally on a ship. A pilot project will probably reveal several challenges and several adjustments will probably be required along the way to find the best solution.

Looking at the example that was described in the base case, with two main engines at 3600kW each, operating at 100%MCR, with a sailing time of 19,1 hours, we can create a case where ammonia is used as the main fuel in the internal combustion engines. The calculations are considering the engines run on 100% ammonia, i.e., without any admixture of pilot fuel. It is also considering that the specific energy consumption of the engine described in the calculations for LNG is the same for ammonia. By using values given in Table 3 – Properties of Ammonia, we can calculate the fuel consumption of ammonia for the whole sailing distance. Starting by calculating the specific fuel consumption:

$$SFOC_{Ammonia} = \frac{Specific\ energy\ consumption}{Gravimetric\ energy\ density} = \frac{7420\ kJ/kWh}{18800\ kJ/kg} = 0{,}3946\ kg/kWh$$

Considering the engine described in the LNG case, the specific fuel consumption is calculated to be 0,3946 kg/kWh. The full energy demand needed for this journey with one engine is 68 760 kWh (engine power of 3600 kW multiplied with 19,1 hours), the amount of fuel used each hour for one engine can be calculated:

$$SFOC_{Ammonia,h} = \frac{SFOC_{Ammonia} * Total\ energy}{Sailing\ time} = \frac{0{,}3946 \frac{kg}{kwh} * 68760\ kWh}{19{,}1\ hours}$$

$$= 1420{,}5 \frac{kg}{h}$$

Having the specific fuel consumption of ammonia each hour, we can calculate the total consumption for the full journey:

$$Total\ F_{consumption} = 2 * 1420{,}5 \frac{kg}{h} * 19{,}1h = \ 54263{,}1\ kg \approx 54{,}26\ tons$$

The calculations shows that the total amount of fuel consumed by MS Nordlys for sailing from Bergen to Trondheim is 54,26 tons of Ammonia. Note that this is the pure amount of Ammonia needed to give the required energy output for both the engines. However, as mentioned in the base case example the vessel will most likely not be operated at maximum speed, and the engines would probably not be driven at 100% MCR, which would further affect the calculations. Another factor is that ammonia must be refrigerated or compressed to be able to store it in liquid state. (Green shipping program, 2021, p. 16) The calculations do not consider the energy consumed by the storage systems required to keep ammonia liquid. The gravimetric energy density of liquid ammonia decreases from 18,8 MJ/kg to 11 MJ/kg when required storage systems is accounted for, which is displayed in Figure 1.

3.3.1 Storage options

The total fuel consumption of Ammonia for the whole voyage from Bergen to Trondheim was calculated to be 54,26 tons. Further the minimum storage capacity needed can be calculated. It is by these calculations assumed that the energy required to keep the ammonia stored at a liquid state is already accounted for by other power systems. The minimum storage capacity required for having a sufficient amount of fuel for the whole journey can be calculated by using the density of ammonia in liquid state of 680 kg/m^3, retrieved from Table 3 – Properties of Ammonia:

$$Storage_{Ammonia} = \frac{Total\ F_{consumption}}{Density_{Ammonia}} = \frac{54263{,}1\ \ kg}{680\ kg/m3} \approx 79{,}8\ m^3$$

According to the above calculation MS Nordlys needs a minimum storage tank capacity of 79,8 m^3 to get from Bergen to Trondheim.

For ammonia to be kept in a liquid state it must be cooled down to -33°C at 1 bar or pressurized to approximately 8.6 bar at 20°C. However, storage at low temperatures requires some energy to maintain. Another solution is to use pressurized storage tanks around 18 bars, also called type C tanks. This corresponds to ammonias vapour pressure at 45°C. This can be a more expensive solution, but it can be more convenient for marine solutions as it eliminates the need for additional systems such as re-liquefaction equipment. Ammonia tanks must comply with a number of requirements and follow international safety standards set by IMO. These are requirements that deal with design and safety standards, minimum distances to the ship's hull, accommodation space, and requirements for material use for ammonia tanks. (ABS, 2020, p. 14) There are also requirements for the tanks to be placed in areas where they are least exposed to damage, requirements for double barriers so that any leaks can be handled safely, as well as leak detection and automatic isolation of leaks to limit the leakage as much as possible. Tank connection spaces and fuel preparation rooms are necessary to have as an extra barrier against leakages, especially in areas where double piping is not possible. And of course, a fuel supply system is necessary. (Green shipping program, 2021, pp. 14, 16-19).

In the figure below, a proposal has been drafted for the placement of ammonia tanks on tank top deck by replacing freezer and cooling rooms, as well as storage space. It is based on the storage tanks designed and presented for the LNG case with a capacity of 58 m^3 each. Modified GA drawing is retrieved from Appendix C. Technical Drawings, Ammonia.

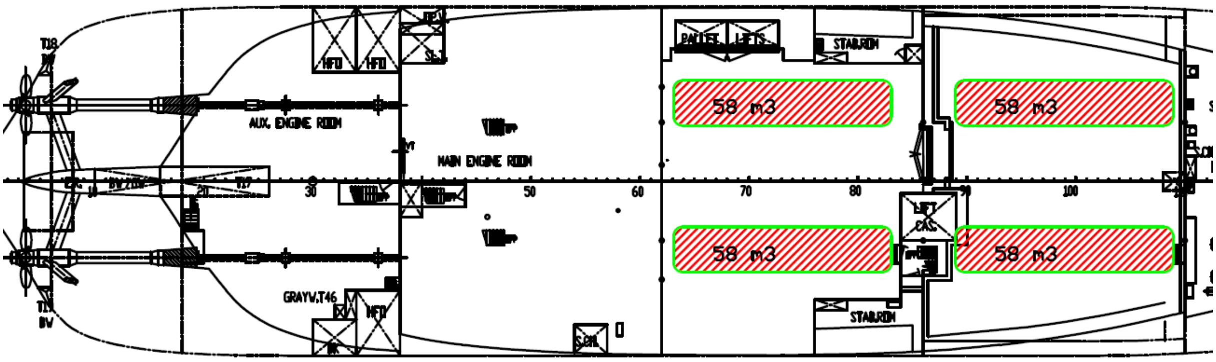

Figure 21 – Potential location for ammonia storage tanks illustrated in GA drawing by AutoCAD software.

The solution presented makes a total storage capacity for ammonia of:

$$Total\ storage\ capacity = 4 * 58m^3 = 232m^3$$

Based on the calculations made for the minimum storage capacity required for MS Nordlys to sail from Bergen to Trondheim, this solution would provide a more than sufficient capacity of ammonia. In this case only installing two tanks would also be sufficient for it to make the journey. However, it must be mentioned that for a cruise ship like MS Nordlys, it would probably be an issue to replace that must storage space. Note that with as far as they have come with the engine technology today as previously described with Wartsila's ammonia engine, it will be necessary to still use some of the MDO storage tanks for MDO since there is no solution for pure ammonia driven engines yet, and it will require MDO as pilot fuel/backup fuel.

3.3.2 Economic feasibility

As the fuel consumption required for the journey from Bergen to Trondheim is calculated to be 54,26 tons of ammonia, the fuel cost can be calculated. According to DNV's tool "AFI" (Alternative Fuel Insight) for checking fuel prices the price is found for green ammonia to be approximately 2800USD/t_{MGO}[10] in March 2023, as displayed in the figure below.

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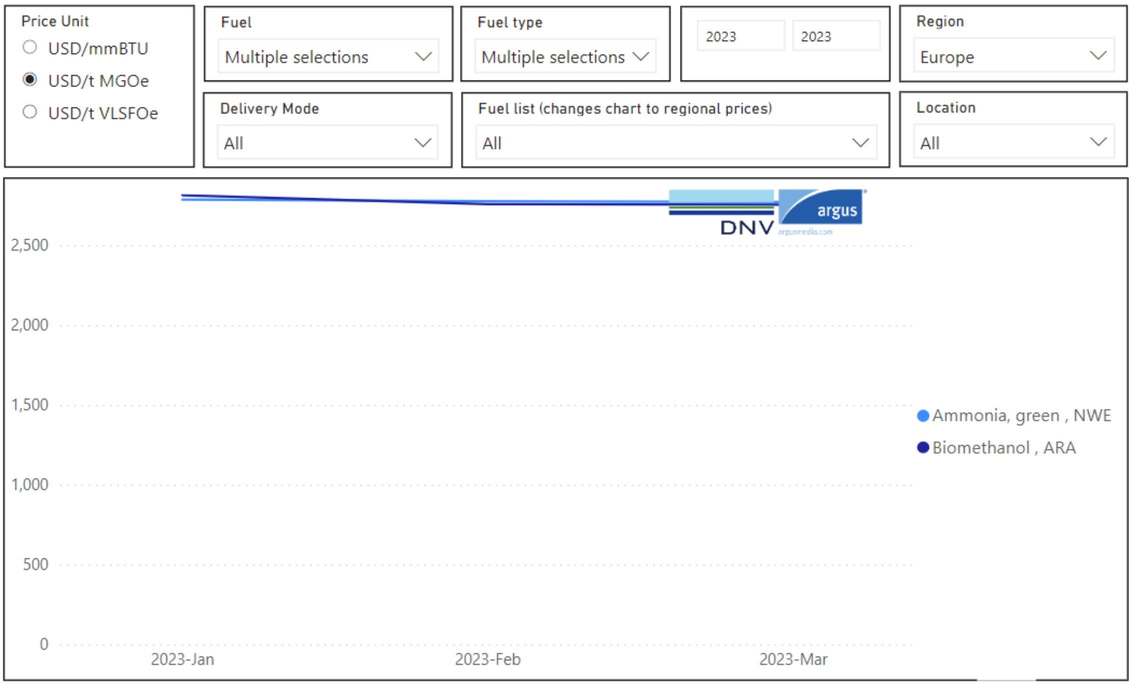
[10] MGO – Marine Gas Oil



Price Unit
○ USD/mmBTU
● USD/t MGOe
○ USD/t VLSFOe

Fuel: Multiple selections

Fuel type: Multiple selections

2023 – 2023

Region: Europe

Delivery Mode: All

Fuel list (changes chart to regional prices): All

Location: All

Figure 22 – Alternative Fuels Insight – Fuel prices for green ammonia and bio methanol (DNV, 2023a)

The price is given in USD per ton MGOe which means, according to “Ship & Bunker”, is the price of an amount of that certain fuel which delivers the energy equivalent of one metric ton of MGO. (Ship & Bunker News Team, 2021)

With the fuel price retrieved and by using the energy density of MDO and ammonia in MJ/tons the cost per ton of green ammonia can be calculated as follows:

$$Cost_{Ammonia,t} = \frac{Price_{Ammonia}}{Energy\ density_{MGO}} * Energy\ Density_{Ammonia}$$

$$Cost_{Ammonia,t} = \frac{2800 \frac{\$}{t_{MGO}}}{0{,}0427 \frac{MJ}{t_{MGO}}} * 0{,}0188 \frac{MJ}{t_{Ammonia}} = 1232{,}8 \frac{\$}{t_{Ammonia}}$$

Further the total cost of fuel for the whole journey can be calculated:

$$Cost_{fuel} = Fuel_{consumed} * Price_{Ammonia} = 54{,}26t * 1232{,}8 \frac{\$}{t} = 66891{,}7\ \$$$

As of April 15th, 2023, the 1 USD was equivalent to 10,31 NOK. (Norges bank, 2023a) Calculating the cost of fuel in NOK:

$$Cost_{fuel,NOK} = Cost_{\$} * Exhange\ rate = 66891{,}7\$ * 10{,}31 \frac{NOK}{\$} = 689653{,}4NOK$$

The cost of ammonia consumed by MS Nordlys on the journey is 689653,4 NOK.

3.3.3 Emissions

In general, the combustion equation for ammonia can be written as such if you assume full combustion:

$$NH_3 + 0{,}75\ (O_2 + 3{,}76N_2) \rightarrow 1{,}5\ H_2O + 3{,}32\ N_2$$

For this combustion the products are just water and nitrogen. Both these molecules are common in atmospheric conditions. However, the above reaction is almost impossible as ammonia require excess air in order for combustion. In a more realistic scenario with excess air ammonia gets partially oxidized and it will from this form nitric acid. The reaction would more realistically look like this:

$$\begin{aligned}
&[Y]NH_3 + [(X)(Y)(0{,}75)](O_2 + 3{,}76N_2) \\
&\quad \rightarrow [1 - C * Y]NH_3 + [Z * C * Y]NO_x + \Big[1{,}5Y - \big[1{,}5[1 - C * Y]\big]\Big] H_2O \\
&\quad + \left[\left(\frac{[1 - Z]}{2}\right) * C * Y\right] N_2 \\
&\quad + \left[\frac{\big[(X * Y * 0{,}75 * 2) - (Z * C * Y * X) - \big[1{,}5Y - \big(1.5 * (1 - C * Y)\big)\big]\big]}{2}\right] O_2
\end{aligned}$$

Whereas ‘Y’ is number of input moles of NH_3, ‘X’ is the amount of air in percent, ‘Z’ is the percent of NO_x formation, and C is the percent of conversion of NH_3. (Erdemir & Dincer, 2020, p. 4830)

There is limited information about the actual emissions from an engine that are run with 100 % ammonia fuel, and several studies research blending ammonia in with hydrogen, or methane to increase the combustion reactivity. Ammonia has some unfavourable combustion properties as it has a low laminar burning velocity, high auto-ignition temperature and a narrow flammability range. The four-stroke spark-ignition engine setup one study used; the following emissions produced can be seen in of a combustion reaction using different hydrogen mixtures in addition to ammonia the following results for emissions was found in this study and can be seen in Figure 23. Although important to remark is that these values were estimated with a 10 % uncertainty. (Lhuillier, Brequigny, Contino, & Mounaïm-Rousselle, 2020, pp. 2, 8) The values are listed in ppmv[11].

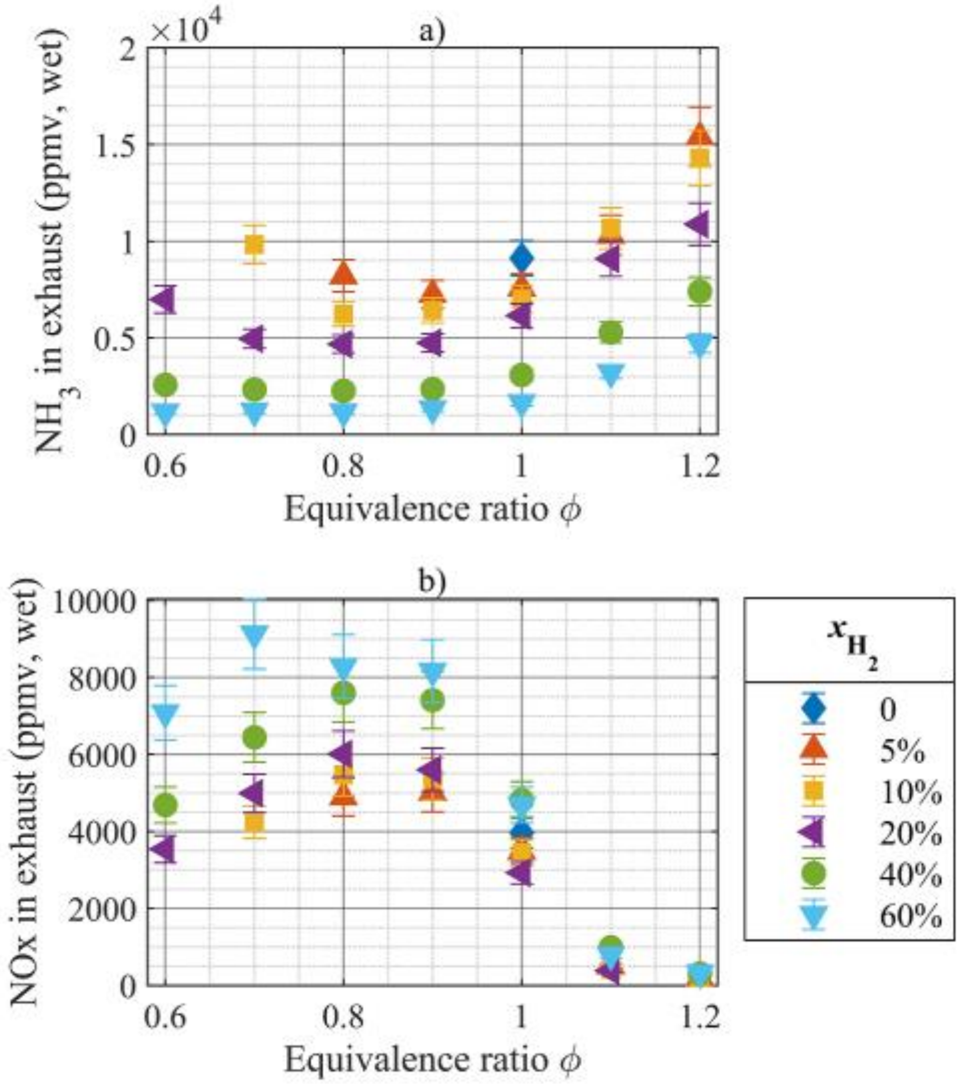


Figure 23 – Pollutant emissions in exhaust at Pin = 0.12 MPa. a) Unburned NH3. b) Total NOx. (Lhuillier, Brequigny, Contino, & Mounaïm-Rousselle, 2020, p. 8)

As the combustion of ammonia as previously mentioned require excess air (oxygen), as it is very hard to achieve a 100 % full combustion, we assume an equivalence ratio of 0,8. However this is also the area where the emissions are at Its maximal. However, this would

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[11] Ppmv means parts per million by volume. In example 1 microliter of CO_2 dispersed in 1 liter of air. (American Meteorological Society, 2017)

perhaps imply the need for strategies of mitigation for NO_x and NH_3 – for instance a SCR catalyst. (Lhuillier, Brequigny, Contino, & Mounaïm-Rousselle, 2020, p. 9) Then we further assume that a blend with 10 % hydrogen is added into the fuel mixture to increase the combustion. This leaves us, according to Figure 23, at a ppmv for NH_3 at $0{,}6 * 10^4$ and for NO_x at 5500. Using these values as basis for our emissions calculations, we need to convert this into ratio mass component/mass exhaust. We then need to assume that the density of the exhaust gas, which is unknown, so in this case we assume the density of a full combustion which leaves the products of water and nitrogen. Reaction is as follows:

$$NH_3 + 0{,}75\ (O_2 + 3{,}76N_2) \rightarrow 1{,}5\ H_2O + 3{,}32\ N_2$$

The mass of the exhaust gas would be, using Equation 2 and the molar weight of nitrogen, hydrogen and oxygen respectively 14,01, 1,008 and 16,00 g/mol (Pedersen, Gustavsen, Kaasa, & Olsen, 2013, p. 288):

$$17{,}034\ kg\ NH_3 + 24\ kg\ O_2 + 79{,}016\ kg\ N_2 \rightarrow 27{,}024\ kg\ H_2O + 93{,}026\ kg\ N_2$$

We can from this calculate the density of exhaust gas assuming full combustion, with the density of water and nitrogen respectively at 998,19 kg/m^3 (The Engineering Toolbox, 2023e) and 1,16 kg/m^3 (The Engineering Toolbox, 2023d) at 20 °C, and is of course a small deviation as we don't know the density with the products with NO_x and NH_3:

$$\rho_{exhaust} = 0{,}225 * 998{,}19 \frac{kg}{m3} + 0{,}775 * 1{,}16 \frac{kg}{m^3} = 225{,}49 \frac{kg}{m^3}$$

Assuming this value for the total density of exhaust gas, we can calculate the ratio mass component to mass exhaust gas, with the density of ammonia to be at 0,7069 kg/m^3 at 20 °C (The Engineering Toolbox, 2023a):

$$\frac{mass\ component\ NH_3}{mass\ exhaust\ gas} = 0{,}6 * 10^4\ ppmv * \frac{1}{10^6} * \frac{0{,}7069 \frac{kg}{m^3}}{225{,}49 \frac{kg}{m^3}} * 100$$
$$= 1{,}8809 * 10^{-3}\ \frac{kg\ NH_3}{kg\ ex.gas}$$

And for NO_x we need to assume a density. NO_x is a common term for several chemical formations involving nitrogen and is toxic gas which is an essential component for pollution.

It consists of NO_2, N_2O_3, NO_3, NO and N_2O. (NOx-fondet, 2023) If we assume that these gases in the exhaust is NO, NO_2 and N_2O and is equal in percentage, we can calculate the density. Respectively these gases have the densities of 1,34, 2,051 and 1,978 kg/m^3 (Pedersen, Gustavsen, Kaasa, & Olsen, 2013, p. 231):

$$\rho_{NO_x} = \frac{1}{3} * 1{,}34 \frac{kg}{m^3} + \frac{1}{3} * 2{,}051 \frac{kg}{m^3} + \frac{1}{3} * 1{,}978 \frac{kg}{m^3} = 1{,}79 \frac{kg}{m^3}$$

From this we can calculate the mass component of NO_x for each mass of exhaust gas:

$$\frac{mass\ component\ NO_x}{mass\ exhaust\ gas} = 5500\ \text{ppmv} * \frac{1}{10^6} * \frac{1{,}79 \frac{kg}{m^3}}{225{,}49 \frac{kg}{m^3}} * 100$$

$$= 4{,}3661 * 10^{-3} \frac{kg\ NO_x}{kg\ ex.gas}$$

The amount of kg exhaust gas assuming a full combustion is, and according to 1 kg of fuel burned:

$$NH_3 + 1{,}41\ kg\ O_2 + 4{,}64\ kg\ N_2 \rightarrow 1{,}59\ kg\ H_2O + 5{,}46\ kg\ N_2$$

The total amount would then be:

$$Mass_{ex.gas} = (1{,}59 + 5{,}46) \frac{kg\ ex.}{kg\ fuel} * 54263{,}1\ kg\ fuel = 382\ 555\ kg$$

Respectively the emissions would then be (not accounting for products from the added hydrogen in the combustion):

$$Ammonia_{Emissions_{NH_3}} = 382\ 555\ kg * 1{,}8809 * 10^{-3}\ \frac{kg\ NH_3}{kg\ ex.gas} = 719{,}548\ kg$$

$$\approx 0{,}72\ ton$$

$$Ammonia_{Emissions_{NO_x}} = 382\ 555\ kg * 4{,}3661 * 10^{-3}\ \frac{kg\ NH_3}{kg\ ex.gas} = 1670{,}27\ kg$$

$$\approx 1{,}67\ ton$$

The total emissions are therefor for un-combusted NH_3 and NO_x respectively 0,72 ton and 1,67 tons. This is further shown in Table 10 for later reference:

NH_3	0,72 ton
NOx	1,67 ton

Table 10 – Total emissions for combustion of Ammonia

3.4 Methanol – Operational efficiency and economic feasibility

Methanol as a marine fuel is used to a small extent in shipping, and according to DNV it is 22 methanol fuelled ships in operation worldwide today. (Thurman, 2023) Still the development on several engine manufacturers goes forward. Wärtsilä has converted one of their bestselling engine types to be able to operate on methanol. However, this is in addition with some sort of pilot fuel. (Wärtsilä, 2023)
Still considering the case described in "base case" with MS Nordlys equipped with two main engines of 3600kW each, operating at 100%MCR with a sailing time of 19,1 hours, the same case can be adapted to investigate the operational efficiency when methanol is used as the main fuel in the internal combustion engines. It is here considered that the engines operate on 100% methanol, i.e., without any admixture of pilot fuel. As the technical data from Wartsila's methanol engine does not provide any information regarding specific fuel consumption or specific energy consumption, it is assumed that the engine described in the LNG case can be adapted to methanol and continue using its value for specific energy consumption. By also using values given in Table 4 – Properties of Methanol, we can calculate the fuel consumption of methanol for the whole sailing distance. Starting by calculating the specific fuel consumption:

$$SFOC_{Methanol} = \frac{Specific\ energy\ consumption}{Gravimetric\ energy\ density} = \frac{7420\ kJ/kWh}{19900\ kJ/kg} = \ 0{,}3728\ kg/kWh$$

The specific fuel consumption is calculated to be 0,3728 kg/kWh by assuming the specific energy consumption is 7420 kJ/kWh. The Nanyang Technological University in Singapore has published a study for methanol as a marine fuel, where specific fuel consumption is calculated and is very close to the result calculated for this case. (Ming & Chen, 2021, p. 5)
By this, the further calculations will continue to use the calculated value of 0,3728 kg/kWh. Continuing using the energy demand needed for this journey, for one engine of 68 760 kWh (engine power of 3600 kW multiplied with 19,1 hours), the amount of methanol used each hour for one engine can be calculated:

$$SFOC_{Methanol,h} = \frac{SFOC_{Methanol} * Total\ energy}{Sailing\ time} = \frac{0{,}3728 \frac{kg}{kwh} * 68760\ kWh}{19{,}1\ hours}$$

$$= 1342{,}1 \frac{kg}{h}$$

Having the specific fuel consumption of methanol each hour, we can calculate the total consumption for the full journey:

$$Total\ F_{consumption} = 2 * 1342{,}1 \frac{kg}{h} * 19{,}1h = \ 51268{,}22\ kg \approx 51{,}26\ tons$$

Based on the calculations the total fuel consumption of methanol for the whole journey from Bergen to Trondheim is calculated to be 51,26 tons. This is the pure amount of methanol needed to give the energy output for both the engines. However, as previously mentioned the vessel will most likely not be operated at maximum speed, and the engines would probably be operated on variable load steps, which would further impact the calculations. This is not accounted for in this case. Another factor is the storage systems required for storing methanol onboard. The calculations do not consider the energy that is consumed by storage and handling systems for methanol. The gravimetric energy density of methanol decreases from 19,9 MJ/kg to 17 MJ/kg when these are accounted for which is displayed in Figure 1.

3.4.1 Storage options

For the whole voyage from Bergen to Trondheim the total fuel consumption of methanol for was calculated to be 51,26 tons. The minimum storage capacity needed can further be calculated. With these calculations it is assumed that the energy demand for storage and handling systems is already accounted for by other power systems. The minimum storage capacity required for having enough fuel capacity for the whole journey can be calculated by using the density of methanol of 790 kg/m^3, retrieved from Table 4 – Properties of Methanol:

$$Storage_{Methanol} = \frac{Total\ F_{consumption}}{Density_{Methanol}} = \frac{51268{,}22\ \ kg}{790\ kg/m3} \approx 64{,}9\ m^3$$

The calculations shows that a minimum storage capacity of 64,9 m^3 is required for MS Nordlys to get from Bergen to Trondheim.

When it comes to storing methanol, because of its lower energy density, it requires at least 2,5 times more storage volume than MDO for the same amount of stored energy. (Bureau Veritas, 2023) This seems reasonable when the calculated result is compared to the result found in base case. Since methanol is liquid at ambient conditions it can be stored like MDO, in conventional fuel tanks integrated in the hulls structure and can further be simpler to apply than other types of fuels. However, IMO and the classification companies have specified rules and regulations for storage of methanol onboard a vessel. Fuel tanks cannot be located in machinery spaces with category A, which basically means it should not be placed present to the main propulsion engines and auxiliary engines. (IMO, 2020) It is often proposed that the storage tanks are located below the waterline, and it promotes that a few of the ballast tanks are used as fuel tanks. The tanks will require special coatings and cofferdams[12] or hold spaces to prevent potential leaks. In addition, a tank ventilation system, gas detection, double piping on supply lines as well as a fuel handling system are required. (ABS, 2021b, pp. 13,15)

Highlighted in the figure below is some of the ballast tanks onboard MS Nordlys which could potentially be converted to methanol storage tanks. (Assumed tank arrangement from “MS Kong Harald” is same as sister ship “MS Nordlys” retrieved from Appendix A. Technical Drawings, Tank Arrangement «MS Kong Harald».

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[12] A structural space surrounding the fuel tank with an additional layer of gas and liquid tightness protection against flammable and toxic vapours between other areas of the ship and the tank as well as external fire. (IMO, 2020, p. 2)

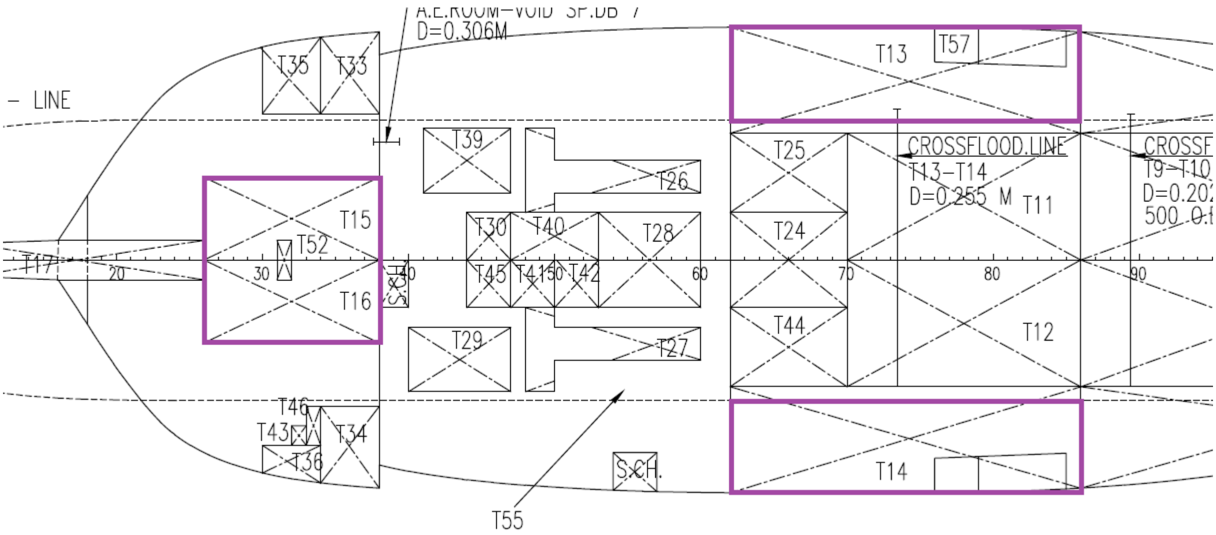


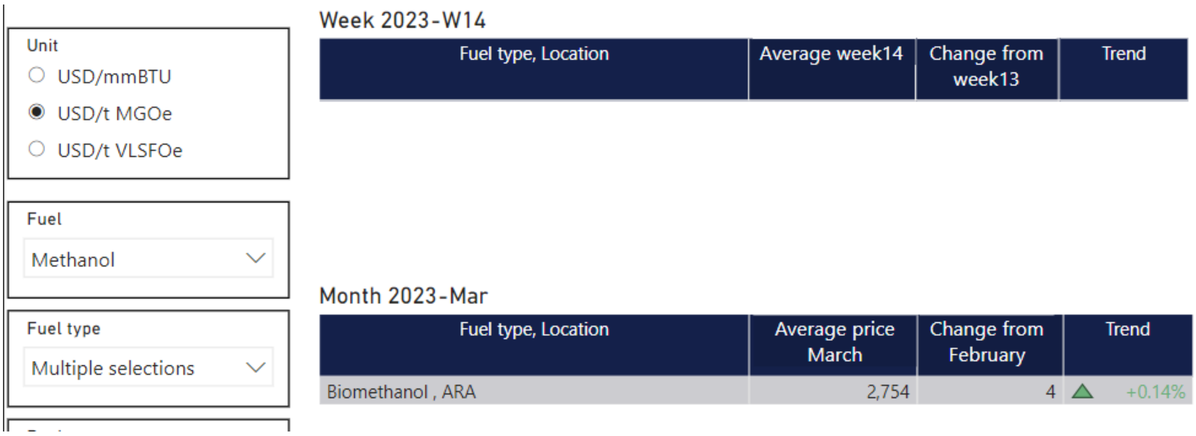
Figure 24 – Potential Methanol tank capacity for MS Nordlys, using tank plan drawing of MS Nordlys

MS Nordlys has a total ballast capacity of 774m^3 (DNV, 2022a) and the tanks named T15 and T16 in the figure has a capacity of 39,360m^3 each, making it a total of 72,72m^3. This would be the more preferred solution as they are placed more secure in terms of potential damage in the event of a collision. (IMO, 2020, p. 5) Based on the calculations this would be a sufficient tank capacity for the ship to get from Bergen to Trondheim. However, having either tank T13 or T14 with a capacity of 70,240m^3 each in addition converted to methanol storage tanks the capacity would have been more than sufficient, but they would then be placed more exposed in terms of potential damage in the event of a collision.

Another possible option can be to use the existing MDO storage tanks, shown in Figure 16, and convert them to methanol storage tanks.

3.4.2 Economic feasibility

Knowing the calculated fuel consumption required for the journey from Bergen to Trondheim is 51,26 tons of methanol, the fuel cost can be calculated. As mentioned in chapter 2.4 Methanol, bio methanol is one of the alternatives that is seen as green methanol and a carbon-free alternative and is therefore the price that is to be used in the calculations. According to DNV's tool "AFI" for checking fuel prices the price is found for bio methanol to be a 2754 USD/t_{MGO} in March 2023, as displayed in the figure below and in Figure 22.



Unit
○ USD/mmBTU
● USD/t MGOe
○ USD/t VLSFOe

Fuel: Methanol

Fuel type: Multiple selections

Week 2023-W14

Fuel type, Location	Average week14	Change from week13	Trend

Month 2023-Mar

Fuel type, Location	Average price March	Change from February	Trend
Biomethanol , ARA	2,754	4	▲ +0.14%

Figure 25 – Fuel price of bio methanol in March 2023 (DNV, 2023a)

By doing similar calculations as described for the ammonia case, the cost per ton of bio methanol can be calculated by using the fuel price retrieved and by using the energy density of MDO and methanol in MJ/tons. Note that the term methanol will be used in the calculations:

$$Cost_{Methnaol,t} = \frac{Price_{Methanol}}{Energy\ density_{MGO}} * Energy\ Density_{Methanol}$$

$$Cost_{Methanol,t} = \frac{2754 \frac{\$}{t_{MGO}}}{0{,}0427 \frac{MJ}{t_{MGO}}} * 0{,}0199 \frac{MJ}{t_{Methanol}} = 1283{,}5 \frac{\$}{t_{Methanol}}$$

Further the total cost of fuel for the whole journey can be calculated:

$$Cost_{fuel} = Fuel_{consumed} * Price_{Methanol} = 51{,}26t * 1283{,}5 \frac{\$}{t} = 65792{,}2\ \$$$

As of April 15th, 2023, the 1 USD was equivalent to 10,31 NOK. (Norges bank, 2023a)

Calculating the cost of fuel in NOK:

$$Cost_{fuel,NOK} = Cost_{\$} * Exhange\ rate = 65792{,}2\$ * 10{,}31 \frac{NOK}{\$} = 678317{,}6NOK$$

The total cost of methanol consumed by MS Nordlys on the journey is 678317,6 NOK.

3.4.3 Emissions

From Table 4 the chemical formula for methanol is CH_3OH, assuming a full combustion and using Equation 1 the combustion of methanol would be as such:

$$2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O + energy$$

And with NO_x emissions accounted for, please remark that the equation is not balanced:

$$2CH_3OH + 3O_2 + (N_2) \rightarrow 2CO_2 + 4H_2O + energy + (NO_x)$$

And according to one study, the "Operational Fuel Emission Factor" for methanol is presented to be 522 g/kWh CO_2 and 3,05 g/kWh for NO_x. (Ming & Chen, 2021, p. 5) This makes it possible to calculate the total amount of emissions released from combustion of methanol on the journey from Bergen to Trondheim. Also, assuming that the two engines deliver a power output of 3600 kW for 19,1 hours. Total emissions are therefor:

$$Methanol_{Emissions_{CO_2}} = 522 * 10^{-3} \frac{kg}{kWh} * 137\ 520\ kWh = 71\ 785{,}4\ kg \approx 71{,}79\ ton$$

$$Methanol_{Emissions_{NO_x}} = 3{,}05 * 10^{-3} \frac{kg}{kWh} * 137\ 520\ kWh = 419{,}4\ kg \approx 0{,}42\ ton$$

The total emissions for sailing from Bergen to Trondheim amounts to be 0,42 tons of NO_x and 71,79 tons of CO_2. This is further shown in Table 11 for later reference.

CO_2.	71,79 tons
NO_x	0,42 ton

Table 11 – Total emissions for combustion of Methanol

3.5 Hydrogen – Operational efficiency and economic feasibility

As many vessels do a changeover now to battery driven propulsion systems, larger vessels cannot be retrofitted as such – as the engines are too powerful for just pure electricity from batteries. In cases such as this, the combustion engine can be modified to allow combustion with hydrogen. It is not feasible as of today to have an engine run 100 % on Hydrogen, as there is limitation with the existing bunkering infrastructure and the need for continuous feed of hydrogen fuel supply into the engine itself. Due of 2021 there was from the recent developments expected an engine to enter the market, this engine utilizes hydrogen mixture with natural gas for combustion. Hydrogen is mixed in with contents up to 20 %, this in turn results in 10 % less emissions of CO_2, this test engine used was a four-stroke engine with a single cylinder hydrogen-fired 645 kW power. At the end of the decade, engines that utilize 100 % of hydrogen is expected. (Gathmann, 2023) However according to Bergen Engines there is possibilities to adapt hydrogen into the fuel mixture together with LNG for the B36:45L6A engine with extensive modifications, this with a mixture of up to 60 % hydrogen. (Bergen Engines AS, 2023c) Considering this it is assumed a case that hydrogen can be utilized 100 % using the combustion B36:45L Bergen engines engine as above mentioned with LNG. This is of course imaginary, as there does not exist a commercially option available as of today considering this. However, for comparison the calculations are as follows for hydrogen without the cooling systems needed to keep hydrogen liquid, the values used is retrieved from Table 5:

$$SFOC_{H2} = \frac{Specific\ energy\ consumption}{Gravimetric\ energy\ density} = \frac{7420\ kJ/kWh}{120\ 000\ kJ/kg} = 0{,}0618\ kg/kWh$$

Then the specific fuel consumption in kg each hour will then be:

$$SFOC_{H2,h} = \frac{SFOC_{H2} * Total\ energy}{Sailing\ time} = \frac{0{,}0618 \frac{kg}{kwh} * 68760\ kWh}{19{,}1\ hours} = 222{,}6\ kg/h$$

According to this, the value of specific fuel consumption in kg each hour is 222,6 kg/h without the cooling systems powered up. As of a case such as this, there must be auxiliary power to keep the hydrogen cooled. When looking at the total consumption for the full sailing distance with two engines this is:

$$Total\ F_{consumption} = 2 * 222{,}6\frac{kg}{h} * 19{,}1h = \ 8503{,}32\ kg \approx 8{,}50\ tons$$

The total fuel consumed for the full sailing duration is 8,50 tons – this is rather promising when powering of the cooling systems is not considered – however the gravimetric energy density of liquid hydrogen is drastically changed when also the cooling systems is accounted for. There is a lot of energy which is lost to cool the hydrogen to a liquid state, whereas this is at -253 °C. From Figure 1 the gravimetric energy density is then only 9 MJ/kg, from 120 MJ/kg.

3.5.1 Storage options

Storage options without cooling systems:

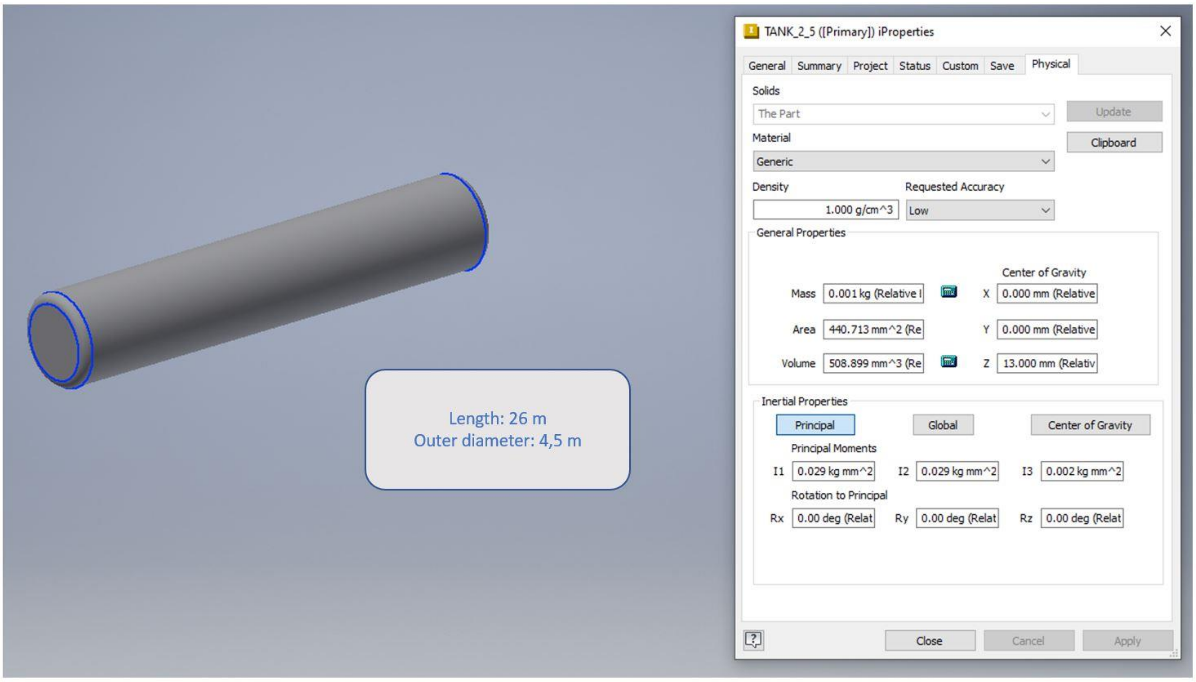
As the fuel needed for the voyage from Bergen to Trondheim was found in calculations above concerning the specific fuel consumption, it can from this also be calculated the minimum storage capacity which is needed for MS Nordlys assuming the energy demand to keep the liquid hydrogen at -253 °C is already accounted for by other power systems. In the following calculations there will be calculated the storage tanks needed to store the hydrogen in a liquid state. The density of hydrogen is from Table 5 and is as previously stated as 71 kg/m^3 in liquid state.

$$Storage_{H2} = \frac{Total\ F_{consumption}}{Density_{H2}} = \frac{8503{,}32\ kg}{71\ kg/m3} \approx 119{,}8\ m^3$$

According to the above calculation MS Nordlys needs to be fitted with tanks with a storage capacity of at least 119,8 m^3 which seems reasonable.

As previously mentioned in section 2.5.1.1 Operational standards, there are several considerations to be made when constructing a facility for use of hydrogen fuel. Safety codes set by IMO that cover storage of liquefied gas onboard ships do also apply for storing hydrogen. And regulations set for associated systems and fuel supply systems, as described for LNG, also apply to hydrogen. However, there are additional considerations that must be taken due to the properties of hydrogen and low storage temperatures. (DNV and partners, 2021, p. 50) Finding volume-efficient ways to store hydrogen is challenging. Hydrogen is usually stored in compressed gas form in pressurized tanks between 350-700 bar, or as cryogenic liquid hydrogen. Since hydrogen molecules are very small, it is a challenge that they can diffuse through many materials, including metals. This is mainly a problem for compressed hydrogen as the molecules are pushed into the storage material. This can cause metal embrittlement and gas leakage, and it shows the importance of correct material selection for storage tanks and the fuel supply system so that safety and integrity are ensured. A challenge with storage tanks for liquid hydrogen at low pressure is that a pressure build-up can occur if the temperature rises. Then the hydrogen will start to evaporate and boil off. It is therefore important that protection against this is installed, such as pressure relief valve arrangements. Due to the very low storage temperatures, the cryogenic tanks will potentially require insulation layers that are two to three times as thick compared to an LNG tank. In any case, the storage and bunkering of hydrogen on ships will require specially designed systems and tanks, and there is so far minimal experience with the use of hydrogen on ships today. (DNV, 2019, p. 20) (ABS, 2021a, pp. 9,17)

Figure 26, a simple design of a hydrogen Type C storage tank is presented. It was designed by using the “Autodesk Inventor” software. Hydrogen storage tank design drawing retrieved from Appendix F. Technical Drawings, Tank Design.



TANK_2_5 ([Primary]) iProperties

Solids: The Part

Material: Generic

Density: 1.000 g/cm^3

Requested Accuracy: Low

General Properties

Mass: 0.001 kg (Relative l

Area: 440.713 mm^2 (Re

Volume: 508.899 mm^3 (Re

Center of Gravity

X: 0.000 mm (Relative

Y: 0.000 mm (Relative

Z: 13.000 mm (Relativ

Inertial Properties

Principal Moments

I1: 0.029 kg mm^2

I2: 0.029 kg mm^2

I3: 0.002 kg mm^2

Rotation to Principal

Rx: 0.00 deg (Relat

Ry: 0.00 deg (Relat

Rz: 0.00 deg (Relat

Figure 26 – Proposal of Hydrogen storage tank of 500m^3 illustrated by Autodesk Inventor software.

The storage tank presented was designed with a capacity of 500 m^3. The figure below displays a proposal drafted in MS Nordlys' GA drawing by using the AutoCAD software, for the placement of hydrogen storage tanks. The proposal shows a storage tank solution that combines the 500 m^3 tank together with two 58 m^3 tanks that were presented in the LNG case in Figure 18. These storage tanks are also suggested located on tank top deck by replacing existing storage space. Modified GA drawing is retrieved from Appendix D. Technical Drawings, Hydrogen.

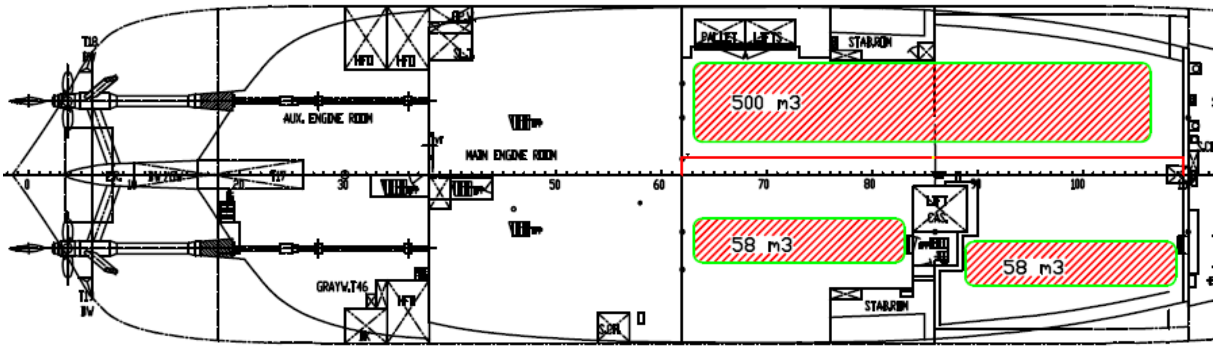


Figure 27 – Potential location for Hydrogen storage tanks illustrated in GA drawing by AutoCAD software.

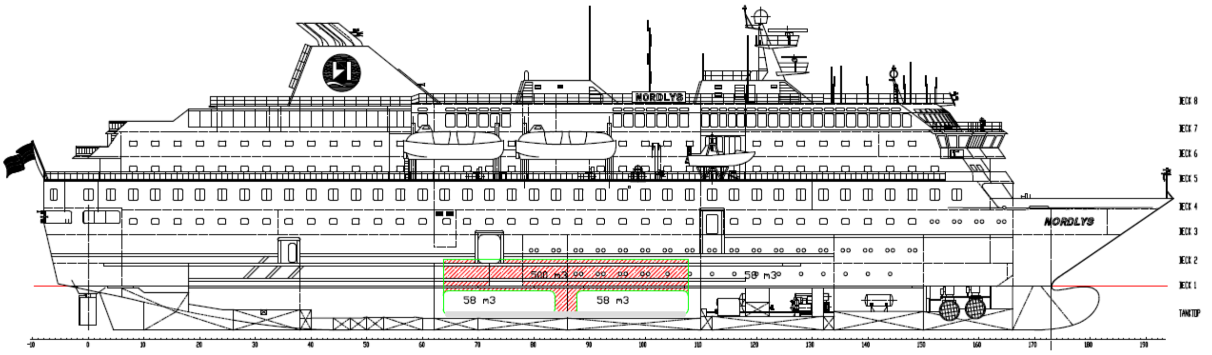


Figure 28 – Potential location of hydrogen storage tanks seen from the side, illustrated in GA drawing by AutoCAD software.

This potential storage tank solution will give a total storage capacity for hydrogen of:

$$Total\ storage\ capacity = 500m^3 + 2 * 58m^3 = 616m^3$$

The previous calculations done considering the minimum storage capacity of hydrogen that is required for the journey from Bergen to Trondheim was calculated to be 119,8m^3, which makes this proposal for storage capacity way more than sufficient. Keeping in mind the additional storage and fuel handling systems required, it would probably be better to downsize to four storage tanks of 58m^3, as the 500m^3 takes up a lot of space and would require a lot of reconstruction of the ship's structure since it is designed through a bulkhead and raises above two ship decks. In addition, as already discussed hydrogen requires enormous amounts of energy to be kept at liquid state, which would be a challenge with the 500m^3 tank. By rather downsize to four 58m^3 tanks the total storage capacity would be decreased to be similar to the proposal presented in the ammonia case of 232m^3.

3.5.2 Economic feasibility

Knowing the fuel consumption that is required to achieve the sailing from Bergen to Trondheim is 8503,32 kg, the fuel cost can be calculated. As carbon free solutions is the focus, the price of green hydrogen will be used for the calculations. There were certain difficulties with retrieving the current price of green hydrogen at a specific date which led to data from a recently completed study being used. Reuters describes a recent study done by "Aurora Energy" which points to a price of green hydrogen between 6-8 euros per kilogram, as of January 2023. (Reuters, 2023) For the calculations, the highest price of 8 euros is considered. The total cost of fuel for the whole journey can be calculated as follows:

$$Cost_{fuel} = Fuel_{consumed} * Price_{Hydrogen} = 8503{,}32\ kg * 8\frac{€}{kg} = 68026{,}6\ €$$

As of April 15th, 2023, the 1 EUR was equivalent to 11,60 NOK. (Norges Bank, 2023b) Calculating the cost of fuel in NOK:

$$Cost_{fuel,NOK} = Cost_{\$} * Exhange\ rate = 68026{,}6\ € * 11{,}6\frac{NOK}{€} = 789108{,}6NOK$$

The total cost of green hydrogen consumed by MS Nordlys on the journey from Bergen to Trondheim is 789108,6 NOK.

3.5.3 Emissions

In essence hydrogen when combusted only have the product of water under stochiometric conditions. It has the clear advantage of not producing any emissions as CO, CO_2, PM (particulate matter) and unburned HC (hydrocarbons) unlike other fuel types when combusted. This implies that for an ICE (internal combustion engine) zero-emissions could be realized. However, for ICE which often use H_2-air mixtures, this will in turn give NO_x

emissions. And since H_2 is a gas, it does not inhibit the properties of lubricating film effects generated by liquid fossil fuels at the intake pipe into the combustion chamber. So previous research has also found that with increasing compression ratio this will in turn generate more NO_x emissions. (Xu, et al., 2018, pp. 21617-21618) To generalize this into a combustion equation for H_2 with oxygen, it will look like this:

$$2H_2 + O_2 \rightarrow 2H_2O + energy$$

However, as previously mentioned internal combustion engines conventionally use air, and one of the products is the formation of NO_x – NO_x is previously described in emissions section for ammonia. And when it comes to burning hydrogen, this generates a very high flame temperature and this in turn splits the normally stable molecules, the following reactions would occur for nitrogen and oxygen (Lewis, 2021, p. 202):

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

These reactions are known as the "Zel-dovich mechanism" and create thermal NO. This mechanism comes into effect with high flame temperatures around 1300°C and they occur in general for all combustions of fuel and air. The issue with thermal NO is that it can in the atmosphere rapidly form into NO_2 which is also referred to as one of the components of the general term "NO_x". NO_2 can in turn contribute to pollution for photochemical ozone, and further can make fine PM. This is why it is globally regulated as an air pollutant – it is also harmful to health. (Lewis, 2021, p. 202) Taking this into account and assuming that the hydrogen is burned with 2 % excess air, this would leave products un-reacted as reactants (oxygen and nitrogen) and would further under high flame temperature split into the reactions as described in the "Zel-dovich mechanism". So, for a hydrogen combustion, we first assume full combustion using only oxygen:

$$2H_2 + O_2 \rightarrow 2H_2O + energy$$

And as previously when we calculated emissions for ammonia, we used air as ratio of 1 O_2 and 3,76 N_2 this is assumed also for this case with excess air of 2 %:

$$2H_2 + 1{,}02(O_2 + 3{,}76\ N_2) \rightarrow 2H_2O + energy + 0{,}02\ O_2 + 1{,}02 * 3{,}76N_2$$

This reaction we need to convert into mass of burned hydrogen so we can study how much oxygen and nitrogen is in excess for the products. Using Equation 2 we convert from molecules into mass, the weight of nitrogen, hydrogen and oxygen respectively 14,01, 1,008 and 16,00 g/mol (Pedersen, Gustavsen, Kaasa, & Olsen, 2013, p. 288), then the chemical reaction will be as such:

$$\begin{aligned} &4{,}032\ kg\ H_2 + 32{,}64\ kg\ O_2 + 107{,}5\ kg\ N_2 \\ &\qquad \rightarrow 36\ kg\ H_2O + energy + 0{,}64\ kg\ \ O_2 + 107{,}5\ kg\ N_2 \end{aligned}$$

And in kg of combusted H₂ dividing the mass of hydrogen through the equation:

$$H_2 + 8{,}1\ kg\ O_2 + 26{,}7\ kg\ N_2 \rightarrow 8{,}93\ kg\ H_2O + energy + 0{,}159\ kg\ \ O_2 + 26{,}7\ kg\ N_2$$

And then if we look at “Zel-dovich mechanism” the first reaction step and is also governed by the first reaction for the others to occur (Lewis, 2021, p. 202) we assume for simplicity for the calculations that the reaction stops there at the first step which is:

$$N_2 + O \rightarrow NO + N$$

The ratio of N_2 to ‘O’ is 1:1. From the above reaction with excess air, we see that the constraint is the product of pure oxygen – as the nitrogen in that equation is un-reacted. As the total hydrogen combusted for a journey for MS Nordlys from Bergen to Trondheim was previously calculated to be 8503,32 kg, we can use this as basis for finding out the amount of excess oxygen and nitrogen:

$$Ex.gas_{O_2} = 8503{,}32\ kg\ H_2 * 0{,}158 \frac{kg\ O_2}{kg\ H_2} = 1\ 349{,}7\ kg$$

$$Ex.gas_{N_2} = 8503{,}32\ kg\ H_2 * 26{,}65 \frac{kg\ N_2}{kg\ H_2} = 226\ 633{,}52\ kg$$

This means that the reaction for formation nitrogen monoxide can be expressed as following in terms of mass per kg of N_2:

$$1\ kg\ N_2 + 0{,}57\ kg\ O \rightarrow 1{,}07\ kg\ NO + 0{,}5\ kg\ N$$

We then further assume that all the oxygen molecules (O_2) in excess after the combustion of hydrogen is split into oxygen atoms as an impact from the high flame temperature. In total there is 1349,7 kg of oxygen atoms as the mass is unchanged, and this equals the same amount of kg N_2 available. This means that the weight amount of nitrogen monoxide and Nitrogen atom in the product of the reaction is:

$$Hydrogen_{Emissions_{NO}} = 1349{,}7\ kg\ N_2 * 1{,}07 \frac{kg\ NO}{kg\ N_2} = 1445{,}6\ kg\ \approx 1{,}45\ ton$$

$$Hydrogen_{Emissions_{N}} = 13\ 497\ kg\ N_2 * 0{,}5 \frac{kg\ N}{kg\ N_2} = 674{,}9\ kg\ \approx 0{,}67\ ton$$

This produces an amount of 1,45 ton of NO and 0,67 ton of nitrogen in atomic state. The remaining nitrogen in atomic state can further react accordingly to "Zel-dovich mechanism" reaction two and three accordingly if the conditions is right. But is not our focus, as this would make the emissions study more complex. As previously mentioned, the nitrogen monoxide has the potential to react rapidly into NO_2. The results for emissions when combusting hydrogen assuming excess air of 2% is shown in Table 12.

NO (Potential to further NO_x formation)	1,45 ton
Pure N, potential further reactivity according to "Zel-dovich mechanism"	0,67 ton

Table 12 – Emissions calculated for combustion of hydrogen

These numbers are of course speculative and assumed that all the oxygen which is left (excess air of 2%) is split and formed into NO_X – realistically these values may not represent the actual chemical reaction occurring in the internal combustion engine.

This could also be seen in relation to combining hydrogen together with LNG, as according to Bergen Engines there is possibilities to adapt hydrogen into the fuel mixture together with LNG for the B36:45L6A engine with extensive modifications, this with a mixture of up to 60 % hydrogen. (Bergen Engines AS, 2023c) Using the above calculations together with the ones for LNG this can be combined to look at the total emissions from this but will in this regard not be studied further.

3.6 Molten salt reactors – Operational efficiency and economic feasibility

In Figure 30 a thorium molten salt reactor is shown and was introduced by Emblemsvåg in one conceptual study he made assessing research that has been conducted on TMSR (Thorium Molten salt reactor), even though there cannot be made accurate calculations back then, it was considered as a technology which was at conceptual design at an early-stage readiness level. (Emblemsvåg, 2021, p. 63) Emblemsvåg looked at one reactor design which was proposed by research Kazuo Furukawa did. (Furukawa, Numata, Kato, & Mitachi, 2005, p. 554) And by changing the primary circuit to accommodate a TMSR while keeping a secondary circuit, as seen in Figure 29.

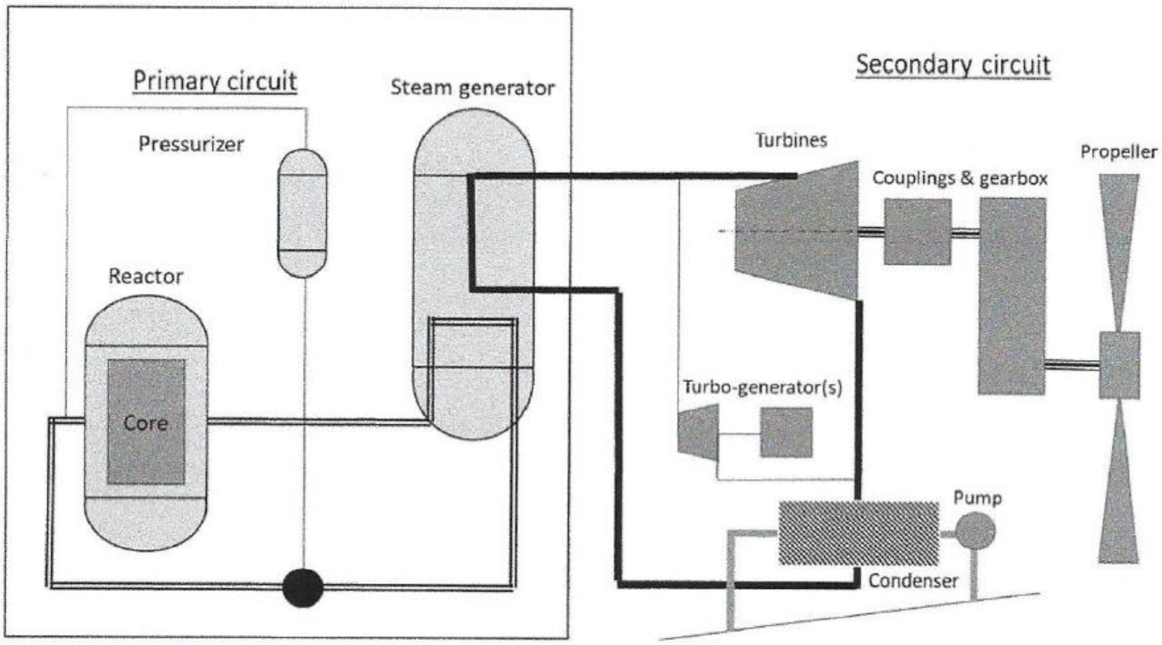


Figure 29 – Primary- and secondary circuit for a marine mechanically driven propulsion plant (Emblemsvåg, 2021, p. 62)

The design shown in Figure 30 consist of a concrete (could also be lead) shield around the reactor for final protection, a pump to transport the molten salt, a heat-exchanger, a reactor vessel containing graphite reflector and graphite moderator, and with the core in the middle. This molten salt is heated and transports over to be heat-exchanged with steam. Whereas the secondary system has turbines for power output to couplings and gearbox, which further runs the propeller. This reactor can give a power output of 160 MWe which correspond to 350 thermal MW, this is of course too big to accommodate the need a marine vessel needs for sailing along the Norwegian coast. Emblemsvåg used linear interpolation to downscale reactor characteristics. It was found that miniFUJI (another TMSR) is suitable for marine applications, which in turn has a power output of 7 MWe. This reactor-vessel would have the dimensions of 1,8 m diameter and is 2,1 m high and weighs about 1650 ton including equipment needed for power conversion. The design life span is approximately 30 years for both the nuclear reactor and the steam-turbine configuration. However, steam turbines only have a thermal efficiency of perhaps 50 %. In his article Emblemsvåg scales the parameters up to 15 MWe, which means the shielding needed would be approximately 1150 tons of concrete with a volume of 450 m^3. (Emblemsvåg, 2021, pp. 63-65) We assume that the dimensions, we will assume that the concrete shielding volume and mass can be used when calculating the storage capacity needed when implementing it for the MS Nordlys.

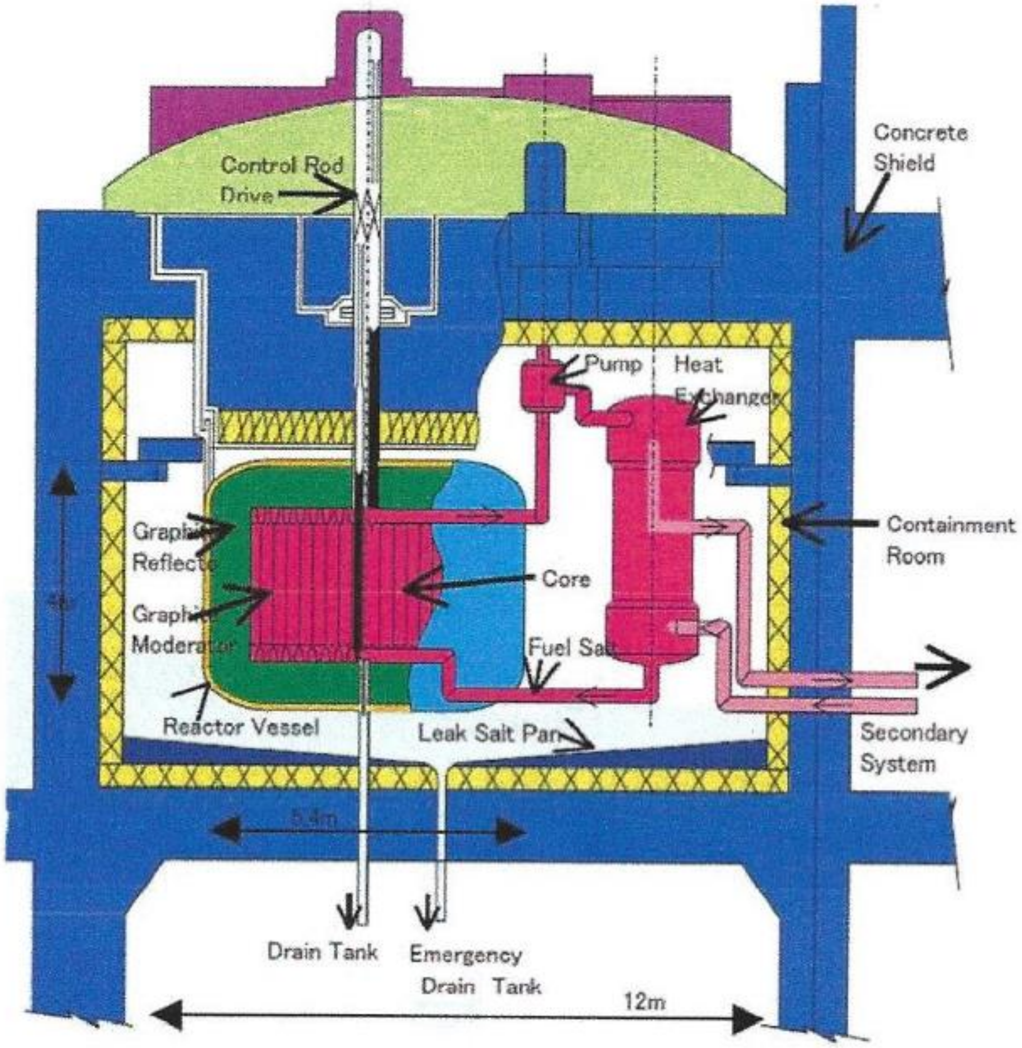


Figure 30 – Molten salt reactor (Emblemsvåg, 2021)

For a conceptual early stage study, it is assumed that the reactor type in Figure 30 can be fitted with a secondary circuit with steam turbines (Emblemsvåg, 2021, pp. 62-63), this is seen in Figure 31 a configuration with molten salt reactor together with turbine for propulsion is shown. This is typically how the configuration would be if it was installed on board a vessel. It is also worth noting that in case of an emergency, a freeze-plug is shown for the emergency drain tank – which will cut the power and stop the reactor – making this a very safe option as this can be stopped at any given time. The benefit of this reactor type with thorium is that there is no event called “fuel melt down[13]”. It does not have any large power surges as the excess reactivity is small – meaning it does not need xenon over-ride. The fission products such as KR, Xe, etc. is constantly removed – so the radioactive materials cannot be released in case of an accident or emergency. The reactor uses molten fluorides, they don’t cause any chemical reactions with air or water as they are ionic – and these are stable, so they do not irradiate on the reactor vessel. The reactor is also compatible with other fuels such as plutonoim, TRU (Trans-uranium) and enriched uranium. The fuel types also do not need to be fabricated, which is a great advantage. As there is a very high temperature on the fuel salt this heat can be used for other high heat-based applications (hydrogen production, etc.) – allowing a high conversion efficiency. If one accounts thorium production for energy 900 TWe years correspond to approximately 2-3 million tons of thorium needed. (Emblemsvåg, 2022, pp. 31-32) Advisable for fuel refuelling, and due to higher levels of fuels enrichment: it is for merchant ships unlike nuclear submarines advised that refuelling should occur on a 5–7-year cycle. This of course is dependant how active the vessel is if it is sailing non-stop or have longer stops over time. On the other hand, even if the refuelling cycle is spanning over several years, the refuelling should take approximately 30 days. (Emblemsvåg, 2021, p. 67)

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[13] Fuel melt-down means that inside the reactor core the fuel melts into molten, and further ruptures the vessel. When this is ruptured the contaminants will overflow into the premises surrounding the reactor. (Marder, 2011)

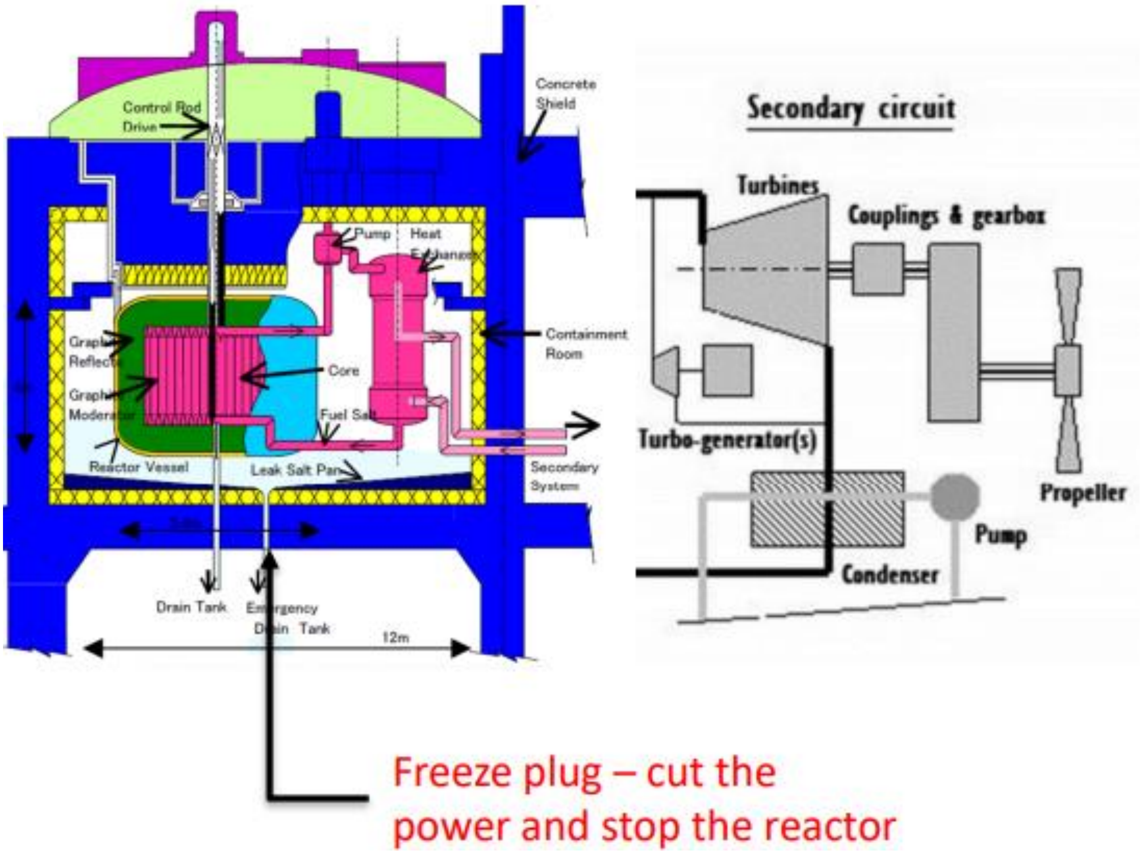

Figure 31 – Configuration with molten salt reactor (MSR) and turbine for propulsion (Emblemsvåg, 2023b)

To calculate how much thorium is needed for reactor vessel that is thought of to be installed on the vessel “MS Nordlys”, the thorium energy amount as specified above for 900 TWe years is assumed can be used. We assume that MS Nordlys sails non-stop for 5 years to calculate the power consumption needed, we further assumed that the reactor is giving an output at 7,5 MW power output on the propellers. This power output means that the reactor itself is giving off a power of 15 MWthermal – the power output on the propeller is at 7,5 MW due to thermal efficiency assumed to be 50 % including gear-box transmissions and the other equipment. Emblemsvåg scales the reactor to 15 MW for the given output (Emblemsvåg, 2021, pp. 65-66), we decide to keep these values for our calculations for “MS Nordlys”.

<u>Calculation of Thorium fuel needed onboard the vessel, 5-year cycle:</u>

So, the total energy generated for a 5-year cycle refuelling cycle, assuming 15 MWt power output from the reactor vessel is:

$$Energy_{Nuclear} = hours_{year} * years * power_{reactor}$$

$$Energy_{Nuclear} = 8760\ h * 5\ y * 15\ 000\ kW = 657\ 000\ 000\ kWh$$

So, the full energy output from the thorium reactor for a 5-year period assuming full operation yields a total thermal energy of 657 000000 kWh, or in conversion to 0,657 TWh.

Now the thorium needs to be converted to KWh/kg according to the potential of 900 TWyear (A year spans 8760 hours multiplied with 900 TWy) for 2 million tons of Thorium:

$$Thorium_{energy} = \frac{Potential\ energy\ yield}{amount\ of\ thorium}$$

$$Thorium_{energy} = \frac{8{,}760 * 900 * 10^9\ KWh}{2 * 10^9\ kg} = 3\ 942\ 000\ KWh/kg$$

As we know the total energy demand for a 5-year cycle assuming full power output from the nuclear reactor, we can calculate the amount of Thorium needed for “MS Nordlys”:

$$Thorium_{MS_{Nordlys}} = \frac{Energy_{total_{5y}}}{Thorium_{energy}}$$

$$Thorium_{MS_{Nordlys}} = \frac{657\ 000\ 000\ KWh}{3\ 942\ 000\ KWh/kg} = 166{,}67\ kg$$

For a 5-year cycle assuming full operation of the ship, the amount of thorium fuel is 166,67 kg. If the above calculations were assumed with 3 million tons of Thorium, the total amount for a 5-year cycle would be 250 kg.

For the sake of comparison, we can also calculate the thorium needed for the voyage spanning 19,1 hours from Bergen to Trondheim, this is also for the later emissions calculations:

$$Thorium_{MS_{Nordlys_{19,1h}}} = \frac{166{,}67 * 10^3\ g}{(24h * 365\ d * 5\ y)} * 19{,}1\ h = 3{,}805\ \frac{g}{h} * 19{,}1\ h = 72{,}68\ gram$$

As shown by the previous calculation it can be seen that nuclear power is a totally different ‘ballgame’ when compared to chemical energy. For instance, the fuel consumed for the same journey was for MDO found to be 23,8 tons, or stated in the same units as thorium energy, 23 800 000 grams!

3.6.1 Storage options

As previously mentioned for TMSR it is assumed that the storage capacity needed to install the reactor on board with also the secondary circuit for steam-power generation, the following capacity can be calculated for weight:

$$TMSR_w = Thorium + TMSR_{Wcircuit1-2} + Shielding_{Wconcrete}$$

$$TMSR_w = 0{,}250\ ton + 1650\ ton + 1150\ ton = 2\ 800{,}25\ ton$$

The needed weight to accommodate storage capacity for TMSR is 2 800,25 ton. It is further assumed that the weight of the salt inside the reactor is accounted for in the variable for primary and secondary circuits.

And as for the volume needed:

$$TMSR_V = TMSR_{reactorvessel} + Shielding_{concrete}$$

$$TMSR_V = (1{,}8\ m * 2{,}1\ m) + 450\ m^3 = 453{,}9\ m^3$$

The volume for the reactor vessel with shielding is calculated to be 453,9 m^3 Although the volume needed for the secondary circuit is unknown – this facilitate the power generation by use of steam turbines, and maybe there must be storage tanks for the steam production – and not just the heat-exchanger together with the condenser. In Figure 32 the potential location for TMSR is shown. The red highlighted area is the TMSR shielding required, and the green highlighted area is the reactor vessel itself. It can be seen, as also estimated in the storage calculations, that the reactor vessel is by far smaller than the reactor shielding required. The illustration is by use of GA drawings from MS Nordlys and was produced by AutoCAD software. Modified GA drawings is retrieved from Appendix F. Technical Drawings, Tank Design

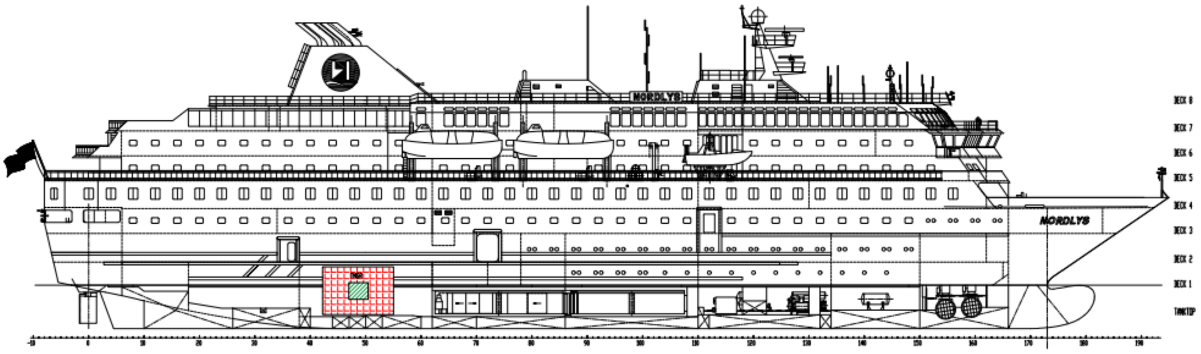

Figure 32 – Potential location for TMSR. Red area is reactor shielding, whereas green area is reactor vessel. illustrated in GA drawing by AutoCAD software. Retrieved from Appendix E. Technical Drawings, TMSR.

It can also be seen that the total volume required impacts that the TMSR needs to be allocated spanning over two decks. This is further illustrated in Figure 33, and specifically those decks are "tanktop" and "Deck 1".

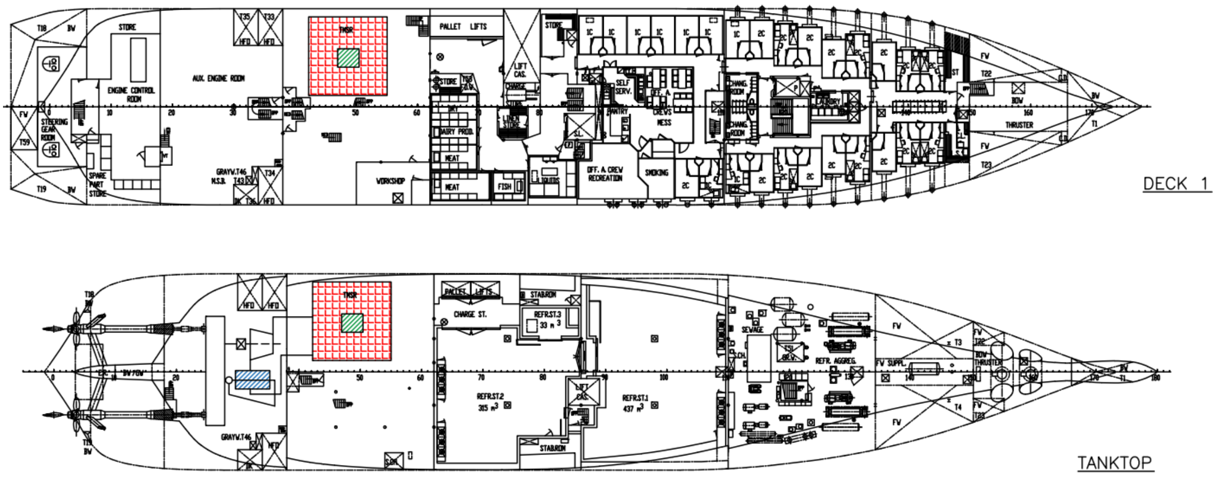

Figure 33 – Potential location for TMSR. Red area is reactor shielding, whereas green area is reactor vessel. illustrated in GA drawing by AutoCAD software. Retrieved from Appendix E. Technical Drawings, TMSR.

In Figure 34 the design concept of TMSR technology implemented on MS Nordlys can be seen in more detail. This shows the reactor vessel with reactor shielding and accompanied with a secondary circuit. The secondary circuit shows a turbine, condenser, couplings & gearbox for power transmission to the propeller. The condensed steam is taken back to the primary circuit (reactor vessel) by a pump (not shown).

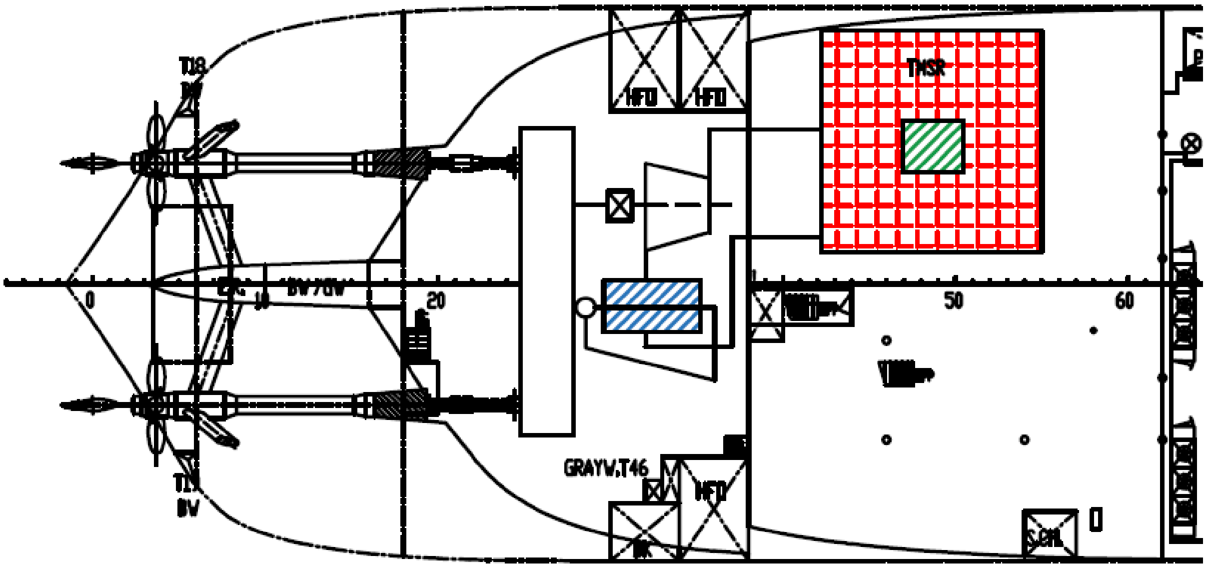

Figure 34 – Design concept of TMSR technology implemented on MS Nordlys. Accompanied with secondary circuit for outtake of power by steam to turbine, and power to propeller. Retrieved from Appendix E. Technical Drawings, TMSR.

As previously mentioned in section 2.7.2 Availability, infrastructure and also in the 3.6.2 Economic feasibility (next section) TMSR is still at an early stage, and the technology must further be developed before this is commercially available for the maritime sector.

3.6.2 Economic feasibility

There has previously been conducted comprehensive estimations for what the cost is for the reactor, this was done by researchers at ORNL[14], this was later in 2002 calculated to cost of electricity for when it comes to TMSR, pressurized water reactor (PWR) and coal (graphite). These calculations where however based on standards that was dating back to 1978. And back in 1978 the safety regulations were different, along with the environmental standard and licensing. These numbers from 2002 is over 20 years old, so these were updated to include inflation, and there is also reduced downtime as of now when it comes to online fuelling that is accounted for. The updated values (Emblemsvåg, 2021, pp. 59-60) found is shown in Figure 35. It is important to remark that although many concepts of molten salt reactors have been developed, these numbers illustrate it from an early-stage readiness level as the technical solution is not commercially available yet. The technical level readiness is indicative, and should not be taken as a fact (Emblemsvåg, 2021, pp. 59-60, 63, 70)

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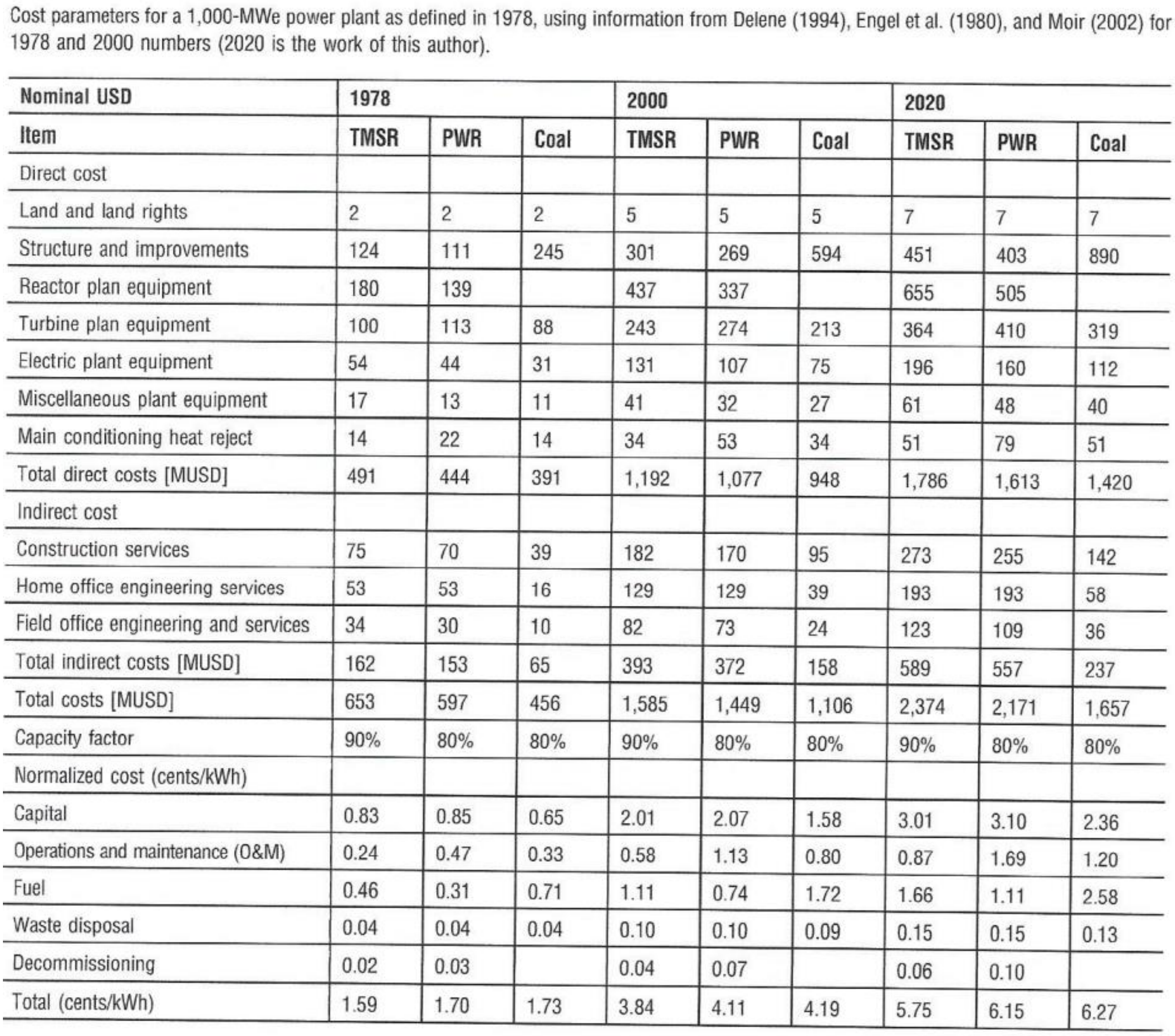
[14] ORNL – Oak Ridge National Laboratory



Cost parameters for a 1,000-MWe power plant as defined in 1978, using information from Delene (1994), Engel et al. (1980), and Moir (2002) for 1978 and 2000 numbers (2020 is the work of this author).

Nominal USD	1978			2000			2020		
Item	TMSR	PWR	Coal	TMSR	PWR	Coal	TMSR	PWR	Coal
Direct cost									
Land and land rights	2	2	2	5	5	5	7	7	7
Structure and improvements	124	111	245	301	269	594	451	403	890
Reactor plan equipment	180	139		437	337		655	505	
Turbine plan equipment	100	113	88	243	274	213	364	410	319
Electric plant equipment	54	44	31	131	107	75	196	160	112
Miscellaneous plant equipment	17	13	11	41	32	27	61	48	40
Main conditioning heat reject	14	22	14	34	53	34	51	79	51
Total direct costs [MUSD]	491	444	391	1,192	1,077	948	1,786	1,613	1,420
Indirect cost									
Construction services	75	70	39	182	170	95	273	255	142
Home office engineering services	53	53	16	129	129	39	193	193	58
Field office engineering and services	34	30	10	82	73	24	123	109	36
Total indirect costs [MUSD]	162	153	65	393	372	158	589	557	237
Total costs [MUSD]	653	597	456	1,585	1,449	1,106	2,374	2,171	1,657
Capacity factor	90%	80%	80%	90%	80%	80%	90%	80%	80%
Normalized cost (cents/kWh)									
Capital	0.83	0.85	0.65	2.01	2.07	1.58	3.01	3.10	2.36
Operations and maintenance (O&M)	0.24	0.47	0.33	0.58	1.13	0.80	0.87	1.69	1.20
Fuel	0.46	0.31	0.71	1.11	0.74	1.72	1.66	1.11	2.58
Waste disposal	0.04	0.04	0.04	0.10	0.10	0.09	0.15	0.15	0.13
Decommissioning	0.02	0.03		0.04	0.07		0.06	0.10	
Total (cents/kWh)	1.59	1.70	1.73	3.84	4.11	4.19	5.75	6.15	6.27

Figure 35 – Estimated cost parameters for a 1000 MWe power plant, work done by (Emblemsvåg, 2021, p. 60)

As the values in Figure 35 is for a 1000 MWe power plant, Emblemsvåg scales this down to fit a 15 MWe reactor, the estimated cost is indicated to be 25,6 million USD each year. This is by looking at a 30-year perspective. This may be insufficient for a shipowner looking at short-term view, as the cash flow will not be favourable the first 5-10 years of operation – however for 20 years or more horizon perspective for the ship owner the decision should be favourable in comparison to HFO. This is also as it is indicated that 81 % of the reactor costs is fuel costs or capital costs is procured initially. (Emblemsvåg, 2021, pp. 67-68, 70)

For simplifying the economic feasibility calculations, we do not consider any uncertainties. If the thorium reactor is to be run for 30 years non-stop, the estimated costs would be, and using the currency conversion factor of 1 USD amounts to 10,31 NOK, retrieved 15 April 2023 (Norges bank, 2023a):

$$Cost_{TMSR,30y} = 25{,}6 \frac{MUSD}{y} * 10{,}31\ NOK * 30\ y = 7\ 918{,}08\ MNOK$$

Assuming that the thorium reactor is in operation for all these hours (neglecting fuelling every 5 years, which is estimated to be 30 days of non-operation (Emblemsvåg, 2021, p. 67)) we re-calculate this into NOK each hour:

$$Cost_{TMSR,hour} = \left(\frac{7918{,}08 * 10^6\ NOK}{30\ y * 24\ h * 365\ days}\right) = 30\ 129{,}68\ NOK/h$$

For the journey from Bergen to Trondheim, the cost with TMSR technology (including full facility) is:

$$Cost_{TMSR,t} = 30\ 129{,}68 \frac{NOK}{h} * 19{,}1\ h = 575\ 476{,}9\ NOK$$

The cost for having a TMSR onboard to utilize power from Bergen to Trondheim is 575 477 NOK, however as mentioned above this assumes that the MS Nordlys is in operation for all the 30 years, so the costs is divided over a longer time period.

3.6.3 Emissions

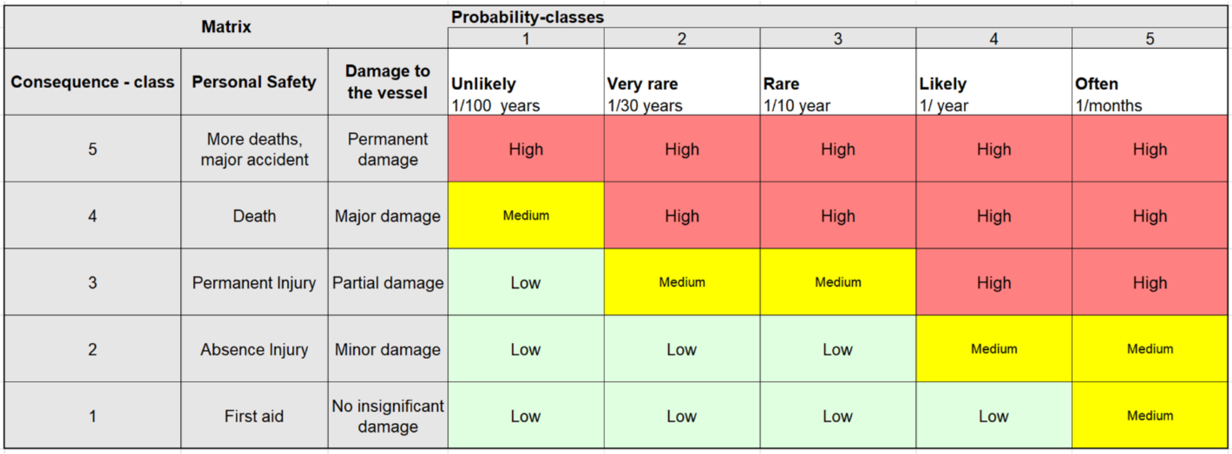
As for when it comes to emissions from TMSR there is zero-emissions from this technology, as previously mentioned with the newly released concept of THOR by Ulstein Group. This ship aims to provide zero-emission based shipping operations in the Arctic. It could also provide electric power to electrically propulsion vessels in this area. (Emblemsvåg, 2022, p. 32) The THOR concept is shown in Figure 36.

Figure 36 – From Ulstein Group, the THOR concept. (ULSTEIN, 2022)

This ship aims to provide zero-emission based shipping operations in the Arctic. It could also provide electric power to electrically propulsion vessels in this area. (Emblemsvåg, 2022, p. 32)

4. Risks associated with alternative fuels

In this chapter the risks associated with the alternative fuels as previously discussed is presented. The defined risks as previously mentioned in the corresponding sections and further investigated risks will first be presented in a list. When the applicable risks have been identified, we will use a risk matrix, see Figure 37, to classify the potential of associated risk and the probability. The risks are then classified and presented in a risk analysis for the specific alternative fuel type.



Matrix			**Probability-classes**				
			1	2	3	4	5
Consequence - class	**Personal Safety**	**Damage to the vessel**	**Unlikely** 1/100 years	**Very rare** 1/30 years	**Rare** 1/10 year	**Likely** 1/ year	**Often** 1/months
5	More deaths, major accident	Permanent damage	High	High	High	High	High
4	Death	Major damage	Medium	High	High	High	High
3	Permanent Injury	Partial damage	Low	Medium	Medium	High	High
2	Absence Injury	Minor damage	Low	Low	Low	Medium	Medium
1	First aid	No insignificant damage	Low	Low	Low	Low	Medium

Figure 37 – Risk matrix for classification of risks

Generally, for the risks they are based on the hazards as previously mentioned in the technical description and is further used as a basis to assume potential scenarios that can occur for the alternative fuels. The potential scenarios are the authors own perception of what may occur, although the main hazards are referenced in the technical description for the specific alternative fuel investigated. The risks are considered for all ships less than 150-meter length that travels along the Norwegian coast.

4.1 Base Case: Diesel as a marine fuel – Identified risks and analysis.

The following hazards are identified for marine diesel oil (From Table 1):

1. Fire
2. Skin irritation
3. Aspiration hazard
4. Toxic to aquatic life with long lasting effect.

These hazards are further used as basis in the next page for the risk analysis concerning MDO.

MS Nordlys – MDO as fuel					RISK				
					SAFETY EVALUATION				
Activity	Hazards / unwanted happenings	Cause	Partial Cause	Comments	C	Comments: Consequences (C)	P	Comments: Probability (P)	RISK
Leakage of MDO to unprotected hot surface (ignition)	**Fire**	Fractured fuel-supply pipe or fracture in fuel equipment, due to material fatigue fracture	Poor engine insulation or in general insulation for hot surfaces	Due to fatigue fracture in the fuel supply pipe, the MDO is leaked onto a hot engine surface which is not insulated properly. This in turn cause the MDO to ignite, and an open fire occurs	5	This accident happened on MS Nordlys leading to two fatalities	2	On 11.09.2011 this accident occurred on MS Nordlys, therefor a probability of 1/30 years is chosen.	High
Fire onboard the vessel in near vicinity to fuel-equipment (gaskets, O-rings, fuel pump, general tanks with MDO)	**General fire**	Fire generated from either faulty equipment or lack of awareness	Fire in for instance engine room, or fire spread from other compartments to close vicinity of MDO	A general fire onboard the vessel occurs and is spread or appears in close vicinity to equipment containing MDO (Engine, fuel tanks, fuel pipes, etc.)	5	Set to 5 due to the accident which occurred at MS Nordlys 11.09.2011	2	Same as above	High
Contact with MDO	**Skin irritation**	Open exposure to liquid MDO by spillage	Not using appropriate personal protective equipment (PPE)	When handling MDO one should wear PPE, leakage of MDO is common	1	First aid is required if one obtains skin irritation when in contact with MDO	4	Considered to occur once a year	Low
Spillage or evaporated MDO in near vicinity of crew.	**Aspiration hazard**	Spillage/leakage of MDO – MDO is evaporated and due to high vapour density, it accumulates near ground in vicinity to crew	Bad quality or fracture of bunkering hose, leakage from fuel supply pipe (un-ignited), material fracture of fuel tanks, etc.	MDO is accumulated by high vapor density and the crew is exposed by aspiration	1	First aid is required if short exposure – can cause dizziness and drowsiness (unless exposed for a very long time or with high amounts of MDO vapour in short time)	4	Likely as exposure to MDO spillage is considered common for short periods	Low
Spillage of MDO to open sea	**Toxic to aquatic life with long lasting effect**	Collision with another vessel or run aground	Poor tank allocation (in ship hull structure), navigational errors/poor awareness.	Due to the poor allocation of the fuel tanks near ship hull these are ruptured upon collision or when run aground causing spillage	3	Fatal for aquatic life (also sea birds, marine environment, etc.) Classified as permanent injury due to long lasting effect	3	Chosen to be 3 as there is a lot of marine trafficking along the Norwegian coastline and many reefs in the sea	Medium

4.2 Liquified Natural Gas - Identified risks and analysis

The following hazards are identified for LNG (From Table 2):

1. **Material embrittlement (exposed to materials not designed to withstand)**
2. **Freeze burn**
3. Hot vapour release from engines
4. Toxic (Release of H_2S gas or ammonia for cryogenic cooling)
5. **Asphyxiation (NO, CO, CO_2, SO_2 in closed compartments)**
6. Pool fire (accidental spill of LNG)
7. **Jet fire (pressurized gas release and ignite)**
8. **Flash fire (Open area, i.e methane slip through exhaust)**
9. **Vapor cloud explosion (Within flammability range in closed compartment)**

The hazards highlighted in “**bold**” are chosen as main hazards concerning specifically LNG.

These hazards are further used as basis in the next page for the risk analysis concerning LNG.

MS Nordlys – LNG as fuel					RISK				
					SAFETY EVALUATION				
Activity	**Hazards / unwanted happenings**	**Cause**	**Partial Cause**	**Comments**	**C**	Comments: **Consequences (C)**	**P**	Comments: **Probability (P)**	**RISK**
Bunkering LNG	**Material embrittlement**	Damage to ship hull by material embrittlement due to leakage of LNG when bunkering, could also be fuel pipe and/or auxiliary equipment.	Lack of awareness when installing hose to fuel pipe. Not aligned properly or connected properly. Hose loosens	Bunkering hose comes loose, LNG leaks onto ship structure and cause damage either by external force interacted on material fatigued surface or the mechanical property of structure is weakened.	3	Partial damage to the vessel, the damaged/fatigued structure needs to be repaired	3	If we consider all ships use LNG, then this would potentially occur every 10 years	Medium
Bunkering LNG	**Freeze burn**	LNG is spilled onto personnel operating the bunkering	Lack of awareness, and lack of appropriate PPE required for bunkering	Bunkering hose comes loose, LNG leaks onto crew and cause freeze burn	3	Permanent injury to personnel	2	Very rare, bunkering with LNG is strictly regulated	Medium
Leakage of exhaust gas containing NO, CO, CO2, SO2	**Asphyxiation**	Fractured gaskets in exhaust pipe leads to high concentration displacing oxygen in engine room (most likely)	Poor maintenance, gas detectors not working	The exhaust gas is leaked onto nearby surroundings by damaged gaskets, crew is not aware and get asphyxiation	2	Injury short lasting assuming that crew is evacuated (In some cases first aid is applicable)	4	Is likely to occur, if for instance the flange is misaligned or wrongly torqued	Medium
Crane/lifting operations or external operations	**Jet fire**	Mechanical damage to fuel supply pipe i.e., crane operations which cause a collision near ignition source	Lack of awareness for the operations and nearby fuel supply pipe	External force impacts fuel supply pipe and fracture causing a high jet flux fire	5	Potential major accident, as the fire can spread and can cause fatalities	1	Very unlikely, the equipment is designed according to a strict regulation, safety barriers implemented	High
Operation of LNG engines, exhaust gas system	**Flash fire**	Methane-slip by exhaust system and is ignited	Ignition source near exhaust pipe (i.e., lightning, exhaust temperature etc.)	Unburned methane gas slips through the exhaust system and is ignited	2	Absence injury for humans close to exhaust system, but may cause damage to exhaust system which may require repair	3	Considered very rare, design of exhaust system for LNG is strictly regulated	Low
Operation of LNG engines, in general	**Vapor cloud explosion**	LNG is leaked in engine room from malfunctioned equipment, and is exploded from the accumulated vapor cloud	Ignition source comes in contact with vapor cloud	Leaked vapor is accumulated from malfunctioned equipment, and the cloud is exploded by ignition source	4	Vessel is (major) damaged and require repair, possible fatality	1	Unlikely assuming fully operational gas detection system which is strictly regulated	Medium

4.3 Ammonia – Identified risks and analysis

The following hazards are identified for ammonia (From Table 3):

1. Highly toxic
2. Asphyxiation
3. Explosive
4. Flammable
5. Highly corrosive

These hazards are further used as basis in the next page for the risk analysis concerning ammonia.

It is important to remark, as previously mentioned, that for ammonia propulsion (Internal combustion engines) it is not common as a fuel type and is still under research and development as of today. This research focus on mixing ammonia together with MDO (namely in ratio of 50-50) but is not commercially available as per 29.04.2023. Experience with these engines when it comes to operation and handling on the ships is today very limited.

MS Nordlys – Ammonia as fuel					RISK SAFETY EVALUATION				
Activity	Hazards / unwanted happenings	Cause	Partial Cause	Comments	C	Comments: Consequences (C)	P	Comments: Probability (P)	RISK
Exposure of ammonia with concentration 400-700 ppm	**Highly toxic**	Leakage of ammonia	Poor maintenance, lack of appropriate PPE, lack of double barriers	Ammonia is leaked from damaged gaskets or malfunctioned equipment, and crew is in near vicinity of ammonia vapor	1	First aid is required (severe irritation of eyes, ears, nose and throat) - no lasting effect for short exposure	4	Considered likely for engine crew	Low
Exposure of ammonia with concentration 2000-3000 ppm (less than 30 min exposure)	**Highly toxic**	Leakage of ammonia	Poor maintenance, lack of appropriate PPE, lack of double barriers	Ammonia is leaked from damaged gaskets or malfunctioned equipment, and crew is in near vicinity of ammonia vapor	4	Even less than 1/2 hours exposure can be fatal	2	Ammonia has a strong odour; crew is likely to evacuate if noticed. Considered very rare	High
Exposure of ammonia with concentration 5000-10000 ppm	**Asphyxiation**	Leakage of ammonia	Poor maintenance, lack of appropriate PPE, lack of double barriers	Ammonia is leaked from damaged gaskets or malfunctioned equipment, and crew is in near vicinity of ammonia vapor	5	Considered high consequence as it is rapidly fatal	2	Crew not able to evacuate due to the rapid fatality. Considered very rare due to gas detection system and double barriers	High
Operation of ammonia engines	**Explosive**	Leakage of ammonia in confined spaces (oil vapor or combustible materials increase the explosive range) further ignited	Malfunctioned handling equipment or fractured equipment (for instance engine parts)	Ammonia is leaked in confined space	4	Can potentially cause a lot of damage and even fatality	1	Is unlikely as there are gas detection systems and is hard to ignite	Medium
General operations (bunkering, engine operation, fuel handling system)	**Flammable**	Ammonia spillage and further ignited	Fractured equipment, corroded equipment, malfunctioned equipment, etc	Ammonia is leaked in confined space and ignited	4	Needs a supporting flame to keep burning (oil contaminants, combustible materials, external fire etc.)	1	Is unlikely as it requires high energy to ignite (requires 30 times more energy than methane ignition) and extremely high temperature (650 °C) to self-ignite	Medium
General operations (bunkering, engine operation, fuel handling system)	**Highly corrosive**	Material fractures on corresponding ammonia tanks, fuel system and engine due to corrosion	Poor material selection	Material fracture in ammonia system due to bad material design (does not withstand corrosion from ammonia)	3	Considered (partial) damage to the vessel, and requires to be repaired for corrosion if bad material quality is present	3	Considered to be rare, errors can occur with poor material selection	Medium

4.4 Methanol – Identified risks and analysis

The following hazards are identified for Methanol (From Table 4):

1. Highly flammable
2. Burns with a nearly invisible flame especially in daylight, with no smoke.
3. Toxic
4. Corrosive
5. Asphyxiation

These hazards are further used as basis in the next page for the risk analysis concerning methanol.

MS Nordlys – Methanol as fuel					RISK SAFETY EVALUATION				
Activity	**Hazards / unwanted happenings**	**Cause**	**Partial Cause**	**Comments**	**C**	Comments: **Consequences (C)**	**P**	Comments: **Probability (P)**	**RISK**
General operations (bunkering, engine operation, fuel handling system)	**Highly flammable**	Methanol spillage and further ignited	Fractured equipment, corroded equipment, malfunctioned equipment, etc	Malfunctioned equipment causes a methanol spill which is further ignited.	4	Confined space, increase the consequence potential (fatal, major damage)	2	Assumed to be very rare	High
Un-detected fire as the flame is near invisible - spread of fire	**Invisible flame**	Methanol spillage and further ignited.	Fractured equipment, corroded equipment, malfunctioned equipment, etc.	Malfunctioned equipment causes a methanol spill which is further ignited. Fire is spread to adjacent materials before detection	5	Methanol flames are particularly hazardous as it has a high flammability range. Assuming it can easily grow into a large fire	2	Assumed to be very rare	High
Accidentally contact or ingestion of methanol in general working operations	**Toxic (ingested or skin absorption)**	Spillage of clear liquid methanol	Lack of awareness and appropriate PPE	Methanol is a clear liquid and can be mistakenly thought as water, and upon removal of the substance accidental contact occurs	4	Can cause blindness, dizziness, and nauseousness, over exposure will be fatal	3	Assumed to be rare	High
Accidentally contact of methanol in general working operations	**Toxic (general skin contact)**	Spillage of clear liquid methanol	Lack of awareness and appropriate PPE	Same as above	1	Can cause skin irritation, dryness, cracking, inflammation and burns. First aid required.	4	Is likely to occur within a year	Low
General operations (bunkering, engine operation, fuel handling system)	**Corrosive**	Material fractures on corresponding methanol tanks, fuel system and engine due to corrosion	Poor material selection	Material fracture in methanol system due to bad material design	3	Tanks, fuel system and engine parts can corrode opting for repairs (partial damage)	3	With poor material design this will corrode over time	Medium
Accidental inhalation of methanol vapor	**Asphyxiation**	Spillage of clear liquid methanol, further evaporated into vapor	Lack of awareness and appropriate PPE, lack of methanol vapor detection systems	Methanol vapor is denser than air and will accumulate near ground in close vicinity to crew. It also has a slightly sweet and strong odour	3	High vapor concentrations can cause asphyxiation, but crew may recognize the strong odour and evacuate	3	Methanol fuel systems is strictly regulated and requires ventilation areas and methanol detection systems	Medium

4.5 Hydrogen – Identified risks and analysis

The following hazards are identified for hydrogen (from Table 5):

1. Fire
2. Fire produces toxic gases in confined spaces (CO from combustible materials)
3. Explosion
4. Hydrogen induced stress cracking.
5. Cold burns, serious skin damage

These hazards are further used as basis in the next page for the risk analysis concerning hydrogen.

It is important to remark, as previously mentioned, that for hydrogen propulsion (Internal combustion engines) it is not common as a marine fuel today, other than in addition to other fuel types (namely in concentrations of 10-20 %), but not for marine trafficking along the Norwegian coast as per 29.04.2023. Experience with these engines when it comes to operation and handling on ships is therefore limited. There are however some ships that operate on fuel cells, such as “MF Hydra”.

MS Nordlys – Hydrogen as fuel					RISK				
					SAFETY EVALUATION				
Activity	**Hazards / unwanted happenings**	**Cause**	**Partial Cause**	**Comments**	**C**	Comments: **Consequences (C)**	**P**	Comments: **Probability (P)**	**RISK**
General operations (bunkering, engine operation, fuel handling system)	**Fire**	Hydrogen leakage that ignites into a fire, and the flame is very hard to detect	Poor material selection, or unproper handling upon bunkering hydrogen.	Wide flammability range, very high flame temperature, require low ignition energy and can also self-ignition, the flame is almost invisible, rapid flame speed. This will in turn cause a massive fire or even an explosion	5	Hydrogen fire is very aggressive, and can cause a major accident / permanent damage to the vessel	3	Occurs rarely, this is seen in relation to material embrittlement	High
General operations (bunkering, engine operation, fuel handling system)	**Fire (Toxic gas)**	Hydrogen leakage starts a fire	Fire in nearby adjacent materials	Fire in carbon-based compounds	4	Inhalation of high concentrations of CO causes death (CO replace oxygen in red blood cells)	3	Occurs rarely, It is a well-established fact that CO poisoning have caused deaths onboard ships in the past (In general for fuels)	High
Operation of hydrogen engines	**Explosion**	Hydrogen leakage exposed to an ignition source (or self-ignites)	Lack of maintenance, material embrittlement, poor handling	Hydrogen has a higher explosion pressure and can cause a very serious incidents in a closed or semi-open compartment	5	Serious incident, many fatalities and vessel is very damaged (major accident, permanent damage)	2	Considered very rare as hydrogen systems are very strictly regulated	High
General operations (bunkering, engine operation, fuel handling system)	**Hydrogen induced stress cracking (material embrittlement)**	Hydrogen diffuses into nearby material (piping, tank surface, etc.) and can lead to metal embrittlement then cracking, further leakage	Poor selection of proper material to withstand hydrogen diffusion	Poor selection of material lead to hydrogen diffusion, cracking and then leakage. It is extremely important to ensure the safety and integrity of the fuel supply system	5	Oxygen can be consumed by hydrogen and reacted into water; this will deplete oxygen in closed compartments. Also, ignition will cause explosion (also self-ignition)	3	With poor material design this will cause hydrogen diffusion into the material	High
Operation by crew, i.e., bunkering, awareness for cryogenic equipment	**Cold burns, serious skin damage**	Human contact on cold surfaces containing cryogenically cooled hydrogen	Un-awareness, lack of appropriate PPE, poor training, poor insulation	Crew accidentally touch a cold uninsulated surface which contains cryogenically cooled hydrogen	3	Can cause cold burns and serious skin damage	3	Assumed to occur rarely	Medium

4.6 Molten salt reactors – Identified risks and analysis

The following hazards are identified for hydrogen (from Table 6):

1. Toxic if exposed (due to radioactivity)
2. Radioactive waste
3. Fuel meltdown (Not with TMSR)

These hazards are further used as basis in the next page for the risk analysis concerning TMSR.

It is important to remark as previously mentioned that for TMSR there is limited research in Norway and is not commercially available in Norway. Therefore, the risk analysis conducted for TMSR is short as there is a need for a knowledge database in Norway.

MS Nordlys - TMSR as fuel					RISK SAFETY EVALUATION				
Activity	**Hazards / unwanted happenings**	**Cause**	**Partial Cause**	**Comments**	**C**	Comments: **Consequences (C)**	**P**	Comments: **Probability (P)**	**RISK**
The concrete in the reactor shielding cracks	**Toxic if exposed openly (Radioactive)**	Wrong type of concrete is used, becomes to brittle with temperature fluctuations, openly exposes the reactor vessel - radioactive radiation occurs	Lack of competence when designing TMSR, poor training.	Crew is exposed to radioactive radiation when the concrete becomes too brittle and cracks open, exposing the reactor vessel	4	Ionizing radiation by thorium can cause cellular damage, that includes DNA breakage, gene-mutations, chromosomal changes, and genetic instability. In essence this means severe skin burns, cancer, then even death	1	TMSR will be very strictly regulated, and design regulations will accommodate the correct type of reactor shielding is used, this requires a well-developed competence network to be in place	Medium
In proper waste handling after reactor is replaced	**Toxic if exposed to environment (Radioactive waste)**	Radiation to environment	Environmental damage, affecting nature and life	The environment is exposed to radioactive radiation due to in proper handling of the waste.	5	Ionizing radiation by radioactive waste can cause cellular damage, that includes DNA breakage, gene-mutations, chromosomal changes, and genetic instability. In essence this means severe skin burns, cancer, then even death. Major accident to the local environment.	1	Very unlikely, as proper handling of waste will be very strictly regulated. This requires a well-developed competence network to be in place	High
Operation of TMSR for power generation	**Fuel meltdown**	Heat generated by the nuclear reactor exceeds the heat removal process and the fuel element melts	Operation of TMSR outside of design limits by crew lacking competence and knowledge	Fuel melt down occurs due to lack of competence among the crew	4	Under an emergency the fuel will be drained into a cooled storage tank, thus the consequence is that the reactor must be replaced (major damage)	1	Very unlikely as alarms will activate, then the freeze plug will be activated to drain the fuel into cooled tanks stopping further fuel melt down	Medium
Operation of TMSR for power generation	**Collision**	Collision with an external object (run aground, iceberg, vessel etc.)	Poor navigation skills by crew, lack of competence	TMSR vessel collides with another object, further exposing the reactor core or is sunk and radioactivity radiates into environment	4	Ionizing radiation by radioactive waste can cause cellular damage, that includes DNA breakage, gene-mutations, chromosomal changes, and genetic instability. Assuming that the ship can be repaired and is not sunk	1	Assumed to be very unlikely, as TMSR vessel would be very strictly regulated and monitored, also when it comes to competence and knowledge of crew.	Medium

5. Discussion: Comparative Study

In the following sections previous data retrieved and calculated for the various fuel types are presented and discussed. This to show a comparison between them and clarify the differences in all the areas assessed for each fuel type.

5.1 Presentation of data comparison for the alternative fuels

Relevant technical data previously presented and calculated, is displayed in Table 13, this technical data will further be discussed in the coming sections.

Fuel	**MDO**	**LNG**	**Ammonia**	**Methanol**	**Hydrogen**	**TMSR**
Energy density $\frac{MJ}{kg}$	42,7	50	18,8	19,9	120	$79{,}42*10^6$
Availability	Very good	Very good	Very limited	Very limited	**N/A**	**N/A**
Fuel consumption in ton[15]	23,8	20,41	54,26	51,26	8,50	$72{,}7*10^{-6}$ [16]
Min. storage capacity, m^3	26,74	42,69	79,8	64,9	119,8	453,9
Cost, k NOK	139,4	180,1	689,6	678,3	789,1	575,5
Emissions, CO_2 ton	73,9	52,39	N/A	71,79	N/A	N/A
Emissions, NO_x ton	0,95	0,18	1,67	0,42	1,45	N/A
Emissions, SO_x ton	0,71	N/A	N/A	N/A	N/A	N/A

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[15] Fuel consumption in ton is for the journey from Bergen to Trondheim.

[16] More realistically TMSR require a five-year fuelling cycle, assuming five years this number would instead be 166,67 kg.

Other emissions, ton	N/A	0,58[17]	0,72[18]	N/A	0,67[19]	N/A
Total risks	Medium	Medium	High	Medium	High	Medium

Table 13 – Comparison of retrieved and calculated data of the alternative fuels

5.2 Energy density

As already mentioned previously in this report with the energy densities for each fuel, the energy density is a measure showing how much energy is available for each kg. The energy densities retrieved from Table 13 is further illustrated graphically for comparison in Figure 38.

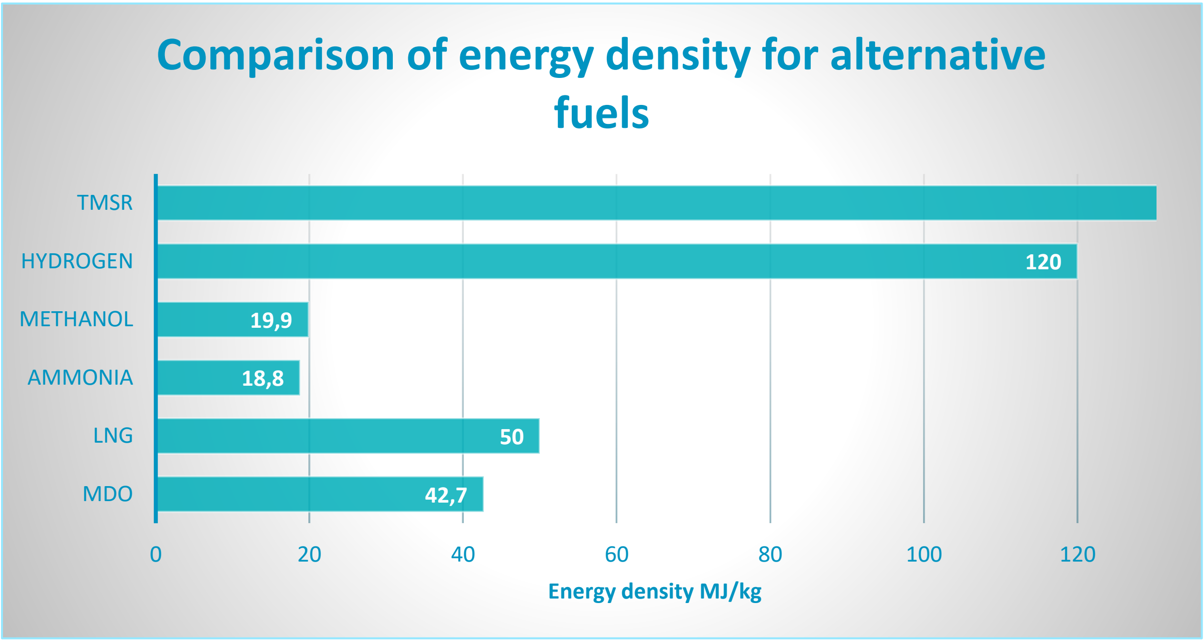

Figure 38 – Comparison of energy density for alternative fuels

As you can see in this figure, TMSR is not shown by value as it spans outside the illustration, due to the energy density is so extreme. This is of course as previously stated the massive energy potential of Thorium. Secondly hydrogen has a very high energy density, as this is of course the first periodic element and is the lightest atom. Importantly to remark for

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[17] From LNG combustion, unburnt CH_4

[18] From ammonia combustion, unburnt NH_3

[19] From hydrogen combustion in air, release of pure N

hydrogen that is not revealed in Figure 38, is that cooling hydrogen requires an enormous amount of energy as it needs to be cooled down to a liquid state at -253 °C, and if the hydrogen itself is the source of power for cooling it down, the energy density is just 9 MJ/kg – further illustrated in Figure 1. LNG on the other hand has an energy density of 50 MJ/kg and has a great potential as it can release a huge amount of energy, however LNG is merely a "bridge fuel" as it does produce greenhouse gas emissions – and other fuel types must be considered in order to achieve the global climate goals set in the Paris Agreement. LNG is also a fuel that is stored in liquid conditions at -162 °C, if LNG is used for the source itself to keep it liquid, the energy density is halved to 25 MJ/kg – as can be seen in Figure 1. Just next to LNG is Marine Diesel Oil, with an energy density of 42,7 MJ/kg – and is a very common fuel as of today and is why this was chosen as the base case when we do our comparison. When it comes to methanol and ammonia, both have corresponding energy densities of 19,9 and 18,8 MJ/kg respectively. These are more than half energy dense than diesel but are considered viable fuels as they can be produced from environmentally green production methods. For instance, methanol can be produced using green hydrogen which is produced from renewable energy sources such as wind turbines or solar power, and carbon dioxide which is stored from biomass, directly taken from air or other processes that produce CO_2 which is stored. Although green methanol release CO_2 when consumed, it is a "zero-emissions" fuel – if the CO_2 is stored and re-used for methanol production again. (ABS, 2021b, pp. 18-19) This is evidently the same for green ammonia, which use hydrolysis with renewable energy sources and takes the nitrogen from the air to produce ammonia. (Øystese, 2020, p. 9) Ammonia requires energy to keep cool and pressurized if ammonia is used as the source itself for this the energy density would only be 11 MJ/kg – as can be seen in Figure 1. In Figure 39 the same illustration as Figure 38 is shown, only this time scaled to also fit Thorium properly. Although as you can see in Figure 39, the other alternative fuel types cannot be seen as they are so small in comparison to Thorium. Thorium has the massive energy density of 79 420 000 MJ/kg and is by far the most powerful fuel type. The downside of Thorium is that it requires a lot of space to accommodate a TMSR (453 m^3 approx.).

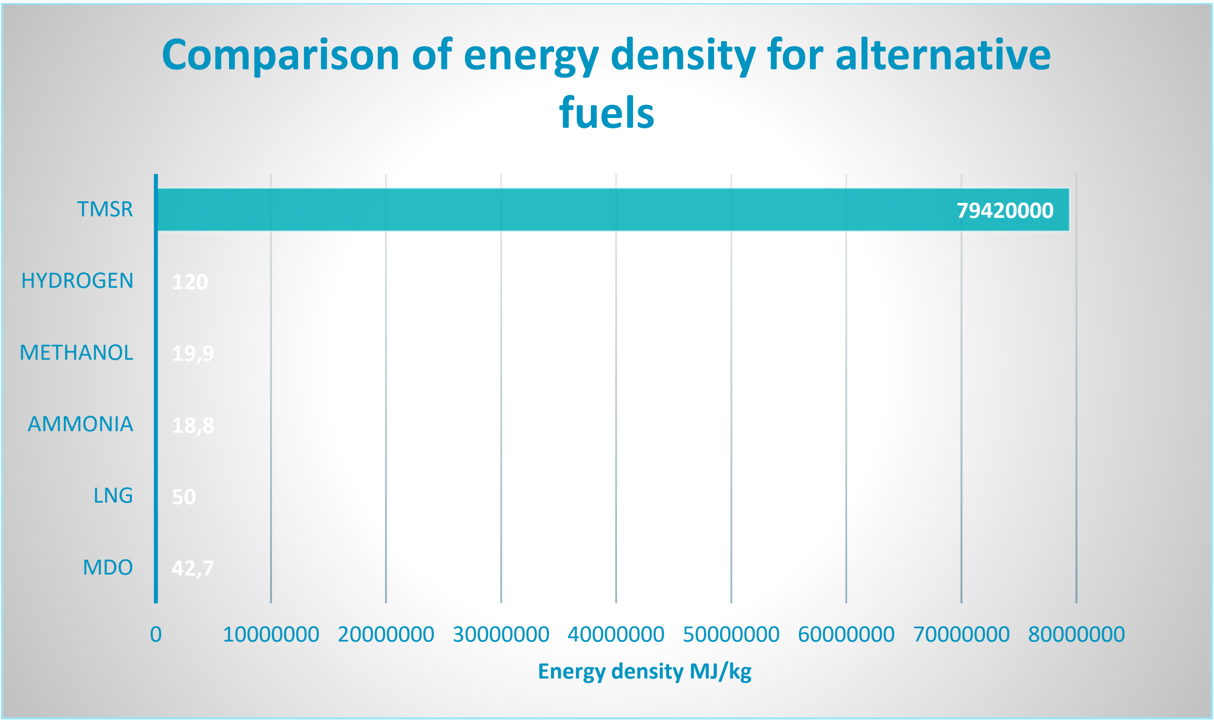

Figure 39 – Comparison of energy density for alternative fuels with Thorium fully illustrated.

5.3 Technical infrastructure and availability

The infrastructure and availability in Norway for the various fuel types was presented in chapter 2. Table 14 shows a comparison of how accessible the considered fuel types are along the Norwegian coast.

Fuel	**MDO**	**LNG**	**Ammonia**	**Methanol**	**Hydrogen**	**TMSR**
Availability	Very good	Very good	Very limited	Very limited	**N/A**	**N/A**

Table 14 – Comparison of availability for the alternative fuels

MDO and LNG are well implemented as marine fuels and are therefore commercially available and easy to access in Norway, which in turn makes them more competitive as a marine fuel type. This clearly has a connection with the fact that MDO has been used as fuel for propulsion engines for a long time, and LNG has had a large growth in the market in recent times as a more emission-friendly alternative.

The availability and infrastructure for both ammonia and methanol are extremely limited in Norway as of today but is considered more available in a global scale. However, green ammonia and green methanol which is considered the potential carbon free options is not commercially available in Norway yet. Based on this, it can be stated that this affects and limits their use in the marine market, and they must be established to a much greater extent in order to be competitive as new marine fuel types. Nevertheless, the infrastructure is expected to improve in the coming years.

For Hydrogen, the infrastructure in Norway is non-existent as of today. As far as for the availability it is assumed that it must be imported from outside of Norway, which presumably will increase the price if Hydrogen is to be procured externally. However, steps are taken to achieve making hydrogen commercially available, and it is expected to see further development these coming years.

As for TMSR this is not commercially available as of today, as there is very limited research and development concerning Thorium. For Thorium power generation there must be established a competence network as well, however this is not a priority in Norway as of today.

5.4 Comparison of fuel consumption

In Figure 40 a comparison of fuel consumed for the voyage from Bergen to Trondheim is presented. The values are in ton for each fuel type and was retrieved from Table 13 and further illustrated. It can be seen from this figure that ammonia is the fuel type that require most tons, 54,26 tons of fuel onboard for this journey, this makes sense as ammonia is also the fuel type which has the smallest energy density of all the fuel types and therefor require more amounts to be combusted. Second highest fuel consumption is methanol, at 51,26 tons, which in turn also makes sense as methanol has the second lowest energy density just 1,1 MJ/kg higher than ammonia. Third highest is of course MDO, which corresponds with third lowest energy density, the total consumption of MDO sits at 23,8 ton. Important to remark is that MDO is however much more dense than the other fuel types (except Thorium), thus this in turn lead to smaller tanks onboard MS Nordlys (as installed today). Fourth lowest is LNG at 20,41 ton, which correspond with the energy density being the fourth lowest, although the expected fuel consumption may be more as the calculations did not account for cooling systems to keep the LNG cryogenically cooled. This is also the case with ammonia and Hydrogen. Next after LNG is Hydrogen with a fuel consumption of just 8,5 ton. This in turn is because hydrogen has a very high energy density. However, 8,5 ton is not an accurate number, as hydrogen requires massive amounts of power to keep cryogenically cooled at -253 °C, so this number is in reality much higher – but was in the calculations assumed that hydrogen would be kept liquid by other means (could for instance be with Thorium nuclear power generation, for instance TMSR).

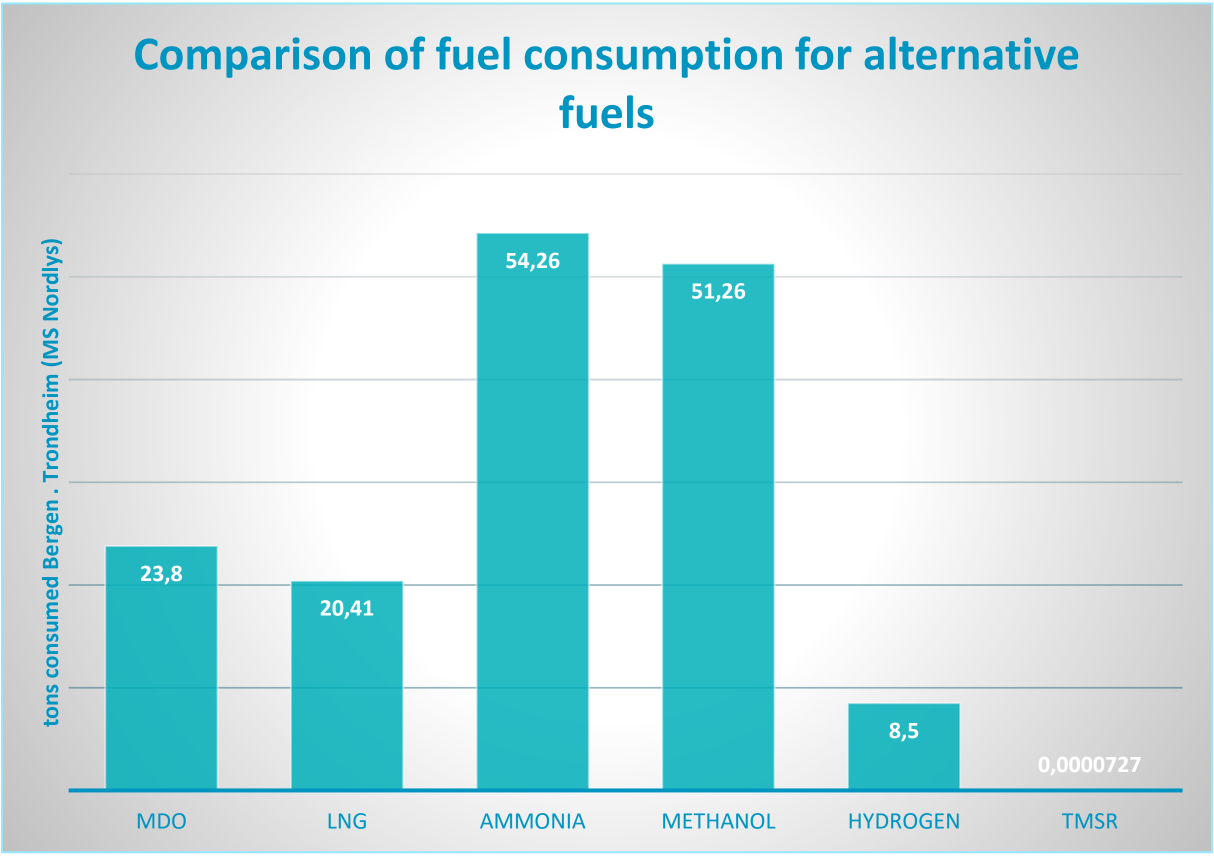

Figure 40 – Comparison of fuel consumption for the alternative fuel types when sailing Bergen to Trondheim with MS Nordlys

At the very bottom with just 72,7 grams is Thorium fuel consumed for the journey from Bergen to Trondheim, which is very low. This also reflects that nuclear energy is a totally different ballgame compared to the other fuels that utilizes chemical energy for propulsion. This is of course because Thorium has a extreme energy density of 79 420 000 MJ/kg. However, when discussing the added weight by each of the fuels, TMSR on the other hand require a reactor vessel, secondary circuit and massive amounts of concrete for radioactive shielding against all radiation that is to occur onboard the ship. Let alone if one where to account for all of this equipment a more realistic weight onboard MS Nordlys would be 2 800,25 ton. And according to DNV vessel register, the DWT (deadweight tonnage) of MS Nordlys is just 850 tons (DNV, 2022a) this would ultimately sink the vessel if the TMSR was installed on board. However, in other cases if a new build is to be designed this can be taken into account to make TMSR operational for the desired vessel to be built. In other words, the ship must be designed specifically for TMSR.

5.5 Comparison of total cost for consumed alternative fuel

The cost of the various fuel types fluctuates in line with the market and is affected by the global economy. The prices for MDO and LNG were obtained on April 15th, 2023, but it must be mentioned that these are prices that can vary from day to day. For the remaining fuel types, the exact daily prices were difficult to obtain and had to be based on monthly or quarterly estimates. For green ammonia and bio methanol prices in March 2023 was retrieved from DNV's tool "Alternative Fuels Insights", while for Hydrogen it had to be based on prices from a study done in January 2023. The cost for TMSR were more challenging and were retrieved form a study done in 2021. (Emblemsvåg, 2021, pp. 59-60)

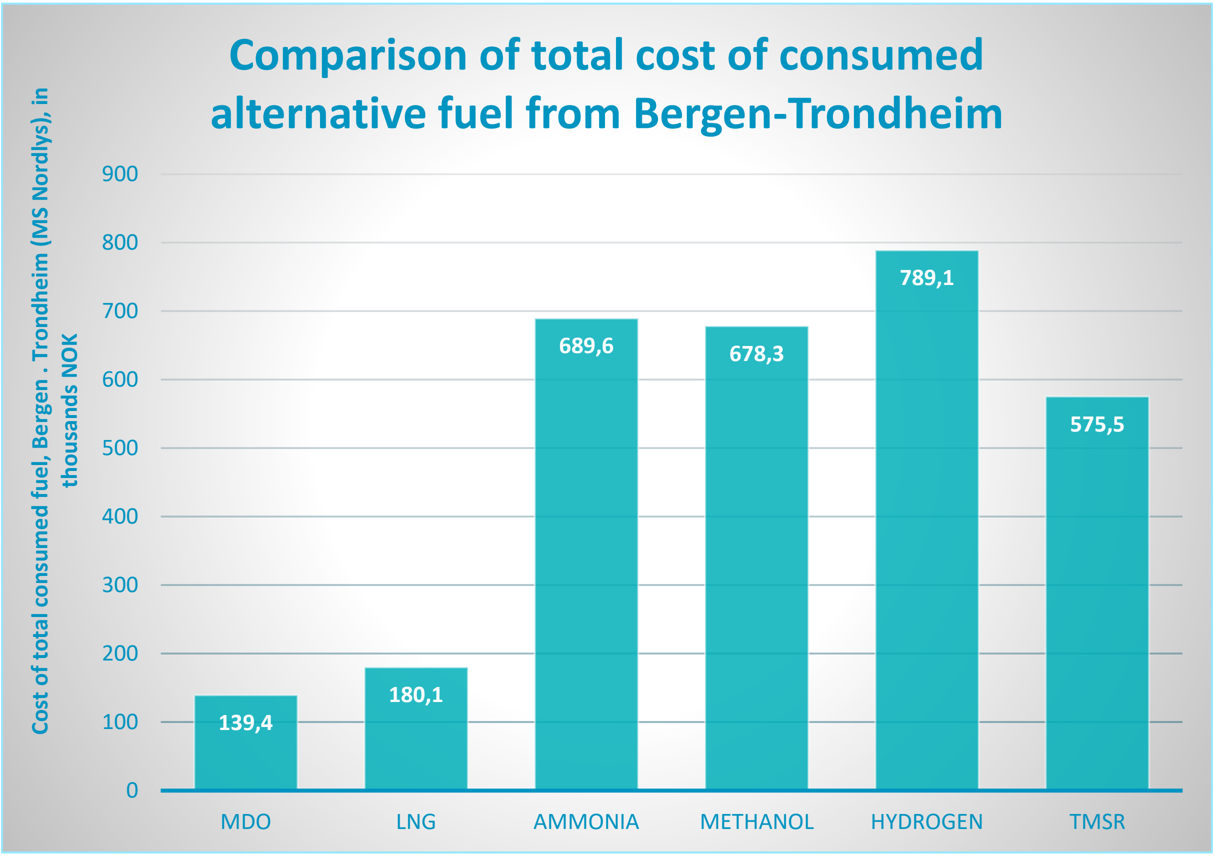

Figure 41 – Comparison of total cost of consumed alternative fuel from Bergen-Trondheim

As Figure 41 displays, MDO has the lowest cost of fuel consumed for the journey from

Bergen to Trondheim with 139,4k NOK, and is closely followed by LNG at 180,1k NOK. One can assume that this can be seen in the context of the fact that these fuel types are commercially available and are well established as marine fuel on the market today. Both green ammonia and bio methanol have a much higher price seen in comparison to MDO and LNG and the cost is almost the same for both being 689,6k NOK for green ammonia and 678,3k NOK for bio methanol. The price was approximately the same in USD per tonne, but the consumption of ammonia was higher, which makes the biggest difference. Hydrogen is definitely the most expensive option with a cost of 789,1k NOK for the entire journey from Bergen to Trondheim. Hydrogen, on the other hand, had the lowest total fuel consumption. The price of hydrogen, ammonia and LNG is expected to increase further as the calculations did not account for the additional energy requirement to keep the fuels cooled and/or pressurized to a liquid state, and is corresponding to an added fuel consumption.

As mentioned in 3.6.2 Economic feasibility for TMSR, the value of 575,5k NOK assumes that MS Nordlys is in operation for all the 30 years, so the costs is divided over a longer time period – this is the total acquisition cost of the full TMSR as thorium cannot be used as fuel for the B36:45L engines.

5.6 Comparison of emissions for the alternative fuels

In Figure 42 a comparison of the calculated CO_2 emissions from the alternative fuel alternatives is presented when assuming a journey with MS Nordlys from Bergen to Trondheim. The values are retrieved from Table 13 and illustrated graphically.

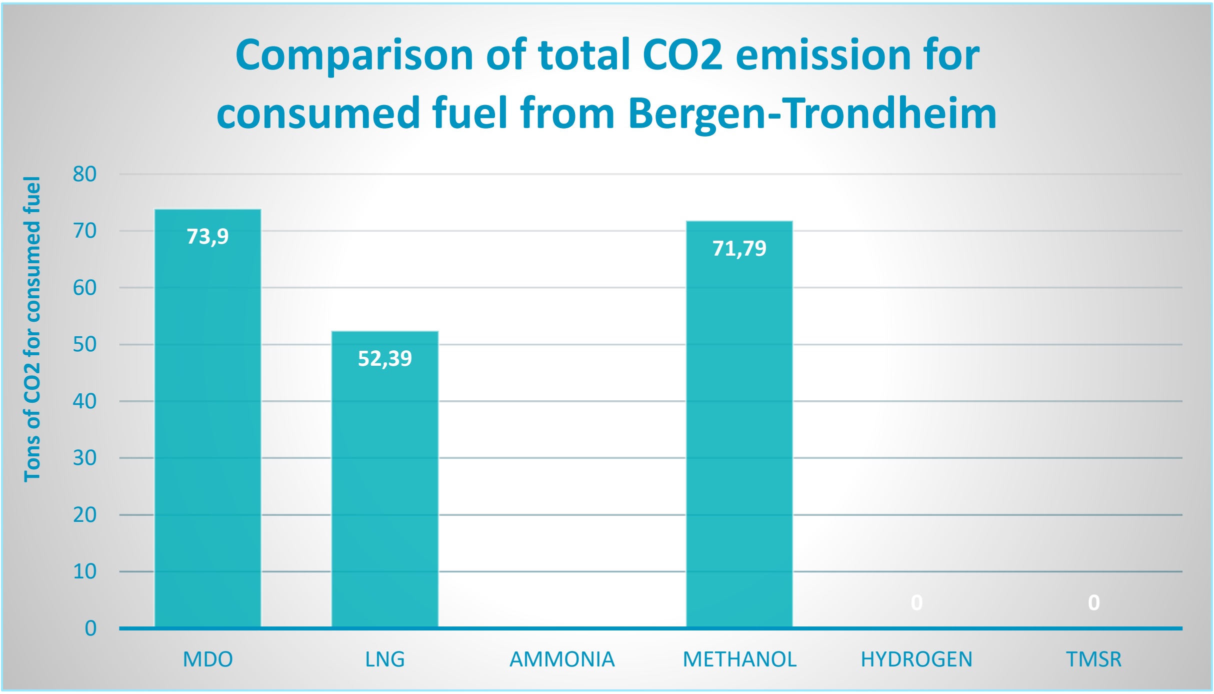

Figure 42 – Comparison of total CO2 emission for consumed fuel from Bergen-Trondheim

As for ammonia (NH_3), hydrogen (H_2) and TMSR (Th-232) they do not contain any carbon reactants, and thus when it comes to combustion (or radioactive fission for that matter) it does not produce any CO_2. However, as for MDO ($\mathbf{C}_{15}H_{32}$), LNG (mainly $\mathbf{C}H_4$) and methanol ($\mathbf{C}H_3OH$) they do contain carbon and when combusted with air this will react by forming CO_2 products. The products that MDO, LNG and methanol produce when combusted is respectively 73,9, 52,39 and 71,79 tons. MDO clearly creates the most CO_2 as it has a high carbon number of 15, this makes sense. However, the large number of CO_2 from Methanol combustion can be explained by the low energy density, thus requiring more methanol fuel to be consumed – and ultimately increasing the product of CO_2 to almost as close as MDO (only 3 % difference). It is very important to remark that the produced CO_2 for combustion with methanol is not realistic, as if green methanol is used there will be no aggregated emissions to the atmosphere due to the photosynthesis (The CO_2 is re-used either by CCS or through biomass for green methanol production). LNG is 52,39 tons CO_2 in comparison to

73,9 tons CO_2 from MDO and is clear from the higher energy density of LNG (50 MJ/kg for LNG, 42,7 MJ/kg for MDO), In addition to LNG being clearly less dense than MDO. This further emphasizes that further developments are to be carried out for carbon capture and storage.

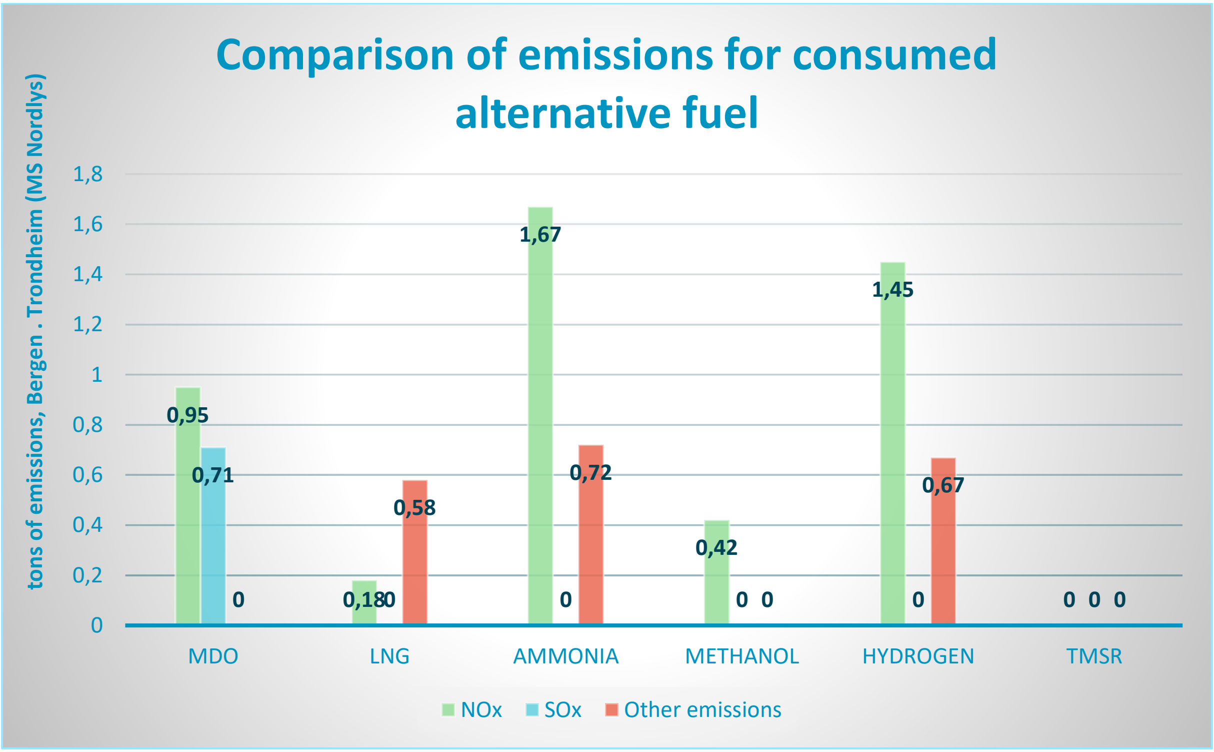

Figure 43 – Comparison of emissions for consumed alternative fuel from Bergen-Trondheim

In Figure 43 it is shown an illustration of a comparison of emissions consumed from the alternative fuels, this is specifically to NO_x, SO_x, and other emissions. The values are retrieved from Table 13. The other emissions is namely for LNG unburnt methane that through "methane slips" is escaped into the atmosphere through the exhaust. As for ammonia, this is unburnt ammonia which is also escaped through exhaust. For hydrogen it is assumed that the hydrogen combustion occurs with air, and thus produces nitrogen in pure form 'N'. This can further react with oxygen under right conditions according to the 'Zel-Dovich mechanism' as previously discussed. It can in Figure 43 be seen that for NO_x emissions ammonia has the highest emission produced, at 1,67 ton. This is of course due to nitrogen present in the fuel type itself, and also accounting for Its low energy density. More ammonia must be combusted to produce the required amount of energy for the journey MS Nordlys is taking. Arguably green ammonia is emphasized as the nitrogen is retrieved from the air together with hydrogen from renewable energy sources to create 'green ammonia'. This makes the emissions of NO_x stable as the amount does not increase in the atmosphere.

Arguably it is the N_2 that is retrieved from the atmosphere in 'green ammonia', not necessarily NO_x which could in turn increase the concentration of NO_x and in turn decrease N_2. If the NO_x is captured and stored for ammonia production, the total NO_x emissions would balance out – if the hydrogen to be combined in production of ammonia comes from a renewable energy source such as wind or solar power. Evidently this could also be argued for hydrogen if combusted in air, that the NO_x is captured and stored for 'green ammonia' production. Hydrogen if combusted in air could produce 1,45 tons of NO_x according to 'Zel-dovich mechanism', and 0,67 tons of pure 'N' could further be reacted according to the reactional equations of 'Zel-dovich mechanism' (this was not further investigated). As mentioned earlier for the emission calculations for hydrogen, this is of course speculative as it assumes a 2% excess air and that all excess oxygen is formed into NO_x. Methanol also produce NO_x when combusted in air, and this is calculated to be 0,42 tons for the voyage from Bergen to Trondheim for MS Nordlys. This ultimately means for methanol to be a viable green fuel, the NO_x must be captured and stored, further used for other industry applications (for instance ammonia production). The NO_x emissions from MDO are calculated to be 0,95 tons. And for LNG this amount is rather low at 0,18 tons. These could also respectively be captured and stored and used for 'green ammonia' production. Another surprising number is 0,58 tons of unburnt methane which is assumed to be escaped through the exhaust (methane slip), whereas methane is 28 times more dangerous to the climate than CO_2 – if this value is recalculated in respect to CO_2 this would mean an additional emission of 16,24 tons of CO_2 – totalling the effect of CO_2 to be as high as 68,63 tons for LNG, this is still lower than MDO totalling to be 73,9 tons. Lastly there is the emission of unburnt ammonia, which sits at 0,72 tons. Released to the atmosphere this can react with acid pollutants like NO_x and SO_2 to produce fine ammonium which contains aerosols and cause air pollutant issues for international transboundary regions. (UK Air Pollution Information System, 2023)

5.7 Comparison of risks for the alternative fuels

According to the main hazards identified for each fuel type, these total risks is maybe not fully investigated and are further based on the author's view on potential scenarios of what may occur. The risk analysis could have contained far more elements, but it was limited to only assessing the main hazards identified and not all aspects of its actual operation. Based on the risk analysis carried out for each fuel type in chapter 4, an assessment has been made of the total risk for each and is displayed in table 15. The total risk is calculated by means of taking the sum of all consequence levels and probability levels divided by identified risks, the corresponding values for consequence and probability is then again assessed according to Figure 37 to find total risk.

Fuel	**MDO**	**LNG**	**Ammonia**	**Methanol**	**Hydrogen**	**TMSR**
Total risks	Medium	Medium	High	Medium	High	Medium

Table 15 – The total risks identified from each alternative fuel.

All risks for MDO are shown in section 4.1 Base Case: Diesel as a marine fuel – Identified risks and analysis. The total risk was found to be 3 for consequence and 3 for probability. MDO is therefore rated with a medium total risk. It is not considered to be particularly dangerous to humans itself, but it is highly flammable and can easily ignite near heat or ignition sources. This in turn can cause great danger to the crew and to the ship itself. In addition, spillage of MDO can be very harmful to the marine environment and have long lasting effects.

All risks for LNG are shown in section 4.2 Liquified Natural Gas - Identified risks and analysis. The total risk was found to be 3,17 for consequence and with a probability of 2,33. Therefore the total risk for LNG was found to be medium. LNG requires more careful handling by the operating crew due to its low cryogenic storage temperatures and if spilled may cause freeze burns if the crew is in close vicinity. Also, when it comes to leakage of exhaust gas, it can for instance if released in closed compartments such as engine room accumulate into a high concentration displacing the oxygen, this in turn could cause asphyxiation if the crew is not evacuated in time. LNG if evaporated into gas could further cause vapor cloud explosion, flash- and jet fire.

All risks for ammonia are shown in section 4.3 Ammonia – Identified risks and analysis. The total risk was found to be 3,5 (rounded up to 4) for the consequence and with a probability of 2,17. This implies that ammonia is considered to have a high total risk. This mainly is emphasized because of its high toxicity and exposure of concentrations over 2000-3000ppm of ammonia can be fatal for humans. This creates operation of ammonia particularly dangerous due to Its toxicity, and precautions must be made when it comes to operational instructions, gas detection systems and PPE. It is also flammable and explosive, however for ammonia the fire is harder to maintain, and is very dangerous if there are other combustible materials in near vicinity of ammonia that is caught fire. Combustible materials may increase the explosive range. Another key point to be mentioned with ammonia, is that it has the property of being highly corrosive. All systems that operate with ammonia confined, must be designed properly according to correct material choices to withstand corrosion, if not this could ultimately lead to material fracture or fatigue and cause spillage.

All risks for methanol are shown in 4.4 Methanol – Identified risks and analysis. The total risk was found to be 3,33 for the consequence with a probability of 2,83 (rounded up to 3). Further implying a total risk of medium. What so is distinctive for methanol is that it is highly flammable, and it burns with an almost invisible flame, so if caught fire this can be very hard to detect before the fire is spread to become an even greater fire. Very common for methanol is that it's very toxic when ingested or absorbed through skin. It can further cause asphyxiation if the methanol is evaporated into a high concentration in closed compartments. This requires extensive awareness and proper handling of methanol by the crew. As similar with ammonia, this is also corrosive and may corrode material equipment confined with methanol if there is poor material design. Fractured components could then in turn cause a spillage.

All risks for hydrogen are shown in 4.5 Hydrogen – Identified risks and analysis. The total risk was found to be 4,4 (rounded down to 4) for consequence and 2,8 for probability (rounded up to 3). This implies a high total risk. Hydrogen is cryogenically cooled and could cause cold burns and serious skin damage if liquid hydrogen is spilled. Hydrogen requires very strict protocols for handling, and extensive training for crew. Hydrogen is also very light and have small molecules which can in turn cause hydrogen induced stress cracking in materials as hydrogen is diffused into the material and cause embrittlement, and further fracture if the surface comes into an impact by an external force. This poses a great threat to hydrogen equipment if it is not proper designed (double walled, material selection etc.). Hydrogen is in turn highly flammable and burns with an aggressive flame, in some instances it could combust almost directly into an explosion with high explosion pressure. If hydrogen is leaked in closed compartments containing air, the hydrogen can react with the oxygen molecules and form into water – this will further deplete the oxygen concentration in that room and is a danger to crew in near vicinity. Systems must be strictly designed to account for such hazards.

All risks for TMSR are shown in 4.6 Molten salt reactors – Identified risks and analysis. The total risk was found to be 4,25 for consequence and 1,0 for probability. Implies a total risk of medium. TMSR is generally as previously described as a safe option as the Thorium fission can easily be stopped in case of an emergency, however it is assumed some risks that may occur. Importantly it must also be remarked that TMSR is not a commercially available option and must be further researched and developed before any full risk assessment can be carried out. Thorium is of course known as a radioactive material, and so is the waste products. Proper handling must be conducted when installing a TMSR on board the vessel as well as proper handling of the waste products once the reactor is depleted and is to be decommissioned. The waste products which are still radioactive must be stored so it can not cause any harm to the environment (for instance buried deep underground and then encapsuled with concrete). There is also a common term called 'fuel meltdown' when discussing radioactive materials for power generation, this is not an issue with TMSR as the fuel is drained into a cooled tank further stopping the fission process. However, assuming this could happen due to lack of competence or training of crew it is considered still as highly unlikely as TMSR will be very strictly regulated. In general, for TMSR the consequences are rated high since thorium is radioactive and if exposed is very dangerous to both humans and environment. Further it is considered in most cases to be highly unlikely.

6. Conclusion

In this master thesis, the focus was to research and assess various alternative marine fuel types that may be used in the future to work towards the goal of zero emissions in the shipping fleet. The focus was to look at potential technical and operational key-aspects, and risks by using the various fuel types in internal combustion engines. MDO and LNG were included even though they are already well-implemented marine fuel types but were a good basis for creating a reference for the other fuel types that were considered. MDO is perhaps a fuel that is to be replaced in the future, while LNG which is a fossil fuel may be used as a bridging fuel to obtain lower emissions. The main alternative fuels considered was methanol, ammonia, hydrogen, and Thorium Molten Salt Reactor (nuclear power). Batteries and fuel cells were included only by a brief technical introduction. MS Nordlys from Hurtigruten was decided as a viable vessel, as the ship length is well within the 150 meters length limit, is operating along the Norwegian coast as of today with passengers. Hurtigruten aims to cut emissions, and the ship itself was seen as a good option to be retrofitted to operate on new fuel types. Considerations was made if it had sufficient space for the storage tanks required.

As MDO was included as the base case for comparison, it was seen that the fuel consumption was at 23,8 tons from Bergen to Trondheim which is a decent consumption compared to the other fuel types. It is also the one that requires the least storage space due to its high (volumetric) energy density (ref. Figure 1). It was the fuel type that was cheapest of them all, presumably due to its high availability. MDO has a high emission of NO_x, and further the highest emissions of CO_2 and SO_x. The total risk for MDO was found to be medium.

LNG was included as it is a well-established fuel type which is commercially available. Considered a bridge fuel to lower the emissions, and together with CCS is a good option. It was a good basis to compare with the alternative fuel types. LNG has a low fuel consumption compared to the others; it is also a cheap option relatively close to MDO. For storage capacity it amounts to 1,6 times greater than MDO. Further it has a high emission of CO_2, due to its carbon in the gas molecules like all other hydrocarbons. In a worst-case scenario it can cause methane slip to the atmosphere which is 28 times greater than CO_2 when looking at the total effect. It has low emissions of NO_x. The total risk was found to be medium.

Ammonia is considered an alternative fuel; however, it must be considered green ammonia to make it a viable alternative to reduce the emissions as this is carbon neutral. It has limited availability, and infrastructure must be developed to make it a considerable alternative. This in turn contributes to a higher acquisition cost of ammonia, and the cost was found to be the second most expensive alternative. The fuel consumption was by far the greatest of the alternatives, and this in turn amounts to a storage capacity 3 times greater than MDO. Ammonia has no CO_2 emissions as there is no carbon in the molecules, but on the other hand it can produce NO_x and unburnt NH_3. The risk is considered as high, mainly due to its toxicity.

Methanol is an alternative fuel that has very limited availability in Norway. The option for methanol production is that it should be produced by green methods or with biomass. The technology is under development and is at a later stage, involving for instance engines from Wartsila with the use of a pilot fuel in addition to methanol fuel. The fuel consumption was found to be the second greatest and requires the storage capacity of 2,5 times more than MDO. Presumably due to its limited availability the cost is expensive and was found to be the third most expensive option of the alternative fuels. For emissions it has a high release of CO_2 when combusted, so this technology is considered green when it is combined with CCS – further using the captured CO_2 to create new methanol with the other compounds. This also means with producing green methanol from biomass (pyrolysis) together with green hydrogen (from renewable energy sources) – this means that there are no added CO_2 emissions, as this gets recycled back to produce green methanol (with photosynthesis and biomass). For the combustion it also releases NO_x when combusted with air so this must be removed to prevent a release to the atmosphere, for instance this can be done by SCR technology. The risk of methanol was found to be medium.

Hydrogen is an alternative fuel that has been given a lot of attention as of lately. There is a large focus to further research and develop hydrogen as a viable fuel alternative to reduce emissions. Despite that, hydrogen is not available in Norway as of today – and if it is to be used as a fuel type this must be externally procured from another country. This makes hydrogen very expensive, and is in comparison to the other fuel types the most expensive option. Since hydrogen has the smallest molecules, it only requires 8,5 tons of fuel for the journey from Bergen to Trondheim. Although it requires the largest storage capacity when compared to the other fuel types (Not compared to TMSR) due to its low density. In comparison to MDO it requires 4,5 times more space. Speaking of storage; hydrogen is stored at -253 °C and requires enormous amounts of energy to keep cryogenically liquid – this in turn makes the gravimetric energy density almost 12 times lower when accounting for cooling systems. It has no emissions of CO_2 when combusted, however combustion in air may produce NO_x and other compounds of pure nitrogen that may form into more NO_x. These products from emission should be removed, for instance by SCR. The risk of hydrogen was found to be high, as it is highly flammable, explosive and can easily slip away from systems if permitted.

Thorium molten salt reactor was included as an alternative fuel, as nuclear power is a technology that produce no emissions to the atmosphere. Arguably, there is waste products that have radioactive radiation, but if accounted for and stored properly this technology can achieve the reduced emissions goals as set out in the Paris Agreement. TMSR is not available as of today in Norway, and this technology must be researched and developed – together with the creation of a competence centre in Norway for exchange of knowledge. TMSR has barely any fuel consumption as it is so dense and have an extreme energy density. Following an acquisition of TMSR, it is estimated to be reasonable when compared to the other fuel types – and this cost is allocated over 30 years. It will eventually become a cheaper option than the other alternative fuels as they have accumulated costs for re-fuelling – while TMSR on the other hand already have most of its cost already incorporated in the yearly cost. The downside of TMSR is that it requires a large storage capacity, and this is mainly due to the radioactive shielding which is required for safe operation. The storage capacity was calculated to be 453 m^3, and a large portion of this is just concrete. Ultimately the weight of the TMSR would be 2800 tons, and if installed on MS Nordlys – this would sink the ship.

To draw an overall conclusion, it can be argued that technology and infrastructure must be developed to a far greater extent for several of the fuel types before it can become a reality to use them as marine fuel. In addition, the price level must fall (which is assumed to improve when infrastructure is developed), in order for shipping companies to even be able to afford to operate their ships on greener fuels at all. As the alternative fuels is not available to a certain extent, it is very hard to conclude on why a specific fuel is better than the other alternatives. So, more research and development are necessary. Green methanol is a very interesting concept as an alternative fuel to reduce the overall emissions – as with this technology no CO_2 is accumulated in the atmosphere with the use of a biomass power plant and green hydrogen. But again, this technology and infrastructure must be developed to make it commercially available. Also, hopefully there can be more research on TMSR in the future as this is a very promising technology to be further explored due to its great potential when it comes to energy density and long-time operation.

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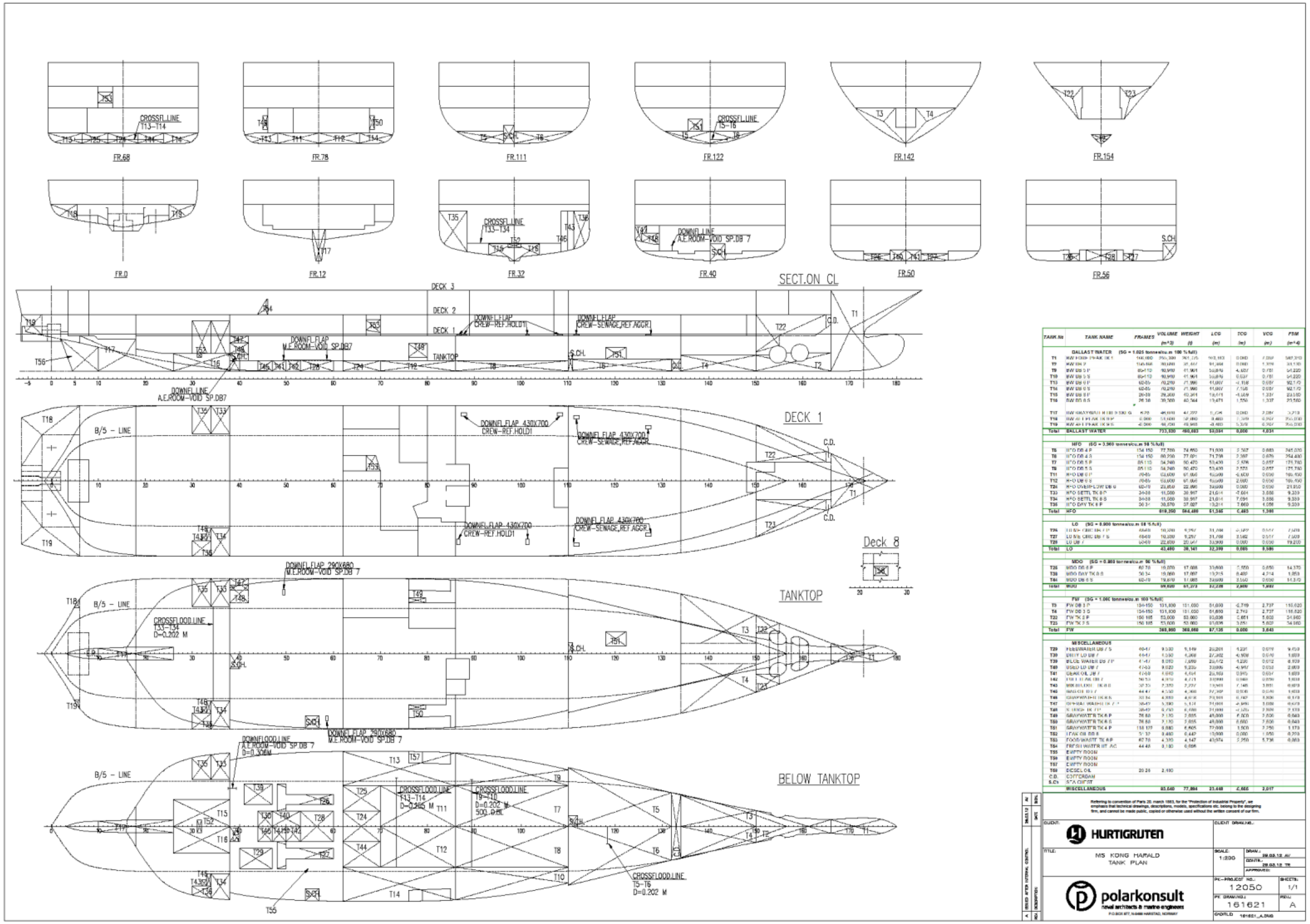
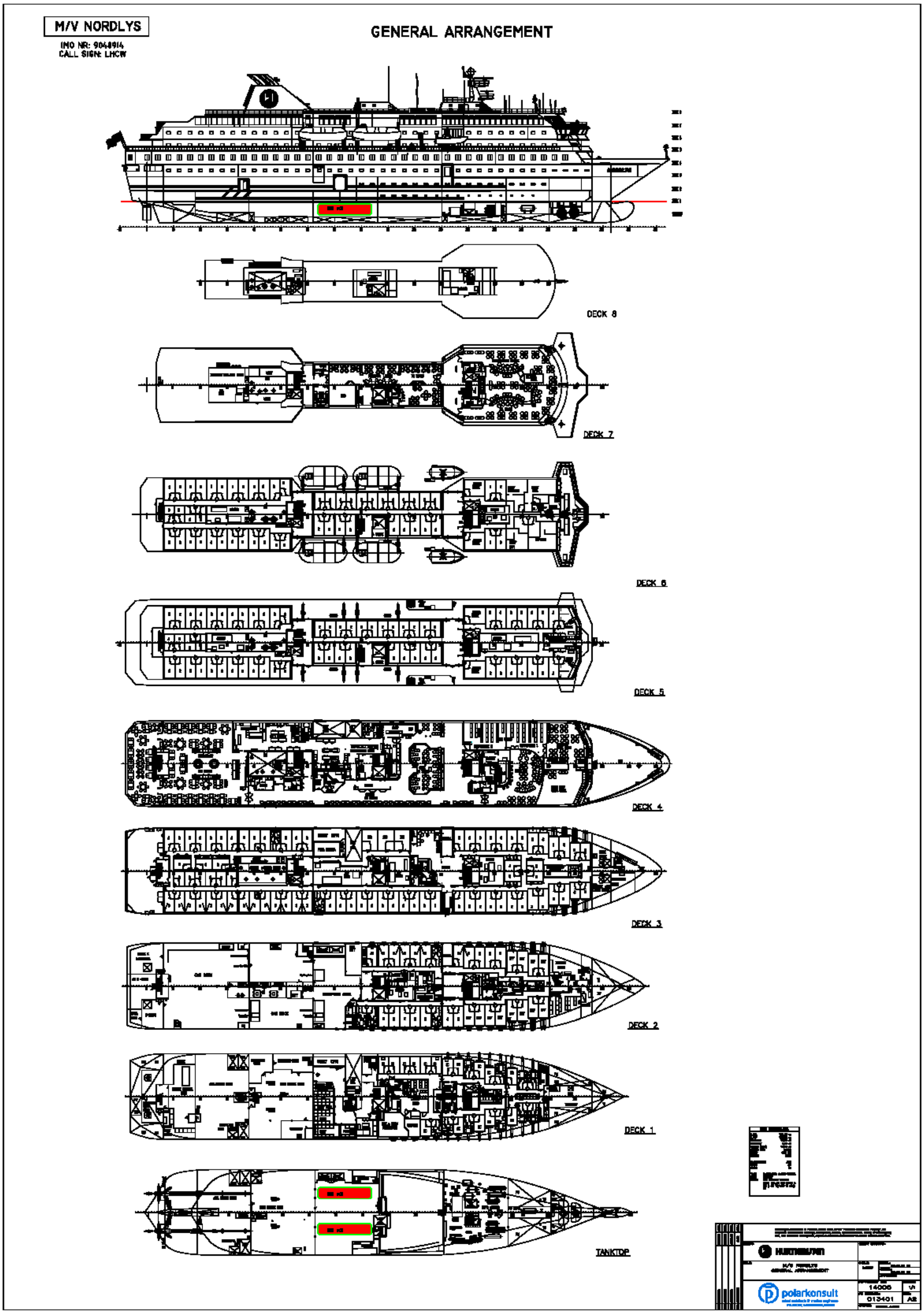
Appendices

- **Appendix A. Technical Drawings, Tank Arrangement «MS Kong Harald»**
- **Appendix B. Technical Drawings, LNG**
- **Appendix C. Technical Drawings, Ammonia**
- **Appendix D. Technical Drawings, Hydrogen**
- **Appendix E. Technical Drawings, TMSR**
- **Appendix F. Technical Drawings, Tank Design**
- **Appendix G. Excel Calculations**

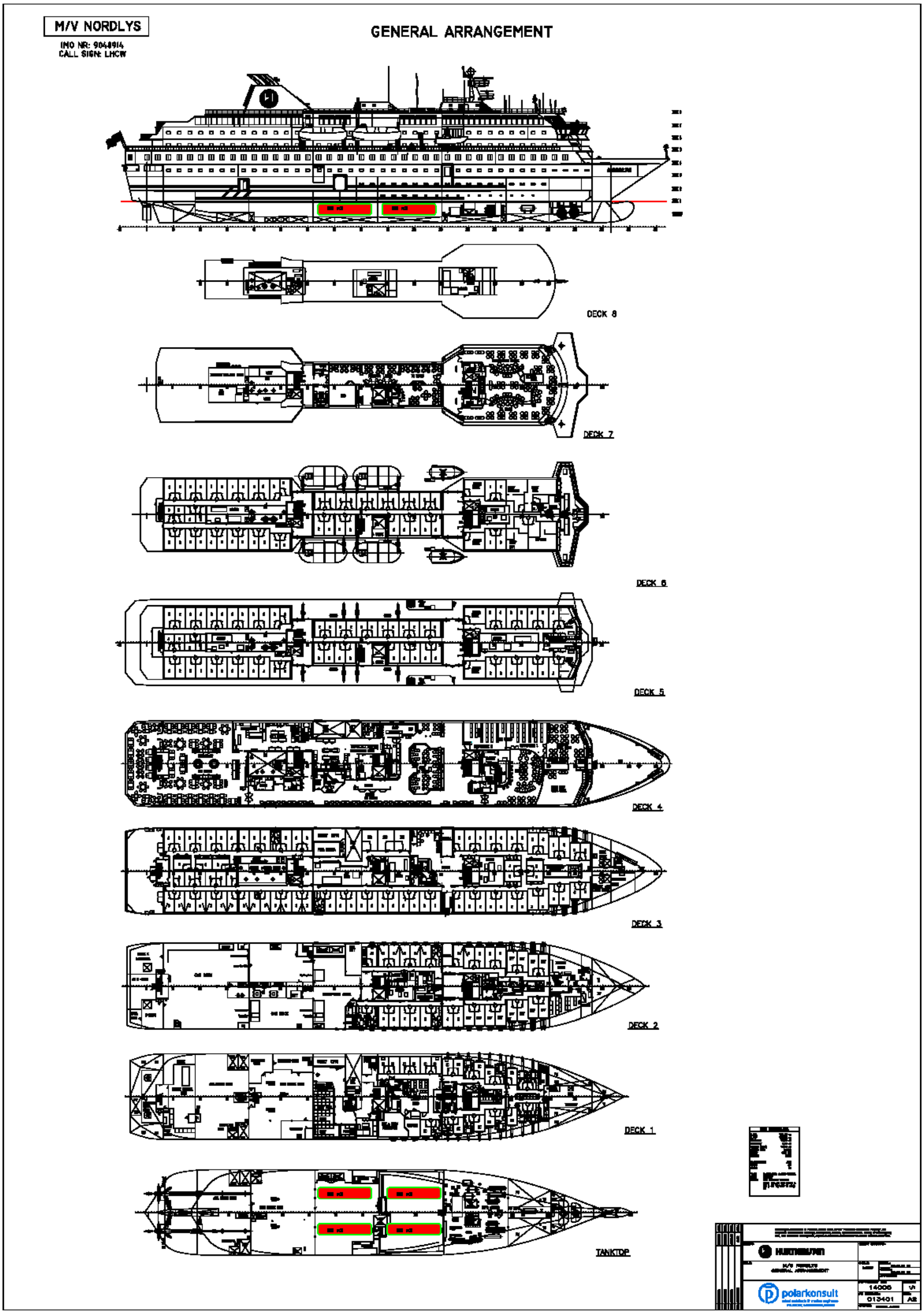
Appendix A. Technical Drawings, Tank Arrangement «MS Kong Harald»



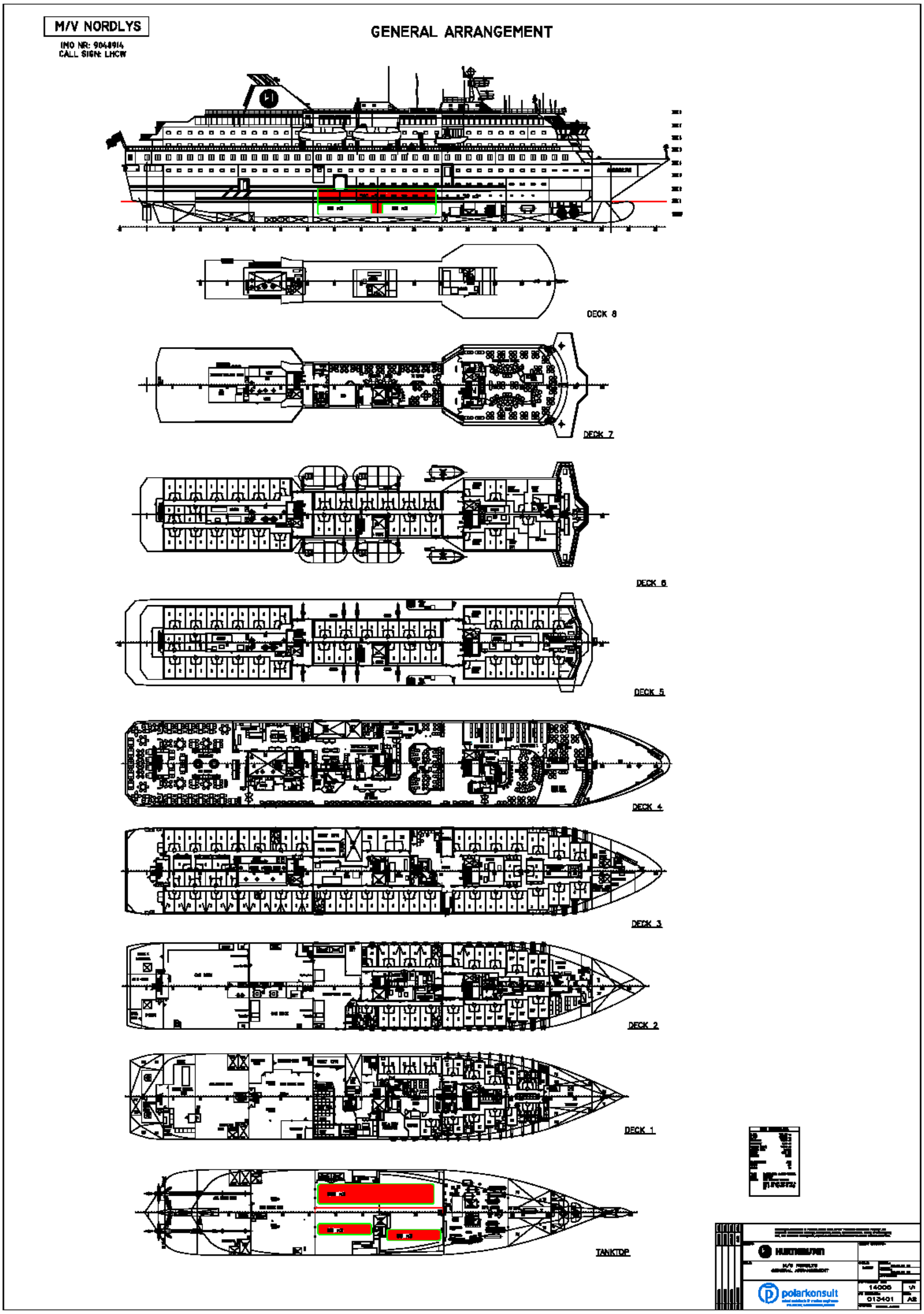
Appendix B. Technical Drawings, LNG



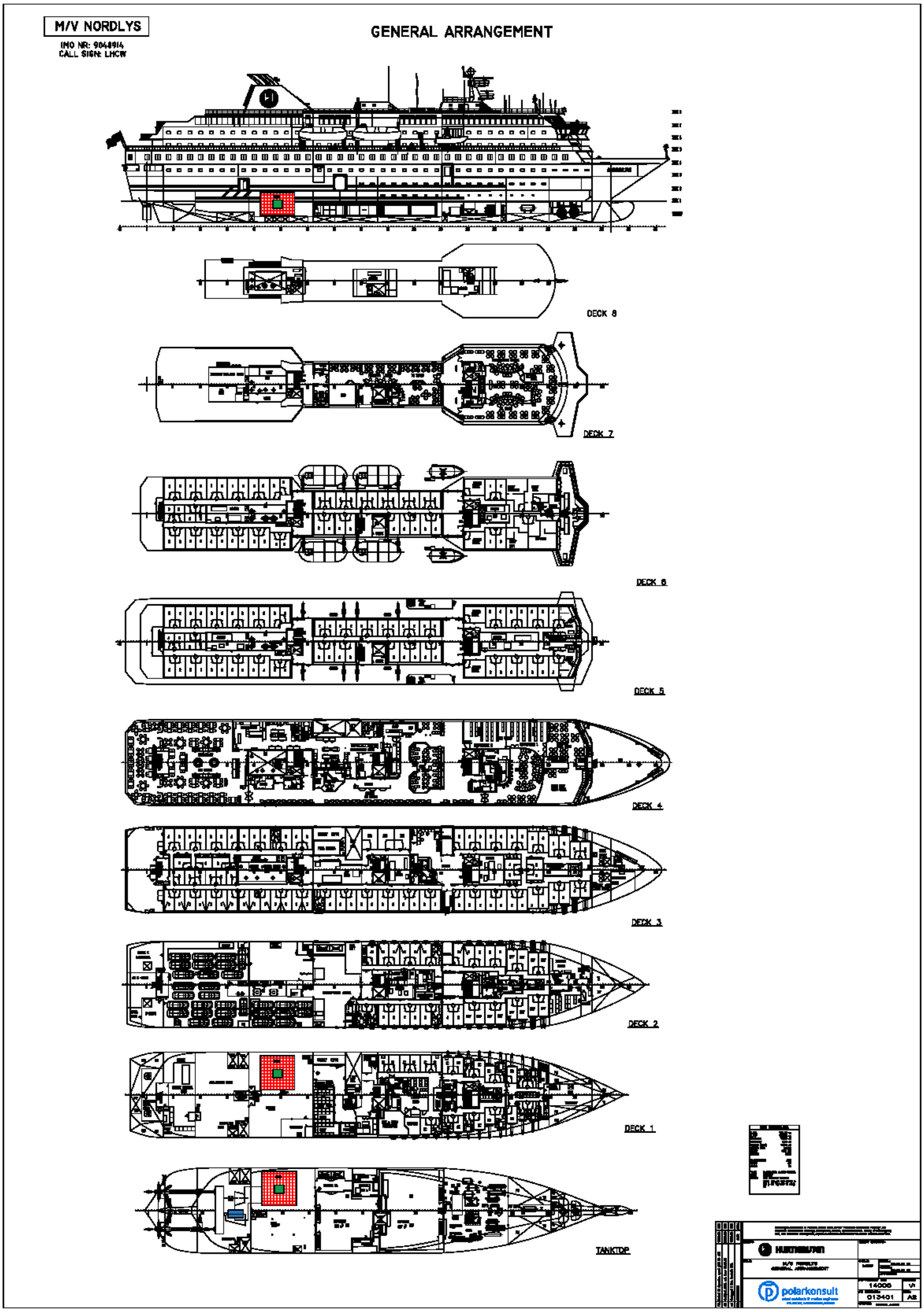
Appendix C. Technical Drawings, Ammonia



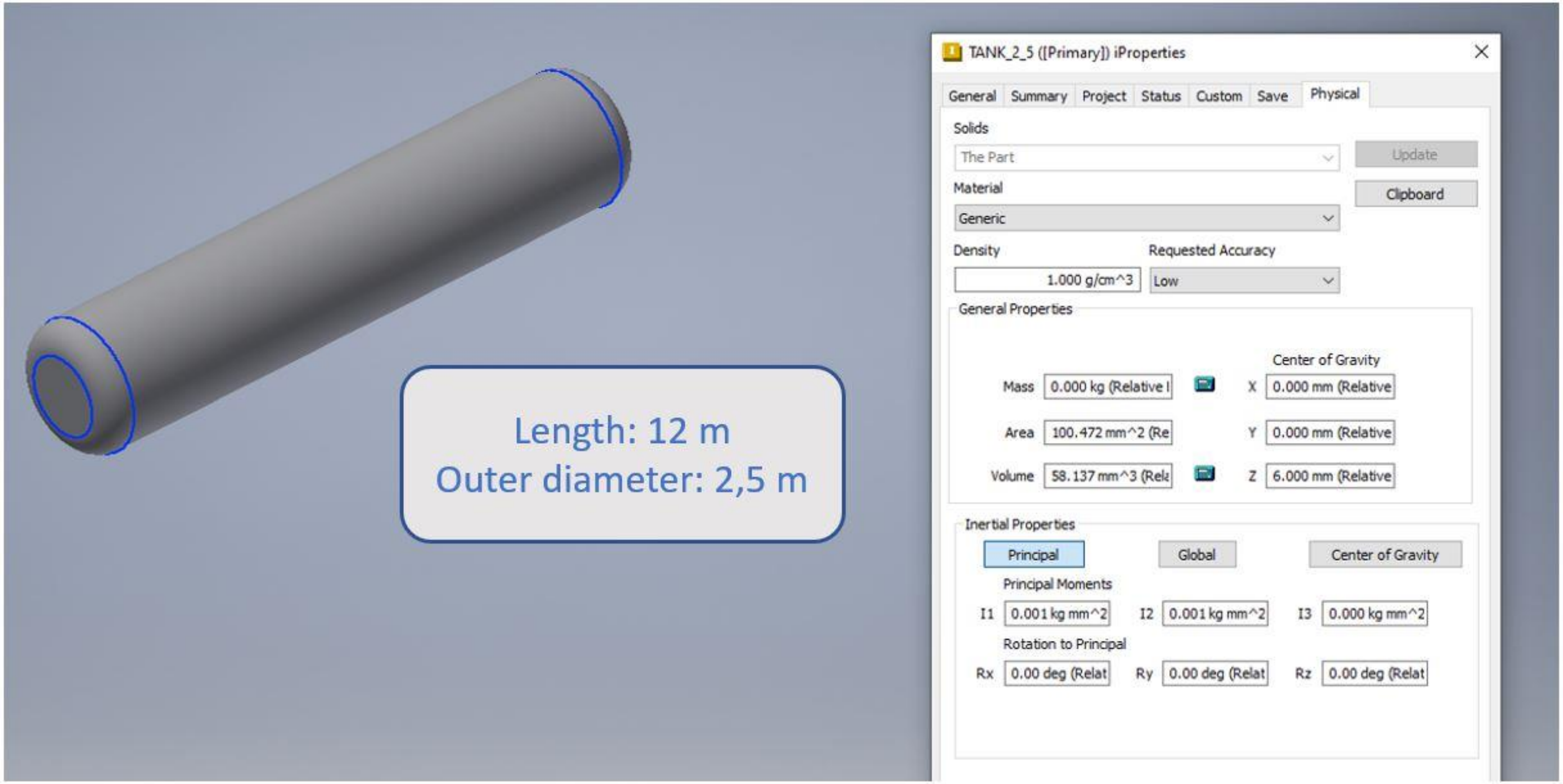
Appendix D. Technical Drawings, Hydrogen



Appendix E. Technical Drawings, TMSR



Appendix F. Technical Drawings, Tank Design



Length: 12 m
Outer diameter: 2,5 m

TANK_2_5 ([Primary]) iProperties

Solids: The Part

Material: Generic

Density: 1.000 g/cm^3

Requested Accuracy: Low

General Properties

Mass: 0.000 kg (Relative I

Area: 100.472 mm^2 (Re

Volume: 58.137 mm^3 (Rel

Center of Gravity

X: 0.000 mm (Relative

Y: 0.000 mm (Relative

Z: 6.000 mm (Relative

Inertial Properties

Principal Moments

I1: 0.001 kg mm^2

I2: 0.001 kg mm^2

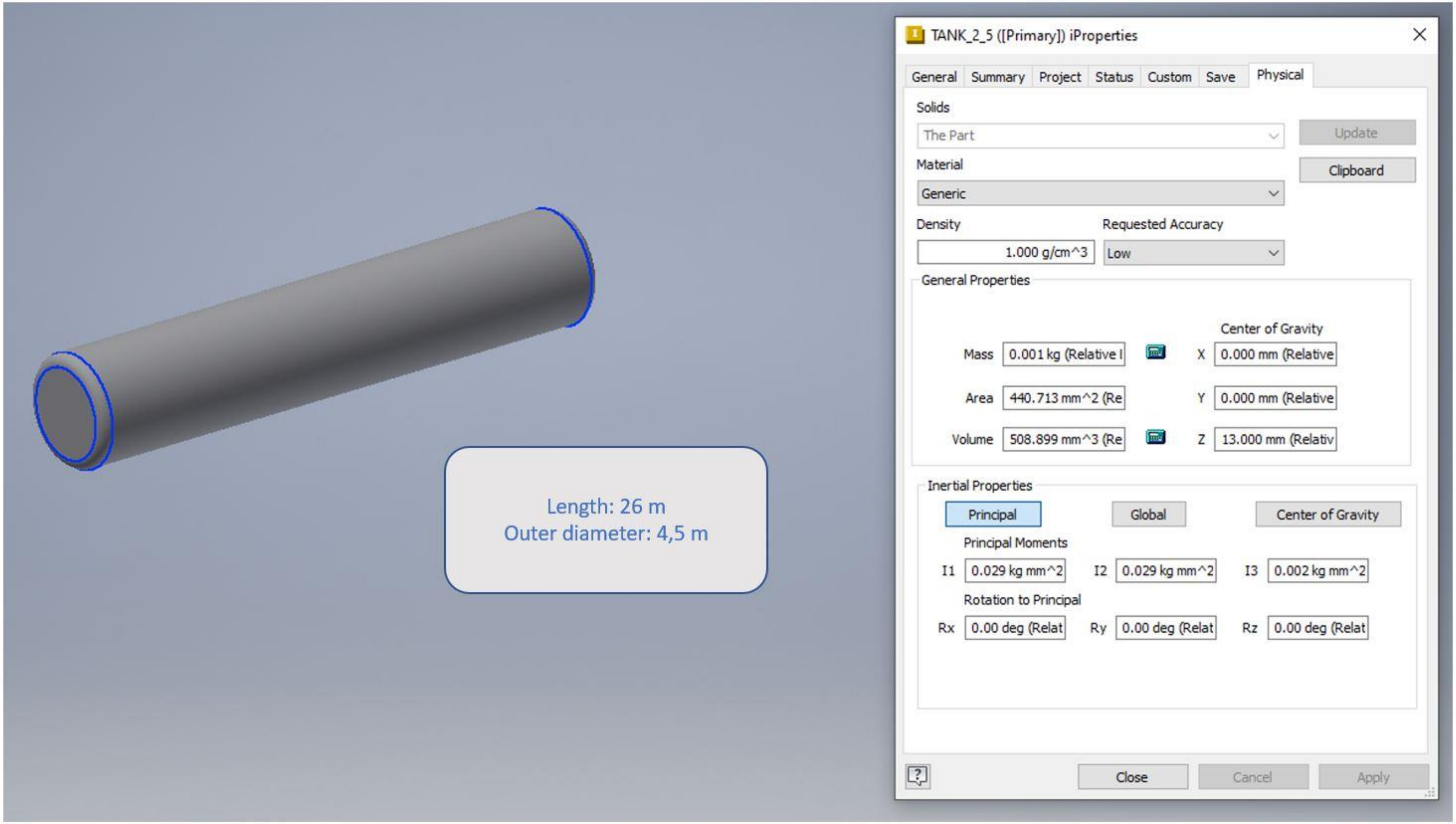
I3: 0.000 kg mm^2

Rotation to Principal

Rx: 0.00 deg (Relat

Ry: 0.00 deg (Relat

Rz: 0.00 deg (Relat



Length: 26 m
Outer diameter: 4,5 m

TANK_2_5 ([Primary]) iProperties

Solids: The Part

Material: Generic

Density: 1.000 g/cm^3

Requested Accuracy: Low

General Properties

Mass: 0.001 kg (Relative I

Area: 440.713 mm^2 (Re

Volume: 508.899 mm^3 (Re

Center of Gravity

X: 0.000 mm (Relative

Y: 0.000 mm (Relative

Z: 13.000 mm (Relativ

Inertial Properties

Principal Moments

I1: 0.029 kg mm^2

I2: 0.029 kg mm^2

I3: 0.002 kg mm^2

Rotation to Principal

Rx: 0.00 deg (Relat

Ry: 0.00 deg (Relat

Rz: 0.00 deg (Relat

Appendix G. Excel Calculations

Enclosed excel worksheets is found together with the thesis (folder) submission.

Excel worksheets:

- Master_Comparison_graphs.xlsx
- Master_Emission_calculations.xlsx
- Master_Risk-analysis.xls