Integration of a tank storage solution for alternative fuels on a RoRo ship

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by

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Master Thesis

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ABSTRACT

Although maritime shipping is one of the most efficient logistical solutions, this sector of activity generates around 3 % of global CO_2 emissions, accentuating the global warming challenges that the world is facing. Therefore, the International Maritime Organisation established a road map to reduce CO_2 emissions to half by 2050 compared to the 2008 levels. To reach this goal, alternative fuels are seen as a solution. Utilising carbon-free/carbon-neutral fuels will cut greenhouse gas emissions. Nonetheless, many alternative fuels are proposed, and each presents different environmental, economic, and technical characteristics.

Fuels such as liquified natural gas, hydrogen, ammonia, and methanol are brought forward as potential substitutes for fuel oil and diesel oil. To determine which fuel is the most suitable for integration onboard a RoRo ship running on conventional fuels, a multiple-criteria evaluation is done. The selected evaluation criteria are the volume and weight requirements, environmental safety, technology readiness, and fuel prices. To rank these fuels based on their performances, the analytical hierarchy process is a commonly used multicriteria decision-making method that allows the selection of the most suitable fuel solutions.

Methanol and ammonia were elected as suitable solutions based on the ranking results. Therefore, the next step was establishing an integration strategy on board the vessel. The integration process is initiated by defining proper locations for the fuel tanks. Tank dimensions are defined in order to reach the required storage capacity while respecting the structural limitation of the ship. Finally, different systems and components related to each fuel technology are defined, including the fuel supply system, the bunkering concept, and the main engine upgrade. Safety equipment and protocols related to fuel storage and handling are defined as per international regulations and class guidelines in order to prevent fires and other hazards.

The viability of ammonia or methanol as fuel solutions for the future has been studied by determining first the impact of the retrofitting process on the ship operation range and carrying capacity. Second, an evaluation of the projected CO_2 emissions for each fuel solution over one year of navigation is estimated based on different fuel pathways and compared to the recorded emissions over previous years to provide a better view of the reduction potential of each fuel solution. Finally, the economical viability of the fuel solutions is determined by calculating the total cost of ownership constituted of the capital cost of the engine and storage and the operating costs that are, in this work, fuel costs only. It becomes clear that the major driver of any energy transition project is the fuel price, where non-fossil-based fuels are relatively expensive. However, it is hoped that costs will be significantly reduced due to economies of scale in the future.

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Contents

1 INTRODUCTION

1.1 Maritime shipping and environmental challenges

1.1.1 Maritime shipping correlation with international trade

Maritime transport of goods is one of the most efficient logistics solutions. According to (Fagerholt and Psaraftis, 2015), it is responsible for moving worldwide billions of dollars worth of goods, with more than 90 % of global trade by weight [1]. The maritime trade growth rate faced a setback in 2019 and scored its worst levels since 2008-2009 due to the dropdown in world gross domestic product growth. Nevertheless, this regression was preceded by a moderate rise of 2.8 % in the year 2018 [2]. The total volume of maritime trade by volume was evaluated by the United Nations Conference on Trade and Development (UNCTAD) in 2019 at 11.08 billion tonnes. A breakdown of maritime trade by cargo type reveals that dry cargo accounts for over two-thirds of the total maritime trade by volume, crude oil, other liquid hydrocarbons, gases, and chemicals occupy the remaining share [2].

In terms of ton-miles, seaborne trade reached 59,503 billion ton-miles in 2019 (UNCTAD, 2020). Where over the past years, trade by containers and dry bulk form animated much of the growth. The gas trade recorded a swift expenditure of 9.9 % while other dry cargo segments, oil, and chemicals scored a slower growth [2].

1.1.2 Maritime transport and GHG emissions

Maritime shipping activity consumes around 13 million TJ representing 12 % of global energy used for transportation in 2015 [3]. In another facet, it impacts negatively the environment negatively. Seaborne trade is responsible for releasing 1,076 million tonnes of CO_2equivalent (CO_2eq) which approximately represent 2.89 % of global CO_2eq emissions in 2018, the main emissions of greenhouse gases (GHG) include carbon dioxides CO_2, and methane CH_4, nitrous oxides NOx, sulfur oxides SOx, and particulate matters. GHG emissions have recorded an increase of 9.6 % since the 2012 levels of 977 million tonnes mainly due to the increase in global seaborne trade [4]. Analysing deeply the global GHG emissions by focusing on each of its components over the years, provide important insight. Methane emissions in 2018 were evaluated to 140 thousand tonnes voyage-based, this represents an increase of 87 % since 2012. The increase is mainly driven by the adoption of LNG as fuel in dual-fuel machinery. SOx emissions in the same year were 9.6 million tonnes voyage-based creating a slight increase despite the stringent regulation in place. NOx emission on the other hand had a slow growth rate due to the increased numbers of vessels equipped to operate with NOx Tier II and Tier III machinery. NOx emissions in 2018 were 17.1 million tonnes voyage-base [4].

A better representation of carbon emissions evolution over the years can be illustrated by bringing forward the carbon intensity generated by a vessel per unit of work in $gCO_2 \cdot t^{-1} \cdot nm^{-1}$ or $gCO_2 \cdot dwt^{-1} \cdot nm^{-1}$, distance travelled in $kgCO_2 \cdot nm^{-1}$, or by running time in $tCO_2 \cdot h^{-1}$. Such representation way per voyage-base, or per vessel base will allow a better understanding of the evolution of international shipping emissions and their correlation to seaborne trade evolution. From Figure 1, it is clear that the growth of the seaborne trade between 1990 and 2008 was associated with a growth in CO_2eq emissions. The period between 2008 to 2014 is quite of a turnover, CO_2eq emissions were reduced despite the growth in maritime trade. Accordingly, carbon intensity is reduced. The introduction of the Energy Efficiency Operation Index (EEOI) and the Annual Efficiency Ratio (AER) made it possible to decouple emissions from the growth in maritime transport. Since 2014, the demand for maritime transport continued to increase over the years. Nevertheless, the carbon emissions CO_2eq followed a trend of slow growth owing to the moderate improvement in carbon intensity reduction.

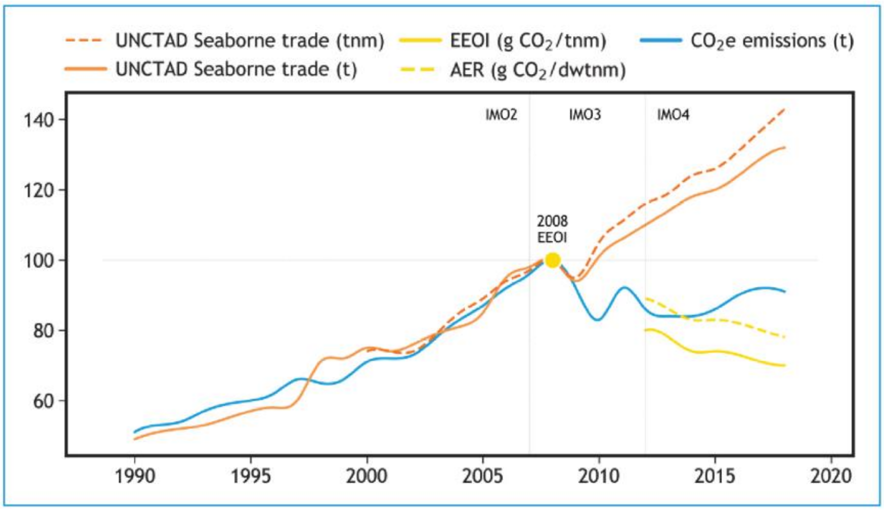

Figure 1. International shipping emissions and trade metrics according to the voyage-based allocation1 of international emissions [4]

Global warming is a major concern nowadays, it is drastically affecting social and economic life. according to (David Ford, 2017): “Global warming affects the geography within which the global economy operates. It shifts the zones of development. It alters the landscape. It alters the environments in which people feel at ease. Furthermore, if humans decide to act, the way industry and people use fossil fuels will alter” [5].

Several countries have agreed to cut GHG emissions under the United Nations Framework Convention on Climate Changes Paris Agreement of 2015, with the goal of keeping temperature rise below 2°C over pre-industrial levels and pursuing further measures to keep temperature rise below 1.5°C. Despite the fact that marine shipping was not included in the Paris Agreement, the International Maritime Organization (IMO) took the lead in setting up a roadmap to decrease GHG emissions. As the maritime industry's regulating authority, IMO is taking steps to promote the use of low/zero-carbon fuels in parallel with ongoing work to increase ship propulsion efficiency at both the design and operation stages.

1.1.3 Shipping emission regulations

IMO strategies are targeting a significant reduction in CO_2 emissions per transport work in this century by 40 % in 2030 and a 50 % reduction of GHGs annual emission from maritime shipping by the year 2050 as per 2008 levels [4]. With such ambitious objectives, IMO has introduced an update on the international convention for the prevention of marine pollution from ships (MARPOL) by featuring the ANNEX VI dedicated to overseeing Air pollution requirements. MARPOL ANNEX VI instore a progressive reduction in global emissions of SOx, NOx, and particles into the atmosphere as well as the introduction of emission control areas (ECAs) where strict regulations related to air emissions are enforced. At the time being, only four ECAs are established in North America and Europe, but it is also planned to create new emission-controlled areas in the near future in the Mediterranean Sea, the entry into force is expected to take place in 2024 [6]. The IMO policy to reduce sulfur content in bunkered fuels is divided into pallets over the years. The sulfur levels dropped from 4.5 % to reach a level of 0.5 % as a global limit and a sulfur level of 0.1 % inside the ECAs. NOx emission limitation strategy over the years is closely linked to the engine RPM, Tier III compliance has entered into force since 2016 on US coasts and in 2021 in the Baltic Sea and North-sea zone, where engine NOx emissions shall be less than 3 $g \cdot kWh^{-1}$. Figure 2 Illustrates the timeline of SOx and NOx reduction strategies. Studies were conducted over several samples of residual fuels to determine the sulfur content. The results of these tests conducted within the IMO strategies of sulfur monitoring showed that only 0.33 % failed to meet the global limitation of 3.5 % in 2016 [3].

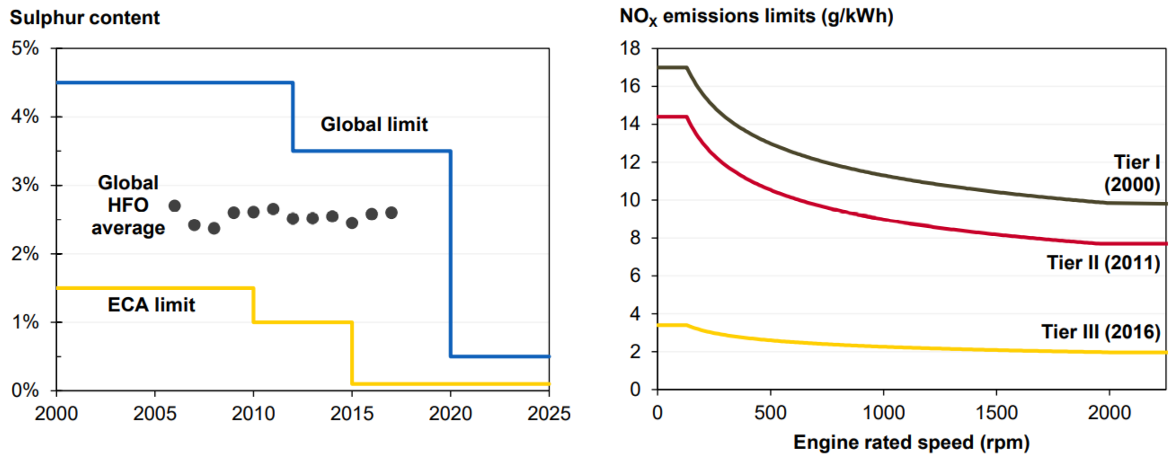

Figure 2. SOx and NOx reduction strategies [3]

In the same pathway, in July 2011 IMO adopted mandatory measures via the marine environment protection committee MEPC-62[nd] session to introduce global energy efficiency standards. The energy efficiency design index EEDI is a set of technical requirements to be applied to large and energy-intense segments of global merchant marine. Entered into force on 1 January 2013, EEDI applies to newly built ships, in order to limit the amount of CO_2 emitted per unit of work (t·nm). The limitation is to be enforced with a gradual reduction factor in three phases ranging from 10 % to 30 % by the year 2025 onwards. MEPC-62 resolution introduces as well ship energy efficiency management plan SEEMP, which provides shipping companies with guidelines to monitor and manage fleets to improve energy efficiency cost-effectively. Composed of two parts, part I of SEEMP has been mandatory for ships over 400 GT since 01 January 2013. From 01 March 2018 part II of SEEMP requires that ships of 5,000 GT and above comply with regulation 22.2 of MARPOL Annex VI. IMO requires a SEEMP onboard all existing ships and newly built ones. It should be customized to meet the characteristics of each fleet; therefore, it is a ship-specific plan. An important addition to IMO´s regulation was a new amendment to MARPOL Annex VI by introducing the Energy efficiency of existing ships Index EEXI and requirements to reduce carbon intensity through carbon intensity index CII on 17[th] June 2021. Entering into force on 01 January 2023 vessels over 400 GT shall comply with EEXI requirements [7].

1.2 World fleet status and challenges

1.2.1 World fleet size

In early 2020, the world fleet counted 98,140 ships of 100 GT and above which is equivalent to 2,061,944,484 dwt of capacity. Compared to 2019 statistics, a growth of 4.1 % is registered, it is the highest rate recorded since 2014. The gas carrier segment takes the lead with the highest growth rate followed by oil tankers, bulk carriers, and then container vessels (UNCTAD, 2020). The composition of the actual fleet by vessel type in terms of dead-weight tons is headed by the bulk carrier segment with a share of 43 % followed by Oil tankers with a contribution of 29 %, and container ships represent 13 %, the rest of the dwt capacity. Figure 3 provides a better illustration of the share taken by each vessel type in the world fleet. General cargo ships take the lead with a vessel number of 15,106 which is 28 % of the world fleet, followed by dry bulk carriers representing 22 % of the total with a size of 12,258 ships. Crude oil vessels and RoRo carrier/passenger fleet are both similar in size counting around 7,000 units, combined they contribute with 26 % of the global composition. Both chemical tankers and container ship fleets count around 5,000 units which is 10 %. The smallest world fleet is the LNG carriers with a contribution of 4 % and a number of 2,032 vessels.

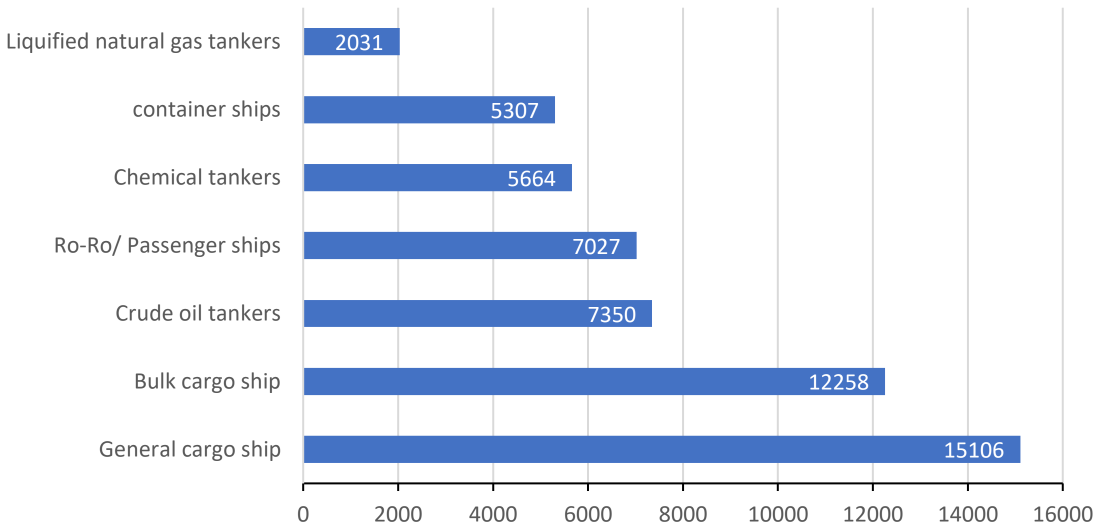

Figure 3. World merchant fleet composition by number as of 01 Jan 2021. Available from Statista 2021.

1.2.2 World fleet age

The average age of the global fleet in 2020 was 21.29 years in terms of the number of ships and 10.76 years in terms of carrying capacity. This is mainly due to the fact that new-built ships were often large-capacity ships to be economically and environmentally efficient. As numbers show, the average size of the ships built between 2016 and 2020 is greater than those built 20 years ago mainly due to the introduction of the economy of scale [2]. The information about ship age is strongly linked with any decarbonization plan, younger vessels are fuel-efficient and eco-friendly thanks to technological advancement. Unfortunately, only 11.64 % of ships are between 0 to 4 years old, 20.11 % are 5 to 9 years old, 17.42 % are 10 to 14 years old and 50.83 % are over 15 years old (UNCTAD, 2020).

Therefore, it is clear that approximately half of the world's fleet requires solutions to maintain their operations. For this purpose, IMO added to the initial agreement, various measures that were implemented in short (2018-2023), medium (2023-2030), and long term (beyond 2030). Short-term measures emphasize carbon emission reduction via speed reduction, route optimization, and endorsing the use of low sulfur fuels. Mid-term and long-term measures are more drastic with the main objective of using carbon-free/carbon-neutral fuels and introducing new propulsion concepts like wind-assisted propulsion.

1.3 Alternative Fuels for the zero-emission pathway

1.3.1 Fossil fuel price evolution

During ship operation, fuel costs account for 76 % of voyage costs which represents 40 % of the total cost of running a ship [8]. Although most of the ships are running on low-quality and cheap residual fuels such as Intermediate fuel oil (IFO 180), price fluctuation can strongly impact their economic performance. Future scenarios are strongly volatile [9]. Four possible pathways are announced based on the oil price in 2020. A drop-in price will be conditioned to the adoption of the net-zero emission (NZE) vision for the year 2050. Another prediction is based on the assumption that governments will maintain their announced pledges (APS) to double clean energy investment over the next decades. Unfortunately, the actions proposed in the APS are defective because of the sharp divergence between countries in terms of implementation speed. The stated policies scenario (STEPS) reflects the expected prices if the governments remain on the same policies. However, if the global economy follows a sustainable development (SD) path, prices will likely grow until reaching a plateau over the next three decades [9].Figure4 illustrates each scenario presented by IEA. With all scenarios showing an increase in oil prices, it became clear that a need to reduce fuel consumption has gained cause in the maritime field. Reducing fuel consumption on board ships leads to considerable savings in operating costs and allows ship operators to remain competitive.

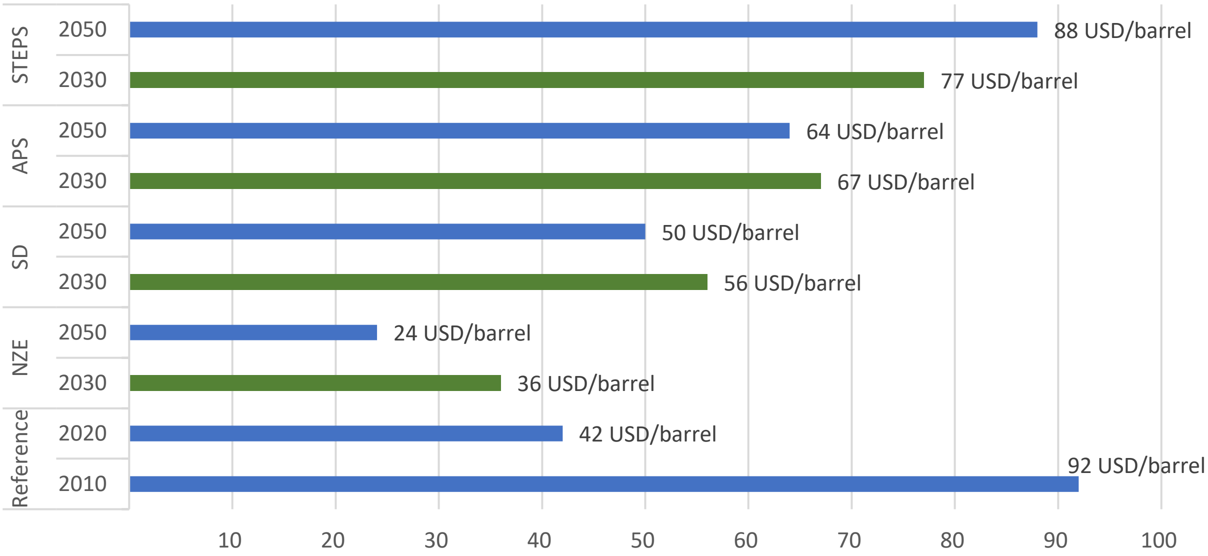

Figure 4. IEA fuel price by scenario [9]

1.3.2 Fuel consumption reduction strategies

Reduction of fuel consumption became a major concern not only to reduce operational costs but also to lower GHG emissions; (P. Gilbert et al, 2018) evaluation of carbon emissions on conventional fuels illustrated that the combustion process is responsible for around 80 % of CO_2eq emitted while the other 20 % are released in upstream [10][3]. GHG emission reduction can be achieved by adopting proper measures both at the design and operation stages. To achieve the highest mitigation potential, the focus has to be oriented toward six main categories: hull design; the economy of scale; power and propulsion systems; speed optimization; fuels and alternative energy sources; weather routing, and scheduling (P. Gilbert et al, 2018).

A well-thought ship design will lead to a greater performance of the ship. The first important solution to adopt is the reduction of vessel weight by introducing new materials with higher mechanical characteristics and adopting optimized designs assuring a better material distribution across the ship structure, in a conventional ship the weight can be lowered by 5 %-20 % with the use of lightweight materials in non-structural areas. Such reduction will allow a 9 % reduction in required propulsion power [10] [11]. Hull form optimization using CFD and model testing has been at the core of research for many years. Finding optimum dimensions and hull shape ratios will significantly decrease resistance, therefore, cutting 10 % of the fuel consumption of a tanker [12]. The economy of scale stands for the increase of cargo transported per voyage; doubling the cargo capacity will only require increasing the power output and fuel consumption by two-thirds, therefore energy-efficiency per freight unit is increased [10]. Increasing the propulsion system global efficiency can be reached by using enhanced propeller designs with optimal interaction with the hull, improved power plants with post-treatment installation such as heat recovery systems, and common rail injection systems. Adopting better fuels both in terms of energy content and emission potential such as LNG reduces energy demand on board for heating and electricity compared to HFO, for a typical ferry at 22 kn of speed, the total saving in energy is up to 4 % [11]. In a ship life time, attention has to be focused on conducting proper maintenance of hull condition. Regular polishing of underwater surfaces and application of hull coating will result in less roughness. During operation, several measures can be undertaken to maintain a low fuel consumption, speed reduction is one option, it will induce a reduction of energy demand, and on a similar journey, 0.5 kn of speed reduction generates a 7 % energy saving [11]. Weather routing and voyage planning on long-distance journeys, the route is chosen based on information about weather and sea state conditions. The voyage path may not be the shortest way between the two destinations, but it is constantly updated to maintain an optimal path through calm seas and favorable wind conditions. Ship trim and draft condition are at the center of different studies. Observing trim condition effect on ship resistance through water for the same draft and speed, it became essential to have a favorable trim condition in order to reduce fuel consumption. CFD simulations helped in a significant way to establish a relationship between trim conditions and ship resistance. Results showed that trim by bow has a pronounced increasing effect on total resistance. The effect of trim by the stern is varying, but the optimum point is at 0.02 trim by stern (S. Sherbaz and W. Duan, 2014) [13]. However, providing a wider overview of the mitigation potential of each measure requires multiple studies considering different ship types, fleet sizes, and scenarios. Figure 5 provides a graphical overview of the mitigation impact for each of the listed measures, where the range of impacts is presented based on several individual literature studies. It is important to highlight the wide range of emission reduction potential for one single measure, i.e. speed optimization impact is between 1-60 %. Such observation indicates the high uncertainty surrounding the effectiveness of such measures. though the same observation can also serve as a baseline for any decision-making process both at the design or operation stages. For a new-built ship, dedicating more time and resources to defining the optimal vessel size, hull shape, and machinery will be more effective as a starting point. For operating ships, measures such as speed and voyage optimization are more effective.

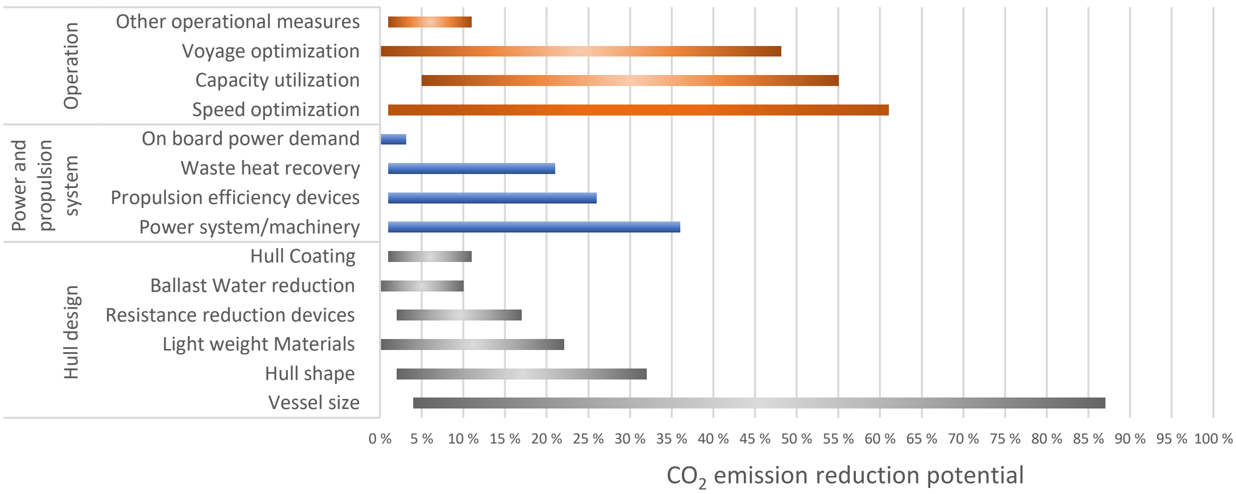

Figure 5. CO_2 reduction potential from individual measures [10]

Nevertheless, with the actual reduction of carbon intensity achieved in maritime shipping, it will remain difficult to meet the IMO´s 2050 ambitions only by energy-saving technologies and speed reduction of vessels. Thus (Mr. K. Lim from IMO) states that the reduction of CO_2 amounts has to start at the fuel level by using zero/low carbon fuels [4].

Many studies have been carried out in order to tackle the transition to zero-carbon/ carbon-neutral fuels, main focus was to examine the impact of such energy transition on how ships are powered and how this may affect shipowners seeking for transition. The main focus is on practical solutions and fuel strategies to achieve energy transition [14]. However, most of these studies are holistic, trying to answer the question of which promising fuels are worth shifting to. It is suggested that the promising fuel candidates for 2050 include ammonia coming from electrolysis (E-ammonia), or from natural gas reformation coupled with carbon capture and storage making blue ammonia, and bio-methanol [14]. Additionally, bio-LNG, bio-marine gas oil (bio-MGO), synthetic liquefied natural gas (LNG), and MGO produced from electrolysis (E-LNG and E-MGO), were promoted as candidates as drop-in fuels for existing ships, and some newbuilds. Due to the relatively long lifetime of a ship, planning a fuel transition is surrounded by large uncertainties, therefore, DNV announce planning a flexible fuel solution and alternative ready solution could ease the transition and minimize the risk of investing in stranded assets.

1.4 Aims and objectives

With the increase in environmental requirements, the main focus of this work is to assist in the decision-making process in the field of energy transition and decarbonization of the shipping industry. The intentions are to perform a study on a RoRo ship built in 2005 running on heavy fuel oil HFO and marine diesel oil MDO so that it can be converted to run with an alternative fuel solution. A novel fuel technology will provide compliance with IMO regulation in terms of GHG emissions. Such an operation poses a series of challenges on several levels. First, out of many promoting fuel solutions, one has to be adopted. The decision is driven by various parameters that are on one side, techno-economic so to say related to the market potential of the fuel in terms of availability trough out the operation area of the vessel, the cost of the fuel per unit of energy, and undeniably the cost related to the transition. On the other side, a modification of the fuel system will induce design alteration. Correction on the fuel storage containment, fuel feed system, and main machinery has to be upgraded while upholding regulations to provide safe and efficient operating conditions. The engineering task is to developpe a solution that meets the design implications and economical expectations.

Design implication related to the implementation of a chosen fuel system, deemed viable from the techno-economic study, has to be carried out. This implies adopting an engineering approach to key systems and components onboard the vessel. The first system to tackle is fuel storage, evaluating optimal storage capacity, tank size, tank type, material characteristics, and design pressure under operation conditions. Along with that, evaluation of additional tank capacity for pilot fuel if required. Then establish an efficient general arrangement that can accommodate the fuel storage system with minimal impact on operations and apply any required structural modification for that intent. Another part to approach is the power plant. Evaluating the consequence of a fuel change on global efficiency and also the consequences on the installations and supply system. Finally, the integration of the fuel system onboard the ship requires verifying its conformity with safety measures established by statutory regulations and class rules.

2 POTENTIAL ALTERNATIVE FUELS FOR ENERGY TRANSITION

One of IMOs fourth GHG study conclusions was that existing carbon intensity reduction strategies will not be sufficient to satisfy IMO targets by 2050 [4], it became crucial for the maritime community to address energy transition to replace Heavy fuel oil (HFO) and Marine diesel oil (MDO). Several candidate alternative fuels have been mentioned in the literature, where their potential to substitute fossil fuel was studied based on a comparison over different aspects [3][10][15][16][17]. Any attempt to select a different marine fuel has to account for the different aspects that surround it, the Figure 6 summarizes these aspects. Technical characteristics relate to the fuel properties and required adaptations for onboard usage. the economical aspect is equally important, where fuel prices and related operational costs can affect the economic performance of the vessel; besides, the integration of a new fuel solution requires large investments. The main incentive for fuel transition is environmental, therefore, the life cycle performance is crucial. A life cycle environmental analysis considers both the upstream during fuel production, also referred to as well to tank (WTT), and the downstream during the fuel combustion referred to as tank to wake (TTW). Another important aspect is related to safe handling and storage, fuel production, supply chain, and infrastructure availability. Differences between ship types and trades influence the choice of fuel systems. In contrast to short sea segments, long-going ships have fewer options for transition. (Hansson et al, 2019) state that alternative maritime fuel options will be ranked differently depending on the priorities and values of various shipping-related entities [18]. Long-going ships require to carry large amounts of energy onboard sufficient to feed in first place the main propulsion system and other related consumers.

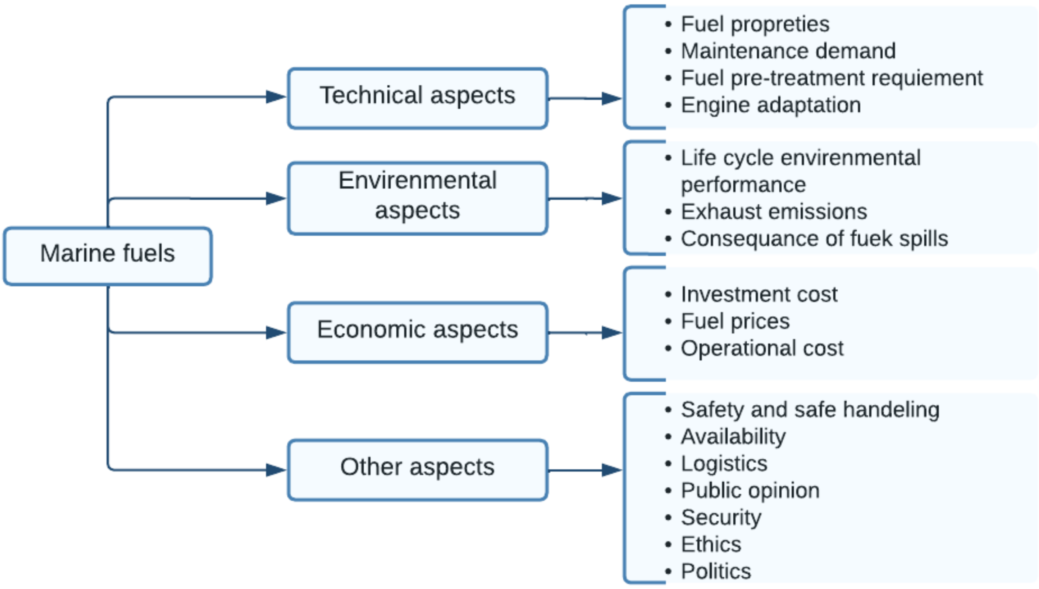

Figure 6. Aspects to consider when selecting future marine fuels [19]

Until June 2021, 99.5 % of the world fleet is powered by oil-based fuels, the remaining 0.5 % represents the uptake of alternative fuels, mainly powered by batteries, LNG, and methanol. In the same year, on order books, ships fuelled with alternative solution orders constitute 11.84 % of the total ordered ships. In addition to LNG and liquid petrol gas (LPG) fuelled ships, hydrogen, methanol, and ammonia are emerging. Figure 7 highlights the share of each emerging solution.

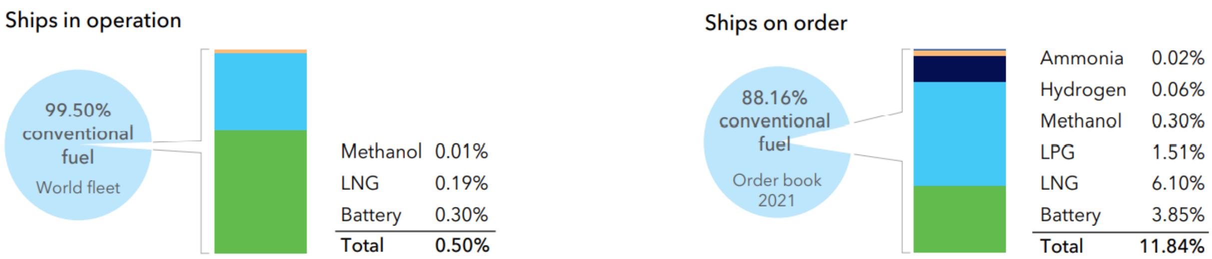

Figure 7. Share of alternative fuels in world fleet and future [14]

2.1 List of alternative marine fuels

Literature studies mentioned above bring forward liquified natural gas (LNG), methanol, hydrogen, ammonia and biofuels as alternatives for fossil fuels. Each fuel solution can be used with different propulsion technologies, the first proposal is combustion engines. Such an approach is considered safe since thermal machines are the most common prime movers onboard ships. Thus, the capital cost to integrate such fuels is relatively low, furthermore, a possibility for retrofitting outdated engines provides suitable solutions to shipowners. Fuel cell technologies are also emerging, they produce electricity from the chemical energy stored in the fuel. This conversion process is done at a relatively low temperature compared to the combustion process [21]. Because of its excellent energy efficiency and low environmental effect, (Yan et al, 2020) affirm that fuel cell technology is considered a very promising technology[22].

2.1.1 Liquified natural gas

Natural gas is a low-carbon fuel mainly composed of methane (CH_4) and small amounts of ethane (C_2H_8). Natural gas is a widely used commodity in different industries. To facilitate the transport and storage of natural gas, liquification process enable a reduction of volume of 600 times. At atmospheric pressure, the required temperature to keep natural gas in a liquid form is – 162°C [3]. LNG density in a liquefied form is 443.5 $kg \cdot m^{-3}$, with each kilogram carrying 13.9 kWh of energy [23]. LNG as a marine fuel has been used on LNG carriers by burning the Boil of gas (BOG) generated during the voyage via steam turbines. later on, for commercial ships, dual fuel diesel engines with a large bore able to burn natural gas are introduced to the market by major engine manufacturers [24]. According to (DNV, 2021), 286 LNG fuelled ships are in operation mainly in Europe. The main incentive for LNG fuel integration on commercial vessels is its low cost compared to other fossil fuels. Figure 8 illustrate how gas price rates over years are considerably low.

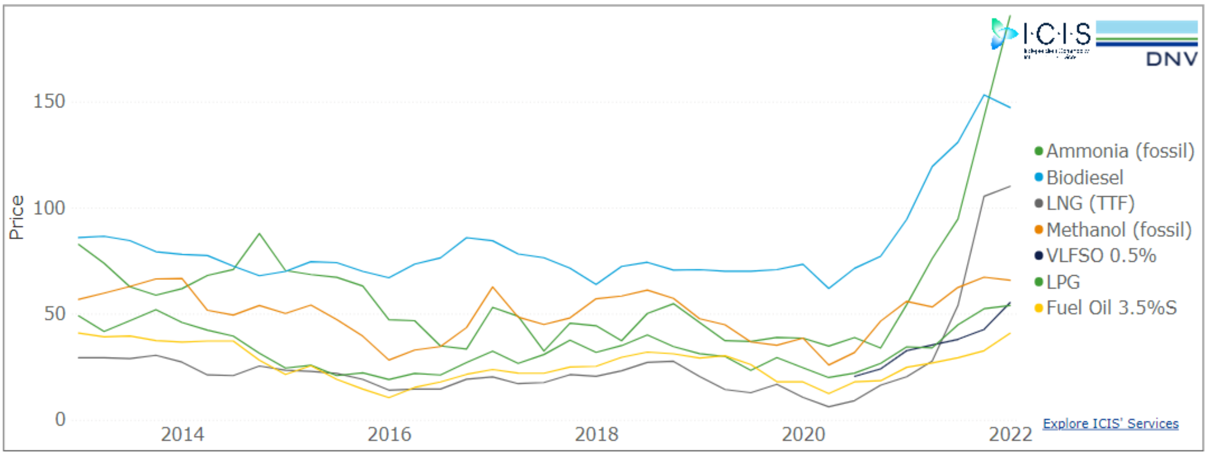

Figure 8. ship fuel prices rates. Available from Alternative Fuels Insight (dnv.com) [Accessed on 08 July 2022]

The environmental impact due to LNG combustion is limited in comparison with heavy fuel or diesel, significant reduction in NOx emission are registered. Being free of sulphur, SOx emission and produced particulate matters are lowered by 99 % with reference to MGO [25]. However, methane leaking from the unburned mixture in the engine or from the bunkering process has a global warming potential 36 times greater than CO_2 [3]. In addition to the use of LNG in combustion engines, LNG can be used in other ways. The high hydrogen content can be extracted to be used in fuel cells to generate electricity.

2.1.2 Methanol

Methanol is the simplest form of alcohol, defined as CH_3OH or MeOH. It is a colourless water-soluble liquid. Flammable and highly volatile compound, it takes a liquid form at room temperature and pressure. Methanol's high hydrogen content compared to similar liquid fuels raised the interest to use it as ship fuel. The commercial fleet of methanol-fuelled ships count 10 units in 2019 [26]. Methanol global production reached 100 million tons in 2020. However, sustainable methanol production constitutes only 0.2 %. In Figure 9 the different pathways of methanol production can be seen, starting from different primary sources. Methanol production requires hydrogen and carbon dioxide, that can be obtained from fossil sources or from renewable ones. The classification on the produced methanol is based on the source of the primary feedstock and the production process, Thus, the lower the carbon emissions in the methanol production process, the more environmentally friendly it becomes.

Methanol prices depend on the source, at the actual rates, fossil methanol is cheaper compared to sustainable methanol, nonetheless, sustainable methanol prices will decrease in view of the economy of scale and the increased taxation over carbon emissions [27].

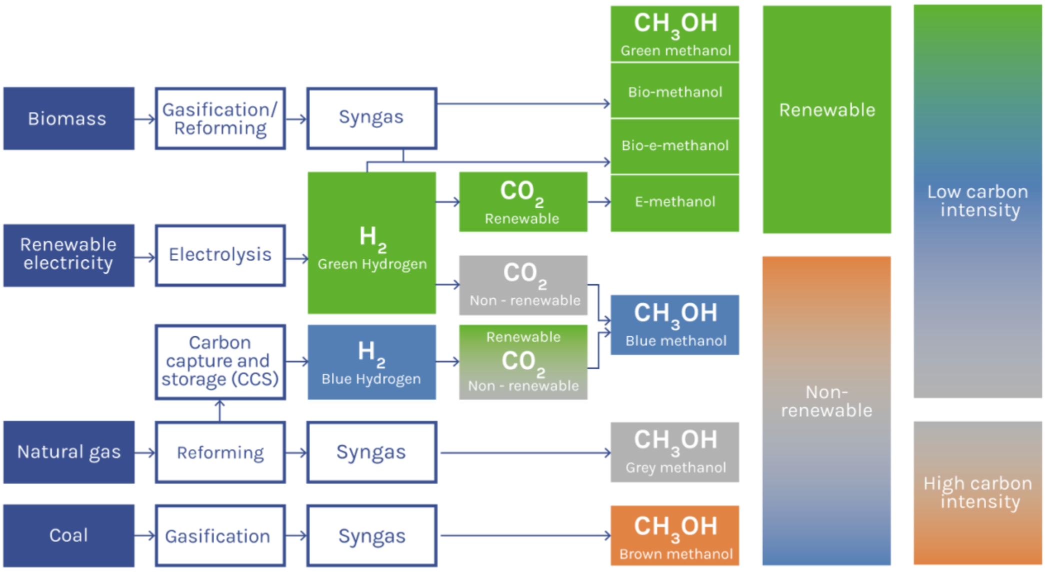

Figure 9. Methanol production pathways. Available from https://cyprusshippingnews.com/2022/03/22/methanol-as-a-scalable-zero-emission-fuel/ [Accessed on 12 July 2022]

Due to its liquid state at room temperature and pressure, methanol can be directly used as drop-in fuel for an internal combustion engine. The combustion process generates water an small amounts of CO_2 emissions. Given the absence of sulphur, no SOx emissions and nearly zero Particulate matters are emitted during the combustion process [10]. The low-temperature flame allows a 60 % reduction of NOx emission compared to fuel oil at the tank to wake [27]. As a consequence of being flammable at low temperatures, methanol is classified as a low flash point fuel; hence, its utilization onboard ships are regulated by the International Code of safety for ships using gases or low flashpoint fuels (IGF-Code).

2.1.3 Ammonia

Ammonia (NH_3) is a well-known compound used mainly in the agricultural industry as fertilizer [28]. The quest to lower GHG emissions raised questions about the feasibility of using ammonia as a carbon-free fuel. According to the International Transport Forum (ITF), ammonia and hydrogen will account for 70 % of the global fuel market in order to fulfil the target of 80 % carbon reduction [29]. Ammonia is a toxic gas with a distinctive smell. Ammonia handling is similar to conventional gas fuels like propane [30]. Ammonia can take a liquid state at room temperature by pressurization at 10 bar. At atmospheric pressure, the liquification process requires a cryogenic condition of -33°C at atmosphere pressure [28].

Several engine manufacturers and ship operators formed consortia to facilitate ammonia integration onboard ships and establish a global supply chain for this commodity [30]. Ammonia production worldwide reaches around 180M tonnes annually; most of this production comes from non-sustainable sources [28]. The Haber-Bosch process uses hydrogen obtained from natural gas fractions and nitrogen captured from the air. (Kobayashi et al, 2019) estimate that this process contributes to 1 % of the global CO_2 emissions. Nonetheless, projects to produce ammonia from sustainable resources are in place aiming to replace the fossil-based production of hydrogen with hydrogen obtained from regenerative sources. Figure 10 illustrate the different path ways to produce ammonia. The pathways are classified depending on the primary source of hydrogen supply. Conventionally hydrogen is obtained by cracking fossil hydrogen carriers like methane, coal or biomass. Sustainable pathways on another hand, procure the hydrogen from water via electrolysis with a green electricity or via thermomechanical reaction. Nitrogen gas is sourced from the ambient air via air separation unit running on green electricity.

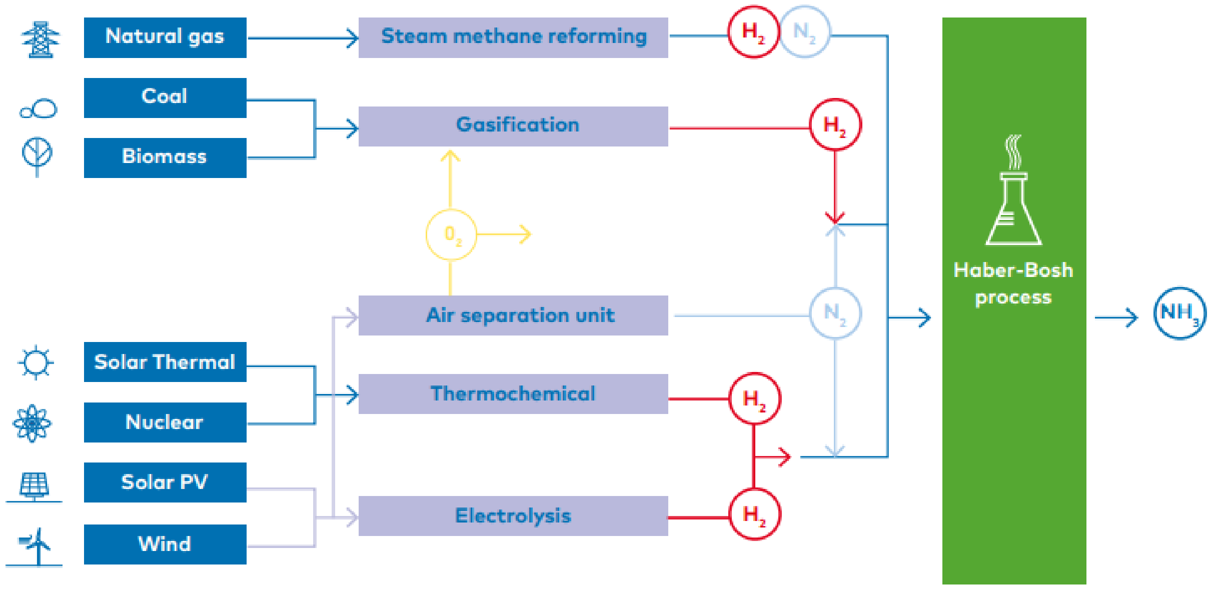

Figure 10. Ammonia production pathways [31]

Since ammonia is a carbon-free fuel, a significant reduction in CO_2 emission can be expected, and the absence of sulfur will reduce SOx and Particulate matter emissions. However, NOx emissions from ammonia combustion are similar to a conventional low-speed diesel engine [32]. Thus, to reach Tier III compliance, selective catalytic reduction system has to be integrated to transform the emitted NOx into N_2O.

2.1.4 Hydrogen

Hydrogen is the lightest atom in the periodic table, it is also the most abundant atom in-universe [23]. However, pure hydrogen gas is the result of the decomposition or reformation of other products. (Safari and Dincer, 2020) declare that about 96 % of hydrogen production is a result of reforming fossil fuels, mainly Natural gas, heavy oil, coal, or naphtha [33].

The main incentives for hydrogen use in combustion engines as per (Zincir and Deniz, 2014) are its wide flammability range, fast flame speed, high diffusion, low minimum ignition energy, zero carbon content, and a reduced quenching gap, all of which contribute to more thorough combustion [34]. Fuel cell technologies likewise require hydrogen, proton exchange membrane (PEMFC) type replicates a reversed electrolysis process using oxygen and hydrogen to produce electricity, water, and heat. The use of hydrogen enables an efficiency of 50 %-60 % [35]. Hydrogen is a very flammable substance because of the low minimum ignition energy of 0.02 mJ, and it´s flammable concentration ranges between 4 % to 75 % [36]. Moreover, the low emitted radiation from the flames makes them invisible to the eye causing detection difficulties, therefore dedicated Multi-spectrum infrared sensors are more suited to detect hydrogen flames. Explosions risk becomes emanant in an environment where hydrogen concentration ranges between 18.3 % to 59 % [37]. Therefore, (Depken et al, 2022) consider that attention has to be focused on detecting hydrogen concentration levels before reaching the lower limits since any leak will mean that hydrogen is spreading into the air, not that air is penetrating the hydrogen tank.

Like any other gas, hydrogen can be stored in compressed form, gas cylinders can handle pressures ranging between 350 bars and 700 bars depending on their application purposes [36]. The liquefication process will require a very low temperature of -253°C with a density of 70.8 $kg{\cdot}m^{-3}$. This intense cryogenic condition requires a super-insulated containment system built with resisting materials such as aluminium and 304 stainless steel (Depken et al, 2022).

The risks arising from pure hydrogen leaking into the air generated a need for a storage alternative. Chemically bonding the hydrogen was another storage method, (Sreedhar et al, 2018) define this process as exothermic where hydrogen is covalently bonded to a material of a higher density, solid or liquid. The liquid organic hydrogen carriers (LOHC) concept allows loading hydrogen (hydrogenation) into a liquid carrier, increasing volumetric and gravimetric density [38]. Hydrogen can be extracted when needed through a dehydrogenation process, the reaction is endothermic and requires the exact amount of heat evacuated in the hydrogenation process. LOHCs are considered safe, cost-effective, and non-toxic. Because LOHCs are in liquid state at room temperature and pressure, transport and handling become similar to conventional fuels [39]. (Teichmann et al, 2012) pointed that the storage and shipping cost of LOHCs are significantly lower than both compressed or liquified hydrogen [40]. Chemical storage can also be in a form of metal hydrides, unlike LOHCs, gaseous hydrogen is bonded to a metal alloy through chemisorption enabling substantial amounts of hydrogen to be stored reversibly in a mouldable pressure body at relatively low pressures. However, the alloy holds only 1% to 2% of its weight in hydrogen, the capacity can be increased up to 5 % to 7 % under the condition of providing active heating to remove hydrogen [41].

2.2 Alternative Fuel evaluation criteria

2.2.1 Fuel physical properties

The characteristics of LNG, ammonia, methanol, and hydrogen are largely different compared to HFO or MDO. Aside from the physical state, each fuel presents different properties listed in Table 1. Low heating value (LHV) describes the amount of energy released by combusting a unit quantity of fuel; liquified hydrogen releases around three times more energy during combustion then HFO or MDO, however ammonia, methanol, and LOHC release much less energy. Unlike HFO and MGO, other fuels store lower amounts of energy per unit volume. The ratio of volumetric density in comparison to HFO range from 1.3 to 4.2. To store gas fuels in liquid form at atmospheric pressure, ammonia require a temperature of -33.4°C which is similar to propane [30]; LNG require a cryotemperature of -164°C while hydrogen liquefaction is the most demanding with a required temperature of -253°C.

Table 1. Fuel properties [22][27][32]

Fuel property	Density [kg·m^{-3}]	Low heating value [kWh·kg^{-1}]	Volumetric energy density [kWh·m^{-3}]	Min. auto-ignition temperature [°C]	Boiling temperature at 1atm [°C]
HFO	1,010	11.17	9,326.39	250	N/A
MDO	837	11.86	9,916.67	210	N/A
LNG	443.5	13.88	5,888.89	540	-164
MeOH	791	5.53	3,527.78	470	65
LNH_3	678.5	5.17	2,944.44	650	-33.4
CNH_3	0.86	5.17	4,138.89	650	N/A
LH_2	70.96	33.33	2,361.11	500	-253
LOHC	913.4	2.1	1,886	500	N/A

Figure 11 illustrates the comparison between the fuels based on their volumetric and gravimetric energy density. The same figure shows how fossil fuel outperform the other fuels both in gravimetric and volumetric the energy density. Liquified hydrogen contains high energy but requires a larger volume, which can be a drawback for application in restricted areas such as ships. Ammonia and methanol show moderate performance, where due to their low energy content storing larger volumes is required.

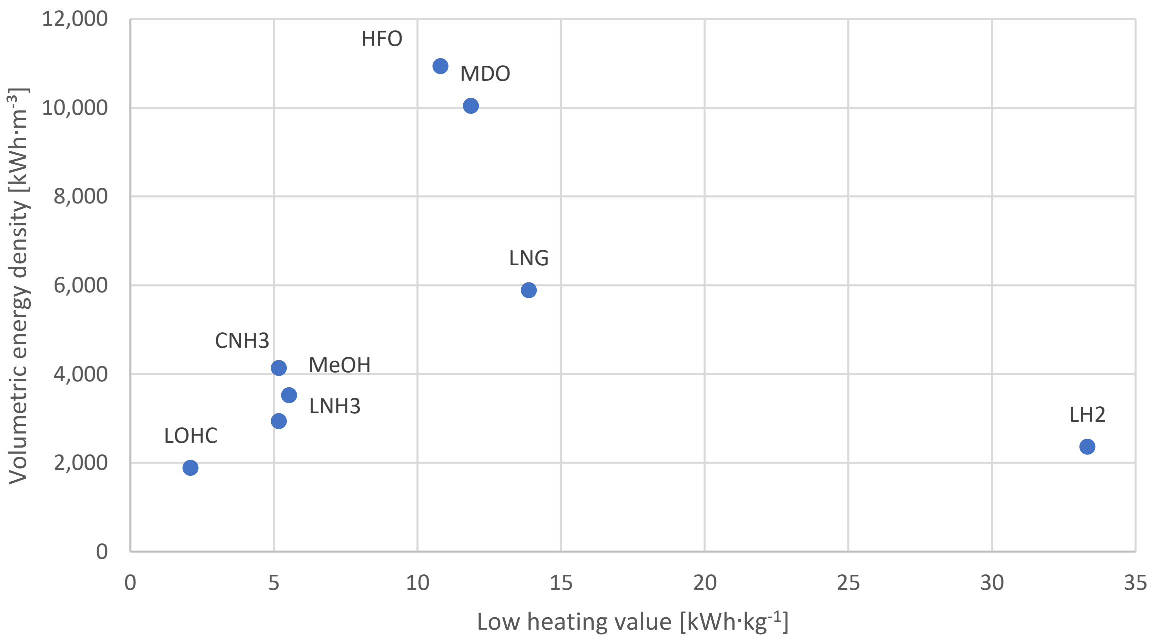

Figure 11. Energy densities of different fuels

2.2.2 GHG emissions and air pollution assessment for alternative fuels

An evaluation of the environmental performance of any alternative fuel requires an assessment of the GHG emission from WTW, accounting for the GHG emissions starting at the production level to the utilisation for power generation. The performance of any fuel will vary depending on the pathways from production, transformation until final use, however, in this work the intended destination of the fuel is to be combusted in IC engines. At the upstream level, alternative fuel production processes are either based on fossil fuels, or based on sustainable resources. Such a variety in the production path will mainly affect the WTT GHG emission. The TTW GHG emission while using IC engines remain similar unless carbon storage systems (CSS) are used. Table 2 present the WTW GHG emissions relatively to HFO. A pathway starts at the origin of the fuel in terms of row product until the resulting gases of its utilisation are released in the air, this includes all transformation processes and supply chain contribution. The combustion of these fuels releases variant amounts of air pollutants mainly SOx, NOx, and particulate matter. Figure 12 presents the air pollutant emissions in grams per kWh shaft output on operation only (TTW). (M.B Gonçalves et al, 2019) suppose that (WTT) emissions are not important in the future when cleaner fuels are used [20]. Hydrogen combustion is the cleanest, where no pollutants are emitted at all. LNG, ammonia, and methanol are sulfur-free therefore there are zero SOx emissions. Ammonia is mainly composed of nitrogen therefore during combustions NOx emissions are high. Compared to fossil-based fuels. Methanol, ammonia and hydrogen combustion emissions of Particulate maters are equal to zero.

Table 2. Relative WTW GHG emissions for different fuels and pathways [15]

Fuel type	**Pathway**	**Relative WTW GHG [%]**
HFO (Base case)	Crude–HFO–ICE	100
HFO (CCS)	Crude–HFO–ICE-CSS	11
MDO [10]	Crude–HFO–ICE	98
LNG	NG–LNG–ICE	92
LNG (CCS)	NG–LNG–ICE–CCS	24
BLUE H2	NG–H2– ICE	17
BLUE NH3	NG–NH3– ICE	34
MeOH	NG–MeOH–ICE	129
BLUE MeOH (CCS)	NG–MeOH–ICE–CCS	51
BIO-MeOH	Biomass–Bio-MeOH–ICE	15

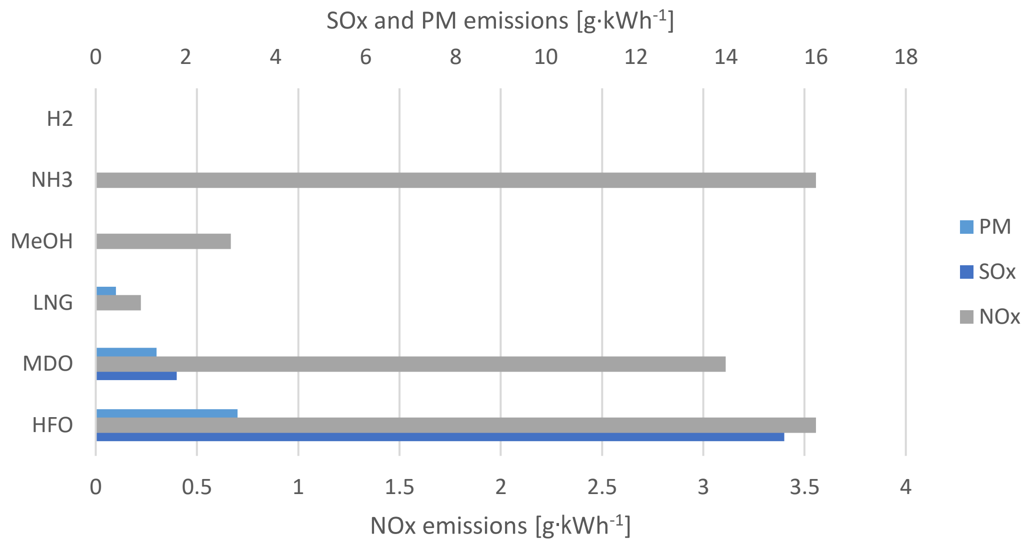

Figure 12. TTW air pollutant emissions [10]

2.2.3 Risks and hazards related to alternative fuels

Before going deep into any evaluation, a proper definition of "risk" and "hazard" is required. A hazard is defined by ISO guide to be a "potential source or situation of harm" to people, damage to properties or the environment or a combination of these [42]. Risk is defined as the combination of the probability of occurrence of harm and the severity of the harm [43]. To evaluate the risk and hazards linked to each fuel, hazard statements of each fuel are combined in Table 3 according to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS). Flammability and explosion risk, toxicity and potential harm for humans and ecotoxicity are the major hazard statements. Conventional fuels (HFO, MDO) present high environmental and human risks. Unlike HFO, MDO liquid and the vapours produces are flammable. Gas fuels are highly flammable, the cryogenic storage requirement provokes other risks for humans and equipment. Ammonia gases similarly to HFO are highly toxic to humans and aquatic life. Despite the high flammability and human toxicity, methanol is not toxic to the ecosystem.

A comparison between fossil and post facile fuels based on several criteria is presented in Table 4. It shows the different levels of impact caused by each fuel while being used for ICEs. The ranking system of 1 to 5 is attributed where 1 is good (no negative impact) and 5 is bad (very negative impact) on environment and safety.

Table 3. Hazard statements of alternative fuels compared to fossil fuels [44]

Hazard statement	HFO	MDO	LNG	NH_3	MeOH	LH_2	LOHC
H220 Extremely flammable gas			X			X	
H221 Flammable gas				X			
H225 Highly Flammable liquid					X		
H226 Flammable liquid and vapor		X					
H227 Combustible liquid							
H280 Contains gas under pressure; may explode if heated				X		X	
H281 Contains refrigerated gas; may cause cryogenic burn or injury			X	X		X	
H304 Toxic if swallowed	X				X		
H304 May be fatal if swallowed and enters airways		X					X
H311 Toxic in contact with skin					X		
H314 Causes severe skin burns and eye damage				X			
H315 Causes skin irritation							X
H331 Toxic if inhaled				X	X		
H332 Harmful if inhaled	X						
H350 May cause cancer	X						
H351 Suspected of causing cancer		X					
H361 Suspected of damaging fertility or the unborn child	X						X
H370 Causes damage to organs, optic nerve, central nervous system							
H373 May cause damage to organs through prolonged or repeated exposure	X						
H410 Very toxic to aquatic life with long lasting effects	X			X			
H411 Toxic to aquatic life with long lasting effects		X					X
H220...281: physical hazard, H304...373: Health hazard, H410...411: Environmental hazard							

Table 4. Comparison of different fuels based on environmental criteria [44].

Criterium	HFO	MDO	LNG	NH_3	MeOH	LH_2	LOHC
GHG reduction potential	5	4	2	2	1	1	1
Air pollutants	5	4	3	3	2	1	1
Aquatic ecotoxicity	5	3	1	3	1	1	3
Human toxicity	3	3	5	4	3	4	3
Flammability	1	4	5	4	4	5	1
Explosion risks	1	1	5	2	1	5	1

1: excellent, 2: very good, 3: moderate, 4: bad, 5: very bad.

2.2.4 Alternative fuels technology availability

Decarbonization of maritime shipping requires not only substitution of fossil fuels but also upgrading the onbord technologies to handle alternative fuels. Alternative fuel technologies are mainly composed of the storage systems, the energy converter which in this work is an ICE, and other relevant systems and functions enabling safe and efficient operations [14]. To have an appropriate evaluation of the technologies related to alternative fuels, the Technology Readiness Level (TRL) is a good indicator. Such a ranking will allow distinguishing the solutions that are ready for commercial applications and others that are under development. In Table 5 fossil fuels are being used on large scale for decades therefore their TRL is 9. Methanol as ship fuel of IC engines reflects a TRL of 9 since it has undergone more than 100,000 hours of operations on multiple vessels. Hydrogen fuel technology is less mature due to the large volume limitation and the high risks associated with its usage, only small-scale dimension models have been achieved mainly dedicated to short sea shipping. Ammonia technology as fuel is limited due to the challenges posed by its toxicity, nitrous oxide (N_2O, NO_X) emissions, and potential ammonia slip. However, several pilot projects are in progress involving ships with several capacities [14].

Table 5. Technology readiness level of each fuel

Fuel solution	**TRL**	**Comment**
HFO	9	actual system proven in operational environment
MDO	9	
LNG	9	
LNH_3	6	technology demonstrated in relevant environment
CNH_3	6	
MeOH	9	actual system proven in operational environment
LH_2	7	system prototype demonstration in operational environment
LOHC (dibenzyltoluene)	8	system complete and qualified

2.2.5 Alternative fuel future prices

The financial performance of any alternative fuel solution heavily depends on the fuel prices. Prices are directly dependent on the offer and demand in the market, along with the combination of the energy source, production and distribution costs. Therefore, fuel prices are subject to a large variation. Consequently, any attempt to predict future prices is hard. Table 6 presents future fuel prices in $\$\cdot t^{-1}$ and in $\$\cdot GJ^{-1}$ presented by DNV [14] and other sources [45][46].

Table 6. Projected fuel prices

Fuel Solution	Price [$·t^{-1}]	Price [$·GJ^{-1}]
HFO	390	9.89
MDO	589	13.8
LNG	390	7.8
LNH_3	426	22.9
CNH_3	426	22.9
MeOH	593	29.8
LH_2	9,000	75
LOHC (dibenzyltoluene)	148	195.76

3 TECHNO-ECONOMIC EVALUATION OF ALTERNATIVE MARINE FUELS: A CASE STUDY OF A RORO SHIP

Exploring the viability of any alternative fuel solution will require a well-defined evaluation model. The model combines ship-related specifications with other fuel-related information to provide case dependent solutions. At the core of the model is a RoRo ship serving as a liner between several ports, navigating on short seas. Figure 13 sketch the flow line of this model. The model is based on two categories of inputs, alternative fuel-related information discussed in chapter 2, and ship specifications. The design implications stand for the engendering effort required by each fuel solution to be implemented onboard. A decision-making process technique will evaluate the worthiness of each solution. The promising fuel solutions will be integrated onboard the ship. The integration process will reveal the wider aspect of an energy transition project on board a ship, starting with the allocation of storage space, bunkering equipment, and supply systems to the engines in compliance with relevant regulations and requirements. An evaluation to determine the induced impact of the fuel technology integration will be conducted. The evaluation will include the economical aspects of operation costs, conversion costs and induced financial losses due to potential reduction in storage capacity. Technical evaluation will focus on the engineering implications related to fuel storage and circulation onbord.

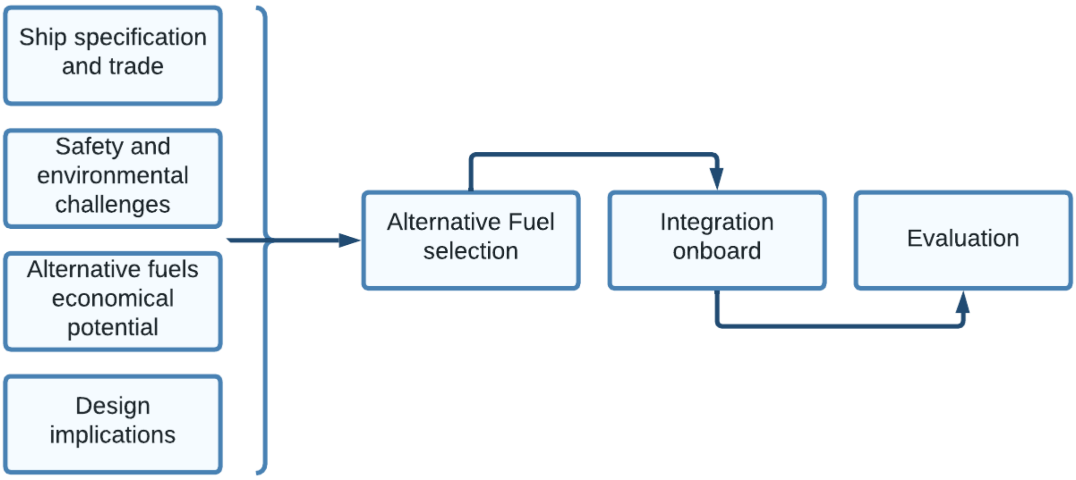

Figure 13. Evaluation model flowline

3.1 Ship geometry and arrangement

The case study ship is a RoRo vessel, designed as a pure car carrier with a capacity of 2,114 cars. The overall length of the ship reaches 148 m, a breadth of 25 m, and a total height of 25.2 m. The ship can navigate at a service speed of 18.90 kn at a design draft of 7.2 m thanks to its main engine developing 9,170 kW. Table 7 lists the principal characteristics of the ship. The overall height of the ship is divided into nine decks with an average height of 2.2 m, a crew accommodation area, and a control bridge constituting the partial decks N°10 and N°11. Moreover, the deck N°4 and deck N°6 respectively located at 11.8 m and 17.77 m above the base plan are water-tight and gas-tight. Longitudinally, the ship is divided into four compartments. Below deck N°4, the engine compartment extends from the aft perpendicular of the ship forward over a length of 40 m. the fore compartment containing tanks and a bow thruster extends from the fore perpendicular backwards by 36 m. In between the two remaining compartments are dedicated to cargo. The space comprised between deck N°4 to deck N°9 is located purely for car storage, car circulation across the decks is secured via multiple moveable ramps.

Table 7. Principal characteristics

Character	**Symbol**	**Value**
Length over all [m]	L_{OA}	148.00
Length between perpendiculars [m]	L_{BP}	134.00
Breadth moulded [m]	B	25.00
Depth to deck N°4 [m]	H_4	11.80
Depth to deck N°9 [m]	H_9	25.20
Design draft [m]	d_d	7.20
Scantling draft [m]	d_{max}	7.90
Displacement [t]	at T=7.90 m	16,160.9
Deadweight [t]	at T=7.90 m	7491.2
Main engine [kW]	MCR	9,170
	RPM	129
Auxiliary engine [kW]	MCR	1,111
	RPM	900
Service speed [kn]	At: Design draft 0.9 MCR 15 % Sea margin	18.90
Crew number	Total number	25 + 4 Suez crew

For the purpose of this work, a 3D representation of the ship is carried out. Such representation will provide better visualization of the actual space availability onboard to facilitate any integration work. Additionally, to evaluate the repercussion of any integration work on the main characteristics and performances of the ship, such a model is very important. Figure 14 shows the perceptive view. In order to ensure the geometrical fidelity of the 3D model with respect to the real ship, a validation process is achieved. The process consists of measuring the hydrostatic characteristics of the 3D model at more than 100 draft points, starting from 3.5 m to 9.5 m, using the commercial software MAXSURF, then compare with the hydrostatic characteristics of the real ship. Figure 15 presents the relative error curves for eight different parameters, total displacement, the volume displaced, tonne per centimetre immersion (TPC), moment to change the trim by 1 cm (MTC), longitudinal centre of buoyancy (LCB), vertical centre of buoyancy (VCB), longitudinal centre of area (LCA), and wetted surface area (WSA).

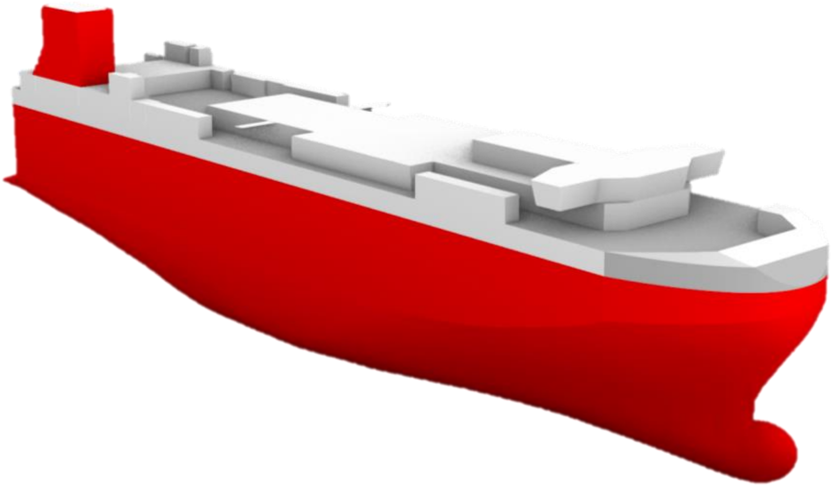

Figure 14. 3D model of the ship

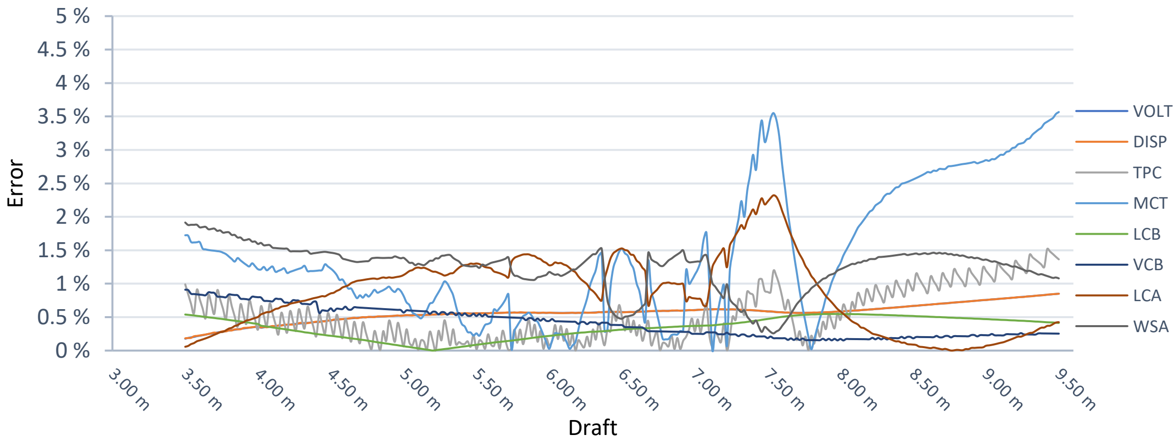

Figure 15. Relative error between the real ship and the 3D model

The average error obtained on the parameter: volume displaced, total displacement, TPC, LCB, and VCB are around 0.34 % to 0.56 %. While, the average error recorded for MTC, LCA, and WSA ranges from 0.85 % to 1.44 %. With such low relative errors, the 3D model is assumed to be similar enough to represent the real ship.

3.1.1 Propulsion system configuration

The ship is propelled with a single propeller shaft arrangement, animated by a single two-stroke engine rotating at 129 RPM and developing 9,170 kW of nominal output. To ensure maximum manoeuvrability, in addition to the rudder, the ship disposes of bow and stern thrusters. The electrical power required to operate the different electrical systems onboard the ship is supplied by three auxiliary generators developing each 1,111 kW of power and 900 RPM. Figure 16 illustrates a simplified concept of the propulsion system disposition. HFO is pumped from the ship bunkering tanks towards the settling tanks, then redirected to the service tank that feeds directly the main engine and the auxiliary engine. The fuel supply goes through several filters and separators to ensure quality.

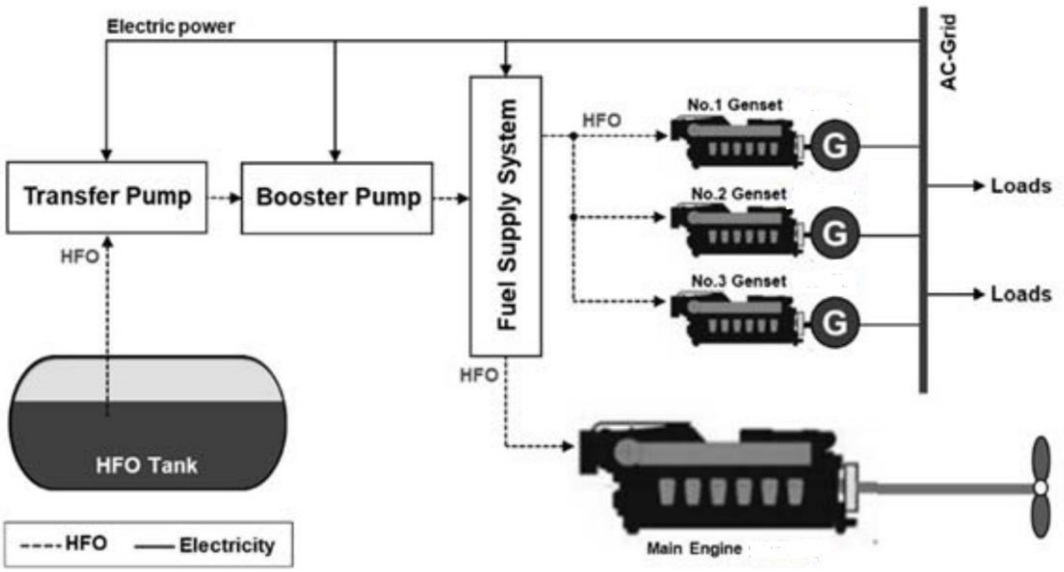

Figure 16. Simplified propulsion system arrangement [30].

3.1.2 Tank arrangement and capacities

The ships dispose of several tanks at different locations and capacities for different fluids. Figure 17 illustrates graphically the tank arrangements onboard, while annex A1 lists the tanks, their capacity, and location on board the ship. The engines on board are diesel engines running on HFO. Therefore, several tanks are allocated across the vessel. Larger fuel tanks located in the centreline are dedicated for bunkering the fuel, while service tanks are located in the vicinity of the engine room. The location of diesel tanks is adjacent to the engine room where they feed primarily the burner to produce heat that is used to keep the HFO at temperatures above 50°C, the heat is used for other ends such as heating the accommodations and keeping the engine warm as recommended by the manufacturer. In addition to lube-oil tanks and sludge, the ship scrubber unit requires two additional tanks, one to store the caustic soda, and the other to recover the sludge from the washing unit. To maintain good stability conditions of the ship and optimal draft, several ballast tanks are distributed across the ship's central body. Aft and fore ballast tanks are dedicated to controlling the ship trim. Note, BW: ballast water, FO: fuel oil, FW: freshwater, DO: diesel oil, LO: lubricant oil.

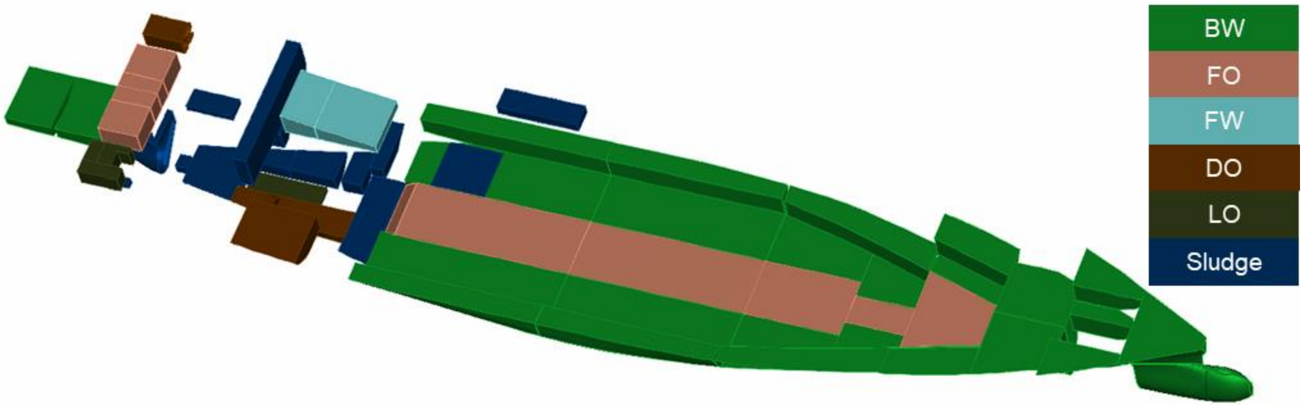

Figure 17. Tank arrangement

3.1.3 Navigation Profile

The RoRo ship navigation area is unrestricted; however, commercial incentives focalized the area into the North Sea and Baltic Sea shown in Figure 18. Consequently, the ship navigates around 97.5 % of the time inside ECAs. Working as a liner, the ship calls several ports respecting a tight schedule going through dense navigation areas including the Kiel canal. Ship chief engineer state that the operation mode is equally divided between harbour manoeuvring and port-to-port navigation. During navigation, the ship's motion is guaranteed by the main engine, while the electric demand is covered by one generator. In harbours or canals, bow and stern thrusters are required to manoeuvre the ship, therefore the energy demand increases significantly, therefore all auxiliary engines are used. Corresponding load profiles result in higher energy consumption per voyage compared to long-going ships. For 8,522.94 hours of navigation, the ship's fuel efficiency was, for 64 % of the time, around 100 kg·nm^{-1}, while for the remaining time, the fuel efficiency was around 50 kg·nm^{-1}. On a yearly basis, the average total fuel consumption of the ship is around 7,400 tons, where HFO represent 95 % and MDO represents the remaining 5 %. with such consumption rates, the total CO_2 emitted to the air is on average 2,300 tons per year; in terms of efficiency, the average CO_2 emission in is 310 kgCO_2·nm^{-1}.

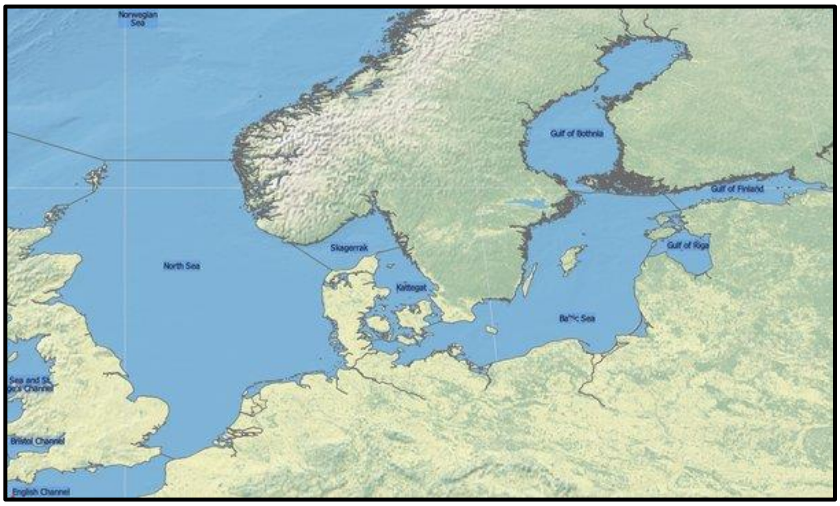

Figure 18. North Sea and Baltic Sea area. Available on https://www.quora.com/Where-do-the-North-Sea-and-Baltic-Sea-meet. [Accessed on 21 June 2022]

3.2 Required volumes and masses of alternative fuels

In order to push forward the fuel transition process, it is important to evaluate the volume requirement related to each fuel type. The evaluation of the volume and mass requirements methods can be done in different ways. The traditional and most common method to evaluate the volumes of fuels required by a vessel is to meet the design range for the operation requested by the shipowner. Another method is based on data analysis, where during a long period of time, auto loggers measure the shaft power delivered. Filtering the continuous dataset from a time domain into voyage based by excluding harbour time and anchorage. Such an approach will allow identifying the maximal energy delivered per voyage and serve as a reference point for measuring volumes and weight of fuels both for retrofitting projects or new-built ships. In this case study, the subject ship was not equipped with an auto logger to record the shaft power output, consequently, this work is based on the energy conservation approach. The assumption made is that the energy delivered to the propeller has to be constant for all fuel solutions, with such an assumption the efficiency of the propulsion system will be accounted for. The same assumption also disregards the auxiliary generators in the scope of this work. Figure 19 illustrates the concept. This same concept also means that for similar energy demands, the refuelling times before and after the fuel switch should be closely similar.

3.2.1 Energy conservation approach

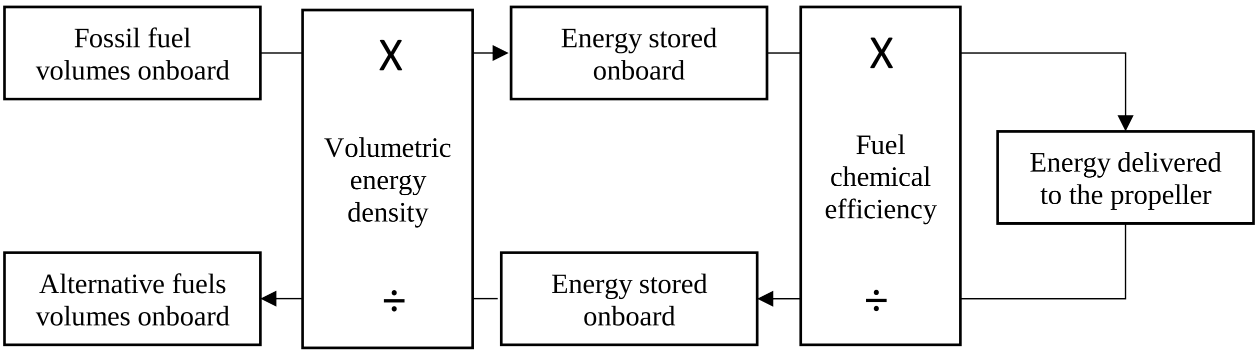

Figure 19. Alternative fuel volume evaluation energy conservation concept

The formulas allow to calculate the energy delivered to the propeller and calculate the volumes of the alternative fuels detailed respectively in Eq.(1) and Eq.(2)

$$E_{delivered} = V_{fuel}.V_{E\,d}.\eta_{fuel} \quad (1)$$

$$V_{fuel} = \frac{E_{delivered}}{\eta_{fuel}.V_{E\,d}} \quad (2)$$

Where η_{fuel} is the efficiency of the fuel potential energy transformation into propulsion [17].

Table 8 illustrate the results of the calculation of the energy delivered to the propeller, considering both HFO and MDO stored onboard.

Table 8. calculation of energies onboard

	Volume [m³]	**Energy density [MWh·m⁻³]**	**Energy in tank [MWh]**	**Energy delivered [MWh]**
HFO	1,412.7	9.33	13,175.39	5,270.16
MDO	187	9.92	1854.42	927.21
Total	**1,599.70**		**15,029.81**	**6,197.36**

The results for the calculated volumes and weights for each proposed fuel are detailed in table 9 These calculations are based on the conservation of energy delivered while considering the efficiency of the chemical transformation of the fuel into power. Heavy fuel oil and diesel are included as benchmarks, and LNG is assumed to be obtained in a non-sustainable way. Note that the calculation considers only the volume of the fuel itself and not the container or any other additional fittings. Figure 20 shows that LNG volume requirement is 1.13 times larger than the volume available onboard, but thanks to its low density, the weight is reduced to a half. Ammonia volume requirement depends on the storage condition, when the cryo-stored ammonia requires a volume of 2,927.89 m^3 compressed ammonia requires 35,007.91 m^3 of storage while the weight is similar for both storage conditions at 1,999.15 m^3. Methanol's low energy density requires added volume and thus added weight. Liquified hydrogen volume is 273.46 % of the existing but, it represents only one-fifth in terms of weight. LOHCs are the most demanding in this selection where they require 5,974.51 m^3 of volume and 5,365.68 t of weight.

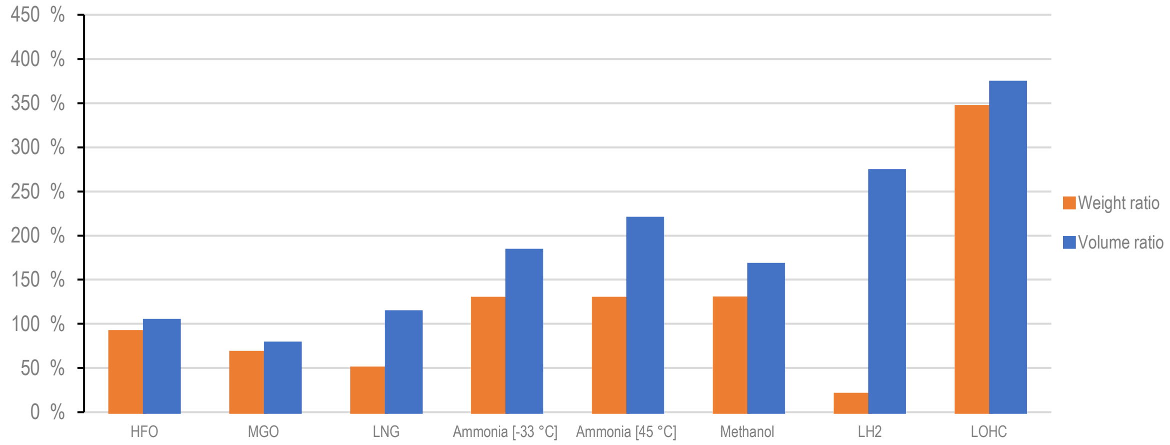

Figure 20. Ratio of volume and weight requirements

Table 9. Alternative fuels volumes and weights

	Fuels	Energy content [MWh·kg⁻¹]	Energy density [MWh·m⁻³]	Efficiency [%][17]	Energy delivered [MWh]	Energy in tank [MWh]	Fuel volume [m³]	Fuel weight [t]
Fossil	HFO	0.010	9.33	40	6,197.36	15,493.41	1,661.24	1,412.06
	MDO	0.011	9.92	50	6,197.36	12,394.73	1,249.89	1,044.99
	LNG	0.013	5.89	58	6,197.36	10,685.11	1,814.45	769.33
Post fossil	Ammonia [-33°C]	0.0051	3.53	60	6,197.36	10,328.94	2,927.89	1,999.15
	Ammonia [45°C]	0.0051	2.94	60	6,197.36	10,328.94	3,507.94	1,999.15
	Methanol	0.0055	4.14	56	6,197.36	11,066.72	2,673.84	2,002.02
	LH2	0.033	2.36	60	6,197.36	10,328.94	4,374.61	309.87
	LOHC	0.0021	1.89	55	6,197.36	11,267.93	5,974.51	5,365.68

3.2.2 Containment system inclusion

To further understand the realistic requirements of each fuel solution, it is intuitive to consider the contribution of the containment systems required to accommodate each fuel type. To achieve this approach, low heating value (LHV) of each fuel type were quantified considering the impact of the storage systems. Table 10 lists the gravimetric energy densities for each fuel solution, based on the work of (McKinlay et al, 2021). However, none of them has considered LOHCs; therefore, it is wise to assume that due to its liquid nature similar to MDO or HFO, the reduction of the gravimetric and volumetric energy density would be in the same proportion. Noteworthy is the fact that using LOHCs requires a dehydrogenation station of moderate size to extract hydrogen. comparable to HFO treatment installations [16].

Figure 21 and Figure 22 illustrate a superposition of the volumes and weights obtained with and without taking into account the storage infrastructure. In the figures, the volumes and weights obtained by including the storage system are noted by the indices “S”, the volumes and weight that do not consider the storage system are marked with the indices “WS”. Volume-wise, fuels stored under cryogenic conditions like hydrogen, ammonia and LNG, increased in volume up to a double. Liquid state fuels, on the other hand, didn´t register a higher increase. Weight-wise, the containment systems had a noticeable impact on fuels that are stored under cryogenic conditions but also ammonia in pressure vessels. nevertheless, liquid fuel requirements including the storage infrastructure were not high compared to the volume comparison. From both comparisons, methanol was the most conservative fuel, since the increase in volume and weight was minimal. Another important outcome from this comparison is related to hydrogen and ammonia; where it became clear that ammonia is advantageous both in weight and volume in any hydrogen storage concept.

Table 10. Alternative fuels volumes and weights including containment system

	Fuels	**Energy content [MWh·kg^{-1}]**	**Energy density [MWh·m^{-3}]**	**Efficiency [%][17]**	**Energy delivered [MWh]**	**Energy in tank [MWh]**	**Fuel volume [m^3]**	**Fuel weight [t]**
Fossil	HFO	0.008	7	40	6,197.36	15,493.4	2,213.34	1,936.68
	MDO	0.009	7.44	50	6,197.36	12,394.72	1,665.28	1,433.23
	LNG	0.0074	3.3	58	6,197.36	10,685.1034	3,237.91	1,443.93
Post fossil	Ammonia [-33°C]	0.0028	2.22	60	6,197.36	10,328.9333	4,652.67	3,688.90
	Ammonia [45°C]	0.0051	1.85	60	6,197.36	10,328.94	5,577.90	1,999.15
	Methanol	0.0028	2.60	60	6,197.36	10,328.9333	3,968.17	3,688.90
	LH2	0.0038	3.97	56	6,197.36	11,066.7143	2,787.59	2,912.29
	LOHC	0.002	1.2	60	6,197.36	10,328.9333	8,607.44	5,164.47

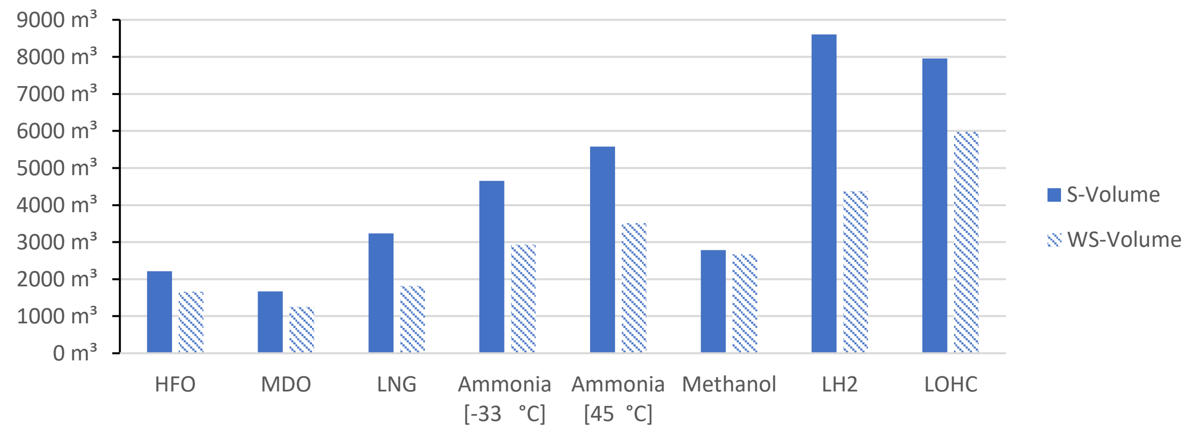

Figure 21. Volume comparison with and without considering the storage infrastructure

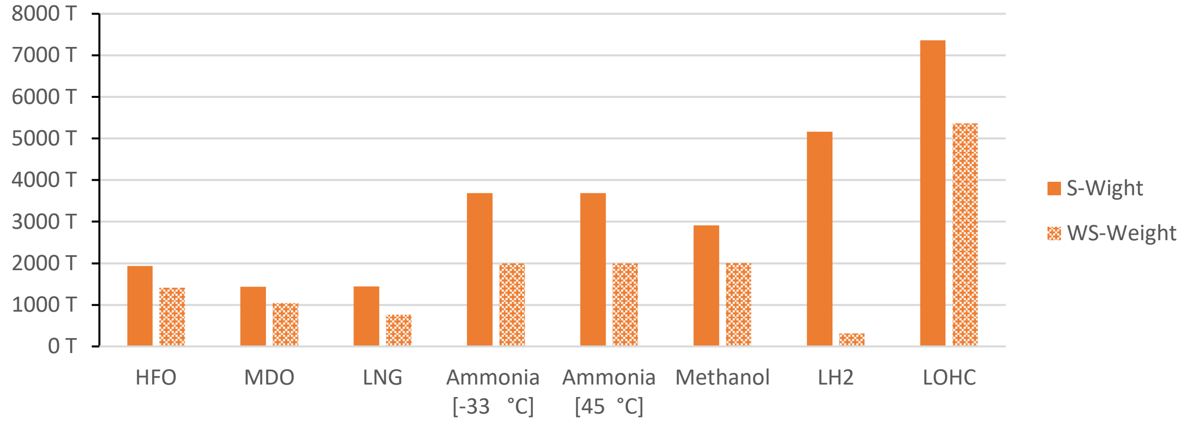

Figure 22. Weight comparison with and without considering the storage infrastructure

3.2.3 Design rang approach

Aside from the energy conservation approach, which is dedicated to existing ships, the common method for fuel tank sizing during the design phase for a new build is the design range requirement. In this method, the fuel volume is determined in order to achieve the desired navigation range at a defined speed e.g. navigate across the Atlantic at 18 kn. The determination of the fuel volume considers a safety margin to avoid any risk of fuel shortage at sea in case of delays in voyage or change of route. The design range is viewed as one of the main characteristics of the ship and should be displayed similarly to the main dimensions and cargo capacities. Therefore, it is important to include the design range approach in this work.

The mass of any fuel required to be stored on board in order to reach a certain range of operation shown in Eq.(3) is dependent on the required range, ship speed, engine power and specific fuel consumption of the engine.

$$M_f = SFC \cdot MCR \cdot \frac{R_d}{S_d} \cdot (1 + S_m) \quad (3)$$

Where:

M_f: Fuel mass in tons

SFC: Specific fuel consumption of the engine. given in Eq.(4)

$$SFC(i) = \frac{1}{\delta \times \eta} \text{ [g·kWh}^{-1}\text{]} \quad (4)$$

δ: Gravimetric energy density [MWh·kg^{-1}]

η: efficiency of the propulsion system

MCR: Engine power at 85 % MCR

R_d: Design range

S_d: Ship speed

S_m: Safety margin

Therefore, the design range for a given fuel quantity can be found using Eq.(5)

$$R_d(i) = \frac{1000 \cdot M_t \cdot S_d \cdot \delta(i) \cdot \eta(i)}{MCR \cdot (1 + S_m)} \quad (5)$$

Table 11 illustrate the theoretical ranges that can be archived with the several fuel types using the same quantity of fuel (1400 m^3)and a safety margin of 20 %. It is clear heavy fuel oil enables higher ranges; compared to fossil fuels, post-fossil fuels offer relatively half of the design range. Methanol and ammonia respectively offer 6,830.37 nm and 5,432.82 nm. The current bunkering frequency is around once per month, since the ship operation is mainly short-sea shipping, increasing the bunkering frequency is a feasible option.

To ensure a higher refuelling frequency, it is primordial to verify the availability of sufficient storage facilities within the area of navigation of the ship. Figure 23 reveals that at the time being, there are sufficient bunkering stations. 20 terminals of methanol are located inside the North Sea and Baltic Sea concentrated in large ports such as Antwerp, Rotterdam, Amsterdam, Hamburg, and Saint Petersburg with capacities exceeding 50,000 t for methanol. Ammonia refuelling terminals are available as well with a count of 25 terminals of different capacities up to 10,000 t.

Table 11. Theoretical design range for each fuel solution

	Fuel type	**Gravimetric energy density [MWh·kg^{-1}]**	**Density [kg·m^{-3}]**	**Propulsion system efficiency [%]**	**Range [nm]**
Fossil	HFO	0.010	1010	51	14,703.94
	MDO	0.011	837	51	13,403.88
	LNG	0.013	443.5	55	9,051.95
Post fossil	Ammonia [-33°C]	0.0051	678.5	55	5,432.82
	Ammonia [45°C]	0.0051	678.5	55	5,432.82
	Methanol	0.0055	791	55	6,830.37
	LH2	0.033	70.96	55	3,676.48
	LOHC	0.0021	913.4	55	3,011.52

Figure 23. Infrastructure availability for ammonia (a) and methanol (b) bunkering inside the North Sea and Baltic Sea available from: Alternative Fuels Insight (dnv.com) [Accessed on 22 June 2022].

4 PROPOSAL OF A MULTI-CRITERIA DECISION-MAKING MATRIX

Energy transition in ship fuels has become a determinant step to reaching the goal of zero-emission shipping set by the IMO. Selecting the next post-fossil fuel reveals to be an ambiguous task to apprehend, mainly due to the large uncertainties surrounding the ship across its lifetime, where external variables related to alternative fuel production, prices, or regulation updates may increase the risks of investing in stranded assets. In this part, an evaluation processed based on multiple criteria evaluations will evaluate and rank the proposed fuel solutions to determine their suitability for the energy transition desired onboard the RoRo ship.

4.1 Multi-criteria decision-making matrix (MCDM)

Also known as Multi-attribute decision making, it deals with decision problems subjected to several criteria [47]. The ability to simultaneously consider a high number of criteria made it possible to improve decision-making problems in engineering from design to manufacturing including material selection and risk assessment [48]. In the framework of this work, MCDM methods can be utilized to evaluate the multiple attributes related to our energy transition problem. These attributes, or design criteria, are economical, technical, and environmental. Weighting factors will be attributed to each criterion in order to appreciate the importance of some over the others; such weighting factors can be determined by objective, subjective, or combined methods [49]. In such considerations, it becomes clear that among several conflicting criteria surrounding engineering problems are not all satisfied still, the solution is a compromise between the considered attributes [49].

4.2 The analytic hierarchy process (AHP)

Several methods can be used to perform an MCDM, the choice of method depends on the number of options, criteria, and their complexity. The complexity of the decision-making process is determined by the degree of interaction between the criteria. In energy transition projects, such interaction is highly present, due to the fact that they are interlinked with several external parameters related to economics, and the environment. Even for a large number of options, it is important to consider all of them in a consistent manner. Consistency will guarantee that the comparison between all the alternatives is persuasive. Several MCDMs can be used as simple tools to evaluate the available options while being subject to several criteria of wavering importance to guide the decision-making process. The analytic hierarchy process is one of the most well-known and often used procedures for decision-making. This approach incorporates the procedures of assessing alternatives and aggregating them to locate the most relevant ones. The method is used to rank a set of alternatives or to choose the best option from a set of alternatives. Rankings and selections are made in light of a broad objective that is divided into a number of criteria [51]. AHP decomposes a complex MCDM into several layers of hierarchies, where it is capable of solving an $(m \times n)$ matrix (where m is the number of alternatives and n is the number of criteria). The proposed is built using the relative importance of all alternatives with respect to each criterion. The general AHP procedure is detailed in Figure 24.

To achieve a good evaluation, it is required to define a well-proposed list of alternatives to which the decision-making process will be applied on, and a well-proposed list of evaluation criteria.

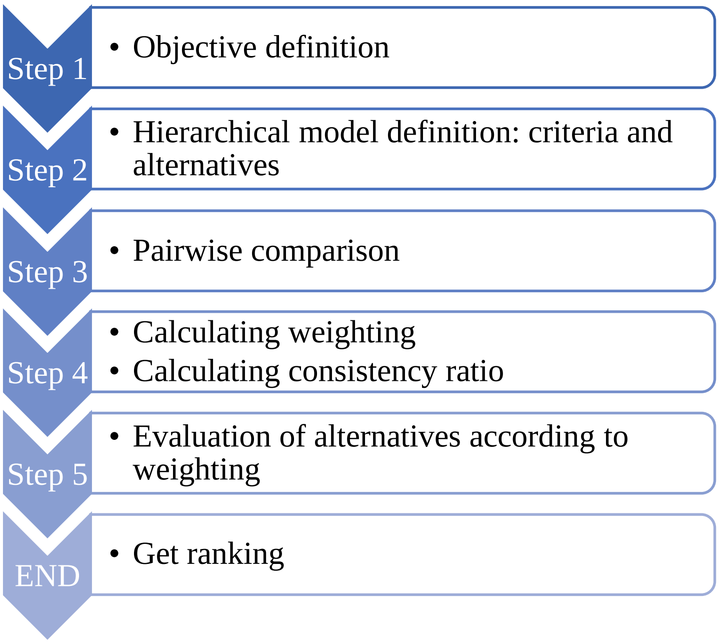

Figure 24. AHP method flow chart

4.2.1 *Elaboration of the decision matrix by expressing the alternatives and the criteria*

The creation of any decision matrix requires a deep understanding of the problem and the implications around it. Considering the project presented in this work, consisting of defining the best alternative fuel solution for energy transition, the list of considered solutions are large and includes LNG, ammonia, methanol, and hydrogen, while HFO and MDO are included for comparison purposes. The list of criteria is selected to include technical, economical, and environmental aspects. Figure 25 schematize the process. The matrix is defined by five criteria and six alternative solutions. The decision process is divided into two main steps. First, attributing weighting factors to the proposed list of criteria to differentiate them with respect to their importance during the selection process. Second, to assign each proposed alternative a ranking based on their performance concerning the weighted criteria. Such organization will allow providing justified decision-making.

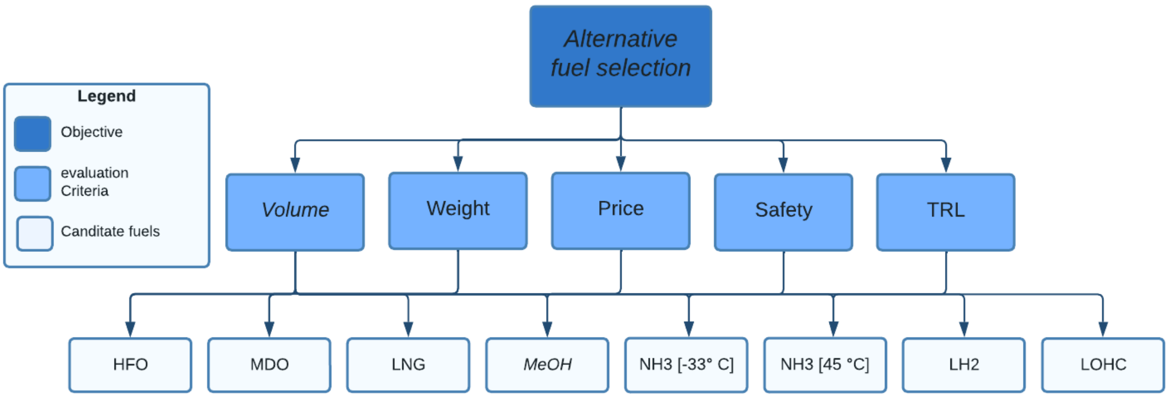

Figure 25. AHP criteria and alternatives definition

4.2.2 *Weighting factors determination*

As mentioned above, weighting factors for the criteria will allow bringing forward the relative importance of each criterion over the others. The weighting factors must be allocated to provide a clear view of the differentiation among design criteria importance. Considering the direct influence of the weighting factors on the potential results of the decision-making process, it becomes crucial to ensure that the weighting is done wisely. The weighting factors are the result of engineering expertise and considerations. Therefore, they are influenced by the degree of knowledge of the decision-makers. In this work, the weighting factors are based on the expertise of several engineers working in the field of the energy transition. The relative importance of each criterion is determined using the pairwise comparison, in which, each criterion is compared one to one with the others. Such a method of weighting will create a set of coefficients with a total sum of 1 (100 %) as a fixed parameter.

4.2.2.1 Pairwise comparison in AHP

Pairwise comparison is one of the basic and simple methods used for criteria weight definition [52]. In the scope of the AHP method, each pair of criteria is compared using a scale of 1 to 9 to rate the importance of each criterion over the others, a square matrix $C_{n\times n}$ is obtained. The diagonal of the matrix takes a value of one, and the obtained matric is reciprocal. From this matrix, a vector of weighting factors is obtained $w = [w_1, w_2, \dots, w_n]$. To validate the results, we can proceed to verify that the weights obtained represent the unique solution to $C_w = \lambda_{max}$, where λ_{max} is the largest eigenvalue of C. The obtention of the results starts by normalizing over the columns of the matrix C using Eq.(6), and the weights are found using Eq.(7)

$$\bar{C}_{ij} = C_{ij} / \sum_{i=1}^{n} C_{ij} \tag{6}$$

$$w_i = \sum_{i=1}^{n} \bar{C}_{ij} \tag{7}$$

Having defined the weights, the weighted sum value is calculated using Eq.(8) for each line of the C matrix.

λ_{max} is the ratio between the weighted sum value (WSV) and the criteria weights, defined by Eq.(9)

$$WSV_i = \sum_{i=1}^{n} C_{ij} . w_i \tag{8}$$

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} WSV_i . w_i \tag{9}$$

The final step is to calculate the consistency index (CI) defined by Eq.(10) and the random index (RI) defined depending on the number of criteria as shown in Table 12. The weighting factors are deemed acceptable for usage if the consistency ratio (CR) defined by Eq.(11) is lower than 0.10. If it is not the case, then the consistence ratio is inconsistent for decision making and one shall reconsider the pairwise comparison again.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (10)$$

$$CR = \frac{CI}{RI} \quad (11)$$

Table 12. Random index for N design criteria [53]

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

4.2.2.2 Determination of the standardized decision matrix

The decision-making matrix is composed of several alternatives, in this work the evaluation counts eight alternative fuels. Each alternative presents a different performance with respect to each evaluation criterion. These criteria are different in nature, where some of them are economical such as cost, environmental or technical. The difference is also the dimensions (units), where we are at the same time considering financial cost in $, volumes in m^3, weights in kg, and also dimensionless entities such us TRL or the safety index. To be able to perform any operation on the alternatives, a normalization process becomes mandatory. A normalization process will deliver a standardized decision matrix that can be used for the evaluation process. Normalization techniques are numerous, but they all share the same end of mapping different attributes (criteria) with different scales into a uniform one. In the scope of this work, we will use a linear (max) normalization technique. Depending on the condition of use, the formula of the normalization process varies. Beneficial criteria are the ones that we try to maximize, or non-beneficial (costs) that we try to minimize. Eq.(12) and Eq.(13) list respectively the formulas for each case.

$$\overline{X_{ij}} = \frac{X_{ij}}{X_{j\,max}} \quad (12)$$

$$\overline{X_{ij}} = 1 - \frac{X_{ij}}{X_{j\,max}} \quad (13)$$

Where X_{ij}: is the attribute of the alternative.

$X_{j\,max}$: is the maximum attribute in column j.

4.2.3 Determination of the weighted standardized matrix

The weighted standardized matrix determination is another step toward determining the best alternative. In this step the degree of compliance of the attributes with respect to their criteria is determined. The obtained matrix will show clearly the better alternatives to consider. The weighted standardized matrix is obtained by the formula in Eq.(14)

$$X^{*}_{ij} = \overline{X_{ij}} \, . w_i \qquad (14)$$

4.3 Results of the AHP to select the best alternative fuel solution

The following part will present the results of the AHP applied in the scope of the energy transition, where we evaluated eight different alternative fuels based on five main criteria. The evaluation process will be conducted according to the steps detailed above section 4.2.

4.3.1 Weighting factor determination

The weight factors are calculated to provide a clear view of the differentiation among design criteria importance, where certain criteria are more important than others. The determination of the weight factors starts by creating the pairwise comparison matrix. The criteria in this work are the volume and weight of the fuel, noteworthy that the volumes and weights used are the ones obtained in 3.2 by accounting for the storage infrastructure. The total prices stand for the cost to purchase the required volume of the fuel, where the proposed unit prices are an estimation for the future. Safety is a very important aspect to consider during the selection of any fuel, safety as a criterion is composed by averaging six sub-criteria, which are GHG reduction potential, air pollution, aquatic toxicity, human toxicity, and flammability and explosion risk. Their detailed evaluation is described in Table 4 of section 2.2.3. TRL is a very important factor to consider as well since it determines directly the possibility of using certain fuel solutions in the time. Table 13 displays the results of the pairwise comparison achieved based on the engendering expertise of several works in the field of energy transition.

Table 13. Pairwise comparison results

	Volume	Weight	Price	Safety	TRL
Volume	1.00	3.00	0.20	0.20	0.33
Weight	0.33	1.00	0.20	0.20	0.33
Price	5.00	5.00	1.00	0.50	3.00
Safety	5.00	5.00	2.00	1.00	3.00
TRL	3.00	3.00	0.33	0.33	1.00
Σ_i	**14.33**	**17.00**	**3.73**	**2.23**	**7.67**

Where the degree of importance is attributed with values from 1 to 9 with: 1 for equal importance, 3 for moderate importance, 5 for strong importance, 7 for very strong importance, and 9 for extremely strong importance.

The normalized pairwise comparison matrix will enable us to define the criteria weights, as defined in the Table 14. From Figure 26 it became clear that the most important criteria to consider are the safety aspect and the costs, then the technology readiness in order to achieve a fast integration onboard for the retrofit projects. Finally comes the volumes and weights.

Table 14. Normalized pairwise matric and criteria weights

	Volume	Weight	Price	Safety	TRL	Criteria weights
Volume	0.07	0.18	0.05	0.09	0.04	0.09
Weight	0.02	0.06	0.05	0.09	0.04	0.05
Price	0.35	0.29	0.27	0.22	0.39	0.31
Safety	0.35	0.29	0.54	0.45	0.39	0.40
TRL	0.21	0.18	0.09	0.15	0.13	0.15

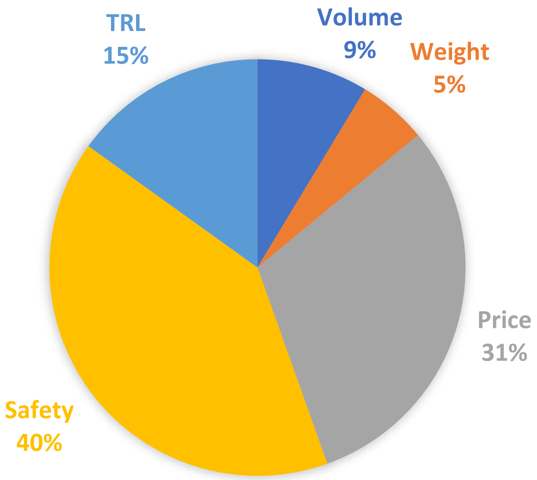

Figure 26. Criteria weights obtained from the pairwise comparison

4.3.2 Validation of the weight factors

Before proceeding with any father work in the decision-making, it is important to validate the consistency of the weight factors obtained in the framework of the AHP method. The verification starts by calculating a new matrix that is the product of the non-normalized pairwise matrix by the found weight factors to calculate WSA and the λ_{max} as described above. Results are listed in Table 15.

Table 15. Weighted sum value calculation

	Volume	**Weight**	**Price**	**Safety**	**TRL**	**WSV**	**WSA/w_i**
Volume	0.09	0.16	0.06	0.08	0.05	0.44	5.08
Weight	0.03	0.05	0.06	0.08	0.05	0.27	5.11
Price	0.43	0.27	0.31	0.20	0.45	1.66	5.44
Safety	0.43	0.27	0.61	0.40	0.45	2.17	5.37
TRL	0.26	0.16	0.10	0.13	0.15	0.81	5.35

Based on (10)and the results of the above Table 15 is $\lambda_{max} = 5.27$

Following (11) the consistency index is $CI = \frac{\lambda_{max}-5}{5-1} = 0{,}068$

Therefore, the random index is $RI = \frac{CI}{1.12} = 0.060 < 0.10$

According to these findings, the criteria weights are judged to be convenient to procced with the evaluation.

4.3.3 Standard decision matrix

The standard decision matrix using the AHP method is formed by organizing each alternative and its attribute forming a matrix of a size $(m \times n)$, where m represents the alternatives, and n represents the criteria. Table 16 represents the decision matrix composed of eight alternative fuels and five criteria. The volumes and weights presented correspond to the results where the storage infrastructure is taken in consideration. The price is the cost of filling the net volume of the fuel without the containment system. The safety is quantified based on a scale of 1 to 5, averaging the six sub-criteria that compose it. The TRL is normally on a scale of 1 to 9 where 9 is the best, however, in this table we reprehend it on a scale of 1 to 5. On a scale of 1 to 5, we attribute 1 for the best and 5 for the worst.

Table 16. Decision matrix

	Fuels	**Volume [m³]**	**Weight [kg]**	**Price [$]**	**Safety**	**TRL**
Fossil	**HFO**	2,213.34	1,936.68	551,627.38	3.3	1
	MDO	1,665.28	1,433.23	615,770.10	3.2	1
	LNG	3,237.91	1,443.93	300,037.91	3.5	1
Post fossil	**NH_3 [-33°C]**	4,652.67	3,688.90	851,517.84	3.0	4
	NH_3 [45°C]	5,577.90	3,688.90	851,517.84	3.0	4
	MeOH	2,787.59	2,912.29	1,187,237.91	2.0	1
	LH_2	8,607.44	5,164.47	2,788,813.88	2.8	3
	LOHC	7,960.09	7,359.18	7,940,919.33	1.7	2

The normalization of the decision matrix will enable us to perform the evaluation process since it brings the different criteria into a homogenous scale. The main objective here is to identify the fuel alternative with the most beneficial aspects. The benefice is to be able to find an alternative fuel with minimum weight, volume, cost, risk, and waiting time. The results, the final score and the ranking are also displayed in Table 17.

Table 17. Normalized matrix and ranking

	Fuels	Volume	Weight	Price	Safety	TRL	Score	Rank
Fossil	**HFO**	0.26	0.26	0.07	0.95	0.25	0.48	3
	MDO	0.19	0.19	0.08	0.90	0.25	0.45	2
	LNG	0.38	0.20	0.04	1.00	0.25	0.50	4
Post fossil	**NH_3 [-33°C]**	0.54	0.50	0.11	0.86	1.00	0.60	5
	NH_3 [45°C]	0.65	0.50	0.11	0.86	1.00	0.61	6
	MeOH	0.32	0.40	0.15	0.57	0.25	0.36	1
	LH_2	1.00	0.70	0.35	0.81	0.75	0.67	7
	LOHC	0.92	1.00	1.00	0.48	0.50	0.71	8
	Criteria Weight	0.09	0.05	0.31	0.40	0.15		

From the above, Methanol is distinguished as the best solution thanks to the advantages that it presents in terms of cost, safety, weight, and volume requirements. Excluding fossil fuels, the next best solution to consider is ammonia stored under cryogenic conditions. Despite its low technology readiness, it remains cost-effective and the presented volume and weight requirements are within the middle ranges. Hydrogen performance as fuel solution in the current context is poor for the both storage solutions, with higher costs, volume and weight requirements. The potential risk to the environment and humans combined with the use of hydrogen has also decreased the expectation for hydrogen use onboard.

5 INTEGRATION OF ALTERNATIVE FUEL SOLUTIONS

The evaluation performed on the proposed list of alternative fuels revealed that the most suitable fuels for an energy transition were methanol, and ammonia stored under cryogenic conditions. This decision was supported by the multi-criteria decision-making method. Methanol and ammonia presented both significantly advantageous technical, economical and environmental characteristics. The volume requirements of methanol and ammonia are relatively higher than fossil fuels. Nonetheless, the reasonable costs and their high potential to reduce GHG emissions are key advantages. To full-fill the energy transition goal, it is important to incorporate the entire fuel technology system onboard the ship. The integration of any fuel solution starts by allocating the space to contain the required volumes of fuel. Then, it is essential to establish an appropriate supply network to feed the fuels to the main consumers onboard. During these operations compliance with regulations is mandatory, since each fuel solution displays different characteristics and induces different risks and hazards.

In this part, we will undergo the process of integrating the best ranked fuel solutions, methanol and ammonia, onboard the RoRo vessel presented in the core of this work. This approach will not only enable us to identify and mention the induced design implication related to each fuel solution, but also quantify the engineering complexity of integrating each fuel solution and the potential capital expenditure needed to achieve it.

The main aspects that are considered in the framework of this proposed work, related to the conversion process of the RoRo ship towards any alternative fuel solution are the following:

- Installation of dedicated fuel tanks to accommodate the required volumes
- Nitrogen purging system
- Fuel supply system and tank connexion
- Bunkering concept
- Provisions for the main engine
- Fire prevention and safety systems and arrangements
- Hazard areas identification

5.1 Methanol integration

Methanol as a fuel solution has been increasingly used in recent years, mainly due to its potential to reduce GHG emissions. Methanol propulsion systems are in general very similar to conventional fuel systems. However, the use of methanol involves additional challenges related to safety and hazard prevention. Methanol is considered a Low-flash point fuel (LFL). Therefore, any projects of methanol usage onboard have to be regulated by the IGF code covering the use of LFL fuels. In the same scope classification societies have published class rules to assist and regulate. The RoRo ship navigates in international waters. Consequently, class approval is mandatory. In the scope of this work, the regulatory framework is composed of IMO regulation: MSC.1/Circ.1621-7 December 2020 entitled “INTERIM GUIDELINES FOR THE SAFETY OF SHIPS USING METHYL/ETHYL ALCOHOL AS FUEL” [54] and the DNV class regulation: Part 6 Chapter 2 Section 6 entitled “LOW FLASHPOINT LIQUID FUELLED ENGINES - LFL FUELLED” [55].

5.1.1 Methanol tanks and tank rooms

As found in the chapter 3 above, the volume of methanol fuel required to operate the ship in the same mode similarly to the current mode is 2,673.84 m^3. This volume of methanol represents around 1.9 times the volume of HFO used onboard. As result, it becomes clear that solutions to store methanol are needed. Methanol has a liquid state at room temperature. Such characteristics will enable us to reuse the existing fuel tanks. Still, additional storage space must be allocated. To this end, we advise creating new tanks dedicated to methanol storage inside the cargo area. Parts of the cargo area that will be reallocated for storage tanks will be no longer accessible for cargo operation and will be rearranged to accommodate the tanks and the subsystems required to ensure safe storage and operation.

To accommodate the methanol tanks, a configuration of tank arrangements is proposed. The tank configurations are characterized, by their locations and the volume of fuel contained. Nonetheless, the creation of new tanks will introduce additional loads to the structure. Due to the additional weight of the fluid and the additional weight of the tank structure. Therefore, during the tank creation process. It is highly important to keep structural limitations into consideration. In the scope of this work and by exploiting the limited data that we had at our disposal, we were able to identify the maximum uniform deck load of each deck. As result, the uniform load applied by the fuel inside the tank shall not exceed the design limitations as shown in Table 18.

Table 18. Design characteristics of the cargo decks

Deck N°	**Area [m²]**	**Uniform deck load [kg·m^{-2}]**
1	964.4	1,000
2	1,371.1	2,000
3	1,410.0	300
4	2,572.8	2,000

The HFO tanks that are located in the double bottom and the fore part of the ship will be able to carry methanol. The additional volume of methanol will be stored in the new tanks to be built in the deck N°1 space. The list of methanol tanks, including the existing fuel tanks are listed in Table 19 where their locations inside the ship and their volumes are mentioned. Noteworthy that methanol is a corrosive substance, especially when it contains water. For safety, the tank's interior should be coated using Sigma Silguard 750, which is a proven product [56]. For the new tanks, the load applied by the fuel on the carrying deck is calculated. A visual representation of the tank configuration is portrayed in Figure 27. Where TCS: tank connection space, BW: ballast water, S.T: service tank, FW: fresh water, DO: diesel oil, and LO: lubricant oil. The scantling of the tanks is detailed in annex A2.

Table 19. List of methanol tanks

	Tank name	**Location [m]**						**Volume [m³]**	**Applied deck load [kg·m^{-2}]**
		Aft	Fore	Port	Starboard	Top	Bottom		
Converted	Tk 2F FO	100.80	110.39	-2.40	2.40	5.55	2.55	222.40	
	Tk 3F FO	81.60	92.80	-3.60	3.60	2.55	0.00	283.10	
	Tk 4F FO	92.80	102.40	-1.80	1.80	2.55	0.00	367.10	
	Tk 5F FO	60.80	81.60	-3.60	3.60	2.55	0.00	385.70	
	Tk 29 FO	5.600	10.40	-8.20	-4.20	11.00	8.10	55.70	
	Tk 30 FO	5.600	10.40	-0.40	3.60	11.00	8.10	53.00	
New built	MeOH TK2 CL	45.80	71.20	-2.90	3.60	3.80	2.55	206.37	988.75
	MeOH TK2 SB	45.80	71.20	3.60	9.80	3.80	2.55	196.85	988.75
	MeOH TK2 PS	45.80	71.20	-3.60	-9.80	3.80	2.55	196.85	988.75
	MeOH TK3 CL	72	100	-2.90	3.60	3.80	2.55	227.50	988.75
	MeOH TK3 PS	72	100	3.60	9.80	3.80	2.55	161.55	903.976
	MeOH TK3 SB	72	100	-3.60	-9.80	3.80	2.55	161.55	903.976
	Total volume							**2,517.67**	

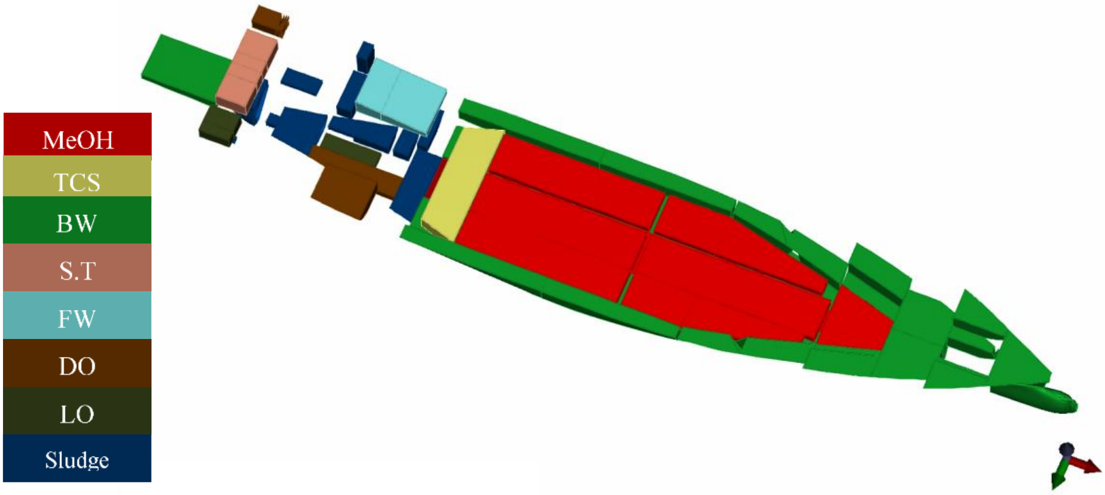

Figure 27. Methanol tanks configuration

As per the DNV regulation 3.2.1 related to the location of the fuel tanks, the added methanol tanks are built away from the machinery area. With a height of 1.25 m only, it will provide a clearance of 1.75 m between the tank top and the ship deck N°2. The fuel service tanks TK29 and TK 30 combined carry 108.7 m³ of methanol which will cover more than 8 h of continuous rating of the propulsion plant and other consumers as shown in Eq.(15)

$$Day\ consumption = P_{85\%} \cdot SFC \cdot (24+6) \cdot 10^{-6} \quad (15)$$

$$Day\ consumption = 78.8\ t$$

Therefore, it can be seen that the service tanks are able to cover the daily demand of fuel.

With respect to the DNV rule 3.2.2, cofferdams are intended to separate the fuel compartments from any other functional area of the ship. Cofferdams are not required on the surfaces bonded by shell plating below the lowest practicable waterline, or additional methyl/ethyl alcohol-containing fuel tanks, or a compartment used for fuel preparation. Where the minimum distance is 600 mm.

The design of the fuel tank is basic, similar to a box girder. It is subject to the combination of local loads and global loads, induced by the fuel pressure and the motion of the ship respectively. Therefore, the dimensioning of the tanks has to withstand during the excitation loads during the ship service life. The scantling of the tanks is based on the regulations set by

DNV regarding hull local strengthening. The scantling summary of the proposed methanol tanks is illustrated in Table 20 and the calculus details are joint in annex A2.

Table 20. Scantling summary of methanol tanks

Structural element	Minimum requirement	Calculated	Selected	Comment
Plate thickness [mm]	6.49	3.88	7	-
Stiffener web thickness [mm]	4.93	0.57	6	L Profile 90×90×6
Stiffener section modulus [cm³]	-	9.18	12.3	
Net shear area [cm²]	-	54	182.5	T Profile 600×20 250×25
Longitudinal stiffener section modulus [cm³]	-	1,717.9	1,871.2	

5.1.2 Atmosphere control of spaces surrounding fuel tanks

5.1.2.1 Inerting

Methanol flash point temperature is 11°C, and the flammability range is from 6 - 36 %vol. Therefore, air/fuel mixture formed in closed tanks can easily generate a fire. As a result, tanks must be constantly inerted to keep oxygen levels below 8 % by volume in any fuel tank to comply with these regulations. A nitrogen inerting system will be used, the nitrogen will be produced from an onboard production plan, suppling an inert gas with a maximum oxygen level of 5 %. With a production rate at least equal to the fuel consumption rate. Figure 28 illustrates the principal layout of a nitrogen production plant.

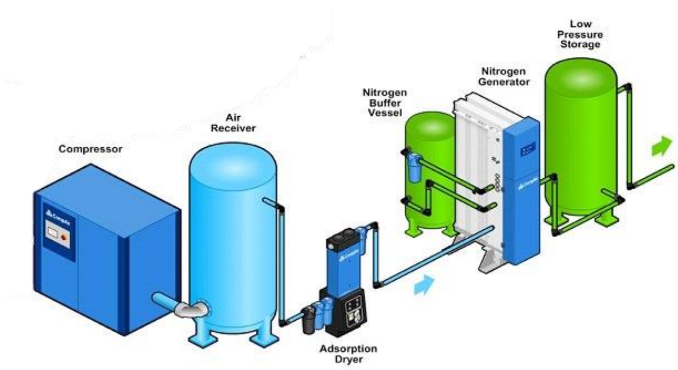

Figure 28. The principal layout of the nitrogen production plant. Available from https://rastgar-co.com/products/nitrogen/ [Accessed 02 July 2022]

5.1.2.2 Tank ventilation

Methanol tanks are constantly inerted with nitrogen to prevent flammable vapours formation, an overpressure of 150 mbar needs to be applied on the free surface of the fuel. Consequently, mechanical Pressure/vacuum (P/V) valves are needed. The same P/V valve will protect the tanks from collapsing in case of pressure drop below 50 mbar [56]. The gas freeing system during operation has to release the gases containing fuel vapours through a venting mast with a height of 3 m above deck N°10 in line with the IGF code regulation [6.4.10]. Figure 29 illustrates the vent mast location on the ship, where the height of the mast is 8.5 m above the deck N°9.

5.1.2.3 Tank room ventilation

To prevent the accumulation of flammable vapours inside the tank space located on deck N°1, ventilation fans have to guarantee a minimum rate of six air changes per hour. On board the ship, we can lean on the available four ventilation fans feeding the deck N°1 space.

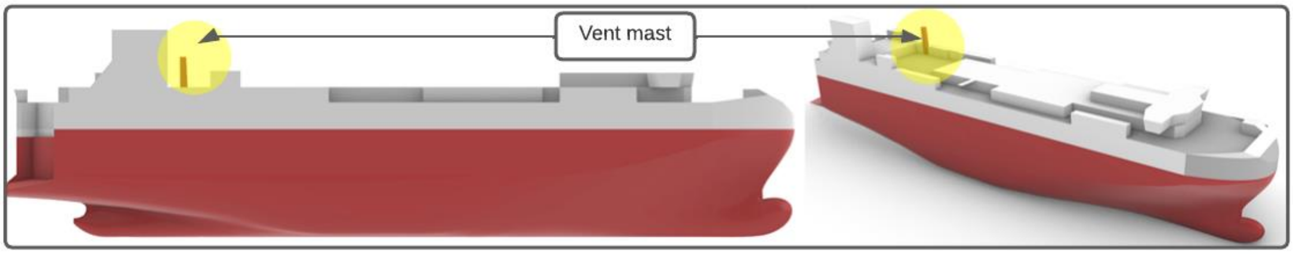

Figure 29. Venting mast location for methanol fuel solution

5.1.3 Fuel supply system and bunkering concept

5.1.3.1 Fuel supply system

The fuel supply system is responsible for bringing the methanol fuel from the tanks to feed the main consumers onboard the ship. For a two-stroke engine, the fuel supply system begins at the storage tanks where fuel is extracted via a circulation pump, the fuel is then conducted to the fuel preparation room where filters capture any present particles and impurities. At the exit of the pump room, pressure is raised up to 10-50 bar, then the pressurized methanol is sent to the engine room directly to the main engine. Figure 31 illustrate the arrangement of the fuel supply system proposed by MAN B&W [27] for two-stroke engines, including details about the ventilation of the rooms and the purging systems required to evacuate methanol from the pipes when needed. On the market, several companies propose Low flashpoint supply systems (LFSS) able to cover the requirements of several consumers simultaneously and within the constructor specifications. Figure 31 illustrates an LFSS able to handle methanol developed by ALFA LAVAL.

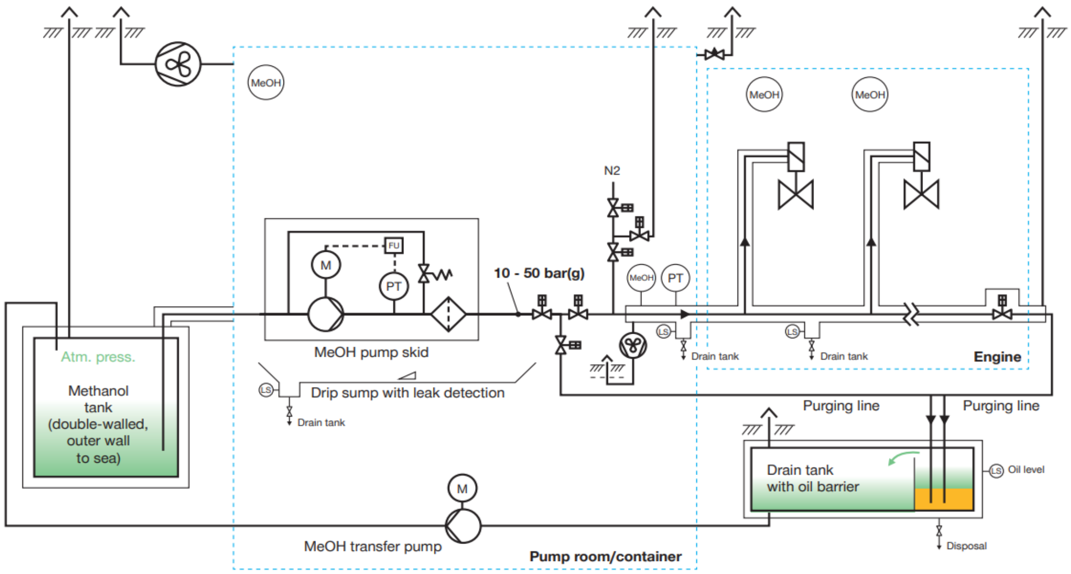

Figure 30. Fuel system arrangement for two-stroke engines by MAN B&W [27]

Figure 31. Low flashpoint supply system by ALFA LAVAL. Available from FCM Methanol | Alfa Laval [Accessed on 03 July 2022]

Due to the high risks linked to any potential leakage of methanol, the safety of the ship depends on containing methanol and fast detection of leakages. Therefore, all methanol pipes have to be made of stainless steel. Also, double-walled except for ones inside the pump room (fuel preparation room). The outer pipe has to be fitted with methanol detectors to be able to shut off the system in case of leakage. Figure 32 pictures a double-walled pipe proposed by MAN B&W.

The fuel preparation room also referred to as TCS in Figure 27 above, is located outside of the engine room in compliance with IGF code requirements. The room will contain the circulation pumps circulating the fuel from the tanks to the engines. For redundancy, a double set of pumps will be used.

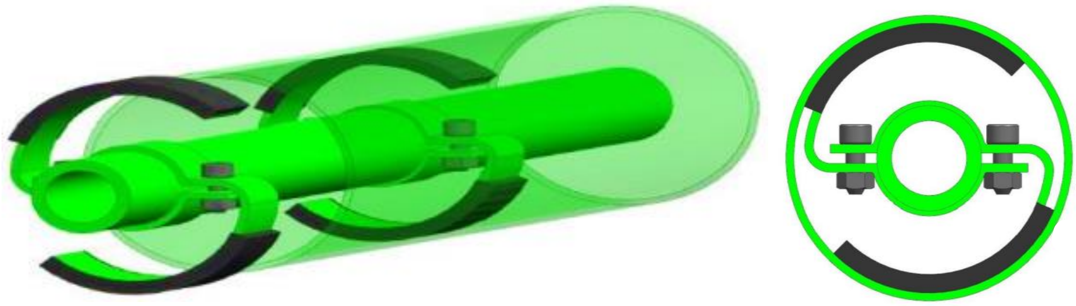

Figure 32. Double-walled fuel supply pipe. Available from https://www.onthemosway.eu/wp-content/uploads/2015/06/Standards-and-Guidelines-for-Natural-Gas-Fuelled-Ship-Projects%E2%80%99.pdf [Accessed on 03 July 2022]

5.1.3.2 Bunkering concept

Due to the differences between HFO and methanol, the bunkering process has to be revised to avoid any accidents during the process. The bunkering stations on the ship are located on deck N°4 at the aft part of the ship both on the port and starboard sides, where they have access to natural ventilation. In compliance with the DNV rules 3.6.1 for the bunkering station, coamings will be fitted below the bunkering station to collect any fuel spill and drain it into dedicated collectors then washed overboard with water. Figure 33 illustrates the predispositions available at the ship´s bunkering station. In addition to the coamings, automatic shutoff valves, and nitrogen connexion for purging are to be installed.

The methanol pipe has to be double-walled and located 800 mm away from the ship’s side shell. The bunkering pipe has to be of a self-drain type. Moreover, the coupling connexion between the hose and the bunker station has to close automatically when disconnected. Figure 34 represents a model of connectors used on board the Stena Germanica (IMO 9145176), both connected or disconnected configurations. The bunkering process can be achieved using different sources, trucks, barges, or ship-shore links are applicable.

Figure 33. Bunkering station predispositions, (Ait Aider, 2022)

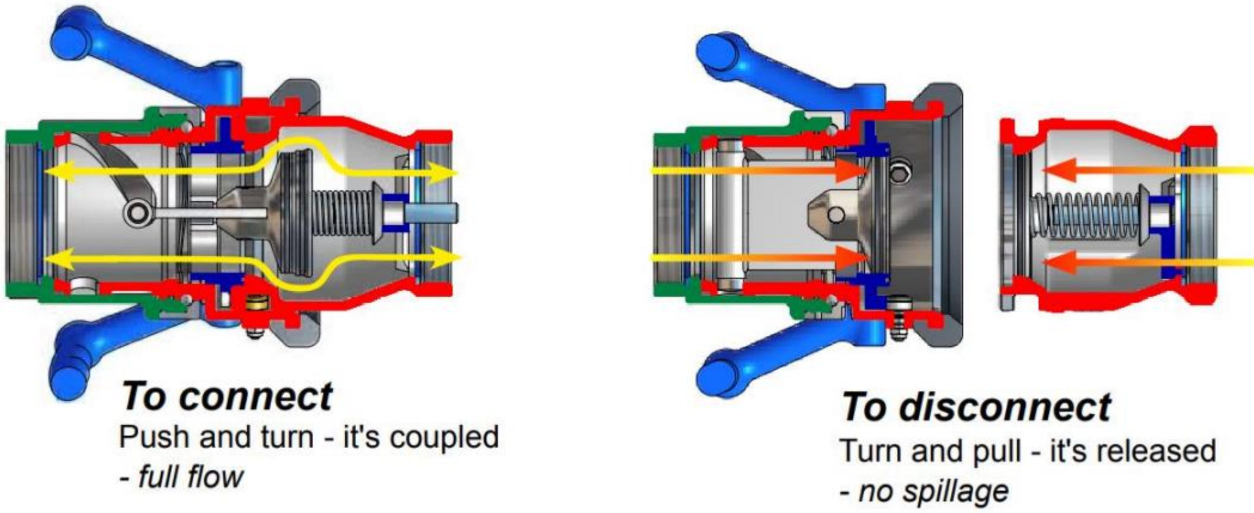

Figure 34. Bunkering connexion between the hose and the bunker station [56]

5.1.4 Provisions for the main engine

To be able to run on methanol, the main engine of the ship has to be upgraded from being a conventional engine. The upgrade has to be towards dual-fuel technology. Dual-fuel operation will enable the ship to run on methanol as primary fuel, and a pilot fuel will be used to enhance the combustion. The pilot fuel is MDO, however, to enable 100 % carbon-free combustion, biodiesel can be used. The dual-fuel concept is highly recommended due to the offered flexibility. A quick transition can be made from methanol to biodiesel if the methanol supply is interrupted due to leakage or due to runout. In this scope MAN B&W, the manufacturer of the engines installed onboard brings forward the concept of liquid gas ignition methanol (LGIM) engines for methanol. This engine is based on the ME-C engines, similar to the one installed on board. The ratio of the pilot fuel is 5 %, however as already mentioned, the pilot fuel has to be compliant in order to meet the NOx emission limitations. MAN, engineers confirm that an upgrade of conventional engines is possible due to the similarity in the functional principles. The upgrade will only concern the top part of the engine at the cylinder heads where the injection system is located. Figure 35 below lists the compatibility of MAN's portfolio of engines with several fuel solutions and the ability to upgrade. The portfolio of engines includes conventional fuelled (C), dual fuel gas ignition diesel cycle (GI) and Otto cycle (GA), gas ignition Ethan engine (GIE), liquid gas ignition methanol engine and LPG fuelled engine (LGIP).

Fuel types	ME-C	ME-GI	ME-GA	ME-GIE	ME-LGIM	ME-LGIP
Fuel oil	✓	✓	✓	✓	✓	✓
LNG	Upgrade	✓	✓	Upgrade	Upgrade	Upgrade
LEG (Ethane)	Upgrade	Upgrade	-	✓	Upgrade	Upgrade
Methanol	Upgrade	Upgrade	-	Upgrade	✓	Upgrade
LPG	Upgrade	Upgrade	-	Upgrade	Upgrade	✓
Ammonia	Upgrade	Upgrade	-	Upgrade	Upgrade	Upgrade

Figure 35. MAN, engine portfolio and their compatibility with different fuels. Available from https://app.gotowebinar.com/unified/index.html#/webinar/1357389307385624332/attend/241427886856405775 [Accessed on 03 July 2022]

The additional components to form an LGIM engine are shown in Figure 36 where we can clearly see the additional methanol supply pipes to the pistons heads in yellow color. The injection system has also endured several modifications, starting with the new double-walled methanol pipe inlet and outlet, methanol nozzle, and hydraulic oil pipes. The hydraulic accumulator's role is to boost the methanol pressure to 600 bar inside the combustion chamber. Note that FBIV-M is fuel booster injection valve-methanol.

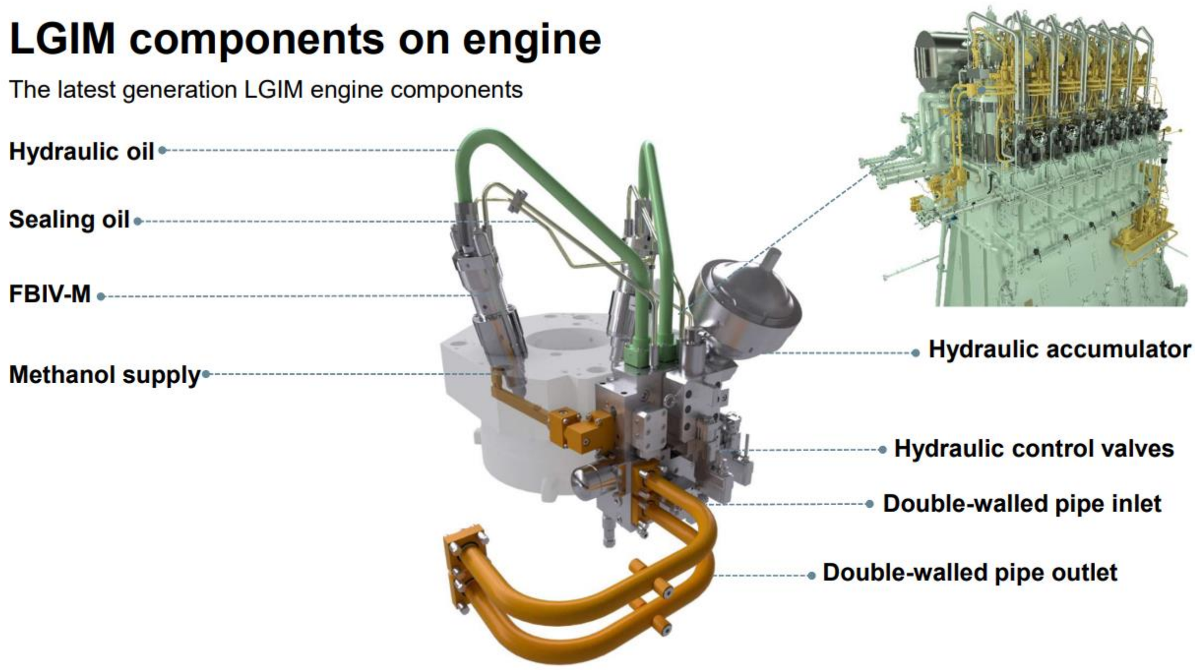

Figure 36. Components of an LGIM engine by MAN. Available from https://www.man-es.com/marine/products/man-b-w-me-lgim [Accessed on 03 July 2022]

5.1.5 Fire prevention and safety arrangements

As already mentioned, methanol is a highly toxic substance for humans, any contact with the skin of the eye requires immediate medical attention, and inhalation or oral introduction of methanol is highly toxic. In addition, methanol vapours and liquids are highly flammable. Therefore, common safety measures used to handle HFO and MDO have to be reinforced.

5.1.5.1 Fire detection

Unlike most fuels burning, methanol fire does not produce a visible flame. Methanol burns in a clean way without producing any soot, hence smoke detectors are not effective to detect a methanol fire [57]. Moreover, the radiation immitted by a methanol fire is lower compared to other fires, making it invisible to the eye. To encounter these difficulties, certified multi-spectrum infrared (MSIR) cameras can be used to capture flames. Thermal imaging is another solution to visualize any potential fire on board. Nonetheless, conventional smoke detectors will be used on board to detect fires that can start from other sources. Also, when a methanol fire propagates, other burning material such as plastic cables starts to emit smoke that can be detected using smoke detectors [56].

5.1.5.2 Fire suppression measures

In case of a fire onboard the ship, the fire suppression system has to be capable of distinguishing a methanol fire. The methanol's low flash point, oxygen availability, and good miscibility with water are factors that demand different fire control measures. Inside areas where methanol is present, the engine room and the tank area in deck N°1 gas extinguishing system have to be used. The gas suppression system floods the compartments with CO_2. The required minimum CO_2 concentration to control a methanol fire is higher than fires from other sources. The minimum concentration of CO_2 to extinguish a methanol fire is 27.2 % [57]. Therefore, the volume of CO_2 carried on board has to be increased. Alcohol-resistant foam-type fire-fighting systems have to be used to cover areas below fuel tanks where a spill may occur, a fixed foam station has to be fitted into each of the bunkering stations. Water sprayers are not of a high effect when extinguishing the fire. However, they act as a cooling agent for the flames and dilute the methanol. Moreover, water spray helps to disperse oxygen and fuel vapours [57]. Figure 37 illustrates the multiple layers of systems used to detect and suppress a methanol fire. A fire source is identified based on the heat, smoke, and radiation that are generated. These indicators are captured by dedicated safety measures, that trigger a response via the fire suppression systems.

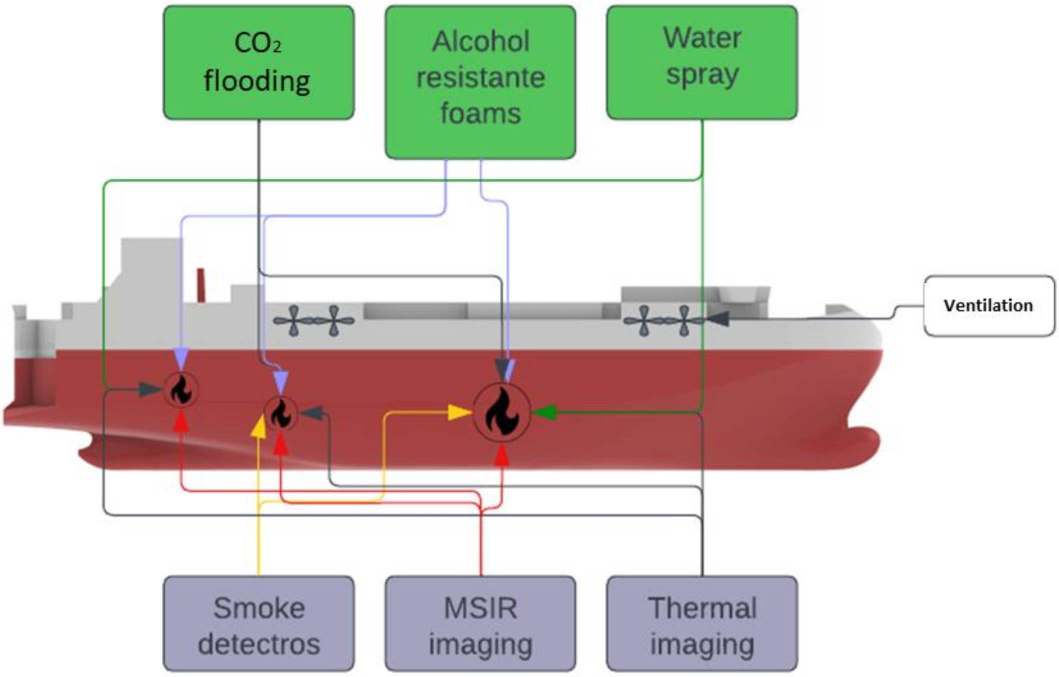

Figure 37. Methanol fire prevention measures diagram

In addition to the fire extinguishers, sensitive areas have to be insulated against fire. The insolation prevents the fire from entering directly in contact with the ship´s structural elements and delays heat propagation. In compliance with the IGF code, the engine room, the tank surroundings, accommodation, and control station must be fitted with A60 insulation at least. Figure 38 illustrates how the insulation covers the ship structural elements.

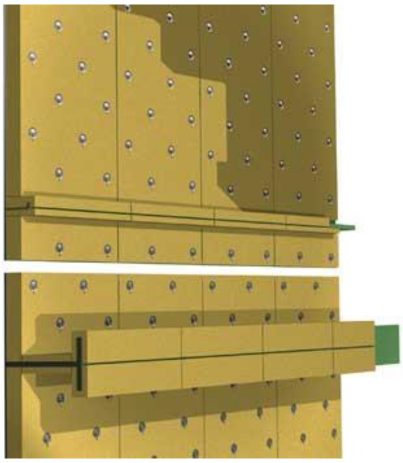

Figure 38. A60 insolation on a ship structure. Available from https://www.paroc.com/applications/marine-and-offshore/bulkhead/a60-steel-bulkhead# [Accessed on 04 July 2022]

5.1.6 Hazardous area identification

The use of methanol as fuel onboard the ship generates a wide range of hazards that endangers both the ship and the crew. Thus, hazardous areas have to be marked on plans according to class regulations and IGF code, with the ultimate objective of alerting about the hazards present in each area so that crew may take appropriate measures while accessing and working inside. A hazardous area plan separates the ship into locations with different hazard categories as defined both by the IGF code and the DNV rules for LFL fuels [Pt6 Ch6 S6]. Table 21, is the definition of DNV regarding the hazard zones and their classification. However, the DNV classification account for explosion risks only, health and environmental hazards are not considered. Additionally, the characteristics of each zone and their location are defined in accordance with the IGF-Code notation. The details of the zone separation are illustrated in annex A6 Methanol tanks located in the double bottom and the inner space of deck N°1 by definition classed as zone 0. The adjacent areas of the deck N°1 space is defined as zone 1, the same goes for the ship sides on the deck N°2 and N°3 due to the presence of openings linking them to the deck N°1 space. The rest of the decks N°2 and N°3 are ranked in zone 2. The bunkering stations port and starboard in addition to the vent mast, are areas where the hazards induced by ammonia is occasional. Therefore, they are considered as hazard areas of zone 1, however, the wider spaces around the zone 1 are considered as zone 2 area to provide an additional layer of safety.

Table 21. Definition of hazardous areas [58]

Hazardous area	Characteristics
Zone 0	Area in which an explosive gas atmosphere is present continuously or is present for long periods. Such as the interiors of storage tanks and slop tanks, any pipework used in pressure-relief or other venting systems for cargo and slop tanks, and any pipes or equipment used to contain or create dangerous gases or vapours.
Zone 1	Area in which an explosive gas atmosphere is likely to occur in normal operation. Which can be, any areas near integrated storage tank (void, cofferdam, pump room). Area up to a height of 2.4 m above the deck or 3 m above the manifold, or within 3 m of any cargo tank outlet, gas or vapour outlet, or within 1.5 m of cargo pump room entrances, cargo pump room ventilation inlet, or openings into cofferdams or other Zone 1 areas. A vertical cylinder with a 6 m radius and an unlimited height can be centred on the outlet.
Zone 2	Area in which an explosive gas atmosphere is not likely to occur in normal operation and if it does occur is likely to do so only infrequently and will exist for a short period only. Such as area located 10 metres horizontally from any gas or vapour outflow or cargo tank outlet. zones in zone 1 that are 1.5 metres from open or partially enclosed places. spaces 4 metres outside of zone 1's cylinder.

5.2 Ammonia integration

Ammonia as fuel solution is considered as one of the fuel solutions that will enable the maritime shipping to meet the 2050 emission goals. Being a carbon-free fuel, the potential of CO_2

reduction 100 % with zero SOx and particulate matters emissions. Nonetheless, the high NOx emissions require a post combustion treatment. Based on the AHP evaluation performed earlier in chapter 4, ammonia stored in cryogenic conditions was ranked second as the best fuel solution for the energy transition. This ranking was the result of the advantageous environmental performance and the moderate price of ammonia. However, the lower energy density and the storage requirements, lead to a total revision in the storage system and its capacity.

Unlike conventional fuels, ammonia is a gas that needs to be stored onboard at a temperature of -33°C. Such circumstances require adequate regulations to guarantee safe integration onboard and safe operations. In the framework of this work, the regulatory base is derived from the IGF code for ships using gases or other LFL fuels and the International Gas Carrier (IGC) code. Class regulations do not have classification rules for ammonia fuelled ships, but ammonia has been shipped as a commodity for a long time. Thus, class regulations for ammonia carriers and refrigerated ships can be used as a regulatory base.

5.2.1 Material selection for ammonia storage

Materials must be carefully selected for cryogenics applications because of the drastic changes in material properties when exposed to extremely low temperatures. In addition, ammonia as a chemical compound is very corrosive to certain materials such as copper, copper alloys and zinc. Carbon manganese steels and nickel steels are also subject to stress corrosion. The risk of stress corrosion increases drastically if oxygen is dissolved in the liquid ammonia. Furthermore, ammonia reacts with CO_2 that can be used in as inert gas [59]. Therefore, the use of aluminium alloys or stainless steel is recommended. Table 22 detail the chemical composition of aluminium alloy 5083-O from the 5000 series, which is reliable for shipbuilding applications and pressure vessels. Alu alloy 5083-O is widely used for low-temperature storage applications because of its good mechanical characteristics and its substantially greater fracture toughness [60]. The mechanical characteristics of Alu alloy 5083-O is shown in Table 24

Table 22. Chemical composition of Alu alloy 5083-O [61]

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ga	V	Ti	Other
0.40	0.40	0.10	0.4-1.0	4.0-4.9	0.05-0.25	-	0.25	-	-	0.15	0.20

Stainless steels are low carbon steels with high nickel content, austenitic stainless steels are characterized by their ability to retain their high mechanical characteristics in very low temperature operating conditions. They are considered sub-zero materials with their ability to handle temperature ranges up to -269°C [62]. Table 23 detail the chemical composition of AISI 316 L stainless steel, a material that commonly contains liquids below their boiling temperatures. The mechanical characteristics are detailed in Table 24.

Table 23. Chemical composition of AISI 316 L stainless steel [63]

C	Si	Mn	P	S	Cr	Mo	Ni	N
0.03	1	2	0.045	0.03	16.5-18.5	2-2.5	10-13	-

Table 24. Mechanical characteristics of the proposed materials

	Alloy 5083-O	AISI 316 L
Density [kg·m^{-3}]	2,700	8,000
Elastic Modulus E. [GPa]	71	200
Thermal Conductivity [W·m^{-1}·°C^{-1}]	117	15
Mean Coefficient of thermal expansion [10^{-6}·°C^{-1}]	17.5	16
Yield stress. at -40°C [MPa]	145	283
Ultimate tensile stress. at -40°C [MPa]	295	717

5.2.2 Ammonia tanks and tank rooms

Because of the low energy density of ammonia, the required volume to meet the autonomy of the HFO was found to be 2,927.89 m³. This volume is approximately two times larger than the HFO, in addition, the cryogenic storage requires dedicated arrangements. As result, the HFO tanks can´t be used again for ammonia storage. New storage concepts have been proposed to store the needed volumes of ammonia. The first concept relays on using independent C-type tanks that can be prefabricated on shore and then dragged to the inside of the ship and fixed into their locations. The second concept is to build inside the ship new independent type B-tanks, they will take prismatic form allowing a better utilization of the available area in a much more effective way. In both concepts, and due to the fact that the fuel is refrigerated, the thermal insulation requirements are taken into consideration. The motivation behind the choice of independent tanks is to avoid the need for major structural modification in the ship´s structure to accommodate the fuel. Figure 39 illustrates the two tank types. The advantages and disadvantages linked to each of these storage solutions are listed in Table 25.

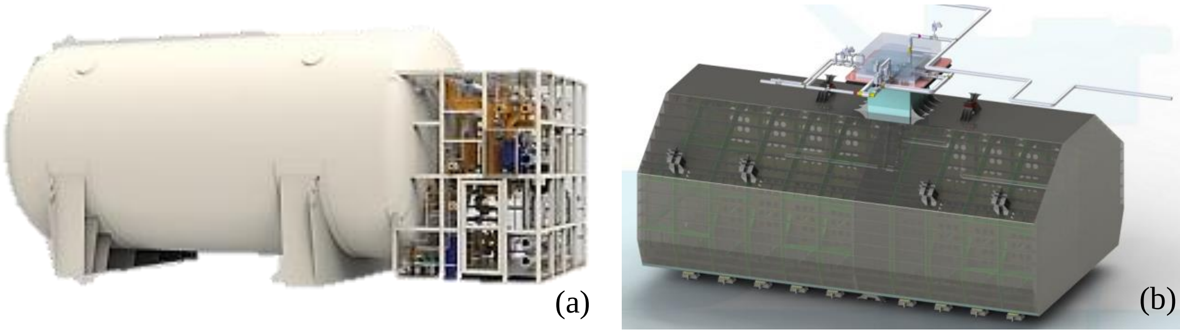

Figure 39. Ammonia tanks respectively type C (a) and type B (b). Available from http://www.artidenizcilik.com/images/galeri/aae603e9efe44c868111193d7903f0d8_torgy-lng-ammonia-ready-systems-vs1.pdf [Accessed on 04 July 2022]

Table 25. Comparison of storage tanks

Storage solution	Working pressure	Advantages	Disadvantages
Independent C-type tank	>2 bar	- Effective space occupation - Efficient for large storage capacities	- High boil-off - High cost - Very sensitive to pressure accumulation - Induces sloshing effect
Independent B-type tank	< 0.7 bar	- Robust design - Easy installation - Minimum maintenance required - Flexible pressure - Low design cost	- Space requirement

5.2.2.1 Type C tank integration

Type C tanks are simple geometrical shapes, made in cylindrical form to hold liquids and pressurized gases. They are mainly designed to handle membrane stresses from a structural point of view. A C-type tank contains the fluid in a cylindrical vessel. In addition to that, other elements are present. Saddles or support fix the tank to the ground, to prevent the liquid motion inside a swash bulkhead subdividing the tank, and a dome where a piping connection can be established. Figure 40 illustrates typical elements of the tank.

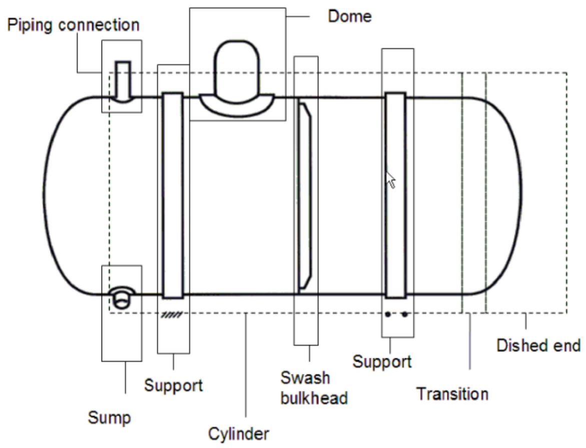

Figure 40. C-type tank components. Available from https://rules.dnv.com/docs/pdf/DNV/CG/2020-07/DNVGL-CG-0135.pdf [Accessed on 04 July 2022]

In our approach to install the fuel tanks inside the RoRo ship, a reallocation of cargo space into tank rooms is inevitable. The amount of ammonia to be carried on the ship has to guaranty the same or close to same operational rang as HFO. During the insertion of the C-type tanks, it is important to respect the maximum height limitation of the cargo decks. Therefore, the tank design and dimensions are proposed by us to fit in the most efficient way inside the ship. Another important constraint to account during the integration process is the maximum load than can be carried by each deck, where the distributed load applied by the fuel tank over the area shall not exceed the maximum loads described in the Table 18.

The new tanks are composed of cylinders of 2 m in diameter and a length of 14.5 m, another set of tanks of 11 m long are also used to fill the deck area effectively. Figure 41 illustrates a rendering of the tanks, where they are based on the design of an ISO container for liquids. The detailed dimension of the tanks and their storage capacities are detailed in Table 26.

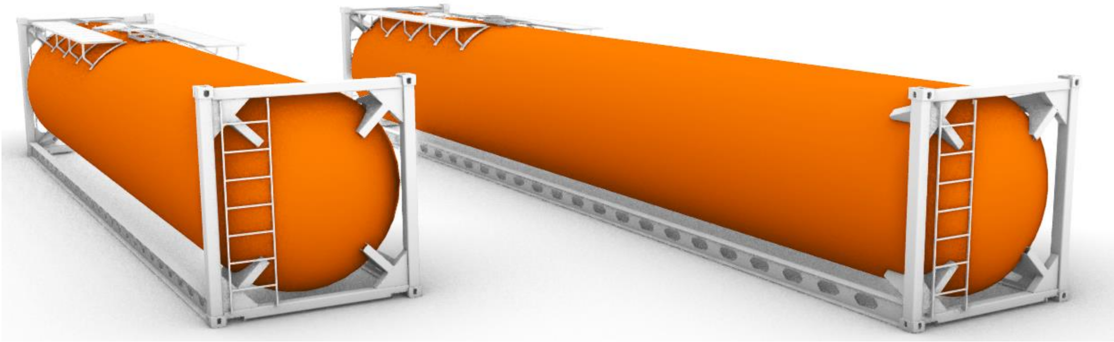

Figure 41. C-type tank rendering

Table 26. Main dimensions of the C-type tanks

	Length [m]	Width [m]	Hight [m]	Diameter [m]	Volume [m³]
14.5 m tank	14.5	2.05	2.18	2.0	44.5
11.0 m tank	11.0	2.05	2.18	2.0	33.5

The proposed tank configuration to reach the required capacity require the reallocation of the cargo decks N°1 and deck N°2. Deck N°3 is a movable deck that can be removed permanently. The tanks will be placed in packs, the packing arrangement will allow a better multi-tank connexion. The tank arrangement is done with respect to the applied regulations of the IGF code 5.3.3, where the clearance to the ship side is between 0.8 m and 2 m depending on the tank capacities. In our concept, the distance between the tanks and the ship side is 4.15 m at the midship. Table 27 lists the tank numbers and their sizes in each deck. Net volume represents the volume of the fuel that can be contained inside the tank depending on the temperatures, as reference net volume is 85 % of the tank volume. Figure 42 illustrates the tank distribution inside the ship, where it can be seen that the same configuration of tanks is used in deck N°1 and deck N°2.

Table 27. Ammonia tank configuration

Deck number	Number of tanks	Volume [m³]	Net volume [m³]	Applied load [kg·m⁻³]
Deck N°1	24	1,035	879.75	193.80
Deck N°2	48	2,070	1,759.50	387.61
Total	72	3,105	2,639.25	

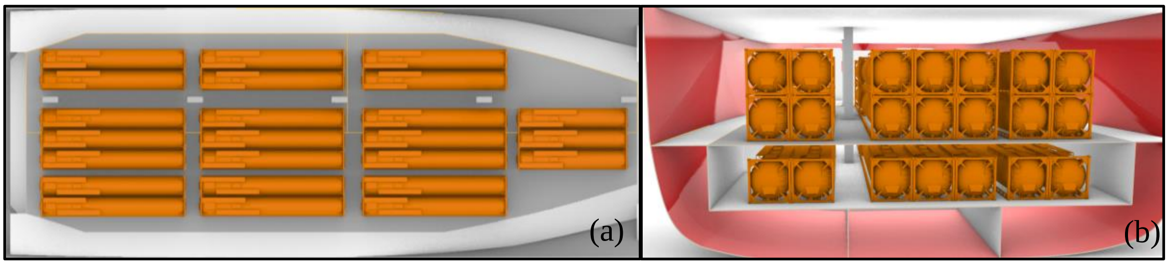

Figure 42. C-type tank arrangement top view (a), transversal cut (b)

The use of ammonia poses a series of engineering challenges in terms of material selection, both the cryogenic storage condition and the corrosive nature of ammonia require the use of materials that can withstand both the corrosion and the low temperature such as aluminium alloys, stainless steel. Within the same scope, the scantling of the cylindrical tanks will be done in compliance with the class rules to determine the thicknesses of the tank shell using different construction materials for comparison purposes. The cryogenic storage conditions require special attention in terms of thermal insulation, the insolation will prevent heat flux from circulating into the tank and raising the fuel temperature. A rise in the temperature will induce evaporation of the fuel referred to as BOG which will raise the pressure inside the tanks.

The determination of the shell thicknesses for a C-type tank is based on the design pressure concept. The minimum design pressure defines the dynamic stresses applied to the shell, in order to guarantee the structural integrity during the life span of the tank. The scantling was done both following the DNV rules and the IGF Code 6.4.15.3. Detailed calculations are attached in the annex A3. Table 28 illustrates the found results based on the DNV [Pt5 Ch7 S22] calculation, using both aluminium alloy and stainless steel with a corrosion margin of 1 mm.

Table 28. Thicknesses of the C-type tank shell

	Stainless steel AISI 316 L	**Aluminium alloy 5083-O**
Minimum thickness allowed [mm]	3.00	7.00
Calculated thickness [mm]	4.77	7.22
Chosen thickness [mm]	5.00	8.00

Thermal insulation is used to prevent heat losses, such limitation will keep the temperature inside the tanks within the required limits. Keeping the ammonia in liquid form is not possible for long periods due to the evaporation at the surface level, referred to BOG. However, good thermal insulation can keep the blow-off rate (BOR) as minim as possible per 24 h. In fact, regulations applied on LNG fuelled vessels stipulate a BOR has to be kept as low as 0.15 % [64] per day. To select the best insolation product, we compared two of the most used insolation materials: polyurethane foam (PU foam) and vacuum perlite insulation. Table 29 lists the required insolation thicknesses required for each material to keep the BOR lower than 0.15 % per day. The detailed calculations are provided in the annex A5. Note that liquid ammonia vapor pressure at -33.9°C is 0.99 bar [65], while the tanks are designed to hold up to 3.9 bar. The vapor pressure is the pressure at which the fluid inside the tank reaches an equilibrium condition between the evaporation and the condensation of the vapours, therefore theoretically no boil-off is occurring. It can be seen that to minimize the boil-off rates, PU foam is not competitive due to its poor insolation capacity, therefore the required thickness is huge. Nonetheless, vacuum perlites are more efficient, where a thickness of 150 mm is able to provide low BOR per day.

Table 29. insolation Thickness calculation for C-type tank

Material	AISI 316 L		Alu alloy 5083-O	
Insolation	PU foam	Vacuum perlite	PU foam	Vacuum perlite
Thickness [mm]	2,000	150	2,000	150
BOR % day	0.32	0.14	0.32	0.14

In order to apprehend the difference related to the use of stainless steel or aluminium, it is important to determine some parameters that allow a reasonable evaluation of the benefits and charges linked to each material. The evaluation parameters that are of interest to provide an evaluation are the weight and the material cost to build the tanks. Table 30 illustrate the calculated weights for each tank and then the total material cost of the tank configuration. A margin of 20 % is added to account for the frames supporting the tanks. Due to its lower density, aluminium tanks are significantly lighter than stainless steel tanks. Additionally, the actual prices of materials are in favour of aluminium, thus, the total cost of aluminium represent only a third of the stainless-steel cost.

Table 30. Weight and cost comparison for C-type tank materials

		AISI 316 L	Alu alloy 5083-O
surface [m²]	**(14.5 m) Tank**	93.50	93.50
	(11 m) Tank	71.50	71.50
weight [kg]	**(14.5 m) Tank**	3,740	2,019.60
	(11 m) Tank	2,860	1,544
Total tank configuration weight +20 % margin [t]		560.73	302.80
Total weight tanks and fuel [t]		2,294.57	2,036.62
Material cost [€·kg^{-1}]		5.5	3.78
Total material cost [€]		3,084,048.00	1,144,574.32

5.2.2.2 Type B tank integration

Type B tanks are prismatic tanks very similar to type A (membrane) tanks. They are self-supporting tanks, insulated from the outside without entering in contact with the ship structure. The design is based on the leak before break criteria, therefore a full secondary barrier is not required, a partial secondary barrier is sufficient. In comparisons to the C-type tanks, B-type tanks enable a better usage of the available area. Figure 43 illustrate a typical arrangement of type-B tank inside a ship, where the tank is fixed to the ship via support points. The tank is self-supported; therefore, it has integrated structural elements to strengthen the plating. To prevent sloshing, the tank is divided with swash bulkheads.

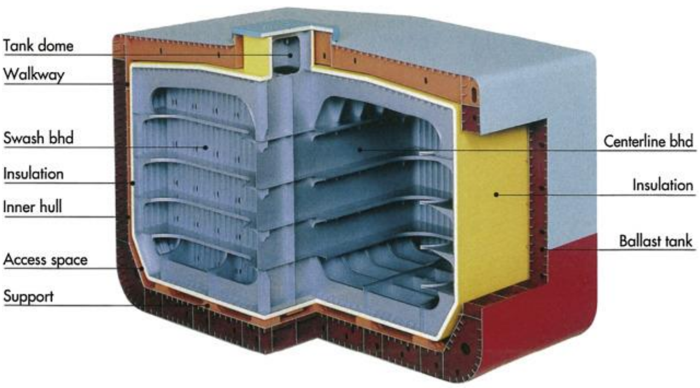

Figure 43. B-type tank arrangement in a ship hold [66]

To provide the best storage solution for liquid ammonia, we will go throw the process of installing Type B tanks inside the RoRo ship similarly to the C-type tank integration. The amount of ammonia to be carried on the ship has to guaranty the same or close to same operational rang as HFO, however, maintaining such operation range will require additional volume. In addition, the cryogenic storage condition will cancel any possibility for a reutilisation of the HFO fuel tanks. The installation of the B-type tanks will be in the deck N°1 and deck N°2 spaces. The installation of the tanks will be done in compliance with the IGF Code regulations and the DNV Class recommendations [Pt5 Ch7 S21]. Moreover, the maximum carrying capacity of the deck, see Table 18, is a constraint that is accounted for during the deign process. Table 31 lists the new tanks, their location, volumes and applied load on the deck structure. Note that the net volume corresponds to 85 % of the total volume of the tank. Figure 44 illustrate the tank arrangements inside the ship hull.

Table 31. B-type tank configuration

Tank name	Deck N°	Location[m]						Volume [m³]	Net volume [m³]	Applied deck load [kg·m⁻²]
		Aft	Fore	Port	Starboard	Top	Bottom			
Tank CL 1	1	46.5	71.5	-2.75	9.25	4.0	2.75	358.7	304.90	811.53
Tank PS 1	1	46.5	71.5	-9.65	-3.85	4.0	2.75	173.3	147.31	811.48
Tank CL 2	1	72.5	99.2	-2.75	9.25	4.0	2.75	341.7	290.45	811.12
Tank PS 2	1	72.5	99.2	-9.65	-3.85	4.0	2.75	125.3	106.51	810.84
Tank CF	1	101.5	109.85	-4.29	4.19	4.0	2.75	66.2	56.27	812.24
Tank CL 3	2	46.5	71.5	-2.75	9.25	8.0	5.75	645.76	548.90	1,460.98
Tank PS 3	2	46.5	71.5	-9.65	-3.85	8.0	5.75	312.1	265.29	1,461.42
Tank CL 4	2	72.5	99.2	-2.75	9.25	8.0	5.75	615.17	522.89	1,460.28
Tank PS 4	2	72.5	99.2	-9.65	-3.85	8.0	5.75	225.68	191.83	1,460.41
Total volume								2,863.91	2,434.32	

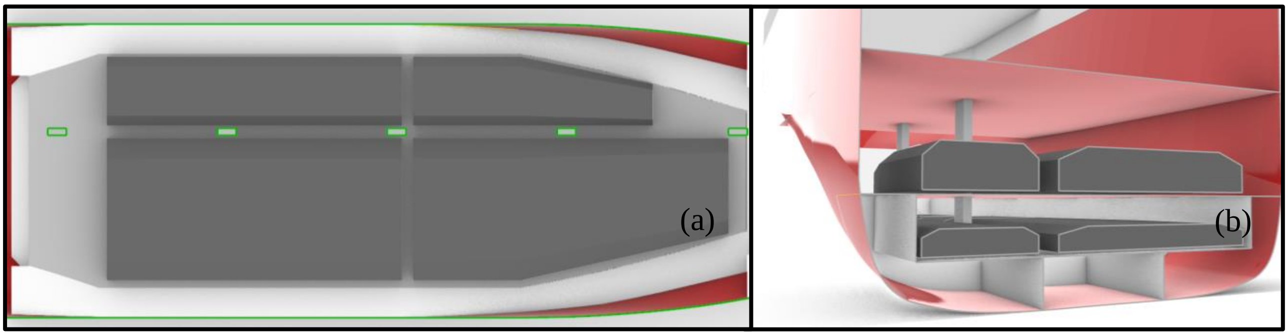

Figure 44. B-type tank arrangement, (a) top view, transversal cut (b)

Similarly, to the C-type tanks, the material selection process is very important to guaranty a safe storage condition. Therefore, the potential of stainless steel AISI 316 L and aluminium alloy 5083-O is explored. In the same scope, the thermal insulation is also considered. While type-C tanks are able to handle design pressures higher than 2 bar (20 kN·m^{-2}), type-B tanks design pressure is limited to 0.7 bar (7 kN·m^{-2}). Such design limitations mean that limiting the BOR is crucial. The B-type tanks are self-supporting and composed of reinforced panels. The cargo inside the tanks and the ship's motion induce local and global loads, respectively. Due to this, the tanks must be dimensioned in accordance with class regulations. DNV released class recommendations for LNG prismatic tanks of types A and B [DNVGL-CG-0133]. The results of the scantling process are listed in the Table 32. Details about the scantling are available in annex A4

Table 32. Summary of the B-type tank scantling

Structural element	**Material**	**Minimum requirement**	**Calculated**	**Selected**	**Comment**
Plate thickness [mm]	AISI 316 L	6.43	6.59	8.00	-
	Alu 5083-O	6.43	9.21	10.00	-
Stiffener section modulus [cm³]	AISI 316 L	-	16.84	21.00	Bulb Profile 120×7
	Alu 5083-O	-	32.87	36.2	L 120×120×10
Longitudinal stiffener section modulus [cm³]	AISI 316 L	-	296.08	331	L 200×9 90×14
	Alu 5083-O	-	573.66	659	L 300×10 90×16

The determination of a suitable insulation material is dependent of the size of contact area between the tanks and the atmosphere, the temperature gradient between the interior and the exterior of the tank, and the thermal characteristics of the tank material in addition to the insulation layers. The role of the insolation is to lower the heat transfer and prevent a rapid evaporation of ammonia, keeping the BOR less than 0.15 % vol per day. The results found using polyurethane foam and vacuum perlites are illustrated in Table 33.

Table 33. Insolation thickness calculation for the B-type tank

Material	AISI 316 L		Alu alloy 5083-O	
Insolation	PU foam	Vacuum perlite	PU foam	Vacuum perlite
Thickness [mm]	2,000	800	2,000	800
BOR [%]	5.5	0.43	5.5	0.43

Due to the large surfaces of the B-type tanks, the heat transfer between the inside and out side are considerably high in comparison to the C-type tank. As result, the BOR are significantly high despite the exaggerated insulation thicknesses. To manage the high BOG, a reliquification plant can be used.

Similarly to the C-type tanks, the difference related to the use of stainless steel or aluminium can be highlighted based on cost and weights, this will allow a reasonable evaluation of the benefits and drawbacks related to each material. The evaluation parameters that are of interest to provide an evaluation are the weight and the material cost to build the tanks. Table 34 illustrate the calculated weights for each tank setup and then the total material cost of the tank configuration. The weight calculation is based on calculating the total steel volume of the plates, a 30 % margin is added to account for the structural elements. Due to its lower density, aluminium tanks are significantly lighter than stainless steel tanks. Additionally, the actual prices of materials are in favour of aluminium, thus, the total cost of aluminium represent only a third of the stainless-steel cost.

Table 34. Weight and cost comparison for B-type tank materials

	AISI 316 L	Alu alloy 5083-O
Tank configuration weight + 30 % margin [t]	351.66	1,48.36
Total weight tanks and fuel [t]	2,294.82	2,091.52
Material cost [€·kg^{-1}]	5.5	3.78
Total material cost [€]	1,934,130.00 €	560,800.80 €

5.2.3 Atmosphere control inside fuel hold spaces

Atmospheric control is about controlling the air follow and the air quality circulating inside the tanks and around them.

5.2.3.1 Inerting

Ammonia flammability range is relatively limited between 14.8 - 33.5 % in atmospheric condition. Additionally, the ignition energy required to combust ammonia is 8 MJ. This required energy is very high compared to gasoline or CH_2 that require respectively 0.14 MJ and 0.018 MJ [67], making ammonia very difficult to ignite. Nonetheless, the environment inside the tanks both for C-type and B-type tanks has to be controlled. The inert gas role is to maintain a non-combustible environment inside the tank and the tank rooms, moreover the inert gas will serve to purge the tanks and the pipes when needed. Nitrogen will be used as inert gas onboard, where it has to be produced from an onboard generator. The production rate of the nitrogen station has to be at least equivalent the consumption rate of ammonia. The oxygen content in the inert gas cannot exceed 5 % by volume as specified in the point [6.5.4] of IGF code. In addition, the inert gas has to be kept dry to prevent icing. The connexion of the inert gas pipe into the tanks has to be arranged to prevent backflow. The details of the nitrogen production plant are illustrated in Figure 28 above.

5.2.3.2 Tank ventilation

In order to prevent the accumulation of ammonia vapours inside the tank and avoid a rise of pressure, the ammonia tanks (B-type or C-type) have to be connected to a vent piping system allowing the release of vapours away in the air to avoid any risk of toxic gases accumulation inside the ship. IGF code 6.7.2.2 require a minimum of a number of two pressure relieve valves for the fuel tanks for redundancy. The location of the venting points has to be arranged at a minimum height of 6 m above the last deck. The arrangement shall offer an interrupted evacuation of the gas, the outlet has to be protected from water or foreign object penetration. Figure 29 illustrate the vent mast location in the ship, where its height is 8.5 m above deck N°9.

5.2.3.3 Tank room ventilation

The ventilation of tank rooms will prevent the creation of a toxic or flammable atmosphere. IGF code provides the ventilation requirements for gas-fuelled ship. However, LNG does not have the same characteristics as ammonia neither the same hazard statements. Therefore, an interpretation of the regulations is necessary to fit with the ammonia fuelled ship.

Tank rooms are considered as hazardous areas, thus their ventilation system is separated from non-hazardous areas ventilation. The airflow from the hazardous areas has to be redirected to open air, and the ventilation system has to guaranty five air changes to make sure that a purging of toxic vapours is achieved. For the tank connexion space, a forced ventilation of extraction type has to guarantee a minimum of thirty air changes per hour. Inside the engine room, the ventilation system has to be independent from the other ventilation systems and shall guaranty thirty air changes to prevent an accumulation of gas pockets.

5.2.4 Fuel supply system and bunkering concept

Ammonia engine technology is more similar to the LPG engines, however the low combustion characteristics showed by ammonia require solutions. A part of the solution to enhance ammonia combustion is to use a pilot fuel, where it is estimated that it will require larger amounts compared to LPG [59]. Therefore, the use of ammonia as a fuel solution in internal combustion engines will be based on the dual-fuel concept.

5.2.4.1 Fuel supply system

The fuel supply system (FSS) developed for two-stroke engines proposed is very similar to the LPG fuel supply system [59]. The main role of the FSS is to circulate the ammonia from the storage tanks to the main engine at the suitable pressure and temperature. The ammonia is pumped at low pressure from the service tank, the FSS will rise the pressure of ammonia up to 70 bar via high pressure pumps, heated then filtrated before being injected to the engine. A recirculation line allows a return of small portions of ammonia from the engine into a recirculation tank to maintain engine performances. The recirculation system is separated from the main supply line to prevent the contamination of the ammonia storage with residues of oil coming from the engine. Ammonia circulates in and out of the engine which is done via double walled pipes with access to nitrogen for purging and an evacuation throw knock-out drums when needed. Such measures will prevent accidental leakage of ammonia within the engine room space. A fuel valve train (FVT) is the link between the fuel preparation and its injection into the main engine. The role of an FVT includes nitrogen-purging and ensuring safe isolation of the engine during shutdown and maintenance providing a safe environment inside the engine room. Figure 45 illustrate the ammonia fuel supply system proposed by MAN for two-stroke engines.

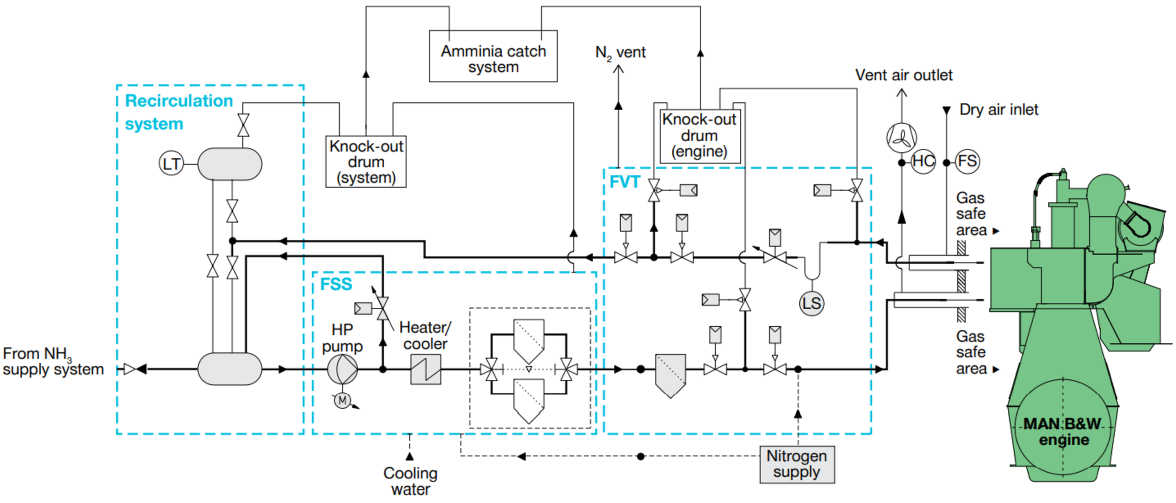

Figure 45. Main components of an ammonia fuel supply system [32]

5.2.4.2 Bunkering concept

The bunkering stations of the ship are located at the aft part both is port and starboard side in semi enclosed spaces at the deck N°4. Due to the low temperature and the chemical nature of ammonia, the materials of the piping system have to be upgraded to stainless steel, where they are conducted at a minimum distance of 800 mm from the ship side shell. A shielding of the pipes has to be done to avoid cold jets effecting the surrounding hull structure. In accordance to the IGF code, the ship structure around the bunkering station has to be protected from entering in contact with the low temperature fuel, moreover, in case of a fuel spill, adequate arrangements have to ensure a safe evacuation. Based on designs for LNG bunkering stations, a drip tray will be used to guide any spilled ammonia out of the ship as illustrated in Figure 46. The hoses intended to contain ammonia and ammonia vapours have to be designed to withhold five times the pressure that can occur from inside the tanks or due to a discharge of pressure. In operation, a nitrogen supply installation has to be provided to purge or inert the bunkering lines.

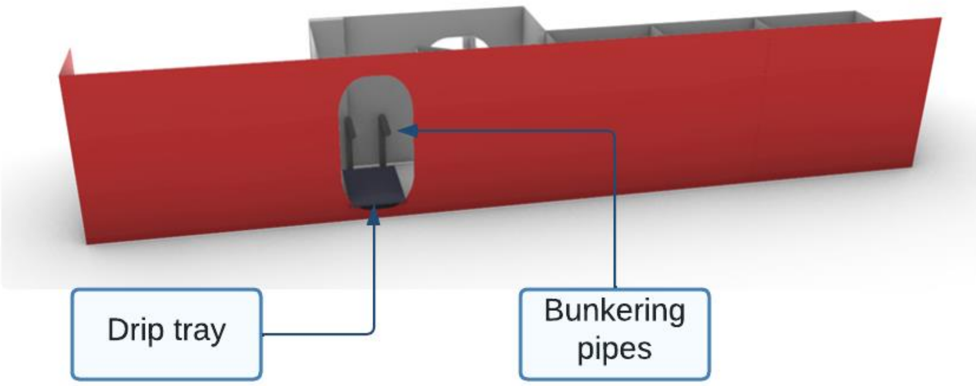

Figure 46. Ammonia bunkering station semi-enclosed arrangement

5.2.5 Provisions for the main engine

Internal combustion engines running on ammonia fuel are still in project phase. However, MAN is undergoing a development project of the two-stroke ammonia engine based on the LPG burning engines on dual fuel operations technology. The project schedule announced by MAN promote the first delivery of engine to the yard in 2024. Based on the ME-LGI engines, the ammonia engine will be able to burn ammonia as gas fuel with the help of pilot fuel. The proportion of the pilot fuel can be as high as 20 % of the fuel mixture. Thus, the carbon-free goal isn´t well guaranteed.

The retrofit of the ship´s ME-C engine can be possible by upgrading some parts of the engines. The cylinder cover containing the injection system has to be exchanged with an LGI cylinder cover shown in Figure 47 . The cylinder cover design contains the ammonia injection unit and the pilot fuel injection heads. A valve control block will control the fuel pressurization and the injection timing, and a hydraulic accumulator is fitted to tackle the transient pressure situations. Additionally, the valve control block contains hydraulic oil and sealing oil. The inlet and return line of ammonia are done via double-walled pipes.

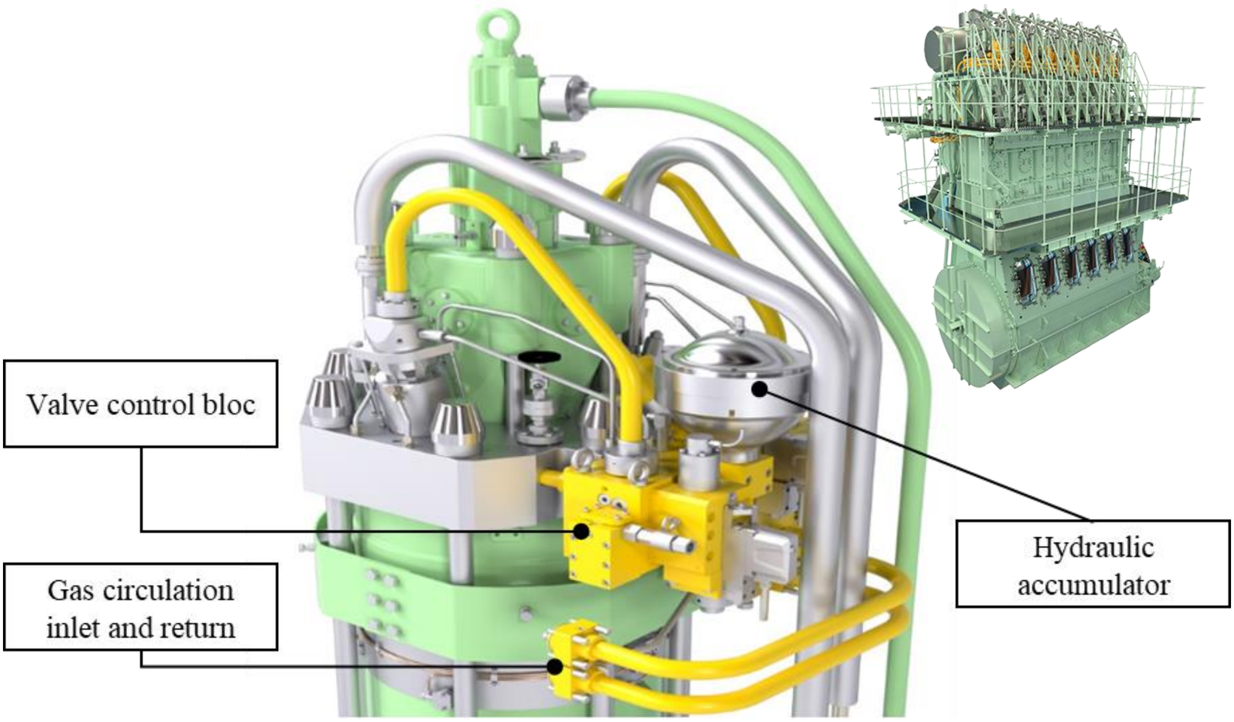

Figure 47. Cylinder cover of an ammonia engine (LPG). Available from https://www.man-es.com/company/press-releases/press-details/2018/09/03/man-energy-solutions-unveils-me-lgip-dual-fuel-lpg-engine [Accessed on 08 July 2022]

However, the use of ammonia comes with two additional difficulties that are high amounts of NOx, N_2O present in the exhaust gases ejected after ammonia combustion and the emission of unburned ammonia into the atmosphere (ammonia slip). To be in line with the standards, the ammonia slip has to be limited to 10 ppm [31]. To mitigate the high NOx emission problem and the ammonia slip, after treatments measures are needed. Selective catalytic reduction (SCR) installation available onboard the ship will be able to treat both NOx and NH_3 by injecting a urea solution into the exhaust gases. Another solution proposed by MAN consists of two-part solution: an ammonia capture system to prevent ammonia slip. A novel design of SCR that NOx and N_2O emissions by injecting small amounts of ammonia into the exhaust gases instead of the urea solution. The resulting gases after passing through the SCR are N_2 and H_2O. Table 35 illustrate the estimated consumption rates of the reducing agents provided by MAN to achieve Tier III compliance [68]. The optimal range of operation temperature at the SCR unit has to be between 300 - 400°C. Higher temperature will burn ammonia and prematurely stop the reaction with NOx. Lower temperatures will cause a formation of ammonium sulphates that can block the catalyst [69]. Figure 48 illustrate an SCR installation with urea injection system working at low pressure.

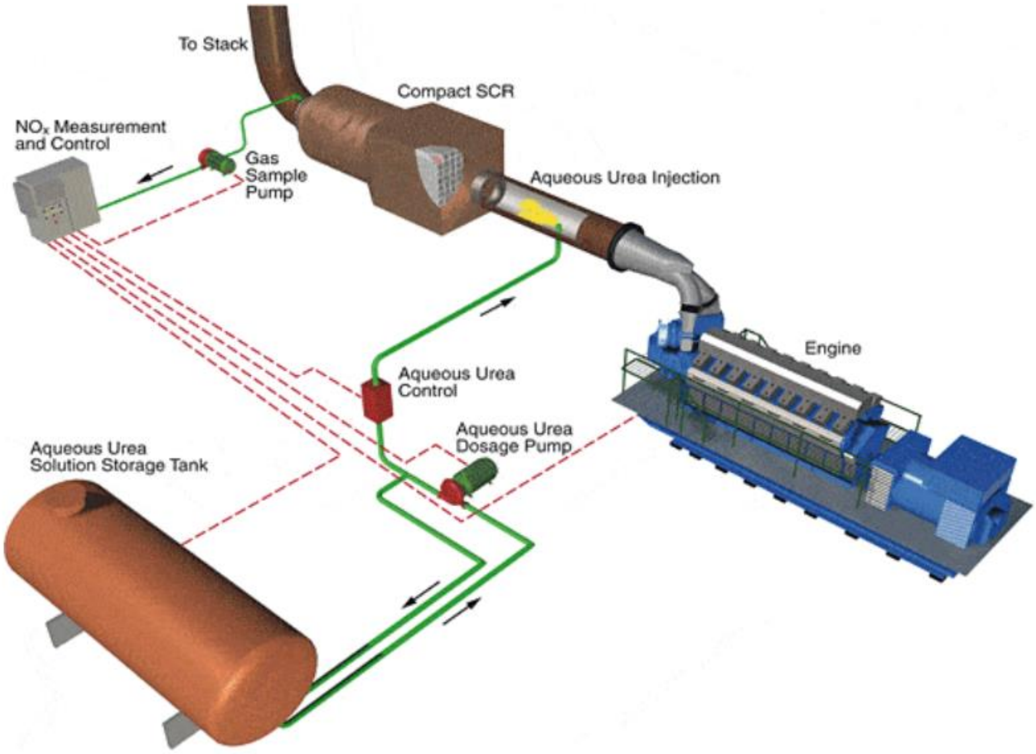

Figure 48. SCR arrangement with a urea injection system [69].

Table 35. Consumption of reducing agent

Reducing agent	$g \cdot kWh^{-1}$	$l \cdot MWh^{-1}$
Urea 40 %	17.9	16.1
Ammonia 24.5 %	16.6	18.4

5.2.6 Fire prevention and safety arrangements

Ammonia fuelled vessels are coming closer to take a share in the world fleet, therefore, fire safety considerations have to be vigorously considered. Ammonia flammability characteristics are different with respect to conventional fuels such as MDO or even gas fuels as LNG, thus a broad evaluation has to be independently realised for ammonia. Moreover, the absence of dedicated regulatory framework for the safe use and storage of ammonia rise the intersect for such evaluation. The safety and fire prevention regulations for ammonia fuelled ship has to meet the requirement of IGF code and IGC code. Ammonia is a flammable product, but due to its narrow flammability range and the high ignition energy required, ammonia is hard to ignite.

In aerated spaces ammonia does not present a fire hazard, but in enclosed areas, the risk of fire is higher especially in the engine room, where room temperatures are around 43°C most of the time. The presence of other flammable produces like lubrication oils increase the risk of having a fire. The toxicity of ammonia presents a high risk of suffocation for the crew if the exposure time is high. Low exposure time, does not induce suffocation still, the corrosive aspect of ammonia can cause skin and eye burns. Inhalation of ammonia vapours can cause internal burns. To summarize the various features caused by an ammonia fire in comparison with LNG fire or MDO fire, (T. Pomonis et al, 2022) established via multiple computer simulations a comparison where the results are highlighted in Table 36 [70]. Form this result, an ammonia fire can be considered less dangerous in comparison to the other fires. An ammonia fire or gas dispersion would still be harmful and potentially fatal, but the consequences would be less compared to conventional fuel fires. Because of ammonia's high autoignition temperature and limited flammability limits, an adequate time window for evacuation in the early phases of the gas dispersion is possible.

Table 36. Comparison of selected feature for different fuel fires

Simulated features	**Ammonia fire**	**LNG fire**	**MDO fire**
Heat release rate temperature	Low	High	Medium
Flammability limits	Low	Medium	High
Visibility levels	High	High	Low
Thermal radiation level	Medium	High	High
Evacuation window	High	Low	Low
Detection capability	High	Medium	Low
Carbon dioxide concentration	-	Medium	High

5.2.6.1 Fire detection

The first layer of any fire detection measure is to detect any leakage or ammonia spill inside the areas where ammonia is present. Ammonia gas detectors will allow to monitor the presence of ammonia in the air circulating inside storage areas and machinery space. A high concentration of ammonia in the air has to trigger an alarm and run the ventilation system to evacuate towards the atmosphere. Liquid leakages can be detected by monitoring the temperature and pressure in the fuel system [71]. The fire detection measures to be applied in case of an ammonia fire can be similar to the ones applied for other gas fuels such as LNG and LPG. Gas and flame detectors have to be installed around areas of ammonia storage and inside the fuel preparation area and the machinery room in accordance with the IGF guidance.

5.2.6.2 Fire suppression measures

In case of a fire start on board the ship, in ammonia storage areas and machinery spaces, the fire suppression systems have to be able to extinguish the fire and prevent the risk of any escalation or propagation to other spaces. The fire suppression system will be composed of several systems. Water spray systems in accordance with the IGF code regulation 11.5. where the main use of water is for cooling purposed in the tank area, preventing excessive heat and reducing the risk of tank explosion. Dry chemical compounds are to be used in remote location with manual activation to control any leak points such us the bunkering stations. The engine room has to be fitted with CO_2 extinguisher installation. Figure 49 schematize the fire detection and prevention arrangement. To protect the ship structure and the tanks from entering in direct contact with flames, A 60 insolation has to be provided.

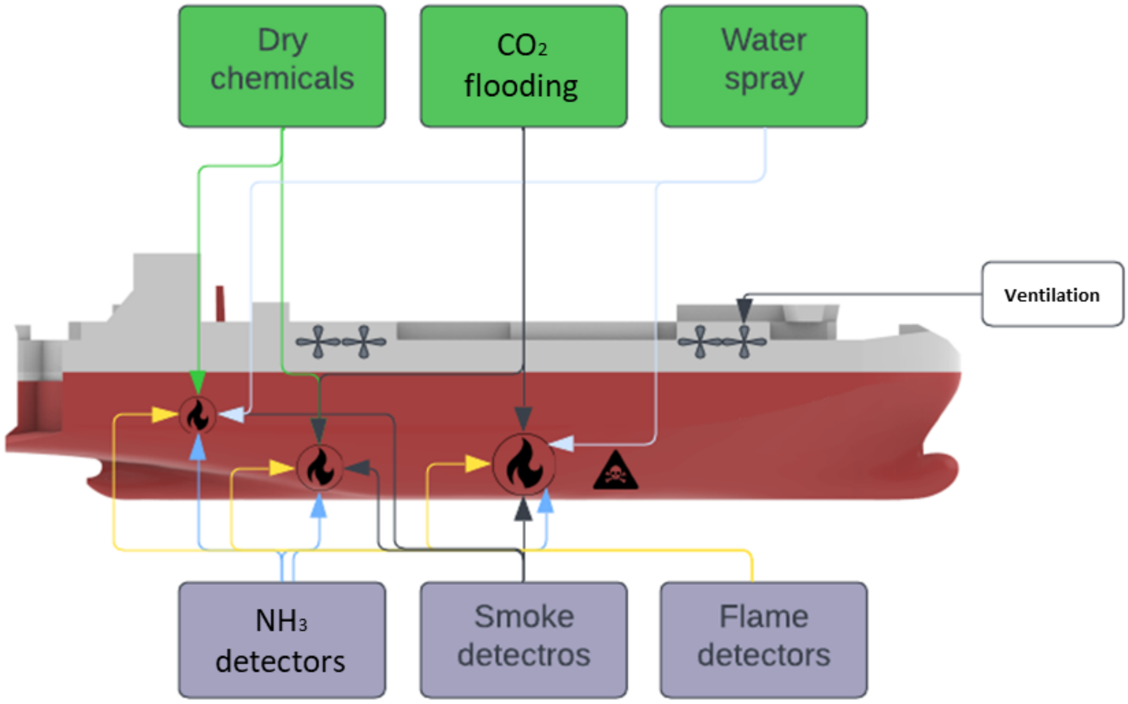

Figure 49. Ammonia fire detection and prevention diagram

5.2.7 Hazardous area identification

The use ammonia as fuel onboard the ship generates a wide range of hazards that endangers both the ship and the crew. Thus, hazardous areas have to be marked on plans according to class regulations and IGF code, with the ultimate objective of alerting about the hazards present in each area so that crew may take appropriate measures while accessing and working inside. A hazardous area plan separates the ship into locations with different hazard categories as defined both by the IGF code and the DNV rules for LFL fuels [Pt6 Ch6 S6]. Table 21 is the definition of DNV regarding the hazard zones and their classification. However, the DNV classification account for explosion risks only, health and environmental hazards are not considered. The detailed drawing of the hazard areas around the type-C and type-B tanks are detailed in annex A6. In comparison to the hazard areas of methanol storage solution, the decks N°1, N°2, and N°3 are now becoming a zone 1 hazard area due to the fact that they due contain ammonia storage tanks.

6 EVALUATION OF PERFORMANCE AFTER CONVERSION

In this section, a thorough evaluation of the integration process is achieved. The target of this evaluation is to be able to provide a view of the ship's expected performance in terms of carrying capacity and operation range. The GHG reduction potential of the ship can be measured depending on the fuel technology based on similar navigation profiles enabling a comparison with the use of HFO. In addition to that, an estimation of the potential capital expenditure required for the integration process of the two proposed solutions is detailed. Depending on the projected future fuel prices, an estimate of the projected cost ownership (TCO) will reveal the economic potential of each fuel technology.

6.1 Technical assessment of the impact of each fuel technology integration

During the integration of the ammonia and methanol fuel solution, many engineering decisions have been made, starting from the creation of new storage tanks. On that account, the technical evaluation explains the following points.

6.1.1 Impact on the ship characteristics

The integration of new fuel technologies on board the ship induced much engineering work. Nonetheless, the elements that had the highest impact on the ship were the storage tanks. Not only the storage tanks are occupying spaces allocated to cargo, but their added weight is also significant. Table 37 delineates the new characteristics of the ship in terms of the remaining car carrying capacity, and added weight. It is clear that the low volume requirement of methanol means that the car carrying capacity was reduced by 5.53 % only while for an ammonia storage solution the transformation of three decks induced a loss of 21.5 %. In terms of added weights from the fuel tanks, C-type tanks are heavier in comparison with the B-type tanks mainly due to the fact that they are able to handle high pressures. Despite the low volume requirement, methanol tanks have a weight that is slightly higher than the weight of the B-type tank, this is mainly due to the density of the material, where methanol tanks are built in marine grade steel, ammonia tanks are in aluminium alloys. Looking at the combination of the tank weight plus the fuel contained inside when filled at the maximum capacity, the range of values is around 2,000 t, where methanol fuel tanks are the heaviest.

Table 37. Repercussions of alternative fuel integration

	Methanol fuel tanks	**Ammonia B-type tanks**	**Ammonia C-type tanks**
Reduced car capacity [piece]	117	454	454
Car capacity reduction [%]	5.53	21.47	21.47
Lost deck area [m²]	964.4	2,781.1	2,781.1
deduced car weight [t]	162.0192	1,200.82	1,200.82
Tank structural weight [t]	151.61	148.36	302.8
Total fuel & tank weight [t]	2,103.26	2,091.52	2,036.62

6.1.2 Operational range and fuel consumption

One of the most important characteristics of ships is the operation range, which is the distance that the ship can undergo before having to refuel again. The range is closely related to the daily fuel consumption. The key factors controlling these two elements are the engine load and the navigation speed. Table 38 lists the estimated daily consumption and navigation range for the proposed methanol and ammonia fuel solutions at a speed of 18.9 kn. The net volume stands for the maximum volume of fuel that can be stored inside the tanks, for liquid fuels such as methanol, the maximum filling levels of the tanks can reach 98 %. However, for gas fuels, the filling limit depends on the density of the fuel during the bunkering operation that will be considered 85 %. The daily fuel consumption is calculated based on the (15) provided in chapter 5 for an engine load of 85 % MCR. Despite the large volume occupied by ammonia tanks, the net volume of the fuel carried is relatively similar to the net volume carried by methanol tanks. The high energy density of methanol results in lower daily consumption of fuel, enabling the ship to reach a higher operation range of about 14,315.3 nm.

Table 38. Fuel consumption and design range of each alternative fuel solution

	Methanol fuel tanks	**Ammonia B-type tanks**	**Ammonia C-type tanks**
Storage volume [m³]	2,517.67	2,863.91	3,105
Net fuel volume [m³]	2,467.31	2,434.32	2,639.25
Day consumption [t]	78.84	85.03	85.03
Operational range [nm]	14,315.29	11,234	12,179.71

6.1.3 Projected GHG emissions

Based on the recorded pattern of the navigation of the ship over the past years, an estimate of the projected CO_2 emission can be made depending on the fuel solution (ammonia and methanol). The estimates will be based on reference information collected from the ship's annual MRVs (monitoring, reporting, and verification). The operation on HFO will serve as a baseline to compare the reduction potential of methanol and ammonia fuel technologies. The calculation of CO_2 emissions will be done based on the travelled distance of the ship per year. Emitted CO_2 is the sum of the main fuel (methanol or ammonia) in addition to the pilot fuel where the ratios as mentioned in the previous chapter were 10 % and 20 % respectively. Because methanol and ammonia can be obtained using different feedstocks and based on different production pathways, resulting in differences in the CO_2 emissions factor. Consequently, the projected emissions are calculated for the following fuel pathways: NG-methanol-ICE, E-methanol-ICE, Bio-methanol-ICE, NG-ammonia-ICE, and E-ammonia-ICE. Their emissions factors are listed in Table 39. Moreover, as both fuel solutions require diesel as pilot fuel, we evaluated the influence of using biodiesel in parallel with fossil diesel. The total CO_2 emissions are represented in Figure 50. It can be seen that in order to achieve a considerable reduction in emission using methanol fuel, E-methanol and bio-methanol are enabling 83.3 % and 62.9 % respectively. While fossil-based methanol offers a very low reduction of about 10.1 %. Ammonia is a carbon-free fuel, therefore, its reduction potential is much higher. In fact, the carbon emissions recorded are mainly related to both the upstream process to produce ammonia (case of the NG-ammonia) and the need for a pilot fuel during the combustion process. It can be seen that E-ammonia combustion releases more CO_2 than E-methanol, this is due to the fact that ammonia combustion requires 20 % of diesel as pilot fuel while methanol only needs 10 %. Figure 51 reveals the share of emissions produced by the main fuel and the pilot fuel.

Table 39. Fuel emission factor [72][73][74]

Fuel	Emission factor [$tCO_2 \cdot tfuel^{-1}$]
NG-methanol	1.68
E-methanol	0.03
Bio-methanol	0.49
NG-ammonia	0.33
E-ammonia	0.00
Diesel	3.45
Bio-diesel	1.91
HFO	3.15

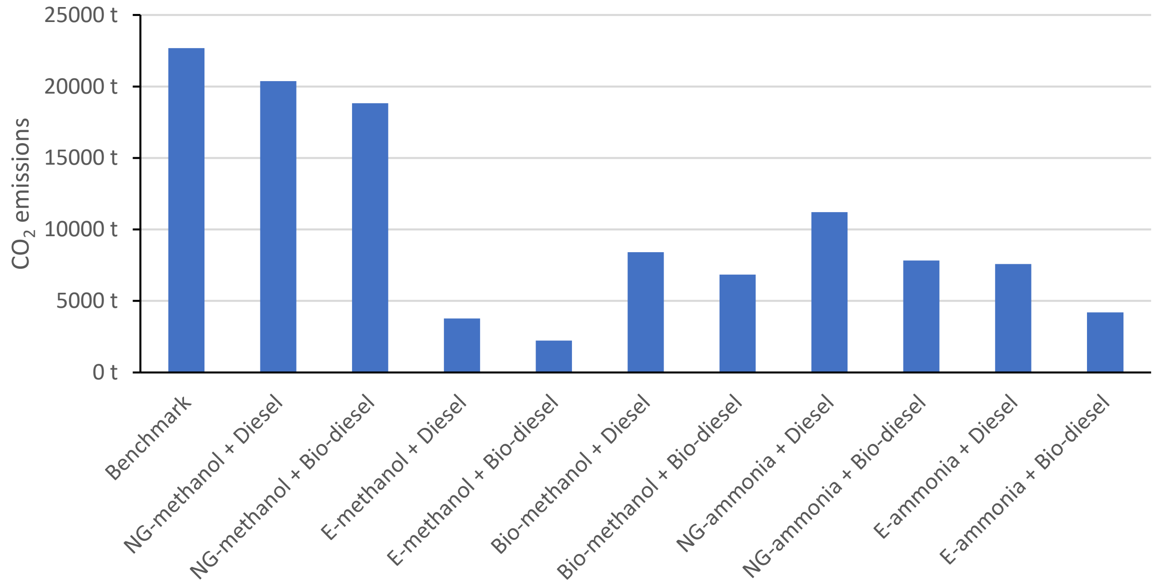

Figure 50. Carbon emissions prediction

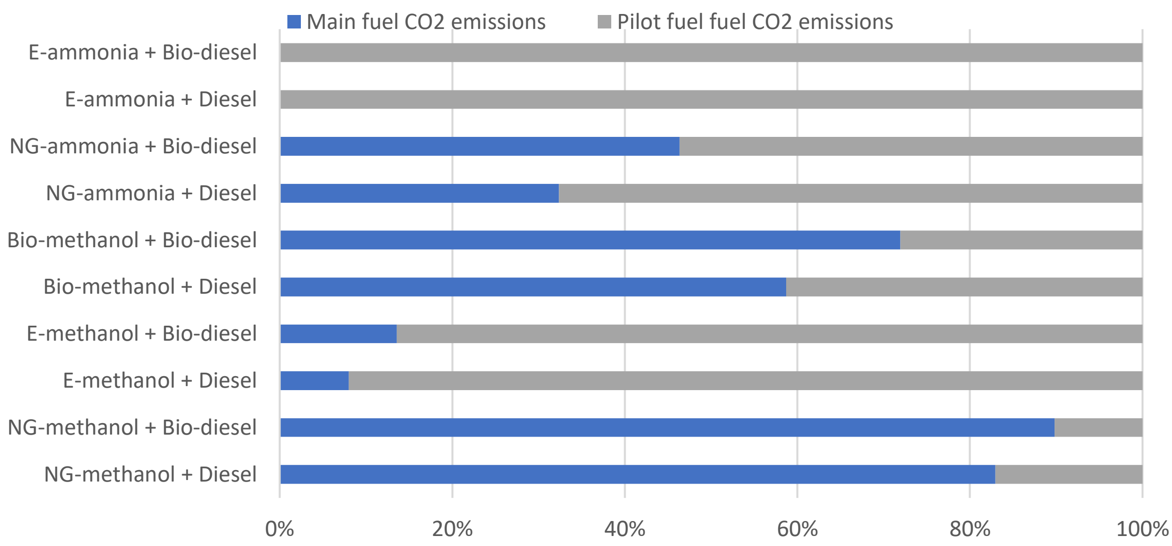

Figure 51. Split of CO_2 emissions between pilot fuel and main fuel

6.2 Financial assessment of alternative fuel solutions

In order to provide clear guidance for a potential energy transition, the financial engagement related to any fuel solution has to be presented. Such evaluation will determine the viability of methanol or ammonia-fuelled RoRo vessels in the future. In this section, we will go through an evaluation of the costs related to the use of ammonia and methanol as fuels, considering the capital expenditure (CAPEX) related to the conversion process, and the operational expenditure (OPEX). OPEX is the endured costs during the project operation of the ship, mainly the fuel costs. Such projections are very case-dependent, they depend on the evolution of energy prices in the future. Therefore, different scenarios are proposed to compensate for the incertitude surrounding future fuel prices. Different sources [14][75] associate the evolution of clean energy prices in the future with an upper limit and a lower limit illustrated in Table 40. Renewable electricity prices are very important because they represent the baseline to price E-fuels. Fossil fuels are a concern as well because they can be the starting point in a production pathway such as natural gas reforming. Carbon taxation was also proposed to penalize carbon emissions from ships, the price proposed in the LR review [75] is assumed to increase from 101 $\$\cdot t^{-1}$ in 2030, to 194 $\$\cdot t^{-1}$ in 2040, and to 288 $\$\cdot t^{-1}$ in 2050.

Table 40. Fuel pricing scenarios [75]

Price scenario	Renewable electricity	Fossil fuel	Bioenergy
Upper limit	High	High	High
Lower limit	Low	Low	Low

6.2.1 Fuel costs

The evaluation of the fuel costs will be based on a year of ship operation, navigating a total distance of 73,817.73 nm. Depending on the fuel energy density, the amounts of fuel required are different. As mentioned before, to cover the incertitude related to the fuel prices, lower and upper limits of the fuel prices are calculated. For the two scenarios, the fuel prices per ton are listed in Table 41. The prices are obtained from the literature [72][75].

Table 41. Fuel prices in $\$\cdot t^{-1}$ for the upper and lower limits

Lower limit [$\$\cdot t^{-1}$]				
	2020	**2030**	**2040**	**2050**
NG-methanol	417.9	363.175	313.425	258.7
E-methanol	1,671.6	1,452.7	1,253.7	1,034.8
Bio-methanol	378.1	417.9	457.7	497.5
NG-ammonia	520.8	483.6	446.4	427.8
E-ammonia	1023	874.2	725.4	558
Upper limit [$\$\cdot t^{-1}$]				
	2020	**2030**	**2040**	**2050**
NG-methanol	676.6	587.05	502.475	412.925
E-methanol	2,706.4	2,348.2	2,009.9	1,651.7
Bio-methanol	398	796	1,213.9	1,611.9
NG-ammonia	855.6	799.8	744	706.8
E-ammonia	1,785.6	1,525.2	1,264.8	1,023

The projected fuel prices in both scenarios, lower and upper are illustrated in Figure 52 and Figure 53 respectively. It can be seen clearly that fuels requiring electricity in their production process (E-ammonia and E-methanol) are quite expensive. Bio-methanol is a cheap option in the beginning but in the future, the price will tend to increase to even overpass E-fuels as projected in the high limit price scenario in Figure 53. Fossil-based fuel offers the lowest fuel cost possible in both cases in the short and long term at the expense of GHG emissions.

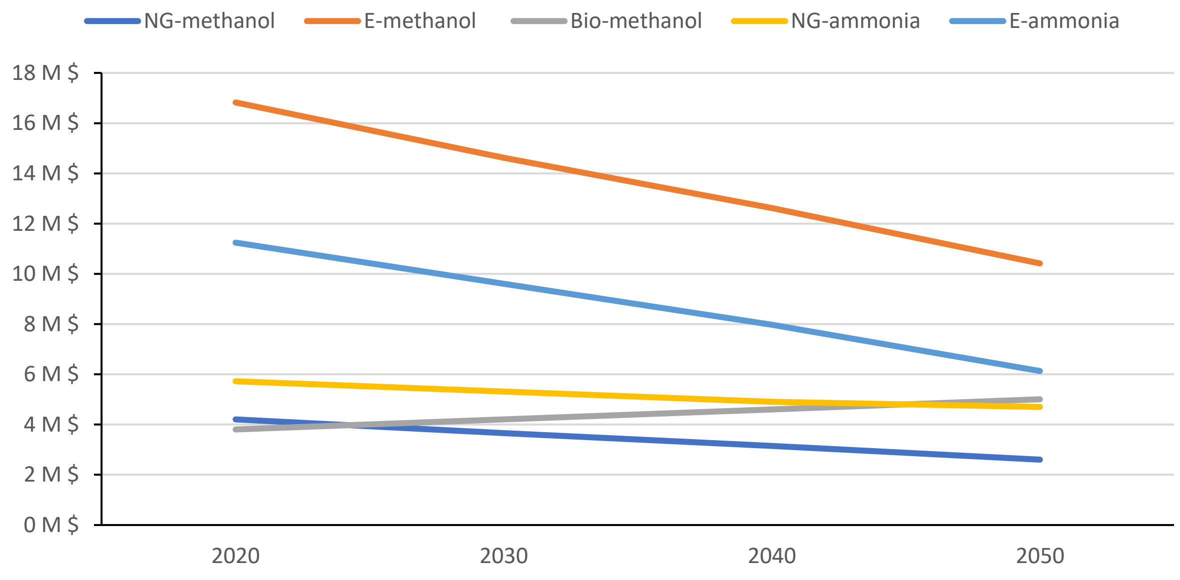

Figure 52. Fuel prices, lower price limit

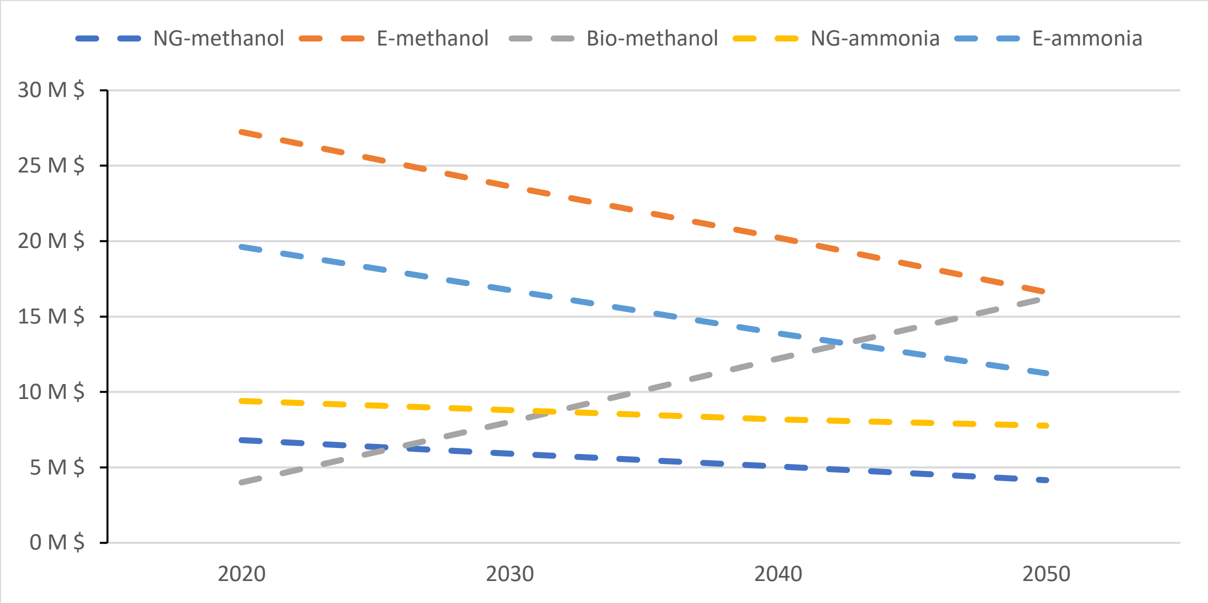

Figure 53. Fuel prices, upper limit

6.2.2 Capital cost

CAPEX is the investment cost needed to convert this RoRo ship from running on HFO to one of the selected alternative fuel solutions methanol, or ammonia. The capital cost of retrofitting a vessel is divided into several sub-costs. In a general way, the capital cost is divided into converter cost and storage cost [75]. Table 42. lists the capital costs used in this work. Important to note is, that the maintenance cost is not considered. Since we already mentioned a possible upgrade of the nonfuel main engine, the capital cost of the engine will be assumed as the gap in the cost between the HFO-fuelled engine and the ammonia or methanol fuelled engines. The storage cost is dependent on the type of fuel and storage conditions. For ammonia type-B tanks, the value is obtained from [75]. Whereas, for the ammonia type-C tank, this cost is assumed based on the cost analysis performed in chapter 5. The cost of methanol storage is obtained from [76]. Figure 54 illustrates the estimated capital cost of integrating an alternative fuel solution. The capital cost is decomposed into converter and storage costs. It is clear that the major part of the cost is defined by the cost of fuel storage, with type-C storage tanks being the most expensive.

Table 42. Capital costs

Description	Unit	Cost
2-stroke diesel engine (ICE)	$\$\cdot kW^{-1}$	400
LS Liquid gas/low flash injection engine (ME-LGI)	$\$\cdot kW^{-1}$	590
LS Gas injection engine (ME-GI)	$\$\cdot kW^{-1}$	590
Type-B storage tank for ammonia	$\$\cdot kg^{-1}$	0.7
Type-C storage tank for ammonia	$\$\cdot kg^{-1}$	1.0
Methanol storage tank	$\$\cdot kg^{-1}$	0.8

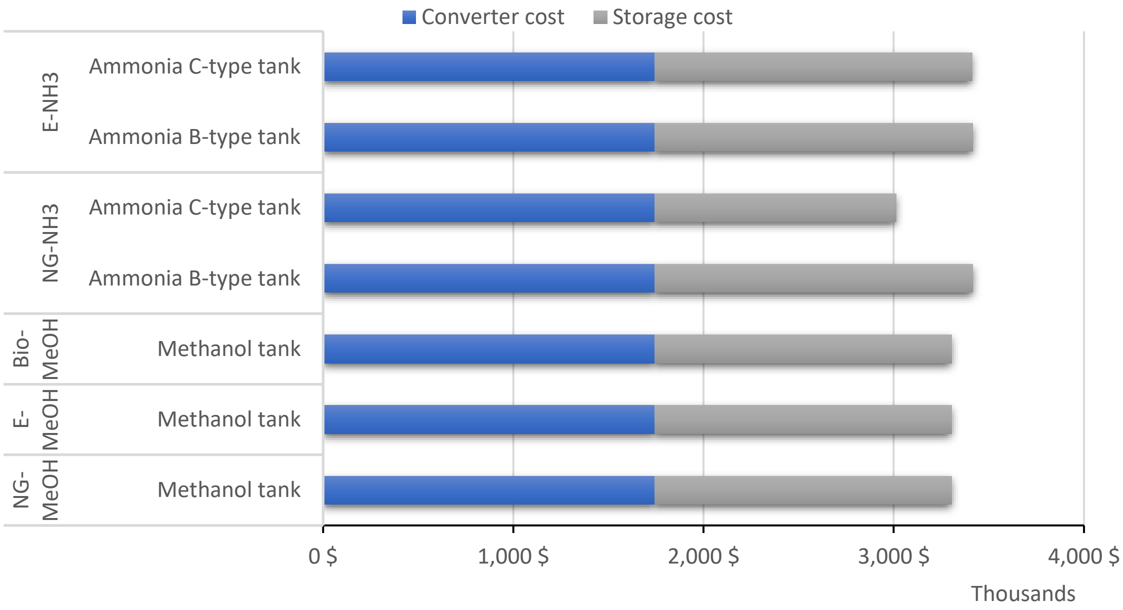

Figure 54. Estimated capital cost

6.3 Total cost of ownership

The TCO is the indicator of the economic viability of any fuel solution. It combines the fuel-related voyage cost and the additional costs related to the conversion of the main engine and the storage systems. According to Lloyds register´s definition [75].

$$TCO = OPEX_{fuel} + CAPEX_{engin} + CAPEX_{storage} + Cargo\ loss \quad (16)$$

Where:

$OPEX_{fuel}$: fuel-related voyage costs per year

$CAPEX_{engin}$: capital cost for the engine conversion

$CAPEX_{storage}$: capital cost of fuel storage system

$Cargo\ loss$: impact on revenue due to the space requirements of the fuel storage system

TCO has to include the impact on revenue due to the loss of cargo area. However, in the absence of accurate economical information to quantify the loss, it is not possible to include it in a graphical representation. Still, it was found that methanol causes a lower reduction in cargo capacity. Figure 55 and Figure 56 illustrate the projected TCO based on 2030 fuel costs lower and upper price limits respectively. The environmental factor of the fuel is included by counting the carbon taxation, where fossil-based fuels are more penalized due to their higher CO_2 emissions. Fuel costs are taking the major share of the TCO, determining the economical potential of each fuel solution. For fossil-based fuels, like NG-methanol, the carbon taxation is significant, making the TCO higher than other alternatives where the fuel cost is higher. The capital cost of storage is a function of two elements, the cost, and the volume requirement. Nonetheless, despite the variation in storage cost, their impact is minimal in comparison to the fuel costs.

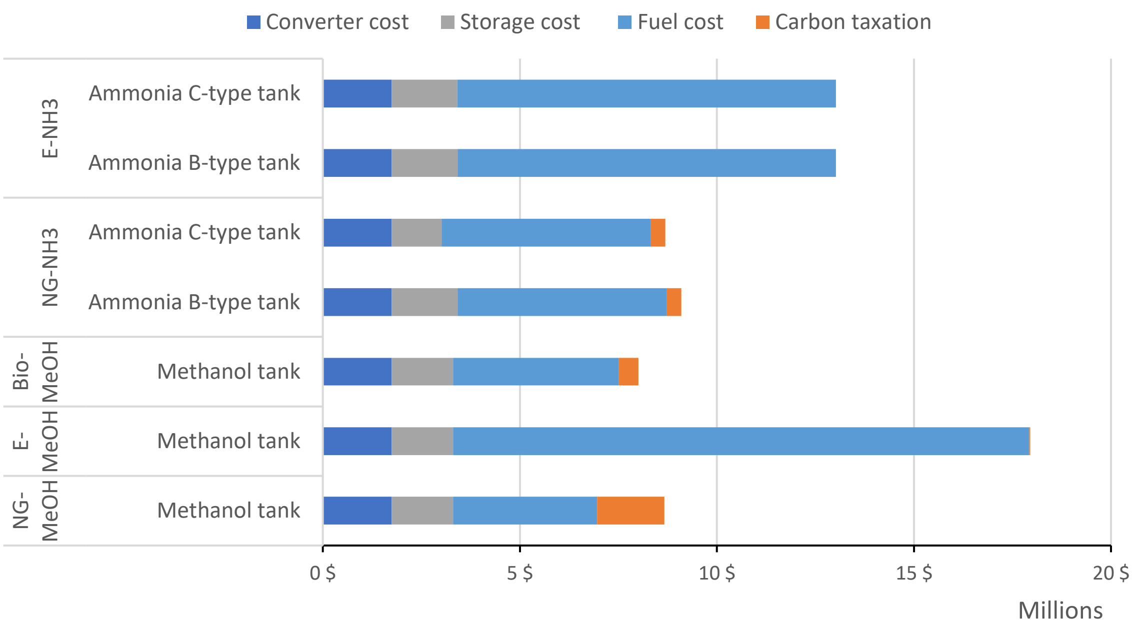

Figure 55. TCO, 2030 lower limit fuel prices

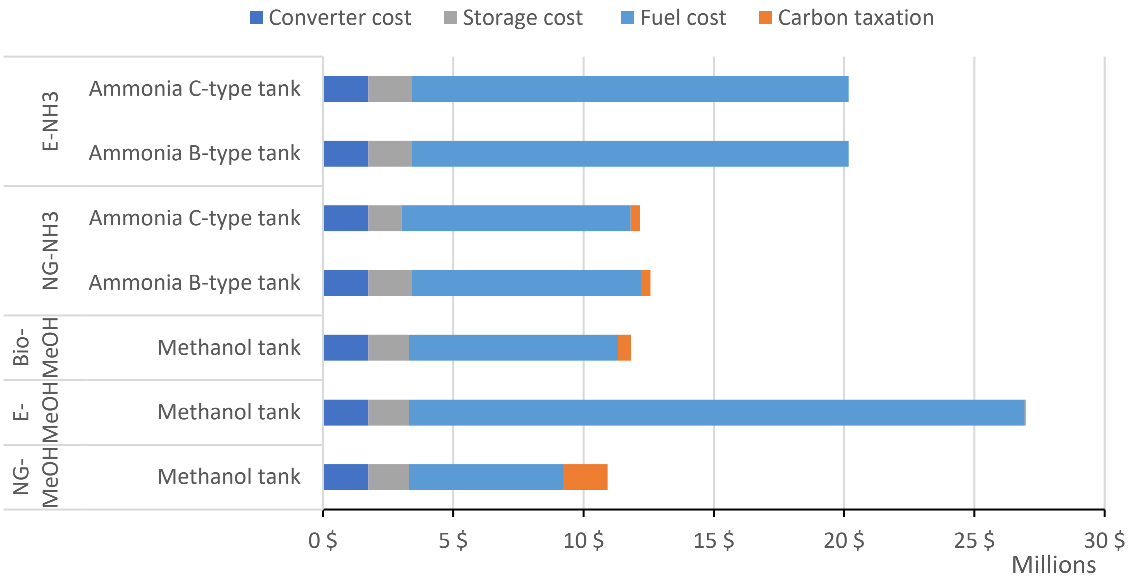

Figure 56.TCO, 2030 upper limit fuel prices

In the short term, the most favourable solution is methanol, under the condition of being bio-sourced. Although conventional methanol is much cheaper the carbon taxation is considerable and the CO_2 reduction potential is not attractive. On the opposite, E-methanol´s reduction potential is more important but the fuel cost is a major drawback. In the long term, the projected drop in E-fuel prices will make the use of E-ammonia more interesting and more competitive with E-methanol. Therefore, it is important to note that there is not one correct fuel technology to enable zero emission shipping, but over the coming years we will have a compilation of solutions to rely on based on their viability with respect to the ship type and its operation mode.

7 CONCLUSION

The originally stated objectives of this work were to assist in the energy transition efforts to decarbonize marine shipping. When several alternative fuels are promoted as potential substitutes for fossil-based fuels, the determination of the most suitable solution has to be achieved by evaluating the potential contribution of each fuel solution. The selection process is founded on several evaluation criteria pointing out the advantages and disadvantages of each fuel. In addition, a RoRo ship, built in 2005, running on heavy fuel oil was at the core of work, by implementing the best-selected novel fuels. The integration was focused on four main aspects, storage tanks, fuel supply systems and bunkering, engine technologies, and safety measures. In addition to the evaluation tool provided in this work enables the ranking of alternative fuels based on multiple economic, technical, and environmental attributes. This work offered insight into the design implications and the engineering work required to achieve the fuel transition on board the RoRo ship.

In this sense, a multi-criteria decision-making method was used to assist in the selection of the best fuel solutions. Methanol and ammonia were seen as the most promising solution because of the advantages they offer compared to the other candidate fuels. In addition to their potential to reduce carbon emissions, methanol, and ammonia are relatively competitive in terms of cost in comparison to hydrogen. Currently, methanol fuel technology has been found to be the most technologically ready for operational usage. Nonetheless, ammonia fuel technologies are also expected to be available in the near future. In order to determine the amounts of ammonia and methanol required to be stored on board, the energy conservation approach was used in this work. It was clear that the substitution of fossil fuels induced an increase in the storage volumes required to achieve a similar operation range. Moreover, the design range approach was also explored in this work, where it appeared that the operation range covered by the ship was reduced by half for the same amount of fuel.

The integration process of ammonia and methanol fuel technologies onboard the ship revealed the high complexity in relation to retrofitting a vessel. The allocation of additional storage space came with a loss of cargo capacity, where the cryogenic condition requirement for storing ammonia induced a more considerable loss in comparison to methanol storage tanks. The fact that methanol has similar physical properties as fuel oil, helped in the reduction of the space required because of the possibility of reusing the available storage space.

In terms of fuel technologies, this study highlighted the major components required to be able to allow the storage and the use of methanol or ammonia to run the ship. The type of storage tanks, their locations, and their capacities. Additionally, the upgrades on the fuel supply system and engine were highlighted following manufacturer requirements. Methanol is a low flashpoint fuel, and ammonia is a gas fuel, therefore this work has also tackled the safety measures for fire detection and prevention in the area of interest where fuel is present.

Regarding the carbon reduction potential, this work brings up again the importance of fuel production pathways. Fossil-based alternative fuels were seen in this work to be not admissible due to the high carbon intensity during fuel production. In addition to that, the need for a pilot fuel like marine diesel for combustion was a source of carbon emissions.

When focusing on the financial considerations involved with alternative fuels, this work revealed that during a year of operation, the cost of ownership is mainly defined by fuel costs. Furthermore, this work pointed out the estimated costs associated with each fuel technology considering the conversion cost of the main engine and the costs related to the installation of storage tanks were only a small fraction in comparison to the fuel expenses on a year of operations.

In the end, this work could assist in the selection process of alternative fuel solutions. Additionally, by providing solutions for fuel storage and treatment onboard, this study was able to quantify the required investments related to the selected fuel solutions. With such ranking, the shipowner will be more confident in selecting one fuel technology over the other, without having the risk of investing in stranded assets.

Nevertheless, the presented work constitutes a first step in the path of the energy transition on already built ships. It is intended to provide ship operators with sufficient insight into the most promising alternative fuel technologies. Many assumptions were made to simplify the process. The non-availability of propeller shaft readings in MWh per voyage pushed us to use another method that is not as accurate as the propeller shaft readings. The absence of accurate information about the engine loads left us to assume a fixed engine load for the entire duration of the voyages, which in the case of short sea shipping may have a large influence on the results. Additionally, during the integration process, the focus was to illustrate the major components and systems needed for each fuel technology, a detailed work will require more time and effort and thus will defeat the purpose of this study to explore the possibilities. the main focus during this work was on the main engine, therefore, the auxiliary engines were not included. Moreover, in the economic evaluation of methanol and ammonia fuel solutions, it was not possible to estimate the loss of car capacity, thus it was not included in the calculus. Maintenance costs and other related costs were not included as well.

To lead the ship's energy transition to an end, further work must be undertaken. In the case of the RoRo ship being the core of this work, improving the data collection about the energy demand onboard over long periods will provide a better evaluation of the volumes of fuel needed. Therefore, the large volume requirement highlighted in this work can be reduced and compensated by increasing the bunkering frequency. Once the ship owner chooses a fuel solution to be integrated onboard, the tedious work of planning the integration process in more detail can be done in compliance with the rules and regulations.

To conclude, ship energy transition is a large challenge that the major industry actors are trying to tackle. In order to be able to substitute fossil fuels, the choice of fuel technology is closely linked to the ship's characteristics and navigation profile. Therefore, it is wise to say that the future of shipping will not be based on one alternative fuel technology. Only a deep study of each individual ship depending on the type, its navigation type, and area will provide an answer about the best fuel technology to adopt.

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Cherif, AIT AIDER.

Abbreviation	Full name
AHP	Analytic Hierarchy Process
CAPEX	Capital Expenditure
CCS	Carbon Capture System
CO_2	Carbon Dioxide
CII	Carbon Intensity Index
CO_2eq	CO_2 equivalent
CNH_3	Compressed Ammonia
DNV	Det Norske Veritas
ECA	Emission Controlled Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency of Existing Ships Index
EEOI	Energy Efficiency Operation Index
GHG	Greenhouse Gases
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engines
IGF-Code	International Code of Safety for Ships Using Gases or other Low-flashpoint Fuels
IMO	International Maritime Organization
LOHC	Liquid Organic Hydrogen Carrier
LH_2	Liquefied Hydrogen
LNH_3	Liquefied Ammonia
LNG	Liquified Natural Gas
LFL	Low Flash-point Liquid
LHV	Low Heating Value
MDO	Marine Diesel Oil
CH_4	Methane
MeOH	Methanol
MRV	Monitoring, Reporting, and Verification
MCDM	Multi-Criteria Decision-Making Methods
NOx	Nitrous Oxides
OPEX	Operational Expenditure
PM	Particulate Matter
RPM	Revolution Per Minute
RoRo	Roll on Roll off
SEEMP	Ship Energy Efficiency Management Plan
SOx	Sulfur Oxide
TTW	Tank to Wake
TRL	Technology Readiness Level
TCO	Total Cost of Ownership
WTT	Well to Tank
WTW	Well to Wake

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Appendix A1

FR: frame number.

VNET: volume net.

XAG: Coordinates of the centre of gravity in the X-axis.

YCG: Coordinates of the centre of gravity in the Y-axis.

ZKG: Coordinates of the centre of gravity in the Z-axis.

IY: moment of inertia.

Table 1. List of tanks and capacities

SPECIFICATION	**FR**	**FR**	**VNET**	**MASS**	**XAG**	**YCG**	**ZKG**	**IY**
Unit	[-]	[-]	[m³]	[t]	[m]	[m]	[m]	[m⁴]
Fuel Oil (RHO = 0.98 t·m^{-3})								
TK 2F FO	126	138	222.4	218	105.24	0.18	4.06	483
TK 3F FO	102	128	283.1	277.4	90.35	0	1.3	382
TK 4F FO	76	102	367.1	359.7	71.2	0	1.3	641
TK 5F FO	48	76	385.7	378	49.86	0.04	1.29	668
TK 29 FO Sett. low sulph.	7	13	55.7	54.5	8.07	-6.4	9.66	34
TK 30 FO Settling	7	13	53	51.9	8.07	1.5	9.66	29
TK 31 FO Service	7	13	22.7	22.2	8.07	-1.5	9.66	2
TK 32 FO Service	7	13	23	22.6	8.07	-3.3	9.66	2
TOTAL Fuel Oil			1412.7	1,384.3	67.7	-0.23	2.65	
Diesel Oil (RHO = 0.89 t·m^{-3})								
TK 15	25	43	66.6	59.3	28.33	3.23	1.14	67
TK 23	30	40	93.9	83.6	28.41	7.97	5.15	190
TK 33	7	13	26.5	23.6	8.01	-11.15	9.9	7
TOTAL Diesel Oil			187	166.5	25.49	3.57	4.4	
Lubricating Oil (RHO = 0.90 t·m^{-3})								
TK 14	26	37	17.6	15.9	24.69	0	1.04	7
TK 36	9	13	13.3	11.9	8.45	6.66	9.88	3
TK 37	7	13	19.9	17.9	8	8.95	9.88	3
TK 38	11	13	2.9	2.6	9.6	5.71	9.88	0
TK 42	7	9	9.5	8.6	6.4	6.66	9.88	3
TOTAL Lubricating Oil			63.1	56.9	12.56	5.49	7.42	
Fresh Water (RHO = 1.00 t·m^{-3})								
TK 40	31	36	81.1	81.1	26.72	-7.4	8.37	146
TK 41	36	46	107.3	107.3	32.35	-7.4	7.94	292
TOTAL Fresh Water			188.5	188.5	29.93	-7.4	8.12	
Sludge (RHO = 1.00 t·m^{-3})								
TK 11	43	48	70	70	36.43	1.25	1.05	459
TK 12	39	42	14.9	14.9	32.43	-3.59	1.13	19
TK 13	31	38	26.4	26.4	27.77	-3.17	1.14	20

TK 16	26	31	7.2	7.2	22.9	-2.94	1.54	5
TK 17	17	25	54.1	54.1	16.91	0	0.99	106
TK 18	15	17	2.1	2.1	12.8	0	1.48	0
TK 20	8	13	39.9	39.9	8.84	0	2.62	11
TK 21	43	45	8.7	8.7	35.23	7.1	2.9	17
TK 22	27	30	33.4	33.4	22.84	-7.17	5.65	91
TK 34	16	23	10.9	10.9	15.6	-4.86	7.4	7
TK 35	28	30	19	19	23.2	11.17	9.45	2
TK 39	11	13	2.8	2.8	9.6	7.6	9.88	0
TK 42 P	52	60	17.4	17.4	44.8	-4.86	2	9
TK 43	62	74	31.3	31.3	54.4	9.92	13.15	13
TOTAL Sludge			338.8	338.8	27.87	0.47	3.68	
Water Ballast (RHO = 1.025 $t \cdot m^{-3}$)								
Forepeak	158	174	266.5	273.2	130.93	0	6.69	221
WB TK 1 PS	138	158	330.4	338.7	116.84	-2.35	6.51	134
WB TK 1 SB	138	158	370.5	379.7	116.36	2.66	6.61	317
WB TK 2 PS	126	138	208.2	213.4	105.47	-4.9	4.58	87
WB TK 2 SB	126	138	185.8	190.5	104.99	4.87	4.42	87
WB TK 3 PS	102	126	288.7	295.9	90.8	-6.58	2.66	436
WB TK 3 SB	102	126	277.7	284.6	90.43	6.57	2.6	445
WB TK 4 PS	76	102	453	464.3	70.88	-8.27	2.29	939
WB TK 4 SB	76	102	453	464.3	70.88	8.27	2.29	939
WB TK 5 PS	48	76	423.3	433.9	51.12	-8.26	2.37	732
WB TK 5 SB	48	76	426.3	437	51.15	8.06	2.29	864
Afterpeak	-8	7	120.8	123.9	0.6	-0.13	7.9	328
TOTAL Water Ballast			3,804.2	3,899.5	83.35	-0.02	3.85	

APPENDIX A2

Scantling of methanol tanks

Methanol tanks are metallic structures designed in a form of box girders, designed to carry a liquid fuel, methanol in this case. As part of the integration process of methanol fuel solution inside the RoRo ship, determining the preliminary thicknesses of the plating and the structural support members constituting the tanks is essential to obtain a first insight into the potential weight of the structure as a function of the applied loads.

In this part, we will proceed to determine the thicknesses of plating and section modules of the stiffeners of a methanol tank. The proposed solution to contain the methanol volumes include the construction of six new tanks; nonetheless, in the scope of this work, we will consider one tank to be the subject of the scantling process. The results will then will be used for the other tanks. For this aim, we selected the longest tank, ‘’Methanol TK 3 CL’’. The dimensions of the tank are listed in Table 1.

The scantling process is conducted based on the DNV rules [Pt3 Ch6 Hull local scantling]. The local scantling is used based on the fact that the new tanks are subjected to local loads only, and do not contribute to the global strength of the ship. Based on the same assumption, the stiffening of the tanks is decided to be transversal, where transversal elements are to be placed each 800 mm and 1,000 mm spacing between longitudinal stiffeners.

Table 1. Tank dimensions

	Length [m]	**Width [m]**	**Height [m]**
Methanol TK3 CL	28	6.5	1.25

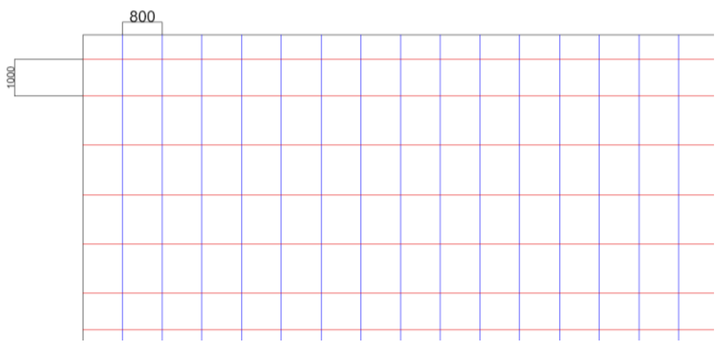


Figure 1. Structural strengthening of the tank

a) Material characteristics

The selected material for the construction of the tank is high-strength steel dedicated to shipbuilding applications. The material grade is NV A27S according to the DNV designation. The material characteristics are listed in Table 2 below. Due to the corrosive nature of ammonia, a coating will be required to protect the material, Sigma Silguard 750 is a proven chemical-resistant coating.

Table 2. Material characteristics

<table>
<tr><th rowspan="3">Grade</th><th rowspan="3">Yield strength R_{eH} [MPa]</th><th rowspan="3">Tensile strength R_m [MPa]</th><th rowspan="3">Elongation A5 minimum [%]</th><th colspan="3">Impact energy, a minimum average [J]</th></tr>
<tr><td rowspan="2">T [°C]</td><td colspan="2">t ≤50 [mm]</td></tr>
<tr><td>L</td><td>T</td></tr>
<tr><td>DV A27S</td><td>265</td><td>400</td><td>22</td><td>0
-20
-40
-60</td><td>27</td><td>20</td></tr>
</table>

b) Minimum thickness requirements

Depending on the location of the plates and the stiffening members, the calculated thickness shall not be less than the minimum thicknesses defined by the formulas given in DNV rules [Pt3 Ch6 S3].

Minimum thickness for the plates

The minimum plate thickness in millimetres is given by the Eq.(1).

$$t = a + bL_2\sqrt{k} \tag{1}$$

Where:

a and b coefficients are defined by DNV rules, for the case of boundary for cargo tanks, water ballast tanks, and hold intended for cargo in bulk.

Table 3. Coefficients definition

Element	Location	a	b
Deck	Boundary for cargo tanks, water ballast tanks and hold intended for cargo in bulk	4.5	0.015

L_2 is defined as the rule length, L, that is not to be taken greater than 300 m in meters.

$\mathrm{L} = 96\ \%\ \mathrm{LBP} = 128.64\ \mathrm{m}$

k is the material factor

Table 4. Material factor K

Specified minimum yield stress R_{eH} [$N{\cdot}mm^{-2}$]	K
235	1.00

The minimum thickness to be applied is $t = 6.49$ mm.

Minimum thickness for stiffeners and tripping brackets

The minimum net thickness specified in Table 5 derived from the DNV rules, must be exceeded by the web and face plate, if there were any, of stiffeners and tripping brackets.

Table 5. Minimum thicknesses for stiffeners

Element	Location	Net thickness [mm]
Stiffeners and attached end brackets	Tank boundary	$3.0 + 0.01L_2$
		4.93

Minimum thickness requirements for the primary supporting members

The minimum thickness in mm of the principal supporting members' web plating and flange shall meet the necessary minimum thickness standards as specified by the DNV rule [Pt3 Ch 6 S3]

$$t = a + bL_2\sqrt{k} \qquad (2)$$

Where:

a and b coefficients are defined by DNV rules, for primary supporting members at tank locations.

Table 6. Coefficient definition

Element	a	b
PSM supporting side shell, ballast tank, cargo tank, and hold intended for cargo in bulk	4.5	0.015

L_2 is defined as the rule length, L, that is not to be taken greater than 300 m in meters.

$\text{L} = 96\ \%\ \text{LBP} = 128.64$ m.

k is the material factor as defined above.

The minimum thickness to be applied is $t = 6.49$ mm.

c) Calculated thicknesses

Thickness calculations for plates under lateral pressure

The plate thickness in millimetres is defined by the Eq.(3) below and shall not be token less than the minimum thickness calculated above.

$$t = 0.0158\alpha_p b\sqrt{\frac{|P|}{C_a R_{eH}}} \tag{3}$$

Where

C_a is the permissible bending stress coefficient for plate calculated as per the formula provided by DNV rules, and equal to 0.8.

α_p Coefficient defined in the rules, and equal to 0.88.

b is the breadth of plate panel, in mm, and equal to 800 mm.

P design pressure for the considered design load set in kN·m^{-2}. In this case, it is equal to total internal pressure due to liquid see [Pt3 Ch4 S6]. In this work, we will account for the static pressure only without the dynamic pressure.

$$P = P_{in} = P_{ls} \tag{4}$$

The static pressure is defined by

$$P_{ls} = f_{cd}\rho g\left(z_{top} - z\right) + P_{pv} \tag{5}$$

Where:

P_{pv} is the design overpressure, in kN·m^{-2}, not to be taken less than 25 kN·m^{-2}and not greater than 70 kN·m^{-2}

τ_{eH}

f_{cd} factor for joint probability of occurrence of liquid cargo density and maximum sea state in 25 years design life, to be taken as:

f_{cd} = 0.88 for strength assessment with FE analysis of cargo tanks filled with for oil or oil products cargo with $\rho_L \leq 1.025$ t·m^{-3}

The maximum static pressure corresponding to a tank full of up to 1.25 m is 25.86 kN·m^{-2}

Based on the all calculated factors, the minimum thickness of the plat is $t = 3.88\ mm$.

Stiffeners subject to lateral pressure

Web plating thickness calculation

The largest value determined for all applicable design load sets as defined shall not be less than the minimum net web thickness, in mm defined above.

The web plating thickness is calculated with the following Eq.(6)

$$t_w = \frac{f_{shr}|P|s l_{shr}}{d_{shr}\ C_t\ \tau_{eH}} \tag{6}$$

Where:

f_{shr} is the shear force distribution factor equal to 0.7 corresponding the most conservative value proposed in the DNV rules.

C_t is the permissible shear stress coefficient for the acceptance criteria being considered equal to 0.75.

d_{shr} is the effective shear depth, in mm, equal to 207 mm.

l_{shr} is the effective bending span, in m, equal to 0.75 m.

s is the stiffener span in mm, equal to 1000 mm.

τ_{eH} is the specified shear yield stress, in MPa, and equal to 152.99 MPa

The calculated web thickness is $t_w = 0.57$ mm

Calculation of minimum section modulus

The minimum section modulus, in cm³, is calculated according to the following Eq.(7), where the chosen section modulus has to be greater than the minimum calculated in the above section.

$$Z = \frac{f_u |P| s l_{bdg}^2}{f_{bdg}\, C_S\, R_{eH}} \tag{7}$$

Where:

f_{bdg} is the bending moment factor token equal to 8.

f_u is the factor for unsymmetrical profiles token equal to 1 (T profile).

s is the stiffener span in mm, equal to 1,000 mm.

l_{bdg} is the effective bending span, in m, equal to 0.8 m.

C_s permissible bending stress coefficient, equal to 0.85.

The calculated section modulus of the stiffeners is $Z = 9.18$ cm^3.

Primary supporting members

Section modulus calculation

The net section modulus, in cm³, of primary supporting members subjected to lateral pressure shall not be taken less than the greatest value for all applicable design load sets defined in the above section. The section modulus is given by the following Eq.(8).

$$Z_{n50} = 1000 \frac{|P| S l_{bdg}^2}{f_{bdg}\, C_S\, R_{eH}} \tag{8}$$

Where:

S is the span of the longitudinal girder, in m, equal to 7 m.

C_S permissible bending stress coefficient, equal to 0.7.

l_{bdg} is the effective bending span, in m, equal to 6.5 m.

f_{bdg} is the bending moment factor token equal to 24.

The calculated section modulus of the longitudinal stiffeners is $Z_{n50} = 1{,}717.9$ cm^3

Net share area calculation

The principal supporting elements' net shear area, measured in cm², when under lateral pressure. The net area is calculated with the following Eq.(9).

$$A_{shr-n50} = 10\frac{f_{shr}\ |P|Sl_{shr}}{C_t\ \tau_{eH}} \tag{9}$$

The net area required is $A_{shr-n50} = 54$ cm^2

d) Summary of the scantling

Table 7. Scantling summary

Structural element	**Minimum requirement**	**Calculated**	**Selected**	**Comment**
Plate thickness [mm]	6.49	3.88	7	-
Stiffener web thickness [mm]	4.93	0.57	6	L 90×90×6
Stiffener section modulus [cm³]	-	9.18	12.3	
Net shear area [cm²]	-	54	182.5	T 600×20 250×25
Longitudinal stiffener section modulus [cm³]	-	1,717.9	1,871.2	

APPENDIX A3

Scantling of the C-type tanks

C-type tanks are cylindrical bodies dedicated to holding liquids and gases. The scantling is based on the design pressure principle. The scantling is performed based on the DNV rules [Pt5 Ch7 S22] about the design of cylindrical tanks of type C. Noteworthy that the calculation is applied on the larger tank of 14.5 m length using two different materials, aluminium alloys, and stainless steel.

Table 1. Material properties

Properties	Material	
	Alloy 5083-O	AISI 316 L
Density Kg.m^{-3}	2700	8000
Elastic Modulus E. GPa	71	200
Thermal Conductivity. W.m^{-1}°.C^{-1}	117	15
Mean Coefficient of thermal expansion 10^{-6}.°C^{-1}	17.5	16
Yield stress. MPa at -40°C	145	283
Ultimate tensile stress. MPa at -40°C	295	717

a) Design vapor pressure calculation

In general, the specification should be followed and the vapor pressure (in MPa) utilized in the design should not be less than the highest permitted relief valve setting (MARVS). Nonetheless, the tank must meet the minimum vapor pressure requirements listed below in order to be classified as a tank-type C. the vapor pressure s provided by the following equations.

$$P_0 = 0.2 + AC(\rho_r)^{1.5} \quad (1)$$

Where:

$$A = 0.00185(\frac{\sigma_m}{\Delta\sigma_A}) \quad (2)$$

With:

σ_m is the design primary membrane stress in $N.mm^{-2}$

$\Delta\sigma_A$ is the allowable dynamic membrane stress range, i.e. double amplitude at probability level $Q = 10^{-8}$ taken equal to:

- 55 $N.mm^{-2}$ for ferritic-perlitic, martensitic, and austenitic steels.
- 25 $N.mm^{-2}$ for aluminium alloy (5083-O).

C is the characteristic tank dimension in m taken equal to max (h; 0.75b; 0.45ℓ)

Results are listed in Table 2.

Table 2. Design pressure results

	A	C	P_0 [MPa]
Alu alloy	0.05	6.525	0.39
Stainless steel	0.039	6.525	0.35

b) Shell thicknesses calculation

For cylindrical shells, the minimum thickness is determined by the following Eq.(3).

$$s = \frac{p_c D_0}{20\ \sigma_t v + p_c} + c \qquad (3)$$

Where

C is the corrosion margin/allowance.

D_0 is the outside diameter.

p_c is the calculating pressure.

s is the shell thickness.

v is the joint efficiency.

σ_t is the nominal design stress at design metal temperature.

Results for both materials are listed in Table 3.

Table 3. Allowable stress calculus

	Stainless steel AISI 316 L	σ_t
$R_{p\ 1.0}$ [MPa]	200	117.64
R_{et} [MPa]	165	103.12
R_m [MPa]	717	265.55
Minimum thickness [mm]	4.77	
	Alu Alloy 5083-O	σ_t
R_{et} [MPa]	145	96.66
R_{mt}[MPa]	250	62.5
Minimum thickness [mm]	7.22	

The results of shell thickness calculation are listed in Table 4.

Table 4. Summary of shell thicknesses sizing

	Stainless steel AISI 316L	Aluminium alloy 5083-O
Minimum thickness allowed [mm]	3.00	7.00
Calculated thickness [mm]	4.77	7.22
Chosen thickness [mm]	5.00	8.00

APPENDIX A4

Scantling of B-type tank

Prismatic type B tanks are designed to hold refrigerated liquids at low temperature, enabling a high tank hull efficiency ratio; when compared to C-type tanks. The B-type tanks are self-supporting, meaning that they are made of reinforced panels. The tanks are subjected to local loads induced by the cargo contained inside and the global loads induced by the ship's global motion. Based on this, the scantling of the tanks must be done in accordance with applicable regulations; DNV issued class guidelines about [DNVGL-CG-0133] dedicated to LNG prismatic tanks of type A and type B. Additionally, the scantling process is conducted based on the DNV rules [Part 3 Chapter 6 Hull local scantling]. the calculations will be done for the biggest tank available board. The local scantling is used based on the fact that the new tanks are subjected to local loads only, and do not contribute to the global strength of the ship. Based on the same assumption, the stiffening of the tanks is decided to be transversal, where transversal elements are to be placed each 800 mm and 1000 mm spacing between longitudinal stiffeners. The tanks will be divided by non-tight bulkheads to minimize both the swash and free-surface effects.

Table 1. Tank dimensions

	Length [m]	Width [m]	Height [m]
Methanol TK3 CL	27	12	1.25

a) Material characteristics

The proposed material to store ammonia under cryogenic conditions are Stainless steel AISI 316 L and aluminium alloy 5083-O, their mechanical and thermal characteristics are listed in Table 2.

Table 2. Material properties

Properties	Material	
	Alloy 5083-O	AISI 316 L
Density $Kg.m^{-3}$	2700	8000
Elastic Modulus E. GPa	71	200
Thermal Conductivity. $W.m^{-1}°.C^{-1}$	117	15
Mean Coefficient of thermal expansion $10^{-6}.°C^{-1}$	17.5	16
Yield stress. MPa at -40°C	145	283
Ultimate tensile stress. MPa at -40°C	295	717

b) Minimum thickness requirements

Depending on the location of the plates and the stiffening members, the calculated thickness shall not be less than the minimum thicknesses defined by the formulas given in section 3 of the DNV rules Pt3 Ch6.

Minimum thickness for the plates

The minimum plate thickness in millimeters is given by the formula

$$t = a + bL_2\sqrt{k} \tag{1}$$

Where:

a and b coefficients are defined by DNV rules, for the case of boundary for cargo tanks, water ballast tanks, and hold intended for cargo in bulk.

Table 3. Coefficient definition

Element	Location	a	b
Deck	Boundary for cargo tanks, water ballast tanks and hold intended for cargo in bulk	4.5	0.015

L_2 is defined as the rule length, L, that is not to be taken greater than 300 m in meters.

L= 96 % LBP= 128.64 m.

k is the material factor

Table 4. Material factor

Specified minimum yield stress R_{eH} [$N.mm^{-2}$]		K
AISI 316 L	283	1.00
Alloy 5083-O	145	1.00

The minimum thickness of the plates is showed in Table 5.

Table 5. Minimum thickness requirements

Material	Minimum thickness [mm]
AISI 316 L	6.43
Alloy 5083-O	6.43

Minimum thickness for stiffeners and tripping brackets

The minimum net thickness specified in 6 derived from the DNV rules, must be exceeded by the web and face plate, if there were any, of stiffeners and tripping brackets.

Table 6. Minimum thickness for stiffeners

Element	Location	Net thickness [mm]
Stiffeners and attached end brackets	Tank boundary	$3.0+0.01L_2$
		4.93

Minimum thickness requirements for the primary supporting members

The minimum thickness in mm of the principal supporting members' web plating and flange shall meet the necessary minimum thickness standards as specified by the DNV rule

$$t = a + bL_2\sqrt{k} \quad (2)$$

Where:

a and b coefficients are defined by DNV rules, for primary supporting members at tank locations.

Table 7. Coefficient definition for stiffeners

Element	a	b
PSM supporting side shell, ballast tank, cargo tank, and hold intended for cargo in bulk	4.5	0.015

L_2 is defined as the rule length, L, that is not to be taken greater than 300 m in meters.

L= 96 % LBP= 128.64 m.

k is the material factor as defined above.

The minimum thickness to be applied is shown in Table 8.

Table 8. Minimum allowable thickness for PSM

Material	Minimum thickness [mm]
AISI 316 L	6.43
Alloy 5083-O	6.43

c) Calculated thicknesses

The thickness calculations, in the scope of local strength of the fuel tanks, are determined based on the rules listed in the [Pt 5 Ch 7 section 20] .

Thickness calculations for the tank shell plating

According to lateral pressure, the tank shell plating's net thickness requirement in millimetres is calculated by the following formula:

$$t = 0.0158b\sqrt{\frac{P_{eq}}{\sigma_{all}}} \quad (3)$$

With:

P_{eq} is the applied pressure in KN.m^{-2}. In the scope of this work it is token equal to 70.

b is the plate width, in mm, also called stiffener spacing.

σ_{all} is the allowable stress in N.mm^{-2}. It is used When estimated using classical analysis techniques, the nominal permissible stresses for primary supporting components (web frames, stringers, girders), secondary members (stiffeners), and tertiary members (plating) for tanks largely made of plane surfaces shall not be greater than the lower of the following:

$$\sigma_{all} = \min(\frac{R_m}{C}; \frac{R_{eH}}{D}) \quad (4)$$

For the shell plating, the calculated thicknesses are listed in Table 9.

Table 9. Allowable stresses and shell thickness calculation

Material	σ_{all} [N.mm^{-2}]	Calculated thickness [mm]
AISI 316 L	257.27	6.59
Alloy 5083-O	131.81	9.21

stiffeners subject to lateral pressure

Calculation of the net section modulus, in cm³, is done based on the equation

$$Z = \frac{|P_{eq}| s l_{bdg}^2}{f_{bdg}\sigma_{all}} \quad (5)$$

Where:

s is the stiffener spacing in mm.

l_{bdg} is the bending span of the stiffener in m.

f_{bdg} is the bending moment factor taken as 10 for transverse stiffeners and vertical stiffeners which may be considered fixed at both ends.

The net section modulus is given in Table 10.

Table 10. Stiffener net section modulus

Material	σ_{all} [N.mm^{-2}]	Net section modulus [cm³]
AISI 316 L	212.78	16.84
Alloy 5083-O	109.02	32.87

primary support members

$$Z = \frac{|P_{eq}|Sl_{bdg}^2}{f_{bdg}\sigma_{all}} \quad (6)$$

Where

S is the longitudinal stiffeners spacing in mm. l_{bdg} is the bending span of the longitudinal stiffeners in m.

The net section modulus is given in the Table 11.

Table 11. PSM net section modulus

Material	σ_{all} [N.mm^{-2}]	Net section modulus [cm³]
AISI 316 L	212.78	296.08
Alloy 5083-O	109.02	573.66

d) Summary of the scantling

Table 12.Scantling summary

Structural element	Material	Minimum requirement	Calculated	Selected	Comment
Plate thickness [mm]	AISI 316 L	6.43	6.59	8.00	-
	Alu 5083-O	6.43	9.21	10.00	-
Stiffener section modulus [cm³]	AISI 316 L	-	16.84	21.00	BP 120×7
	Alu 5083-O	-	32.87	36.2	L 120×120×10
Longitudinal Stiffener section modulus [cm³]	AISI 316 L	-	296.08	331	L 200×9 90×14
	Alu 5083-O	-	573.66	659	L 300×10 90×16

APPENDIX A5

Insulation and BOG

Ammonia has to be stored at -33.4°C, therefore the tanks have to be insulated to limit the heat loss and reduce the blow-off gas rates.

The heat loss, in w, is defined by the following formula Eq.(1).

$$Q = U \times A \times dT \qquad (1)$$

Where

A is the area of the tank shell, in m².

dT is the temperature gradient, in °C, between the ammonia temperature and the ambient temperature of 25°C.

U is the heat transfer rate in W·m^{-1}·°C^{-1} .

For multilayer elements the heat transfer ratio is given by the Eq.((2)

$$\frac{1}{U} = \frac{1}{A} \sum_{i=1}^{n} \frac{l_i}{k_i} \qquad (2)$$

l_i is the thickness of each layer of material or insulation in m.

k_i is the thermal conductivity coefficient, in w·m^{-1}°·C^{-1} for each layer

the calculation of the amount of ammonia evaporating inside the tank is possible via the following (Eq(3) of boil-off rates in % vol per day

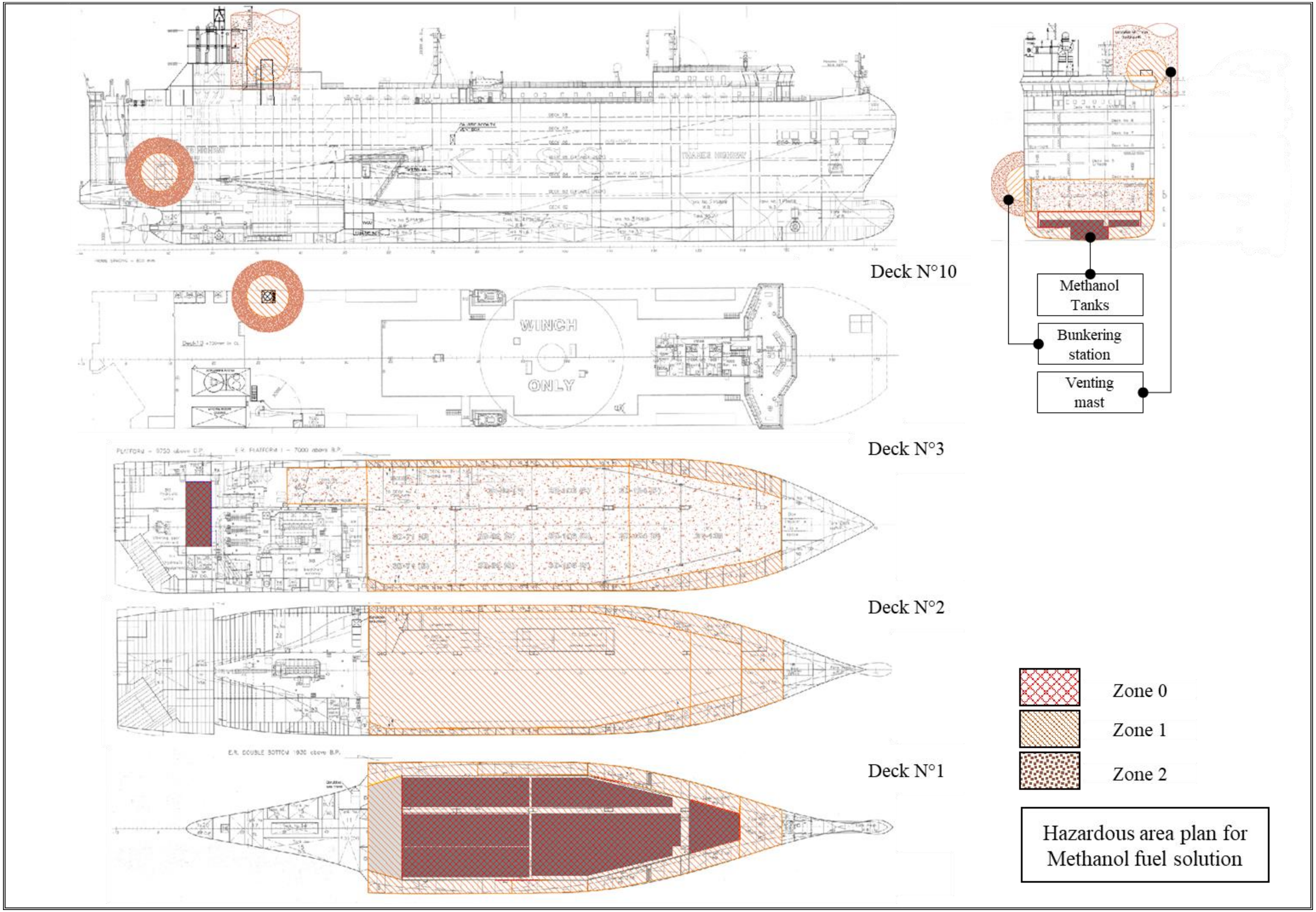
$$BOR\,\% = \frac{U.A.dT}{\Delta H.\rho\, V_{NH_3}} \times 24 \times 3600 \times 100 \qquad (3)$$

With

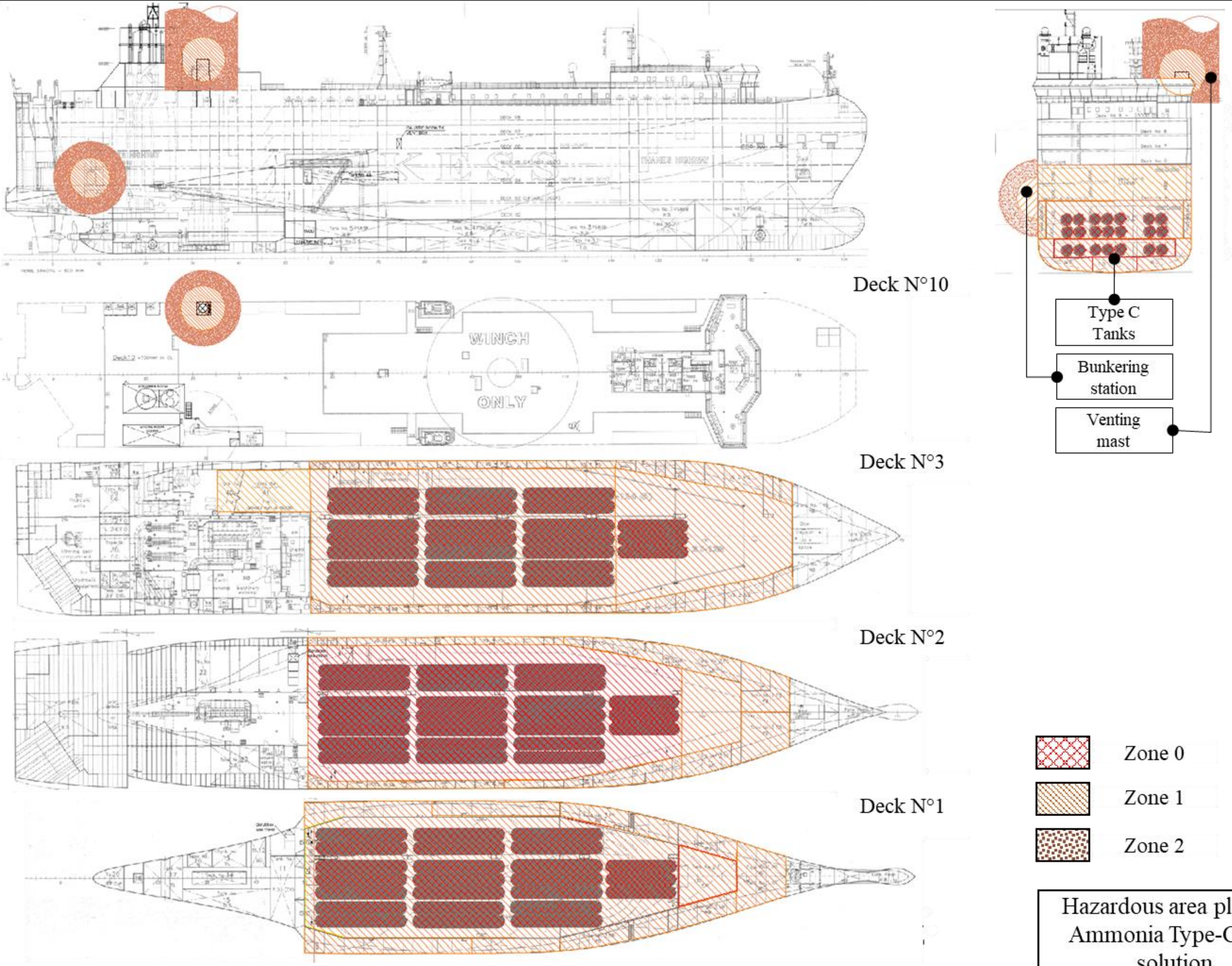
ΔH the latent heat for ammonia evaporation in J·kg^{-1}.

V_{NH_3} the volume of the ammonia inside the tank corresponding to 85 % of the total tank volume in m³.

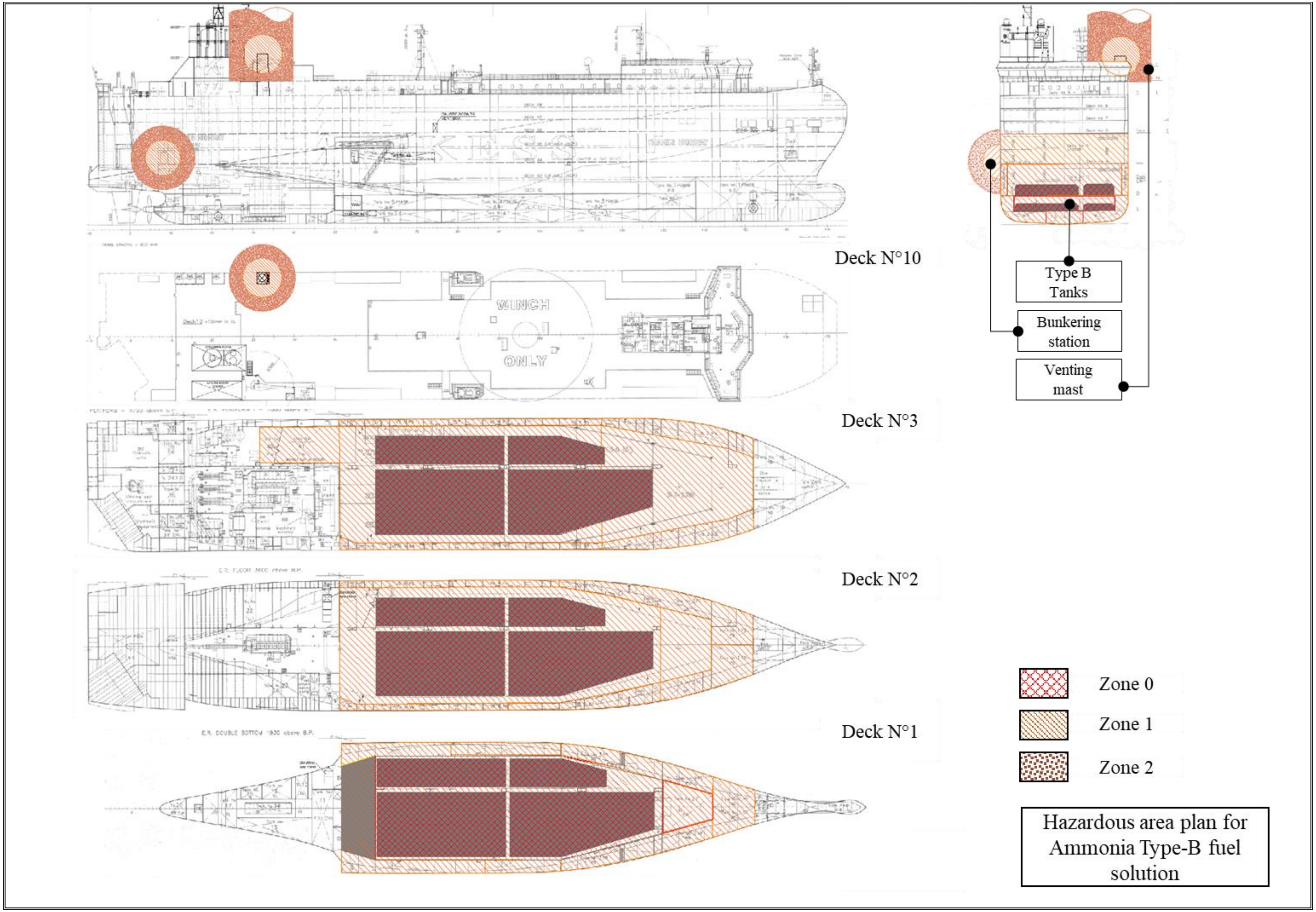
ρ the density of ammonia in kg·m^{-3}.



Deck N°10
Deck N°3
Deck N°2
Deck N°1
WINCH
ONLY
Methanol Tanks
Bunkering station
Venting mast
Zone 0
Zone 1
Zone 2
Hazardous area plan for Methanol fuel solution



Hazardous area plan for Ammonia Type-C fuel solution



Hazardous area plan for Ammonia Type-B fuel solution