Gastech 2020 - T2.7 Ethane & Ammonia as a Fuel

'Ammonia :The Green Fuel' - An Assessment of Practical Aspects

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Summary

The paper explores technical and financial feasibility of using ammonia as a marine fuel. Ammonia is considered as one of the zero carbon options for marine industry to achieve its carbon emission reduction targets. Although free from carbon emissions, ammonia being a toxic gas with low energy density brings about a set of safety challenges and commercial considerations. Paper discusses how Risk-Based Design (RBD) methodology can be applied to identify and manage critical safety challenges associated with the design of an ammonia fuelled Newcastlemax bulk carrier. It further evaluates the financial viability of this vessel taking into consideration of possible implementation of a maritime carbon pricing.

List of abbreviations

Abbreviation	Description
NH_3	Anhydrous ammonia
GHG	Green House Gas
ZEV	Zero Emission Vessel
SOx	Sulphur Oxides
CO_2	Carbon dioxide
N_2O	Nitrous Oxide
NOx	Nitrogen Oxides
BLEVE	Boiling Liquid Expanding Vapour Explosion
ESD	Emergency Shutdown
ERS	Emergency Release System
ICE	Internal Combustion Engines
PPE	Personal Protective Equipment
GWP	Global Warming Potential
TCS	Tank Connection Space
FVT	Fuel Valve Train
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
HFO	Heavy Fuel Oil
LNG	Liquified Natural Gas
LPG	Liquefied Petroleum Gas
RBD	Risk Based Design

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1 Introduction

Drive towards a low carbon future for the maritime industry is gaining momentum with the IMO establishing a vision towards reducing greenhouse gas emissions from shipping. It has set the Green House Gas (GHG) reduction pathway of at least 50% by 2050 based on a 2008 baseline, with a strong emphasis on reducing to 100% by 2050 if this can be shown to be possible (1).

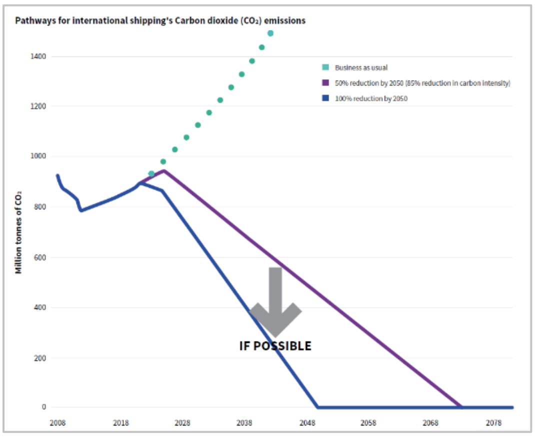


Figure 1 Pathways for international shipping's carbon dioxide (CO2) emissions.

However, the fourth IMO GHG study has shown a growth in emissions from shipping. Total GHG emissions from shipping increasing from 977 million tonnes in 2012 to 1,076 million tonnes in 2018, a 9.6% rise (2). The study has also projected emissions to increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 for a range of scenarios (2). These statistics are an indicator of the challenge that needs to be addressed by the maritime industry.

Studies undertaken by Lloyd's Register (LR) has indicated that Zero emission vessels (ZEVs) should be entering service by 2030 for the industry to achieve emission reduction targets set by IMO (3). To evaluate various zero carbon options, LR's approach (1) has been to carryout an assessment of:

- Technology readiness – Technologies, equipment and systems considered to be critical for the application of zero carbon fuels should be available and safety considerations addressed.
- Investment readiness – Proposed application should be economically viable.
- Community readiness – Development and implementation of strong international policy and regulations. Broader air pollutant standards applicable for future fuels.

Ammonia has been identified as one of the zero-carbon fuels and its use as fuel minimizes carbon dioxide (CO_2) emissions and could allow compliance with the GHG emission targets. However, its application as marine fuel is currently not validated and poses several safety, technical and commercial challenges.

1.1 Objective and Scope

The paper explores possibility of adopting ammonia as fuel for a Newcastlemax bulk carrier (~210,000 DWT) and how these challenges could be addressed.

First part of the paper collates a background analysis on ammonia, its limitations for marine application and an overview on systems development and regulatory affairs.

Further, an assessment from technology and investment readiness perspectives was undertaken for the case vessel. The significance of community readiness as identified in our earlier studies are referred to.

Under the 'Technology readiness' segment, systems and arrangements required for the vessel are identified. The arrangements are then evaluated using risk-based approach to classify the specific safety hazards to the vessel due to these arrangements. In addition, the fundamental preventive and mitigation measures that could be applied are analysed.

In evaluating the 'Investment readiness', ammonia fuelled vessel is compared against an LNG fuelled reference vessel of same specifications. Economic viability under varying energy price scenarios and impact of carbon pricing were assessed.

2 About Ammonia

Ammonia (NH_3) is a toxic, flammable, corrosive, colourless gas, that can be liquefied for storage under pressure or temperature alone. It has a boiling point at approximately -33.3℃ and the vapour pressure at ambient temperature is approximately 8.5 bara. Ambient ammonia vapour is lighter than air. The minimum ignition energy is significantly greater than most other hydrocarbon fuels and depending on the environment and arrangements it can be explosive.

Ammonia is highly miscible in water and will form ammonium hydroxide. The aqueous ammonia remains flammable, toxic, and ammonia will evaporate from solution with increasing temperature.

At present, ammonia production is primarily using natural gas as the energy source, which undergoes a conversion to ammonia through steam reformation in combination with a Haber-Bosch process (4). An alternative and 'greener' approach is electrolysis of water using renewable electricity to produce so-called Green Ammonia or renewable ammonia.

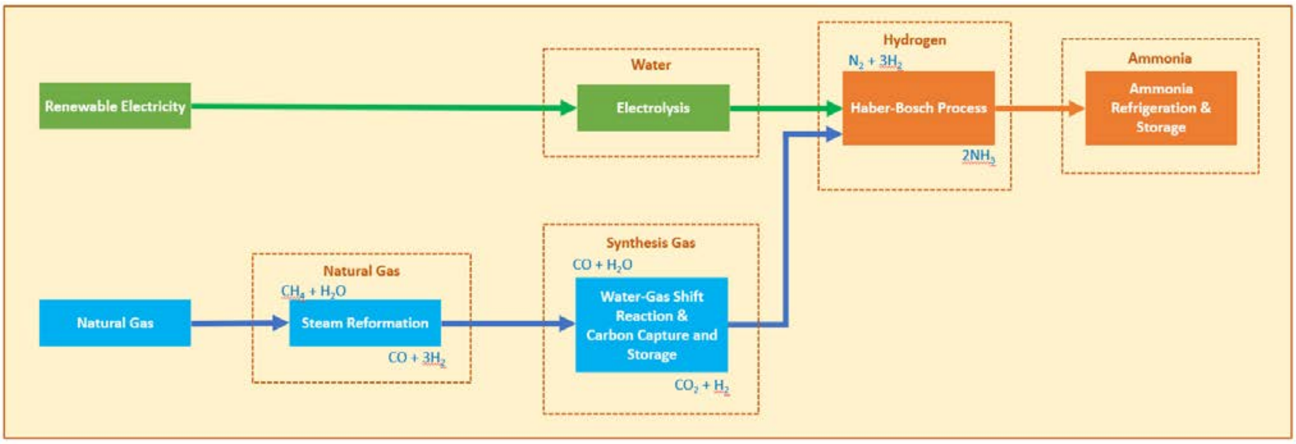


Figure 2 Ammonia Production (4)

Ammonia is mainly used in production of fertilizers containing nitrogen and as an industrial refrigerant. It is also used for production of a range of industrial chemicals for cleaning, fermentation etc. (5).

Ammonia is a zero-carbon fuel and a mono-fuelled ammonia consumer's exhaust would be free of CO_2 emissions. Furthermore, the exhaust would not contain sulphur oxides (SOx), particulate matter (PM) or unburned hydrocarbon (6). However, exhaust emissions from internal combustion engines could contain Nitrous Oxide (N_2O), Nitrogen Oxides (NO_x) and possible unburnt ammonia (7). It should also be taken into consideration that engines currently being developed for marine application uses pilot fuel, which could result in exhaust from these engines containing a proportional amount of carbon, SOx and particulate matter.

2.1 Safety Hazards

Application of ammonia could be associated with several safety hazards. Potential consequences of 'ammonia release to atmosphere' could include exposure related hazards from Toxicity, Asphyxiation, Cold burns, Frostbite as well as Fire and Explosion related hazards.

Flammability – Ammonia is flammable within a flammability range of 14-28% in air, burning with a yellow flame forming water vapor and nitrogen oxides. Fire resulting from the accidental ignition of unintended ammonia releases (e.g. leakage) are likely to cause harm or damage as a result of conduction, convection, and/or radiant heat transfer. The likelihood of a sustained ammonia fire may be less likely due to the much higher ignition energy required to ignite a release (8).

Toxicity - Ammonia is toxic to humans as well as aquatic life. Lower concentrations cause eye irritation. Slightly prolonged exposure could result in severe lung irritation. Exposure to higher gas concentrations may cause temporary blindness and severe eye damage. Direct contact to the eye and skin would cause severe eye and skin burns. High gas concentrations in the air may also cause blisters and chemical burns to the skin (9).

Exposure by Inhalation	Physiological effects
16-510 ppm	Irritation and hyperventilation following exposure for up to 4 hrs
100 ppm	Slightly irritating to eyes
250 ppm	Bearable by most personal for 30-60 mins
2500-4500 ppm	Fatal in approximately 30 mins
5000 - 10000 ppm	Rapidly fatal in humans
Source: Compendium of Chemical Hazards: Ammonia (9)	

BLEVE Potential - Boiling Liquid Expanding Vapour Explosion (BLEVE) is a violent release of pressurised superheated liquid ammonia to the atmosphere which may be expected following a catastrophic failure of fuel containment equipment such as a tank or piping. Such equipment failure may be the result of exposure to an external fire, flame impingement, failure as a result of collision or due to over pressurisation caused by entrapped liquified gases vaporising (8). Reported ammonia BLEVE's are limited to large industrial systems (10). Vessel designs are to take this potential into account while deciding on the location of ammonia fuel storage and service tanks.

Reactivity with other Chemicals/Gases - Ammonia reacts with CO_2 forming carbamates. On ships with flue gas system, inert gas produced by combustion of hydrocarbon fuels could contain up to 15% of CO_2. If used for inerting ammonia tanks, it would react with ammonia to produce carbamates leaving deposits on tank walls and pipelines (11). Therefore, it is important that all purging and venting operations are performed solely using high purity nitrogen and all piping kept inerted with nitrogen.

Material Compatibility - Ammonia has varying degrees of compatibility with elastomers and sealants (8). Ammonia is also corrosive to alloys with a nickel concentration larger than 6% and plastic (6). Components made of aluminium, copper, zinc, silver and its alloys (eg. brass) are not suitable for ammonia service due to its highly reactive nature. Stainless steel, mild steel etc. are considered appropriate for containment (5).

Stress Corrosion Cracking (SCC) – It is a failure mechanism caused by tensile stress and a corrosive medium i.e. ammonia. SCC encourages cracks and fractures that could cause a sudden structural failure. Two types of SCC can exist in ammonia fuel systems, cracking of carbon steels that is susceptible to SCC in anhydrous ammonia, and some copper alloys are liable to SCC in ammonia solution (8). The design and construction should eliminate or reduce susceptible materials, reduce the tensile stress, and mitigate the corrosive environment.

3 Ammonia - Development as marine fuel

3.1 Equipment & systems development

For marine applications, MAN Energy Solutions (MAN ES) have been developing solutions towards using ammonia as a fuel on their two-stroke engines. Development is ongoing in terms of adapting the ME-LGI engines to be able to burn ammonia as fuel instead of Liquified Petroleum Gas (6).

Wartsila has also initiated development of ammonia fuelled engines and have successfully carried out combustion trials in four stroke engines. Full scale, long term testing is also planned to commence on marine engines (12).

Application of ammonia as propulsion fuel could also be through Fuel Cells. Project to install world's first ammonia powered fuel cell on a ship is currently underway. The European Union funded ShipFC proposes installation of a 2MW ammonia powered fuel cell onboard offshore supply ship 'Viking Energy' (13).

Lloyd's Register has been working with stakeholders in the marine industry in supporting ammonia's application as fuel. It includes projects such as development of an ammonia-fuelled tanker with Samsung Heavy Industries (SHI), MISC Berhad and MAN Energy Solutions, Approval in Principle to Dalian Shipbuilding Industry Co. (DSIC) for an ammonia-fuelled 23,000 TEU Ultra-Large Container Ship (ULCS) concept design etc.

3.2 Other considerations with using ammonia as marine fuel

In addition to the safety risks associated with its usage, following are some of the key challenges that needs to be dealt with on technical, commercial and operational fronts.

Fuel Type	Specific Energy (MJ/kg)
HFO	40.5
LNG	50.02
Methanol	18
Ammonia (liquid -33℃)	18.6
Hydrogen (liquid -253℃)	142
Source: MAN ES (6)	

Lower energy content in comparison with other fuel types. The energy density of ammonia is significantly lower than HFO or other hydrocarbon fuels. This would necessitate carrying nearly three times the volume of HFO or twice that of LNG for achieving the same endurance. The tank size could impact vessel's cargo carrying capacity.

Higher OPEX and Fuel Costs – The lower energy content would contribute to higher fuel consumption when compared to HFO or LNG resulting in higher fuel related voyage costs. Higher compensation could also be applicable for crew who are specially trained and possibly exposed to ammonia's toxicity risks. The vessel insurance premiums could also be higher when compared with traditional fuels.

Requirement for additional auxiliary machinery - When compared with traditional fuels, storage and processing of ammonia requires additional machinery, including fuel processing equipment, safety systems, pressure relief systems and possibly re-liquefaction plants. These would increase the vessel's CAPEX when compared to a conventional vessel.

Disadvantages as Fuel in Engines – Ammonia's high auto-ignition temperature (615 °C), its low flame speed, narrow flammability range (14-28%) and high minimum ignition energy does not promote efficient combustion (6). These are challenges to be addressed in technology development of engines.

Exhaust Emissions - Exhaust emissions from ammonia fuelled internal combustion engines could contain Nitrous Oxides (N_2O), Nitrogen Oxides (NO_x) and possible unburnt ammonia.

N_2O is a potent greenhouse gas and environmental impact from NO_x is being regulated.

Ammonia injected to the engine cylinder may not be completely consumed, especially when the engine is in part or low load condition and could be released to the atmosphere along with the exhaust gas. The importance of addressing this becomes clearer when we consider the ambiguity and uncertainty faced by the industry in terms of methane slip from LNG fuelled engines. Measurement of ammonia slipping through the exhaust must be undertaken and quantified. Sufficient control and monitoring systems should be put in place to address this risk.

Another aspect to consider is the potential perception by general public, for instance, when an Ammonia fuelled vessel is at port. Once a ship berthed at port release ammonia via exhaust, it would inevitably cause noticeable odour that could be experienced by the public and even pose a significant danger.

3.3 Regulatory & Classification Aspects

Currently there are no prescriptive requirements for the use of ammonia as fuel for ships. For gas carriers with ammonia as cargo, its use as fuel is currently not permitted under the IGC Code.

Flag Acceptance - Use of ammonia as fuel would require approval from the vessel's flag administration. It should be demonstrated to the Administration that the proposed arrangements would deliver equivalent level of safety, reliability and dependability provided by oil fuelled marine machinery. This can be considered via SOLAS Reg. II-1/55 Alternate Design & Arrangements and guidelines published in MSC.1/Circular.1212 and MSC.1/Circular.1455.

Rules Application/ Reference - Carriage of ammonia onboard gas carriers and its application for refrigeration has been taking reference from the following rules and statutory requirements. These should be considered as to their relevance to the use of ammonia as fuel.

(i) IGC Code - International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
(ii) Lloyd's Register Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquefied Gases in Bulk
(iii) Rules and Regulations for the Classification of Ships
(iv) Rules and Regulations for the Classification of Ships Part 6, Chapter 3 Refrigerated Cargo Installations

In addition to the above, following must be applied for the application of ammonia as fuel.

(i) IGF Code - International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels -Parts A and D (applicable to all gas/low flash point fuels)
(ii) Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels

The IGC Code stipulates significant protective measures for carriage of ammonia in cargo area of the ship.

Requirements from IGC Code	
Ship Type	2G/2PG
Vapor Detection	Toxic gas vapor detection
Gauging	Closed
Special Requirements - Personnel protection	14.4 Self Contained Breathing Apparatus and Gas tight protective clothing for all onboard personnel. Decontamination shower facilities
Special Requirements - Material compatibility	17.2.1 materials such as mercury, copper and copper-bearing alloys, and zinc not to be used for construction of cargo tanks and associated pipelines, valves, fittings and other items of equipment normally in direct contact with the cargo liquid or vapour
Special Requirements -Stress Corrosion Cracking	17.12 Requirements to minimize stress corrosion cracking in containment and process systems made of carbon-manganese steel or nickel steel

4 Risk Based Design

Recent years have seen an increase in the uptake of complex novel technologies by the marine industry including the adoption of gaseous fuels such as LNG, LPG for propulsion. The prescriptive nature of classification and statutory requirements, which deals with known hazards, are inadequate alone to provide sufficient assurance to these technologies.

Risk Based Design methodology provides an alternative by systematically identifying the hazards and thus addressing the associated risks at the design stage (14). The Risk Based Design process as developed by Lloyd's Register is shown in figure 3. The process is detailed in 'ShipRight Additional Design Procedure Risk Based Designs (RBD)' (15).

Figure 3 Process for Risk Based Design (15)

An RBD process can start with defining the extent of application of additional systems for the specific vessel– including fuel storage, processing, consuming etc. i.e. defining the system boundary. The safety objectives are established taking into consideration of the functional requirements of these systems and input from stakeholders. It is then followed by identifying deviations from current classification/statutory requirements. This would provide the foundation for identifying hazards, which can be carried out using a HAZID workshop or other recognised methodologies as per ISO 31010. It would also involve determining how these hazards could occur, what the consequences would be and the likelihood of these occurring. Applying these to the risk acceptance criteria, it can be checked if the safety objectives are being met. The appropriate measures to prevent when possible or otherwise mitigate should be evaluated in detail. Design can then be modified to bring the risk to an equivalent level of safety. By systematically evaluating the risks and addressing these during the design stage, a safe design could be achieved.

5 Technology Readiness

The technical feasibility of applying ammonia as fuel for a bulk carrier is examined in this section. The systems and arrangements required for such application are identified. Furthermore, the arrangements are evaluated using risk-based approach to classify specific safety hazards to the vessel. The fundamental preventive and mitigation measures that could be applied are also discussed.

5.1 Case Vessel – Newcastlemax Bulkcarrier

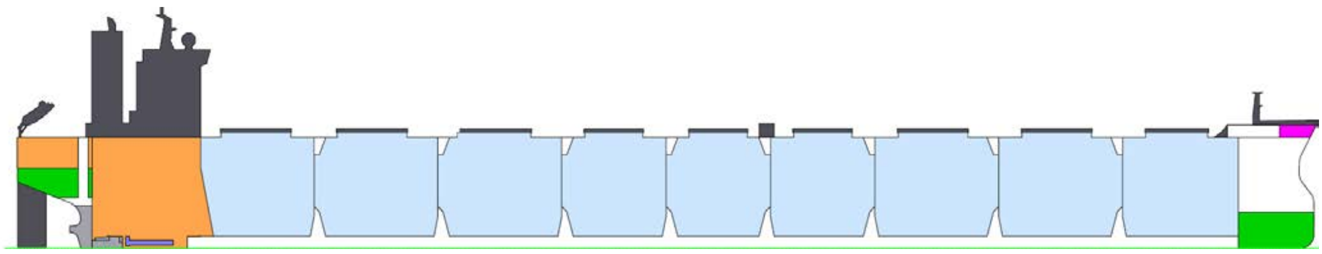


Figure 4 Case vessel - profile

Ammonia fuel capacity to cover a cruising range of 12,000 nautical miles was established to provide flexibility in trade routes and options for bunkering the vessel. This was carried out based on the operational trade routes between China and Australia and including sufficient margin for fuel capacity. It takes also into consideration that bunkering can be carried out at both ports or on a round trip.

Vessel Particulars	
Length (BP)	296.0 m
Breadth (Moulded)	50 m
Depth	25 m
Draught	18.43 m
Gross Tonnage (GT)	107,000
Deadweight (DWT)	209,600
Main Engine (kW)	16,040

Propulsion Machinery - Earlier LR studies had explored the Internal Combustion Engine (ICE) and fuel cell and electric motor combination. ICE outcompeted the fuel cell and electric motor option at current estimates (3). When used with fuel cells, the higher onboard storage requirement increased capital cost and reduced the available cargo space and thus revenue (3). Accordingly, the ICE option was chosen for this case study.

5.2 Design and Arrangements for using Ammonia as fuel

The following section provides a brief description on the systems and arrangements that has been considered based on MAN ES LGIP Engine adapted for using ammonia as fuel. It includes provision for bunkering, storing, processing, supplying and consuming the fuel onboard. In addition, the ship will need to be equipped with safety arrangements for the crew and environment.

5.2.1 Ammonia Fuel Tanks

Several tank types are suitable for storage of ammonia as fuel. Independent Type A tanks, Prismatic or Spherical Type B tanks, Membrane tanks or Independent Type-C tanks. Independent Type-C tank was chosen for this study. Consideration could also be made towards adopting a storage solution that would permit a range of alternate fuels to be bunkered.

With the vessel's operational profile and expected endurance, estimated ammonia fuel tank capacity of 6500 cbm would be required to cater for a round trip. Two Type C fuel tanks each with 3250 cbm storage capacity and design pressure of 3 barg were chosen.

Several locations were considered for the fuel tanks including the engine room area, aft part of the accommodation, spaces adjacent to the accommodation area as well as the forward area of the vessel. One of the fundamental considerations is to avoid proximity to the accommodation block. However, this has to be balanced with the requirement to reduce the fuel supply/return piping length and minimising any pipe routing in cargo area. In doing so, reducing the likelihood of ammonia release and/or loss of propulsion due to damage of the fuel piping in service during cargo operations. Taking these into consideration, it was proposed to locate the tanks inside the aft cargo hold, within segregated fuel storage hold spaces. Proposed location for the tanks was evaluated using the probabilistic approach to verify compliance with the current requirements applicable for LNG tanks as indicated in the IGF Code.

The estimated reduction in cubic capacity of the vessel's overall cargo volume, due to fuel tank installation in the aft cargo hold, is approximately 4.5%.

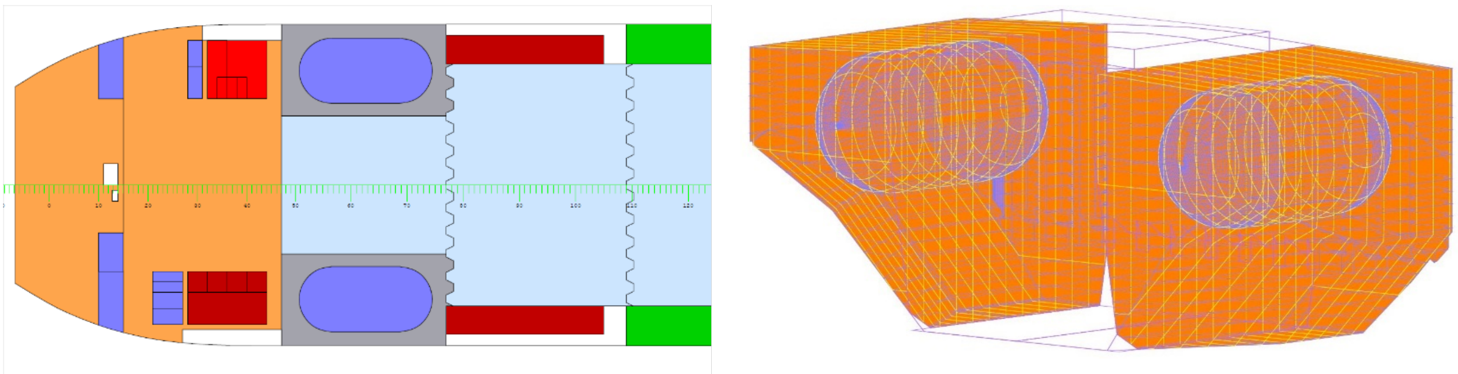


Figure 5 Ammonia fuel storage tank location on the vessel

Fuel transfer pumps are provided within the fuel tanks. Pumps of deepwell design have proven service experience in ammonia trade and could be considered for this application. Tank Connection Space (TCS) to contain the connections to each tank is located on the open deck. It may also be located within the fuel storage hold space and would be a key item for consideration during risk assessment. Pressure Release Valves (PRV) and associated venting arrangements, provision for gauging and other instrumentation such as temperature, vapour sampling, and access arrangements etc. are provided for the tanks.

5.2.2 Bunkering Arrangement

The bunkering station includes the liquid loading manifolds and the vapour return lines. Liquid lines and vapour lines are routed to the fuel storage tanks. Necessary isolation valves, metering & sampling systems, Emergency Shutdown (ESD) arrangements, firefighting systems, drip tray, provision for fuel sampling (closed loop), Quick Connect/Disconnect Couplers (QCDC), hose handling system etc. are provided at the bunkering station.

The arrangements at the station caters to the functional requirement of bunkering the vessel and include the essential safety and personal protection systems as indicated in Chapter 14 of the IGC Code as applicable for ammonia.

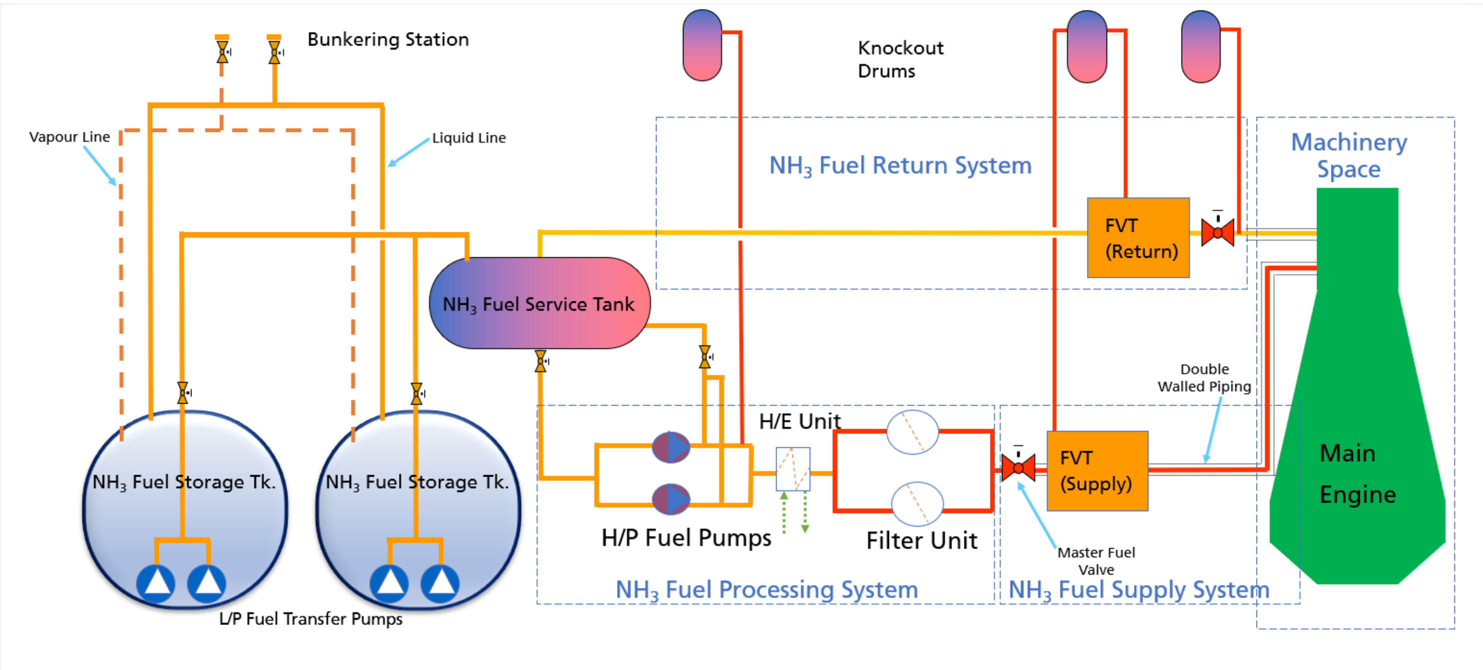


Figure 6 Arrangements for Ammonia as Fuel (6) (3)

5.2.3 Ammonia Fuel Processing System

Ammonia is injected to the engines in liquid form. The temperature, pressure and flow conditions for fuel at the engine is to be arranged by the fuel processing system. The system could include the following (6).

Fuel Service Tank –A fuel service tank is provided within the fuel supply system. The service tank prevents the fuel in storage tank from being contaminated by any remains of pilot fuel oil, engine sealing oil or other substances returned from the engine (6). It will also prevent any impact on the fuel supply pumps and instrumentation in the fuel storage tank due to presence of oil content. Additionally, it will enable maintaining a higher fuel supply pressure within the system without pressurizing the fuel storage tanks.

High Pressure Fuel Pumps – It is estimated that ammonia should be supplied to the engine at a pressure of 70 barg. High pressure fuel supply pumps are required. These take suction from the service tank and supply pressurised liquid to the fuel heat exchanger units as described below.

Fuel Heat Exchanger Unit & Filters- Fuel heat exchanger units heat/cool pressurised ammonia to the temperature required by the engine. Water glycol heating system would be used. Fuel filters are provided to remove any possible solid particles which could affect to the engine. These are provided with redundancy and with provision for change over.

5.2.4 Fuel Supply and Return System

The fuel supply system to the engine would involve the following.

Master fuel valve – The master fuel valve would form an integral part of the fuel supply system and return system to/from the engine room. Subject valve, integrated to the safety system, would safely isolate the fuel supply to/from engine room as required. It should be located outside of the engine room.

Double Walled Piping– The fuel supply lines from the Fuel Preparation Room (FPR), located downstream of the master fuel valve, is provided with double walled pipe with ventilation or equivalent arrangement.

Supply/Return Fuel Valve Train – Essentially a double-block and bleed arrangement, the fuel valve train would have provision for supply line venting, connection from nitrogen system for purging, fuel fine filtering, ventilation and control of fuel supply parameters – including temperature, pressure and flow rate (6). When the fuel supply to the engine is stopped, the block and bleed valve arrangement would initiate depressurisation and purging.

Knock-out drums – These are small units to which the relief valves from the fuel supply and return lines are led to. As the relief valve will be venting liquid ammonia at high pressure, leading these directly to the vent mast or venting to the open presents a safety risk. The knockout drums will provide a buffer station to collect the released liquid. Arrangements to minimise release of ammonia should be in place.

5.2.5 Engine Technology

MAN ES ME-LGI engine is being developed for ammonia to be used as fuel. These engines are currently capable of burning LPG (propane/butane mixture) – ME-LGIP and methanol – ME-LGIM. Based on current development for the ammonia fuelled engine, there would be a pilot fuel injection to ensure a controlled combustion of ammonia. Fuel supply pressure will be approximately 70 barg and the injection pressure 600 to 700 barg (6).

Considering the toxic nature of ammonia vapour and the high fuel supply pressure, Gas Safe Machinery space concept is considered for this design.

5.2.6 Other Systems

Nitrogen System - Nitrogen is required for purging ammonia fuel supply and return lines, bunkering operations and necessary maintenance in service. Complete purging of fuel supply and return lines is required upon stopping fuel supply to engines. Nitrogen generator units and buffer tank vessel is provided.

Ventilation – Ventilation is provided for fuel processing compartment, double walled fuel supply and return piping, machinery spaces etc.

Water Glycol System- Water glycol system would provide the essential heat exchange medium for heating/cooling of the ammonia fuel during the fuel processing phase.

Ammonia Detection – Provision is made for detection of any ammonia gas leakage at various locations and detection of any liquid leakages throughout the fuel supply system.

Fire Detection & Fire Extinguishing – Additional fire detection and fire extinguishing measures required to address the fire hazards presented by the possible release of ammonia.

Control Systems- Control systems integrating various alarms, parameters like pressure, temperature, level, gas/fire detection systems would also form part of the key installations.

Additionally, provision for separate bilge pumping and electrical equipment arrangement in accordance with the hazardous zone classification are also provided.

5.3 Application of Risk Based Design in addressing the hazards

Installation of the above equipment and systems would present hazards associated with ammonia storage in tanks, toxicity of ammonia vapour, corrosivity, material compatibility, asphyxiation, etc. Identifying these hazards in the specific context of the ship and its arrangements would be the first step in the application of Risk Based Design.

In order to evaluate this, the system is divided into various 'nodes' based on the process section. Hazards shall be eliminated where possible. Inherently safer design, where all single points of failure are identified and when possible eliminated, shall be sought. Preventive and mitigation measures should be established in accordance with the risk control hierarchy. The fundamental intend is to demonstrate that the level of risk is equivalent to that achieved with new and comparable conventional oil-fuelled main and auxiliary machinery.

Based on the arrangement as discussed above, following could be a sample of various nodes. The hazards associated with these nodes are then identified. Examples of preventive and mitigation measures are detailed as well. These are not considered to be an exhaustive list of all the possible hazards or provision for safety measures.

5.3.1 Ammonia Fuel Bunkering

Bunkering of ammonia is a critical operation. Personnel involved in this operation are exposed to numerous safety risks. Several risks including leakage of ammonia and the associated toxicity and low temperature risks, fire considerations, fuel contamination, layout hazards etc. are to be considered. There are also risks to the environment, particularly to the marine life.

Location of the bunkering station and whether it will be open on deck or enclosed/semi-enclosed is to be considered in detail during the risk assessment session. Adequate preventive and mitigation measures are to be in place to minimise the impact of these risks, having in consideration the particularities of hazards represented by ammonia. For instance, water curtain used for LNG bunkering may not be appropriate for the protection of the hull while bunkering ammonia.

In addition to provision for arrangements such as emergency shutdown, emergency release, firefighting system; measures such as personal protective equipment, decontamination showers, eye wash, respiratory equipment for the crew involved in ammonia bunkering, personal emergency escape respiratory protection for crew, toxic gas detection, remote monitoring of the bunkering parameters and the bunkering station, provision for firefighting including dry power, water spray system etc. could be required to manage the associated risks effectively.

Further, a compatibility study between the ammonia fuelled vessel and the bunkering vessel or shoreside bunkering arrangements should be carried out to identify any concerns. A detailed bunkering operational procedure should also be available.

The bunkering operation would also be required to be considered as part of the HAZOP studies. The safety zone considered for bunkering should take into account of the specific characteristics of ammonia, which is different from the approach used for determining safety zones associated with LNG bunkering.

5.3.2 Ammonia Fuel Tank & Fuel Storage Hold Space

With respect to the fuel tanks and the fuel storage hold space, key considerations include tank structural integrity, location on the vessel and dealing with any liquid/gas leakage from the tank connection piping. These are taking into consideration of ammonia's toxicity and flammability hazards.

Established standards on pressure vessel design and requirements from IGC/IGF codes can be followed for tank design. In addition, by following IGF code requirements, tanks are placed in a protective location and tank hold spaces separated from the machinery space with suitable structural fire safety measures.

In order to address potential leakage from the tank connection points, these are located within the tank connection space which is provided with ventilation, gas detection and associated safety systems. Additionally, bilge pumping arrangements allows safe disposal of any fuel or contaminated water from the space.

It is also to be considered that in the event of a failure of the tank containment, the requisite action will be to transfer the tank contents out and to gas free the tank. With two fuel tanks and dedicated fuel transfer pumps, it would be possible to undertake this operation onboard. However, it is also important to have emergency procedures in place to address the possibility of having to deal with a leakage scenario requiring shore transfer or ship to ship transfer.

5.3.3 Ammonia Fuel Processing

Components of the fuel processing system including high-pressure fuel pumps, heat exchangers, other pressure vessels in the system could be subject various failure modes leading to ammonia leakage and the associated toxicity and low temperature risks within the fuel preparation room. Focus should be on engineered prevention of failure which would include minimizing the number of connections, higher level of reliability and redundancy etc.

For fuel pumps there could be concerns from pump pulsation (depending the type of pumps) inducing fatigue, pump seal leakages, vibration issues etc. leading to pump failure. Adequate means for monitoring these components and provision for redundancy for the pumps could be required to address these risks.

There are also possible failure modes associated with fuel piping leading to small- or large-scale jet leakages. It could be due to fatigue failure of piping in service, vibration and other ship motions influencing the fuel process system, failure at pipe connections etc. A pipe stress analysis would be expected during design phase. Additionally, as indicated in earlier sections, provision for ammonia gas & leak detection, means of redundant ventilation arrangements, fire detection and fighting arrangements should be considered and installed.

The fuel processing system should also be reviewed in detail with a HAZOP study to identify process related operational and maintenance hazards.

It is important to emphasize at initial design stage that the use of ammonia as fuel is aiming to achieve zero CO_2 emissions, therefore the traditional safe alternative of switching to conventional fuels shall be limited to emergency condition. Therefore, maintenance and availability assessment of the ammonia fuel supply system would be expected.

5.3.4 Engine room – Ammonia Fuel System in the machinery space

Components to consider includes fuel supply piping, fuel consumer (engine), ventilation arrangements for double walled piping, gas detection, fire detection, engine safety system etc. Hazards to assess would include ammonia leakage in engine room, fire in engine room, ventilation failure, ammonia leakage to ancillary systems, ammonia slip from engine due to incomplete combustion etc.

The preventive and mitigation methods should include an inherently safer design for the engine and associated control systems, emergency shutdown, toxic gas detection, fire detection, fixed fire extinguishing system, structural fire protection, firefighting systems – fire main, portable fire extinguishers, personal protective equipment, decontamination showers, eye wash, crew training, use of appropriate procedures & checklists, ventilation arrangements, emergency escape arrangements etc.

Ammonia slip from the engines through exhaust gas when engine is at part/low load conditions is a possibility. Detailed evaluation of these emissions and their risks shall be carried out by the engine maker to quantify the amount of emissions. The safety risk for ship crew, shore staff etc. are to be taken into consideration.

5.3.5 Vents

Vents includes openings for ventilation air intakes/exhaust openings, vent masts to which fuel tank relief valves are led to, outlets for various pressure relief valves including those from fuel supply and return lines, knockout drums vent outlets etc.

Location of these openings and vent masts have an impact on hazardous zone classification, toxicity impact to humans, location of air inlets and other openings to accommodation/service and machinery spaces. Hazardous area classification for ammonia should be specifically considered as the standard approach applied for natural gas e.g. dispersion models, criteria etc. would not be appropriate. For vent masts, the possibility of two-phase flow should be considered and detailed gas dispersion analysis carried out to determine the impact of pressurised ammonia release. Considering the toxicity risk and possibility of human exposure during release, possibility of leading it through a scrubber unit/ similar arrangement could also be considered.

5.4 Technology Readiness – Further developments

There are several other aspects that would require further development for the safe application of ammonia as fuel for maritime applications. Following includes an overview of some of these.

Standards & Regulations - Development of statutory requirements, international standards, technical guidance to cover safe carriage, processing and use of ammonia as fuel for ships is essential.

Machinery & Exhaust Emissions - Full scale, long term testing of engines and fuel processing auxiliaries using ammonia is required. It is also important to address ammonia slip, other potentially harmful emissions such as N_2O, NOx, CO and particulate matter associated with its use on ICE.

Evaluation of allowable exposure levels – In case of accidental exposure to ammonia, ship staff will not have rapid access to medical attention as onshore personnel does. Considering this, it is not unreasonable to expect the allowable exposure levels for personnel should be maintained below the current onshore industrial standard. Further evaluation is necessary to establish limits towards allowable exposure levels.

Large Scale Testing – Further studies should be conducted to evaluate the impact of large-scale leakage, fire and explosion due to ammonia.

Bunkering - Establishing requirements and standards to cover ammonia to be safely bunkered, ensure fuel quality, bunkering procedures and development of bunkering infrastructure are also key.

6 Investment Readiness - Economic Analysis

The economic viability of the ammonia fuelled bulker was analysed against an LNG fuelled bulker, of the same specifications and size, to evaluate its performance on a financial basis.

6.1 Considerations

The Capital Expenditure (CAPEX) towards building these two vessel types, Operating Expenditure (OPEX) and fuel related voyage costs were taken into the analysis. It also examines how carbon pricing can influence the operation of these vessels.

Data used for the financial analysis are based on Lloyd's Register-UMAS publication – 'Techno-economic assessment of zero-carbon fuels' (LR-UMAS Report).

Total Cost of Operation The economic viability, defined as the Total Cost of Operation (TCO), is the sum of the additional costs involved for both LNG and ammonia fuelled options. The TCO is a function of the fuel-related voyage costs, the capital investment costs due to the new engine and fuel storage system and the impact on revenue due to additional space requirements of the fuel storage (1).

Impact due to additional space requirements for fuel storage for ammonia fuelled vessel and LNG fuelled vessel has been equalised in this case by assigning the same fuel capacity and tank locations.

OPEX and Voyage Costs - The primary driver for competitiveness would be the costs attributable towards fuel. Although it is difficult to have absolute certainty about how fuel costs will evolve, an understanding of potential upper and lower ranges and how sensitive the TCO is to changes in fuel prices will help in managing any risks and exposure from an economic perspective.

Scenarios	Biofuel price	Renewable electricity price	Natural gas price	Carbon price
1	Lower	Lower	Lower	Yes
2	Upper	Upper	Upper	Yes

Energy source price scenarios – Fuel price projections for ammonia as identified in LR-UMAS Report were applied in the analysis (1 pp. 11,43). The Upper and Lower bound fuel prices from two scenarios (Scenario 2, 4) from the report, that considers carbon pricing are taken into this analysis. The scenarios were defined by varying the prices of the primary energy sources.

Fuel densities (1 p. 59), operational and economic specifications (1 p. 61) as detailed in LR-UMAS Report were used.

CAPEX - CAPEX differential for both ammonia fuelled and LNG fuelled options attributable to onboard technology costs, engines, fuel tanks and associated machinery were estimated based on LR-UMAS Report (1 p. 60).

Carbon Emissions - In establishing the CO_2 emissions for each propulsion option, the non-dimensional conversion factor C_F between fuel consumption and CO_2 emissions based on the carbon content of the respective fuel as referred to in IMO guidelines MEPC. 212(63) was used. The equivalent carbon emissions corresponding to the consumption of each type of fuel was calculated based on these emission conversion factors.

Carbon Pricing considerations – The possibility of a carbon pricing scheme being implemented in the marine industry is taken into consideration in the analysis.

6.2 Results

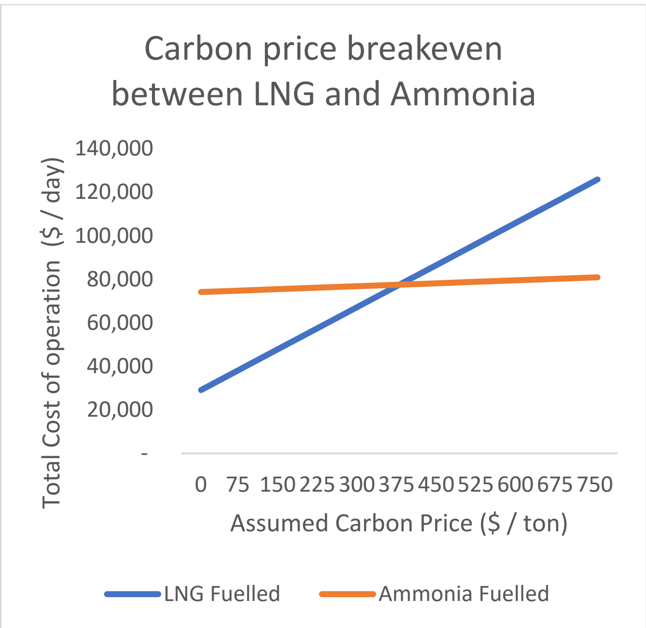
CAPEX Impact - The additional costs involved in building both ammonia fuelled and LNG fuelled options with fuel tanks, modified engines and fuel supply systems was estimated. Although significant when compared to the cost of building a conventional HFO fuelled vessel, this additional CAPEX forms a small element when the total cost of operation for ammonia/LNG fuelled vessels is considered.

Fuel related voyage costs – The fuel related voyage costs were estimated for both ammonia fuelled and LNG fuelled vessels under lower bound energy source price scenarios (Scenario 1) and upper bound energy source price scenarios (Scenario 2). These costs for ammonia fuelled vessel are considerably higher than the LNG fuelled vessel. It is due to ammonia (18.6 MJ/kg) having a lower energy content than LNG (50.02 MJ/kg) and its higher fuel price.

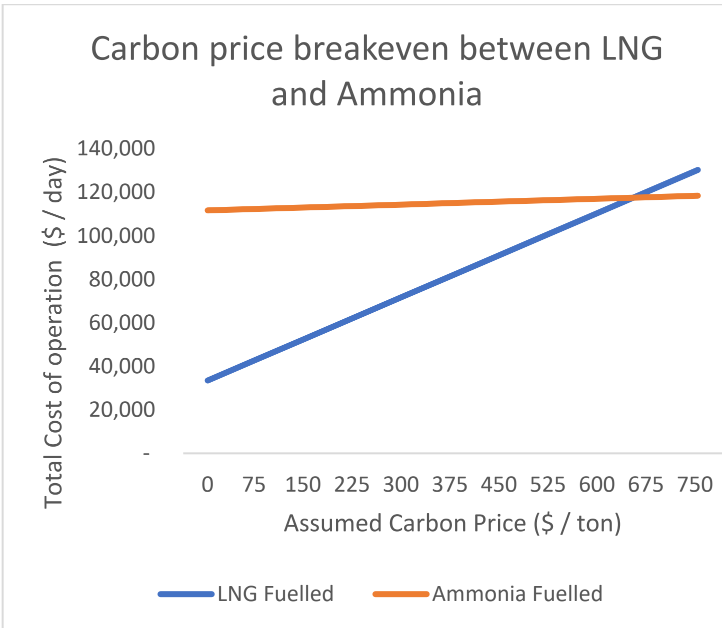
Total Cost of Operation - Higher fuel related voyage costs associated with ammonia fuelled vessel contributes to a higher total cost of operation when compared to LNG fuelled option, making it financially unfavourable in current market conditions. This is in line with Lloyd's Register's findings in an earlier study which concluded that achieving net zero is an 'OPEX not a CAPEX challenge' (16).

Carbon pricing considerations - The graphs indicate the total cost of operation for both ammonia fuelled and LNG fuelled vessels under both energy source price scenarios plotted against an assumed range of possible carbon prices.

Scenario 1
Fuel Price Projections based on Lower Bound values



Scenario 2
Fuel Price Projections based on Upper Bound values



The lower bound fuel price projections show the breakeven point to be in the region of a carbon price point of \$375/ t. The ammonia fuelled vessel would be commercially competitive than the LNG fuelled vessels when the carbon price is at or above this level.

For the upper bound fuel price projections for ammonia, the required carbon pricing would be much higher to obtain a competitive position for the ammonia fuelled vessel.

Carbon Pricing/Equivalent - The results suggest that fuel price being the key factor, higher fuel prices would require higher carbon pricing or equivalent to make the ammonia fuelled vessel competitive when compared to the reference vessel.

Applying a carbon price to the end fuel means that the economic case is more viable by making the fossil-based fuelled ships less attractive.

A tailored investigation is recommended for each ship type/size because of the different technical and operational specifications that may lead to different conclusions.

7 Community Readiness

In addition to investment and technology readiness, community readiness is an important driver of change. Lloyd’s Register-UMAS publication – ‘Techno-economic assessment of zero-carbon fuels’ discusses these challenges in detail, following text has been adapted from the report (1).

Life cycle emissions perspective- The IMO initial GHG Strategy and any future IMO regulation is likely to be constrained to operational emissions from shipping. There are several energy sources that might be zero GHG in operation/combustion on a ship but have significant upstream emissions in production. Therefore, there is a material risk that by addressing the emissions from shipping, the problem is moved upstream to another sector (1).

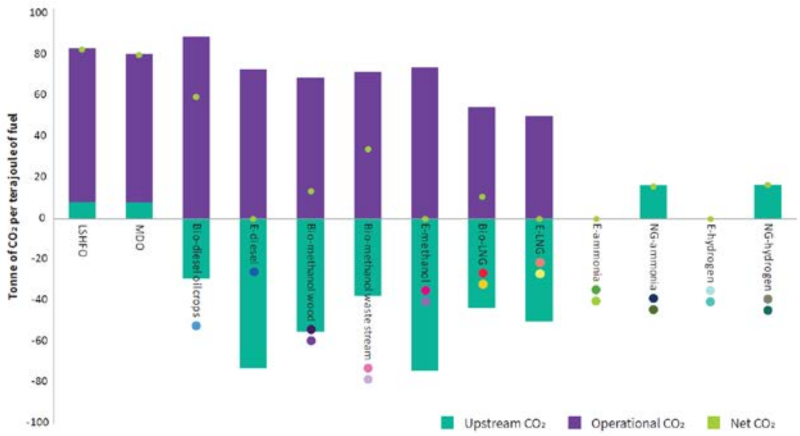


Figure 7 Upstream, operational and net CO2 emissions for various Zero Carbon Fuels (1)

Future fuels will be expected to meet not only GHG emission criteria, but also other air pollutant standards as well as contribute to broader sustainability criteria at regional and national levels. These broader criteria will increase acceptability to stakeholders as potential options for maritime applications given that they will neither have unintended impacts on local air quality, nor shift problem to an increase in upstream emissions (1).

Policies & Regulation - Another key aspect in the transition will be the development and implementation of strong international policy and regulations. Irrespective of the price uncertainties, the market will not drive the transition to zero carbon fuels as the price difference between fossil-based fuels and zero carbon fuels are significant (1).

8 Conclusion

Maritime decarbonisation is one of industry's key challenges for the coming decades. For the industry to achieve the targets set by IMO's greenhouse gas reduction pathways, vessels using zero carbon fuels should be entering service by 2030.

Application of ammonia as fuel reduces CO_2 emissions and it is being considered as a promising zero carbon fuel option. However, using ammonia as fuel poses safety, technical and commercial challenges.

The technical systems explored in the Newcastlemax case study demonstrate that many of the necessary technologies remains under development. The study emphasizes that key consideration will be for ammonia fuelled vessel to achieve an equivalent level of safety as a conventionally fuelled vessel. To attain that, safety challenges associated with its application should be addressed using a rigorous and robust risk assessment methodology and should lead to the development of an inherently safe design.

Commercially, the higher fuel related costs for ammonia fuelled vessel, due to its lower energy content and higher price position, makes it less competitive when compared to the LNG fuelled option. Fuel price being the key driver, the analysis brings us to the significance of carbon pricing/equivalent in making ammonia fuelled vessels competitive to operate.

Furthermore, community readiness would be an important driver of change and would influence the adoption of ammonia and other zero carbon fuels.

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Having joined LR in 2006, Sobhith has worked globally in LR offices in Korea, London and Singapore, where he is currently Team Lead - Engineering. He has been involved in multi-functional services including design appraisal, survey, environmental solutions and gas technology.

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