GSP AMMONIA-POWERED TANKER PILOT

Green Shipping Programme

equinor

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Executive Summary

The international shipping industry carries around 80% of world trade flows and is responsible for around 3% of global greenhouse gas (GHG) emissions annually. The initial International Maritime Organization (IMO) GHG Strategy, for reducing GHG emissions from ships, was adopted in 2018. The strategy includes an ambition to reduce the total annual GHG emissions from international shipping by at least 50 % by 2050, compared to 2008 levels.

In June 2021, the IMO introduced extensive new carbon dioxide (CO_2) regulations applicable to existing ships: the Energy Efficiency Existing Ship Index (EEXI) addressing the technical efficiency of ships; the Carbon Intensity Indicator (CII) rating scheme addressing the operational efficiency; and the enhanced Ship Energy Efficiency Management Plan (SEEMP) addressing the management system. In addition, the IMO is discussing an enhanced ambition level for 2050 as the goal at the time of writing (spring 2023) is not aligned with the 1.5°C goal in the Paris Agreement.

In parallel the European Commission has launched the "Fit for 55" package. With proposals intended to reduce the EU's total GHG emissions by 55% by 2030, aiming for net zero by 2050. The proposals will impact the maritime sector through a carbon price on emissions (included in the EU Emissions Trading System); GHG intensity limits imposed on energy consumed onboard (FuelEU Maritime Initiative); and taxation reforms that remove tax exemptions for marine fuels (Energy Taxation Directive).

Equinor launched climate ambitions for maritime activities in 2020 that address our own maritime activities and our role as supplier of fuel to the maritime sector.

As a buyer and user of fuel in the maritime sector, Equinor's current ambitions are:

- By 2030: Halving maritime emissions in Norway compared to 2005 emissions.
- By 2050: Halving global emissions compared to 2008 emissions.

At the time of writing, these ambitions are in line with the goals set by the Norwegian authorities and the International Maritime Organisation (IMO) for global shipping.

As a supplier of fuel to the maritime sector, Equinor's ambitions are:

- By 2030: Escalate the production and use of low-carbon fuels.
- By 2050: Strongly increase production and use of zero-emission fuels.

The decarbonisation of large ships in deep-sea segments is critical for achieving the IMO ambitions. Blue and green ammonia are promising fuels for zero-emission ocean transport. It is technologically feasible, and there is comprehensive industry experience in handling and transporting ammonia at sea. In addition, a safety handbook developed in the Green Shipping Programme (GSP) and class rules are available for effective design and approval, and engine manufacturers have come far in testing engines.

The GSP pilot draws on short-sea experience with low-carbon fuels like LPG and LNG to explore their potential use for ocean transport – with all key players in the value chain involved. Equinor, as an active global charterer in the shipping market, with approximately 2,500 yearly voyages and close to one hundred chartered tankers, is heading up the pilot study. The pilot is a key step towards potentially chartering a dual fuel ammonia vessel.

The pilot study is building on available documentation, with emphasis on operational safety, on-board storage systems integration and bunkering infrastructure. The study aims to improve the decision basis for realising an Equinor-chartered ammonia-powered tanker. This is assessed through investigating the (technical and economic) applicability of implementing ammonia-eligible engines, fuel- and bunkering-systems on a large generic tank ship design (newbuild), understanding operational safety aspects, de-risking key elements of the design and identifying barriers.

The starting point for this study is a typical Aframax tanker specification that Equinor would charter for new dual fuel vessels, but the main ammonia related design considerations will be valid for a general tanker of both larger and smaller sizes, including clean product tankers.

The main activities and results from the pilot study are summarised in the following:

Safety considerations for ammonia powered vessels

A mapping of available documentation for technical implementation and safety considerations for ammonia-powered vessels is conducted, resulting in an overview of technologies and technology providers, maturity levels, safety aspects, costs, rules, and regulations.

There is an elevated level of maturity related to ammonia production, storage, and transport infrastructure. With increased production and new ammonia applications, it will be important to build on this experience.

The maritime industry has experience with transfer and carriage of ammonia in gas carriers and as a refrigerant, but not as a fuel. The latter will impose new challenges related to safe bunkering, storage, supply, and consumption.

The following hazardous properties of ammonia need to be understood and controlled; flammability, causticity and toxicity, the latter being the most critical to control. Historically, large, catastrophic accidental releases of ammonia have been rare, and those that happened were preventable with safe design and good procedures.

To ensure safe handling, the ammonia production industry has put in place strong chemical process risk management systems. An important principle applied when defining control measures is their efficiency hierarchy, Hazard isolation, Hazard reduction and engineering controls.

One of the main risks reducing measures is to handle ammonia in a fully refrigerated form to a large degree as possible, in the value chain.

Onboard implementation

The pilot study evaluates the requirements for onboard fuel storage, fuel supply system, and fuel conditioning system for Ammonia fuelled tankers. The implications of these requirements on ship design, such as heavier fuel tanks, are assessed. A new design draft is suggested to accommodate the larger tanks, which may reduce cargo capacity in certain conditions with limited draft. The increased power demand due to the new design draft at the design speed is approximately 3% but could be optimised with optimising the vessel design.

For a sailing distance of 15,000 nautical miles at 13 knots speed, a larger fuel storage capacity, of 6,000 m^3, is required due to the lower energy density of ammonia compared to conventional fuel. The recommended configuration includes two 3,000 m^3 type-C fuel tanks located on deck with fully refrigerated low-pressure ammonia storage, which reduces safety risks and lowers tank costs. Special considerations for material selection of the fuel tank should be made due to the stress corrosion cracking risks of ammonia containment.

A reliquefication unit is necessary to control the pressure and temperature in the fuel tank, which can be used during bunkering operations if a vapour return line is not available. A thermal oxidiser unit serves as a backup solution.

The fuel gas supply system will resemble the LPG fuel supply system, with low-pressure and high-pressure sides. The low-pressure side consists of fuel tanks with submerged pumps delivering liquid ammonia to the high-pressure side located inside the fuel preparation room increasing the pressure as required for main engines. Tank connections must meet specific requirements.

An Ammonia Release and Mitigation System (ARMS) is mandatory for all marine vessels using ammonia as fuel to limit the ammonia concentration in the release. Development is underway with a goal to have a system commercially available by the end of 2023.

Engine manufacturers are developing ammonia marine engines, with the main challenge being achieving proper combustion with control of NH3 and N_2O slip, while reducing pilot fuel usage. It is anticipated that ammonia engines for marine applications will be ready by 2025. While ammonia firing boilers have not been utilised in the maritime industry to date, testing of boiler performance using ammonia is currently underway.

The report also provides detailed requirements for piping, engine exhaust systems, nitrogen usage, gas/ventilation systems for fuel tanks, fire safety measures, and control monitoring and safety systems. These requirements ensure safe and reliable operation of the fuel installation, including leak detection and alarms, automatic fuel supply shutdown in case of faults, maintenance of propulsion in the event of single failures, and timely restoration of propulsion power. Manual intervention options are also provided for operators.

Bunkering risk and mitigation for tankers

For the Aframax tanker case the most flexible and cost-efficient option is to bunker with a Ship-To-Ship transfer from a gas carrier or dedicated ammonia bunker vessel. Based on current industry experience and knowledge from LNG bunkering and ammonia cargo operations, an outline of bunkering procedure and required safety barriers is presented.

Safety standards and regulations for bunkering of ammonia are yet to be fully established but the following focus areas are highlighted for further standardisation work:

- Use of risk assessment and Quantitative Risk Assessment (QRA) for dispersion analysis

- Automated operations to minimize human factors during transfer authorization, purging & gas freeing sequences (sequential automated steps, valve position monitoring, interlock, permissive, etc.).
- Interface standardisation to avoid misuse of adaptors.
- Tailor made check list integrated to Standard Operating Procedures for pre/post bunkering steps.
- Proper NH_3 detection technology selection to ensure reliable and early leak detection associated with automatic and quick isolation.
- Ammonia leak consequence mitigation practices, including water curtains and first aid measures "Dos and don'ts".
- Provide a working environment for always free of ammonia scent (to keep early warning by smell as efficient as possible)
- Tailor made training program for operators (initial and continuous) including theoretical & practical steps with performance assurance process (written exams, certified senior operator as companion for competence final validation).
- Safety leadership program to ensure active supervision of operational discipline.

Well to wake carbon footprint and fuel cost analysis

Two different cases for energy cost was defined to show the sensitivity on fuel price by the energy prices (gas and electricity cost) using historical values from 2019 pre-covid/war (case 1) and values from 2022 (case 2).

The NavigaTE v.1.2 model [1] is used to estimate fuel production cost for low-carbon fuels like blue and green ammonia and e-methanol as these fuels currently have high focus in deep sea shipping. An important finding is that the marine gas oil (MGO) and very low sulphur fuel oil (VLSFO) costs differentiate by a factor of 2 between the cases, while the low-carbon fuels typically increase with a factor of 2.5 to 3.3. The increase of the liquefied natural gas (LNG) cost is about 4 times. Further, of the emerging fuels, blue ammonia is less sensitive to the increased energy cost.

The well to wake carbon intensity of blue and green ammonia (and e-methanol) fuels is assessed with an inhouse Equinor model. The analysis shows that both blue and green fuels can have a very low footprint in a Well-to-Wake perspective, but the footprint of electricity is key for green fuels and the footprint of natural gas and carbon capture rate is key for blue fuels. The Norwegian location-based footprint of electricity and natural gas from the Norwegian Continental Shelves combined with more than 95% capture rates results in a low footprint at around or below 10 gCO_2e/MJ. However, the actual certified footprint is essential when selling or buying low-carbon fuels and not the colour blue, green etc. (Furthermore, clear regulations for counting of recycled carbon used in e-methanol and other synthetic fuels production is required.)

The abatement cost is used to calculate the difference in emissions and fuel cost between the alternatives compared to a reference case of conventional fuel (VLSFO). In the following results from Case 1 is described.

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[1] Model developed by Maersk Mc-Kinney Møller Center for Zero Carbon Shipping /13/ .

Based on the fuel costs and footprint of the fuels, the abatement cost for switching to a low-carbon fuel can be calculated. Illustrating that even without taking the ship modification cost into account an abatement cost of about 300 USD/tonne of CO_2e on a TtW basis should be expected even for blue ammonia which is the most cost-efficient alternative. This can be compared to required ETS cost to break even with conventional fuels.

The Equinor ship cost model was used to compare the greenhouse gas (GHG) emissions footprints and the abatement cost for fuel switching and indicate the effect on the cargo transport cost including the capital expenditure (CAPEX) difference of the newbuilds.

Re-running the abatement cost calculation based on the Equinor ship cost model, the abatement cost on a TtW level increases as it includes the added investment for a dual fuel system. The TtW abatement cost shows that blue ammonia is the most cost competitive option compared to the reference case of approximately 350 USD/tonne CO_2e abated. Taking the current ETS price into account it shows a gap to be commercially attractive for the Case 1 cost level.

Green ammonia is the most cost efficient of the green fuels at 547 USD/tonne CO_2e. (E-methanol from point source carbon capture is even higher at 662 USD USD/tonne CO_2e.)

Case 2 represents higher energy cost levels showing even higher abatement costs and highlights the importance of maintaining fuel flexibility with a dual fuel option to switch to conventional fuel if energy prices spikes.

The abatement cost can be further reduced by optimisation of the ship design and implementation of energy efficiency technology. Due to the higher fuel cost, technologies that are not economically feasible when running on conventional fuels will be when running on blue and green ammonia. The effect of rotor sails was investigated and a significant reduction in abatement cost and more than 10% reduction in fuel consumption was estimated. Development and smart integration of energy efficiency technology will be key for newbuild ship design.

Switching to LNG only reduces the total WtW emissions with 11%, while switching to lower carbon fuel alternatives more than 75% reduction can be achieved. This can be further reduced by reducing the need for pilot fuel and shore power connections (Cold Ironing).

From an economic feasibility point, the introduction of low-carbon fuels for deep sea shipping seems feasible when viewing the required investment on the CAPEX side, however additional energy efficiency measures and optimal design of the vessel will be required to reduce operational expenditure (OPEX). The OPEX is significantly higher than for conventional fuels even with the lowest energy price option of blue and green ammonia and current ETS price. Additional incentives like Contracts for difference to close the gap between cost of conventional and low-carbon fuels will be required.

Key findings

Necessary safety, technical and market developments for ammonia-power operation is identified. The results should be applicable for a variety of ship segments in addition to crude and product tankers.

What we have learned

- Blue and green ammonia and e-methanol can significantly reduce WtW GHG emissions.
    - Actual GHG intensity in the value chain is key and must be certified.
- Blue and green ammonia gives more cost efficient decarbonisation than e-methanol.
    - Current carbon pricing (ETS) will not close the gap.
    - Contracts for difference are currently required for economic feasibility.
- Framework for safe design of ammonia fuel systems and bunkering is maturing.
    - Safe ammonia cargo handling is proven technology on gas carriers.
    - Bunkering guidelines should be developed based on LNG bunkering and ammonia cargo handling.
- Technically feasible to integrate a DF ammonia system on an Aframax tanker.
    - CAPEX comparable to LNG.
    - Sufficient range for deep sea trade with ammonia fuel.
    - Ship to Ship is a flexible bunkering option for first movers.
- Ammonia technology is under development.
- Energy efficiency and reduction of fuel consumption is key in newbuild design utilising low-carbon fuels.
    - Optimised hull design, onboard energy system, energy efficiency devices and wind assisted propulsion.
    - Tanker specific requirements and design optimization including optimised Inert gas system and electrical driven cargo pumps.

Way forward

- Optimised ship concept development.
    - Optimise energy efficiency and reduce fuel consumption.
    - Layout and ship arrangement.
    - Cargo operations (inert gas and pumps).
    - Shore power.
- Ammonia specific equipment development.
- Further de-risking of ammonia fuel handling.
    - Operators and crew training.
    - Water curtain barrier efficiency.
    - Liquid spill / spill to sea.
    - Risk analysis of bunkering process (Ship to Ship).
    - Synergy with Equinor ammonia PSV retrofit projects.

Together with the industry - bring the use of ammonia to the required safety levels for cost efficient decarbonisation of shipping!

Participants in the GSP Ammonia-Powered Tanker Pilot

A total of eighteen companies joined the Equinor-led pilot, contributing to new insight and sharing competence within their fields of expertise. A special thanks to the main contributors from DNV, Brevik Engineering, Yara and Altera, and to Grieg, Wärtsilä and Breeze Ship Design, who have worked hard to make this pilot study a success. Equinor and the contributors would also like to thank the Norwegian Maritime Authority for their interest in the pilot.

Abbreviations

ARMS	Ammonia Release and Mitigation System
ARU	Air Release Units
BECCS	Bio-Energy with Carbon Capture and Storage
barg	Bar gauge
BOG	Boil Off Gas
CCS	Carbon Capture and Storage
CII	Carbon Intensity Indicator
CSCF	Company Specific Carbon Footprints
DAC	Direct Air Capture
DF	Dual Fuel
EEOI	Energy Efficiency Operational Ship Indicator
EEXI	Energy Efficiency Existing Ship Index
EPA	Environmental Protection Agency
ESD	Emergency Shut Down system
ETS	Emissions Trading System
FGSS	Fuel Gas Supply System
GHG	Greenhouse Gas
GSP	Green Shipping Programme
GVU	Gas Valve Unit
HFO	Heavy Fuel Oil
IGC Code	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships Using Gases or Other Low flashpoint Fuels
IMO	International Maritime Organization
IOGP	International Oil and Gas Partnership
LCA	Life-Cycle Assessment
LGC	Large Gas Carrier
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LR	Long Range
(S)MCR	(Specified) Maximum Continuous Rating
MDO	Marine Diesel Oil
ME	Main Engine
MGO	Marine Gas Oil
MJ	Mega Joules
MRV	Monitoring Reporting and Verification
NCS	Norwegian Continental Shelf
NM	Nautical mile
ORC	Organic Rankine Cycle
PS	Point Source (CO_2 capture)
PSV	Pressure Safety Valve
RED	Renewable Energy Directive (EU)
RFNBO	Renewable Fuels of Non-Biological Origin
ROTTS	Port of Rotterdam
SCC	Stress Corrosion Cracking
SEEMP	Ship Energy Efficiency Management Plan
SGMF	Society for Gas as a Marine Fuel
SIGTTO	Society of International Gas Tanker and Terminal Operators
SMR	Steam Methane Reforming
TC	Time charter
TTF	Title Transfer Facility (Gas trading)
TtW	Tank to Wake
VFD	Variable Frequency Drive
VLSFO	Very Low Sulphur Fuel Oil
WHR	Waste Heat Recovery
WtT	Well to Tank
WtW	Well to Wake (WtT + TtW)

1 Introduction

The international shipping industry carries around 80% of world trade flows and is responsible for around 3% of global greenhouse gas (GHG) emissions annually. The initial International Maritime Organization (IMO) GHG Strategy, for reducing GHG emissions from ships, was adopted in 2018. The strategy includes an ambition to reduce the total annual GHG emissions from international shipping by at least 50 % by 2050, compared to 2008 levels.

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The starting point for this study is a typical Aframax tanker specification that Equinor would charter for new dual fuel (DF) vessels. Main particulars are listed in Table 1-1.

Aframax tankers are used worldwide for transport of crude oil including export from producing assets on the Norwegian Continental Shelf (NCS). Mongstad is one of the key terminals for crude export from Norway and is used as the base bunkering location for this case.

With the specified range, it is likely that a DF ammonia-powered tanker can operate mainly on ammonia with bunkering only at Mongstad while availability of new ammonia bunkering locations and green corridors is developed. Ship to ship bunkering is also considered as the most likely bunkering solution for larger vessels in the initial introduction phase of ammonia as a fuel.

The case is built on a potential newbuild Aframax tanker, but the main ammonia related design considerations will be valid for a general tanker of both larger and smaller sizes, including clean product tankers.

Table 1-1 Main particulars for a typical Aframax tanker chartered by Equinor

Length o.a.[2]:	252.80 m
Length b.p. [3]:	242.00 m
Breadth moulded:	44.00 m
Depth moulded:	20.80 m
Draft, design:	14.10 m
Draft, scantling:	15.20 m
Air Draft:	41.00 m

The main pilot study activities and outputs are summarised below:

- An Overview of technologies and technology providers, maturity levels, safety aspects, costs, rules, and regulations. Based on mapping of available documentation for technical implementation and safety considerations for ammonia-powered vessels.

[2] Length overall is the maximum length of a vessel's hull measured parallel to the waterline.
[3] Length between perpendiculars is the length of a ship along the summer load line from the forward surface of the stem, or main bow perpendicular member, to the after surface of the sternpost, or main stern perpendicular member.

- Analysis of on-board implementation of ammonia fuel tanks and systems for a generic, newbuild tanker ship design.
- Analysis of technical, safety and market barriers for bunkering of ammonia with reference to ongoing standardization/best practice initiatives.
- Identification of necessary safety, technical and market developments for ammonia-power operation. The results should be applicable for a variety of ship segments, but the analysis is primarily based on an operational case from Equinor's midstream activities. Explore governmental support opportunities.
- Well-to-wake carbon dioxide equivalent (CO_2e) emission analysis and fuel cost analysis for blue and green ammonia compared to a VLSFO reference case.
- Input for a best practice (recommended) tanker design for using ammonia as fuel.

2 Safety considerations for ammonia-powered vessels

2.1 Regulatory and policy framework for use of ammonia as a fuel

Regulations for handling ammonia as a cargo on gas carriers are established under the IGC Code[4]. However, ammonia is considered a toxic substance, and the IGC code prohibits the use of toxic cargo as fuel. The IGC Code is currently under revision in IMO, aiming for a new IGC edition in 2028.

Currently there are no international statutory standards beyond the IGF Code[5] "alternative design approach" for implementing ammonia fuel systems on ships. However, the development of guidelines for ammonia fuel is included in the extensive plan related to low-carbon fuels in IMO. This pilot study can draw on experience from marine transport of ammonia and the use of ammonia as refrigerant onboard. Also, DNV and other classification societies have issued initial class rules and guidelines for the use of ammonia as fuel.

The Society of International Gas Tanker and Terminal Operators (SIGTTO) is a non-profit organisation that represents owners of gas carriers and terminals. SIGTTO has developed guidelines and industry standards for handling of liquefied gases including ammonia.

The Society for Gas as a Marine Fuel (SGMF) is a non-governmental organisation (NGO) established to promote safety and industry best practice in the use of gas as a marine fuel. SGMF has established a work group on ammonia /8/.

The GSP has published a safety handbook for ammonia as a marine fuel giving a high-level overview of safety related properties of ammonia and discussing how the ship arrangement is affected by the ammonia fuel installation /5/.

2.2 Current practice for Ammonia transportation and storage

There is an elevated level of maturity in ammonia production, storage, and transport infrastructure because of the global use of ammonia in fertilizer production.

By volume, ammonia is among the top five chemicals produced and used worldwide. It is a key component in mineral fertilizer and essential for global food security. More than 180 million tonnes of ammonia are produced yearly, with approximately 20 million tonnes per year traded as merchant ammonia. Ammonia infrastructure already exists, with international shipping routes and ports worldwide capable of handling ammonia at large scale.

The onshore storage capacities of ammonia plants vary from 5 to 50,000 m^3. Liquid ammonia is transferred to cargo carriers with loading arms. Ammonia is normally transported by a selection of gas carriers up to large gas carrier (LGC) size 60,000 m^3. The vessels are designed for ammonia transportation, with cargo tank capacities between 6,000-12,000 m^3. The ships are like liquefied petroleum gas (LPG) carriers, but corrosivity, toxicity and reactivity are taken into consideration. Ammonia is normally transported in a fully refrigerated state, i.e., cooled down to -33.3 °C.

[4] The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)
[5] The International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)

2.3 Ammonia properties and hazards

Ammonia as fuel will impose new challenges related to safe bunkering, storage, supply, and use.

Under atmospheric temperature and pressure, ammonia is a colourless, toxic gas with a sharp and penetrating odour. Ammonia is hygroscopic, which means it has a high affinity for water. The basic properties of ammonia are listed below:

- Boiling temperature at atmospheric pressure: -33.3ºC
- Vapor pressure at 45ºC: 18 bar
- Liquid density at -33.3ºC: 0.68 t/m^3
- Flammability range 15-28%
- Autoignition temperature 651°C

The following hazardous properties of ammonia need to be understood to ensure appropriate control:

- Ammonia is mildly **flammable** and can generate moderate explosions. However, the explosivity window is narrow, the activation energy is relatively high, and the consequences of a cloud ignition are relatively mild, i.e., no critical pressure wave.
- Ammonia is **caustic** and can generate chemical burns. It can also corrode material such as copper or brass. Stress corrosion cracking (SCC) in vessels made of carbon steel needs to be avoided through design (pressurized or atmospheric). Extensive knowledge has been gathered among the fertilizer industry, and today the SCC degradation mechanism is well understood. Inherent safe design choices in construction materials or welded flanges etc. can significantly reduce possible exposure.
- Ammonia is **toxic**. In gaseous form it is lighter than air. However, due to its hygroscopic properties, released anhydrous ammonia will rapidly absorb moisture from air and form a dense and visible white cloud that may have a higher density than air. The greatest risk of harm is to employees and workers exposed to high concentrations closest to the release. Acceptable human exposure limits for ammonia are defined by legislation and are typically a function of concentrations and exposure time, ref. Table 2-1 from the US Environmental Protection Agency (EPA) Acute Exposure Guideline Levels /9/.

Of these three hazardous properties, **toxicity** is the most critical to control.

Table 2-1 EPA Acute Exposure Guideline levels

Ammonia 7664-41-7 Expressed in ppm

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

AEGL 1: Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.

AEGL 2: Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.

AEGL 3: Life-threatening health effects or death.

In some situations, a phenomenon called forced vaporization can occur. Ammonia at equilibrium under atmospheric pressure is liquid at -33,3°C. In this condition the vapor phase in the vicinity of the liquid pool is saturated with ammonia vapor. If a flow of gas such as nitrogen is blown onto the surface of that liquid pool, the equilibrium is broken. The vapor phase in the vicinity of the liquid is no longer saturated with ammonia vapor. The system will then try to go back to this equilibrium state by increasing drastically the vaporization rate, doing so, the liquid phase will rapidly decrease its temperature. Depending on the equilibrium gap generated by the nitrogen flow, the temperature decrease can reach down to -70°C. To minimize this phenomenon during purging/inerting operations, it is recommended to add an intermediate step with hot ammonia gas flushing to ensure that no liquid remains trapped in low point in the system before introducing nitrogen. Avoiding the possibility to trap liquid ammonia is also important to consider during the design phase.

Historically, large, catastrophic accidental releases of ammonia have been rare, and the known incidents could have been effectively prevented with safe design and good procedures. To ensure safe handling, the ammonia production industry has put in place robust chemical process risk management systems, i.e., Yara's efficiency hierarchy in Figure 2-1 below.

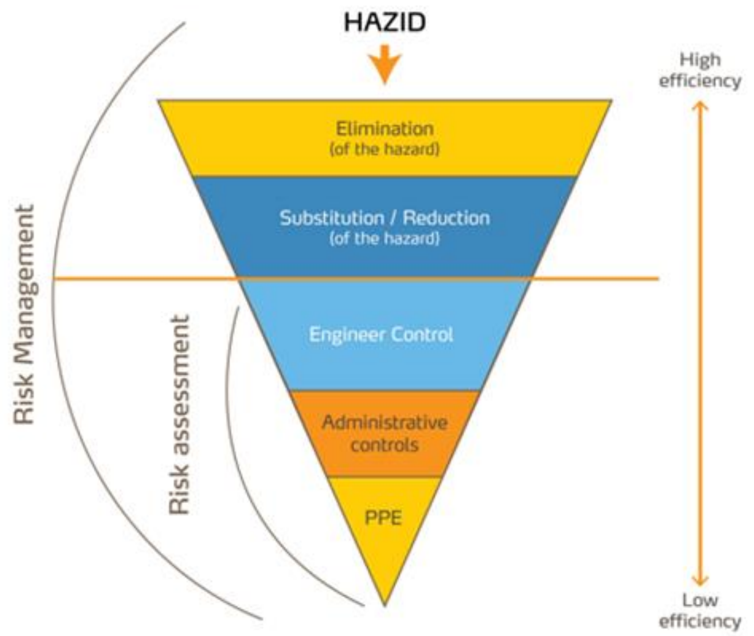


Figure 2-1 Yara risk control measures hierarchy principle

Applying Yara's risk control measures hierarchy principle to the maritime segment for ammonia fuel storage and bunkering operations, the following approaches are relevant for the technical design:

Hazard isolation/elimination: Ammonia storage and associated equipment used for the bunkering activity shall, as far as practical, be removed from possible external impacts, for example tank location requirements (as outlined in the IGF Code), to reduce the likelihood of a significant leaks affecting individuals outside of the ship and/or at the port. In addition, use of secondary confinement, in specific safety zones (such as pipe in pipe systems), is a very efficient mitigating measure for many potential leak consequences.

Hazard reduction: Liquid ammonia stored and handled in its fully refrigerated and atmospheric form is inherently safer than warm and pressurized ammonia. The initial flash occurring on the liquid phase release being much reduced in its cold state, significantly impacting the initial size and dispersion of the toxic cloud.

Engineering controls: Integrating safety features as early as possible in the design stages is the most efficient approach for managing safety, where a good balance between cost and safety level can be achieved. Fortunately, the long experience available in ammonia handling from onshore terminals provides a wide variety of safety solutions to select from.

For the overall risk management strategy, the maturity of the safety culture, driven by high class safety leadership and commitment from management, is paramount, as well as solid training programmes and active supervision.

3 Onboard implementation

3.1 New build design evaluation

Equinor has outlined the following key requirements in the newbuild specification for and ammonia powered Aframax tanker:

- Class notation: +1A, Tanker for Oil, E0, ESP, CSR, LCS, BWM(T), Clean (Design), VCS (2, B), Coat-PSPC (B, C), BIS, GAS FUELLED Ammonia, SPM, TMON
- Principal dimensions (max): LOA 250m; Breadth 44m; Scantling draft 15.2m; Ari draft 41m
- Deadweight: 109,000 to 115,000 tonnes
- Cargo capacity (100% filling): 128,000 m^3
- Service speed (min): 14.5 knots at design draft with main engine at normal continuous rate (NCR), including 15% sea margin and shaft generator engaged. Economy speed 13 knots in ballast and laden conditions
- Cruising range 15,000 NM in ammonia mode or back up fuel mode

An existing Aframax ship design from the Breeze design portfolio was selected as the basis for the technical evaluations for implementing an ammonia dual fuel system. A newbuild is assumed, but for this study the design implications are evaluated based on the existing design without redesigning the vessel.

Requirements for onboard fuel storage, the fuel supply system and fuel conditioning system are evaluated based on the class requirements for ammonia fuelled tankers.

Ship design implications of these requirements (mainly heavier fuel tank) were assessed and a new design draft (14.1m instead of 13.6m) was suggested. In the following sections, the terms old and new design refer to this iteration to comply with the ship design rules.

3.2 Ship Design

3.2.1 Main Particulars

See Table 3-1 for main dimensions and Figure 3-1 for the general arrangement of the Aframax tanker fitted with ammonia fuel tanks. The vessel is a single-decked, single-screw tanker for oil and products with transom stern, machinery and accommodation located aft and wheelhouse located above accommodation. It has double bottom and double skin within cargo tank region, straight line camber in main deck, and corresponding sheer and one (1) casing / funnel abaft accommodation.

The cargo tank compartment is subdivided into a centre section for cargo and wing sections for water ballast by double skin longitudinal bulkheads. The centre section is subdivided by five (5) transverse bulkheads and one (1) longitudinal bulkhead at the centre line. All bulkheads are plane type. The total number of cargo tanks is 12. Slop tanks are arranged aft of cargo tanks. The total number of slop tanks is 2.

Table 3-1 Main dimensions

Length o.a.:	252.8 m
Length b.p.:	242.0 m
Breadth moulded:	44.0 m
Depth moulded:	20.8 m
Draft, design:	14.1 m
Draft, scantling:	15.2 m

Air Draft:	41.0 m

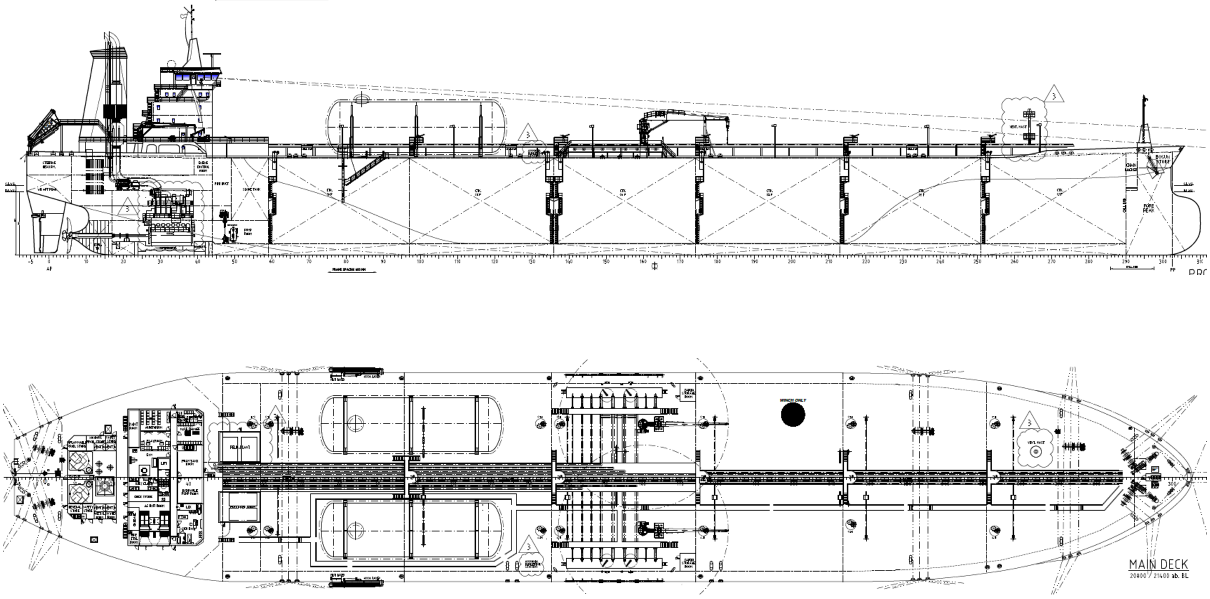


Figure 3-1 – General arrangement Aframax Tanker fitted with Ammonia fuel tanks

3.2.2 Ship resistance and fuel consumption

The speed and power curve for the new design draft at 14.1m is estimated and are presented in Figure 3-2 and Table 3-2. The increased power demand at design speed is approximately 240kW at nominal speed (13kn). The rated engine power being 12 MW at SMCR, the impact of this increase in power is within safe operating margin without increase of MCR. However important to consider when assessing the fuel consumption increase. The curves include 15% sea margin.

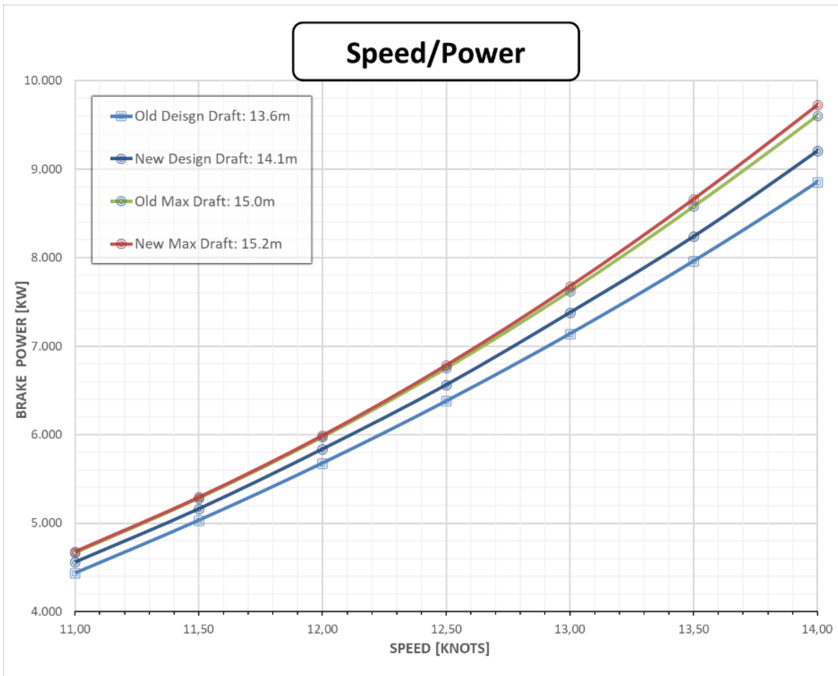


Figure 3-2 Estimated speed and power curve for new design draft at 14.1m

Table 3-2 – Required Power (kW) including 15% Sea Margin

Speed (knots)	*Old Design Draft 13.6m*	*New Design Draft 14.1m*	*Old Max Draft 15.0m*	*New Max Draft 15.2m*
11	4434	4558	4666	4680
12	5678	5835	5973	5992
13	7139	7378	7621	7678
14	8855	9204	9606	9724

The nominal selected design speed is 13 knots with a range of 15 000 NM. Fuel consumption is based on 12 MW SMCR, 10% pilot fuel and 15% sea margin and the operating profile, ref. Table 3-3.

Table 3-3 – Operational profile

Steaming laden	*Steaming ballast*	*Slow steaming laden*	*Slow steaming ballast*	*Port manoeu-vring*	*Port loading and waiting*	*Port discharge and waiting*	*Anchor / idle*	*Total round-trip*
23.3 days	23.3 days	2 days	2 days	0.5 days	1.7 days	1.7 days	1 day	56 days

For estimating the onboard fuel storage capacity, a remaining fuel margin at end of voyage of 15% is assumed. The required minimum level of ammonia can potentially be reduced below 15% to enable larger utilization of working volume in the fuel tank. The limiting factor is not to keep the tanks cold as for LNG, but rather practical operational limit for suction head for fuel pumps during sailing and ensuring required working volume for operation of reliquefication plant.

Ref. Table 3-4 and Figure 3-3 and for the required volume of the storage tanks depending on speed and sailing distance and including filling limit and operational margin. For 15 000 nm sailing distance at 13kn speed, a fuel storage capacity of 6000m^3 is required. For comparison, Equinor currently has DF LNG vessels of LR2 (product tanker of same size as Aframax) design on charter with LNG tank volume of 4300m^3.

Table 3-4 – Net fuel volume (m^3) with sailing distance

Speed (knots)	*5 000 nm*	*7 500 nm*	*10 000 nm*	*12 500 nm*	*15 000 nm*
13	2 170	3 151	4 131	5112	6092
12.5	2 075	3 003	3 931	4859	5787
12.	1 987	2 867	3 747	4627	5507
11.5	1902	2 735	3 568	4402	5235

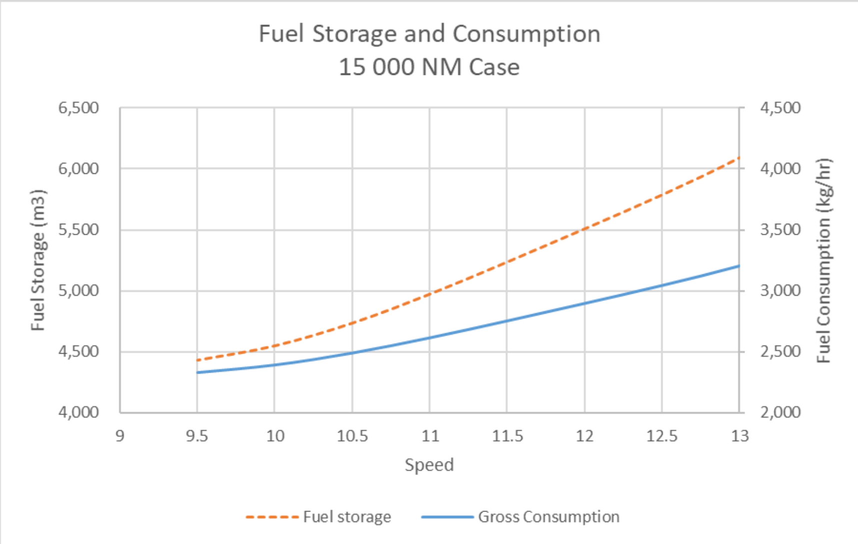


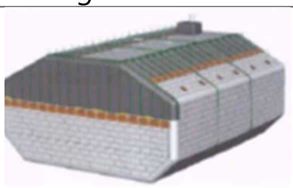
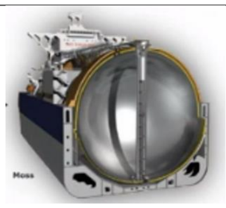
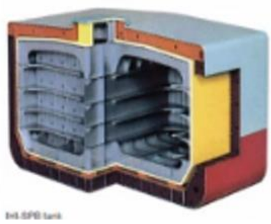
Figure 3-3 Fuel consumption and storage as function of speed

3.3 Fuel system configuration

3.3.1 Fuel tank integration

As per IMO classification of liquefied gas containment systems, there are three categories for independent tanks: Type A, Type B and Type C. These are differentiated regarding maximum design pressure and the requirement for secondary barriers (ref. Table 3-5).

Table 3-5 – IMO classification of liquefied gas containment systems

Independent tanks		
Type A	Type B	Type C
P<0.7bar	P<0.7bar	P>2bar
Full secondary barrier	Partial Secondary barrier	No Secondary barrier
Based on classical ship structure design rules	Based on first principle analysis and model tests	Pressure vessels based on pressure vessels code
 Prismatic	 Spherical (Moss)	 Cylindrical
	 Prismatic	 Bi-lobe

Some considerations need to be made for Ammonia fuel tank type selection:

- **Design pressure:** a margin from the operational pressure is beneficial to allow for some flexibility in the pressure management philosophy.
- **Secondary barrier:** the requirement for a full or partial secondary barrier will limit the flexibility for the fuel tank installation and impact cargo capacity.

A configuration with two 3000 m^3 fuel type C-tanks was investigated. The tanks are arranged between the accommodation area and the bunkering manifold on each side of the cargo piping. The tanks' location is based on the proximity to the engine room and the large unoccupied deck area. The tanks, despite their large size, do not hinder the intended operation of the vessel nor line of sight. However, more ammonia is required to achieve equal endurance as a VLSFO alternative, due to its lower energy density, resulting in reduced cargo capacity under certain conditions (draft limitation). The placement also contributes to the trim by stern, caused by engine room and accommodation placement in the aft part of the vessel. This is compensated for by filling ballast water to have even keel. A set-up with four smaller tanks was also considered to have a better weight distribution on the vessel. This solution was not selected due to increased cost and complexity of the fuel system as well as the risks of hindering the line of sight.

The last solution explored was with integrated type B-tanks. This would eliminate the challenges with the arrangement of tanks on deck, exposed ammonia piping and equipment which could be damaged, challenges with increased trim and global and local strength consideration. The downside with type B-tanks including secondary barrier is the reduced cargo capacity (approximately 7500 m3 or 6% reduction). This could be compensated for by increasing the beam by approximately 2m, but that would increase the total cost of the vessel and increase fuel consumption.

In the pilot case there is available area on deck for the type-C fuel tanks and these tanks in combination with fully refrigerated low pressure ammonia storage is the preferred solution.

3.3.2 Fuel tank design

Due to the corrosivity of ammonia, special requirements for the material selection of the fuel tank should be considered. The main risk is stress corrosion cracking of the containment. Reference is made to IGC Code Section 17.12 that lists the measures to be taken to minimize this risk. A high-level summary is provided below:

- Carbon-manganese steel made of fine-grained steel with limited yield properties can be used. Post weld heat treatment for steels with higher yield properties
- Water content in ammonia can help reduce the stress corrosion cracking and a minimum content should be ensured.
- Steels with more than 5% Nickel content shall not be used.
- Dissolved oxygen content in ammonia needs to be controlled with proper purging operations.

Two (2) cylindrical fuel type C tanks each with a capacity of 3000m^3 (ref. Table 3-6) are recommended to be installed on the main deck.

Tank calculations are performed in accordance with DNV regulations (2019), to meet the required fuel capacity. All calculations should be considered as estimates only, actual calculations should be performed by the tank supplier. The tank material selected for the calculation is a low-cost carbon manganese steel.

Table 3-6 Fuel tank main parameter summary

Parameter	*Value*	*Unit*
Length	38	m
Outside diameter	10,5	m
Volume	3000	m^3
Minimum thickness (cylindrical shell/dished ends)	16,7 / 19,5	mm
Weight	181	t

The operating pressure was selected to be as low as possible to reduce the risk of accidental release from high pressure ammonia. Another criterion to be considered is the compatibility with bunkering vessels which will most probably operate in fully refrigerated conditions. Therefore, an operating pressure close to 0 barg is chosen.

The implication of selecting a fully refrigerated concept is the requirement for boil off gas management system (see chapter 3.3.3).

To allow for some operational window and pressure accumulation due to heat ingress in the tank, a maximum operating pressure is to be set. This increase in pressure and temperature will cause the liquid to expand in volume which will reduce the loading limit to avoid overfilling the tank. The maximum loading limit is calculated as per DNV Pt 5 Ch7 Sc15.

At ambient pressure, the equilibrium temperature of ammonia is -33,3°C and ref. Table 3-7 for the loading limits as function of the maximum pressure (PSV set point). To maximize the utilization of the tank it is therefore recommended to select a PSV set point at 2 barg giving a loading limit of 93,53%.

Table 3-7 Loading limit at different PSV settings and loading temperatures

Loading conditions			*Loading limit at T&P as a function of PSV setpoint*					
Temperature	Pressure	Density	2 barg	3 barg	4 barg	5 barg	6 barg	7 barg
[°C]	[barg]	[kg/m^3]	[%]	[%]	[%]	[%]	[%]	[%]
-33.326	0	681.97	93.53%	92.12%	90.93%	89.89%	88.97%	88.13%

Each tank shall be equipped with two (2) PSV 100% capacity each to allow for redundancy and maintenance. These valves shall be mechanically interlocked, preventing both valves from being inoperable. The dimensioning relief scenario is vapours generated under fire exposure / fire case. Based on preliminary calculations a 350 mm outlet piping is required to allow for a safe release in such a scenario. Figure 3-4 show the operating window based on the setpoint, and the characteristic of the PSV.

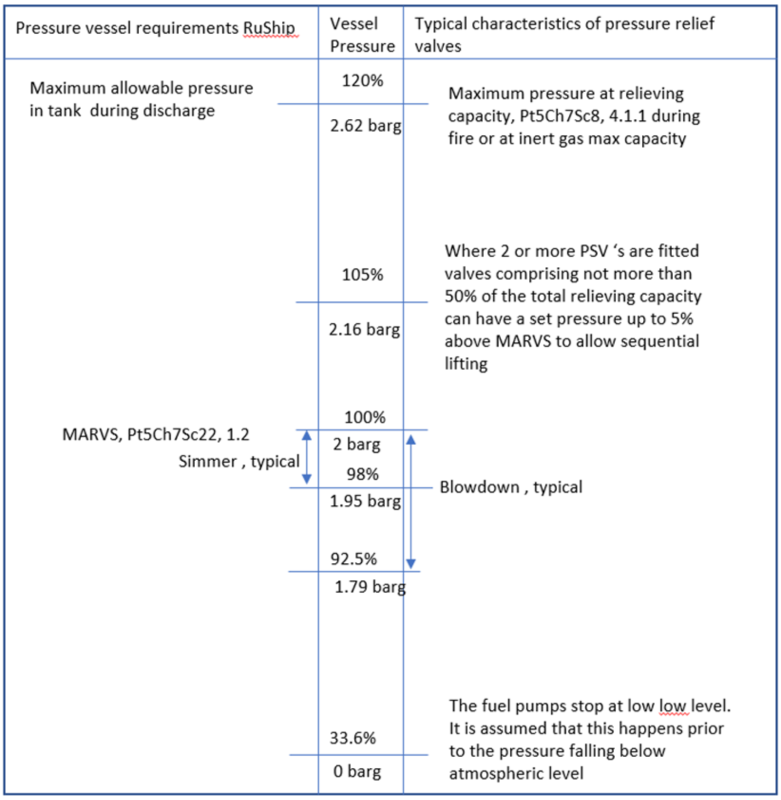


Figure 3-4 Diagram showing the fuel tank operating window

3.3.3 Boil off gas (BOG) management

Requirements for ammonia fuel tank pressure and temperature control are set in DNV rules Pt. 6 Ch.2 Section 14:

"4.6.1.1 Means shall be provided to keep the fuel tank pressure and temperature within their design range at all times including after activation of the safety system required by these rules. Systems and arrangements to be used for this purpose may include one, or a combination of, the following:

- *energy consumption by the ship (engines, gas turbines, boilers, etc.)*
- *re-liquefaction*
- *thermal oxidation of vapours (gas combustion unit)*
- *pressure accumulation."*

A system to manage the pressure is required as the selected tank design pressure is not sufficiently high to allow for pressure accumulation at ambient conditions. Based on two 3 000 m^3 tanks insulated with 200mm polyurethane foam installed on deck, heat ingress from ambient is estimated to 11,5 kW per tank and 23kW for 2 tanks assuming max outside air temperature of 38,5°C. The boil off gas rate is estimated to 61 kg/h at 0barg. This corresponds to a BOG rate of about 0.036% of the contained liquid during 24 h.

Reliquefication of boil off gas vapour uses a semi-open refrigeration loop of same principles as conventional cargo reliquefication units on LPG carriers however smaller in size and capacity. The smallest current commercial reliquefication unit from e.g., Wärtsilä has a net cooling capacity of 206 kW at 36°C seawater temperature and 1 bara suction pressure. This capacity is multiple times the needed capacity, but it will be used as basis for this study. The unit is designed for direct condensation against seawater and return of condensate back to the fuel tank(s). Unit weight is 27 metric tonnes, dimensions is given in Figure 3-5. The unit shall either be in a dedicated room or inside the fuel preparation room, both alternatives requiring active ventilation as per regulations.

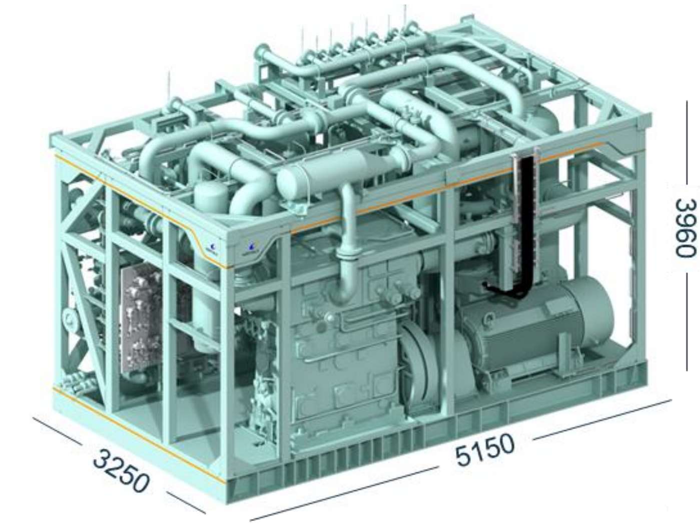


Figure 3-5 Typical boil off gas liquefaction unit (Wärtsilä). Dimensions in mm.

Oxidation of boil off gas vapour can be an option in combination with re-liquefaction system if a gas combustion unit/boiler is installed fulfilling the requirements in DNV Pt. 6 Ch.2 Section 14 [4.6.1.2].

Each unit shall operate independently from each other and there shall be two independent vapour lines from each of the two-fuel tank manifold together as two independent vapour headers running towards the re-liquefaction and boiler units.

3.3.4 Fuel supply system

Currently, the IGF code does not apply for any other gases or low flash point fuels than LNG, however there is an opening for other gases or low flash point fuels through Clause 2.3 Alternative Designs. DNV Pt.6 Ch.2 Section 14 Gas fuelled ammonia will be used for the design of the fuel supply system.

Deck tank(s) IMO type C with submerged pumps will function as fuel tanks and feed liquid fuel to the fuel gas supply system (FGSS). The FGSS interfaces to the main engine for liquid supply, liquid return, and engine vent. FGSS operation and control will be interfaced to the ship control system. The FGSS will to a large extent resemble the Wärtsilä proven systems for LPG liquid fuel supply system. The fuel system will be divided into one low pressure side and one high pressure side where the low-pressure side comprises the fuel tanks with deep well pumps sending liquid ammonia at pressures in the range of 21 – 24 barg to the high-pressure side. The high-pressure side located inside the fuel preparation room comprises both the fuel treatment and fuel return system. All tank connections (piping and instruments) will be inside a tank connection space, see DNV Pt. 6 Ch.2 Section 14 Paragraph 3.3.2 for requirements.

Figure 3-6 present a generic fuel flow diagram with ARMS.

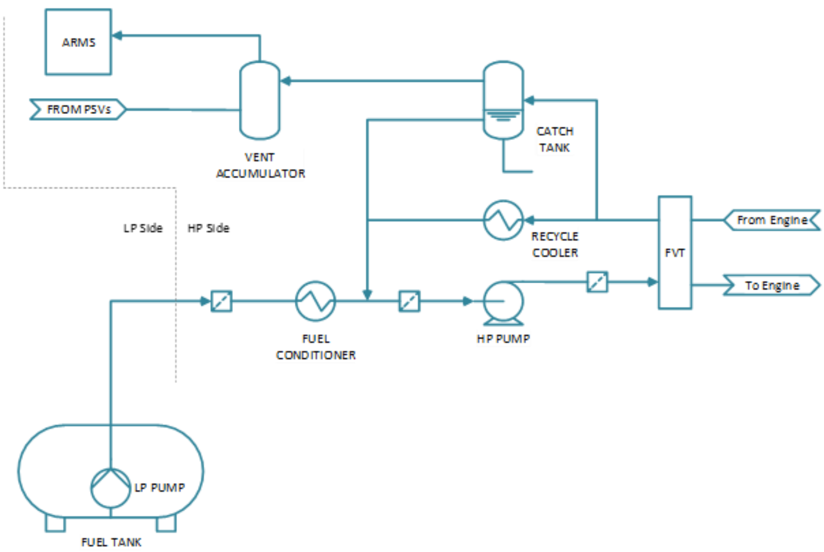


Figure 3-6 Generic fuel flow diagram w/ARMS

FGSS operation and control will be interfaced to the vessel's control system and fuel flow regulation will be via pump VFD control (ref. Table 3-8). Essential utility for the ammonia fuel system will be the Nitrogen supply system, the ship will not be allowed operating on ammonia without a fully functioning nitrogen system. Hence this system should be fully spared on essential equipment (see chapter 3.6.3).

Table 3-8 – FGSS main equipment

Fuel Tank	2 x 3050 m3 (gross capacity)
LP Pumps	Deep well pumps, two in each tank where one is in operation and one in standby.
Fuel conditioner	One Plate Heat Exchanger to adjust the temperature to correct level by heat exchanging with glycol / water mixture.
HP Fuel pump	Two pumps, one in operation one in standby
Recycle cooler	One Plate Heat Exchanger used to cool down the returning flow from the Fuel Valve Train (FVT).
Catch tank	Liquid collection tank to recover liquid fuel from the fuel lines after shutdown, fuel change or ESD

3.3.5 Vent, collection, and release system

As per requirements, an Ammonia Release and Mitigation System (ARMS) is required on all marine vessels using ammonia as fuel. The requirement is definite and dictates that any releases shall not have ammonia concentration exceeding 30 ppm[6]. There are several known principles that may offer ARMS functionality (ref. Figure 3-7), but no system is yet commercially available for marine installation. Absorption/scrubbing with water or an acid solution is frequently used onshore but adds a logistic element not desired on a ship. Another promising alternative is oxidation of the releases where ammonia is oxidized to water, nitrogen, and nitrogen compounds. The ARMS regardless of the principles shall collect ammonia from piping and engine during purging or draining operations, handle releases from safety valves on

[6] Maximum normal operation discharge limit proposal to increase to 300 ppm (from vent mast) in 2023 DNV Rules.

piping system (not safety valves on fuel tanks) and any other operational releases. Examples of ammonia release handling systems is illustrated in Figure 3-8.

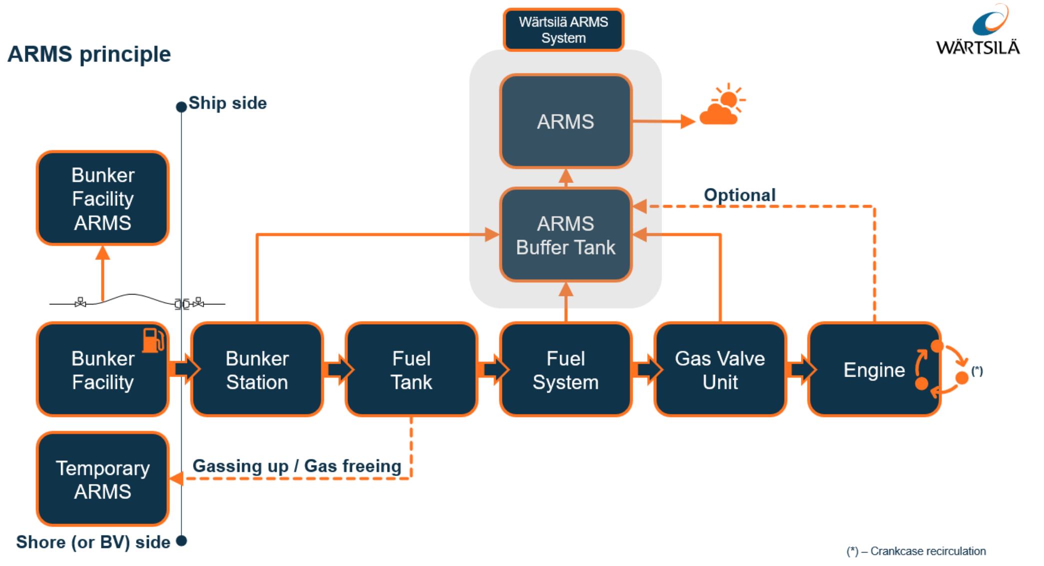


Figure 3-7 ARMS principle

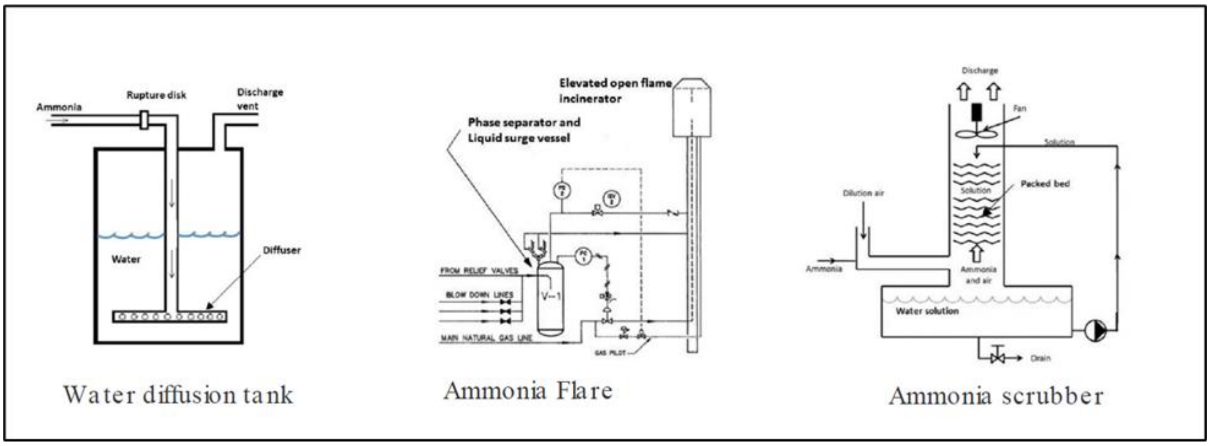


Figure 3-8 Examples of ammonia release handling

3.3.6 Bunkering Arrangement

The fuel bunkering system will preferably be located near the fuel storage tanks on open deck area and should at least have the following features:

- Control and monitoring of bunker operation shall be possible from a safe location where tank pressure, tank level and overfill alarm is easily available to monitor.
- A water spray system (water curtain) designed to limit the spread of ammonia vapour in case of any leakages occurring. All possible leakage points at the bunkering station shall be covered.
- Remote start of water spray pumps as well as remote operation of any normally closed valves shall be in a readily accessible position that is not made inaccessible in case of fire or leakage of toxic gases in the areas to be protected. Further, remote operation of water curtain system shall also be available at the bunker station control platform.

The bunker lines are without secondary enclosures[7] and shall be drained after bunkering either to fuel tanks or bunker vessel. Drainage must also be possible during ESD. When not in operation the bunker system shall be drained and purged with nitrogen.

The bunker manifold shall be equipped with dry-disconnect couplings and break-away devices protecting the transfer system from overstressing in case of drift-off, ref. Figure 3-9.

The bunker station shall have the option of bunkering with vapour return to shore/bunker vessel as well as being able to bunker without vapour return. Bunkering without vapour return will still be possible thanks to the over capacity of the BOG reliquefication unit (see chapter 3.3.3) but will limit the loading rate to about 600 m^3/h.

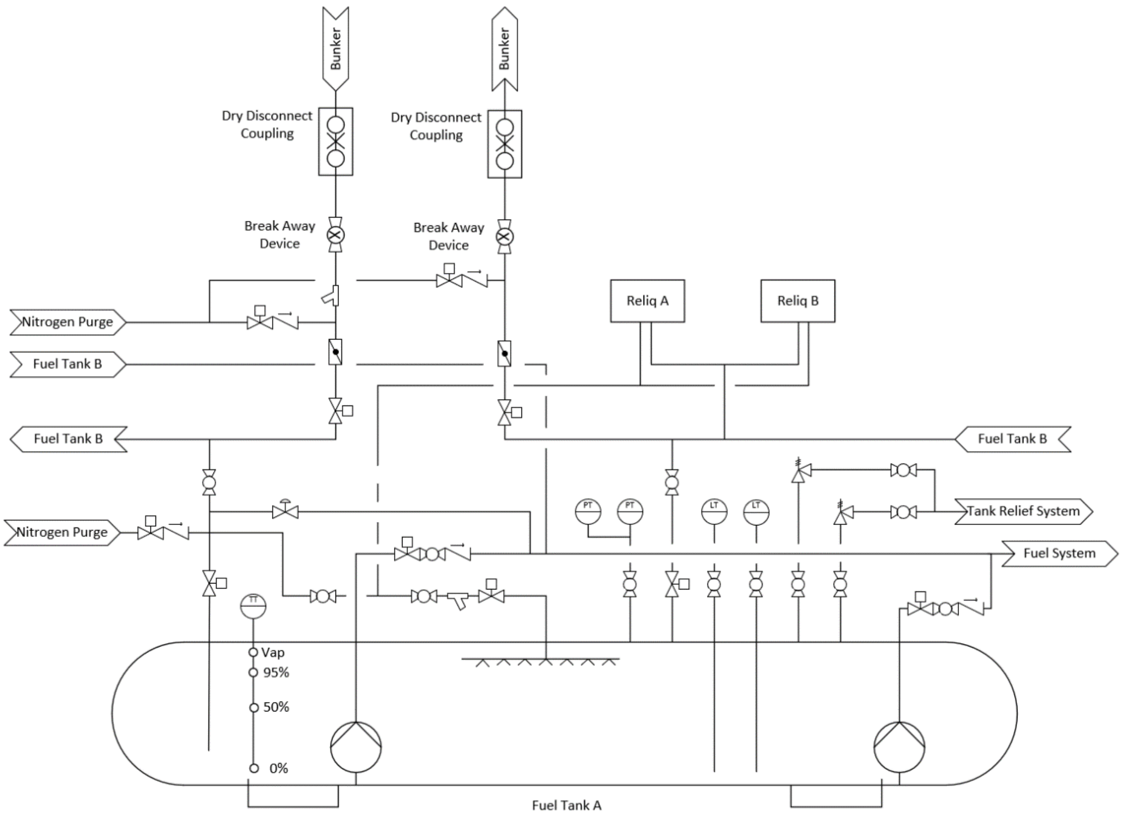


Figure 3-9 Bunker manifold and fuel storage

3.4 Engine Technology and Machinery Configuration

Ammonia marine engines are developed by several engine manufacturers. The main engine manufacturers are listed below with a status and timeline of their technology development. It is foreseen to have Ammonia engines for marine application ready by 2025, ref. Figure 3-10.

[7] Bunkering lines are proposed to be required to be contained in secondary enclosure from 2023 DNV Rules, aligning with IGF Code 2024 update.

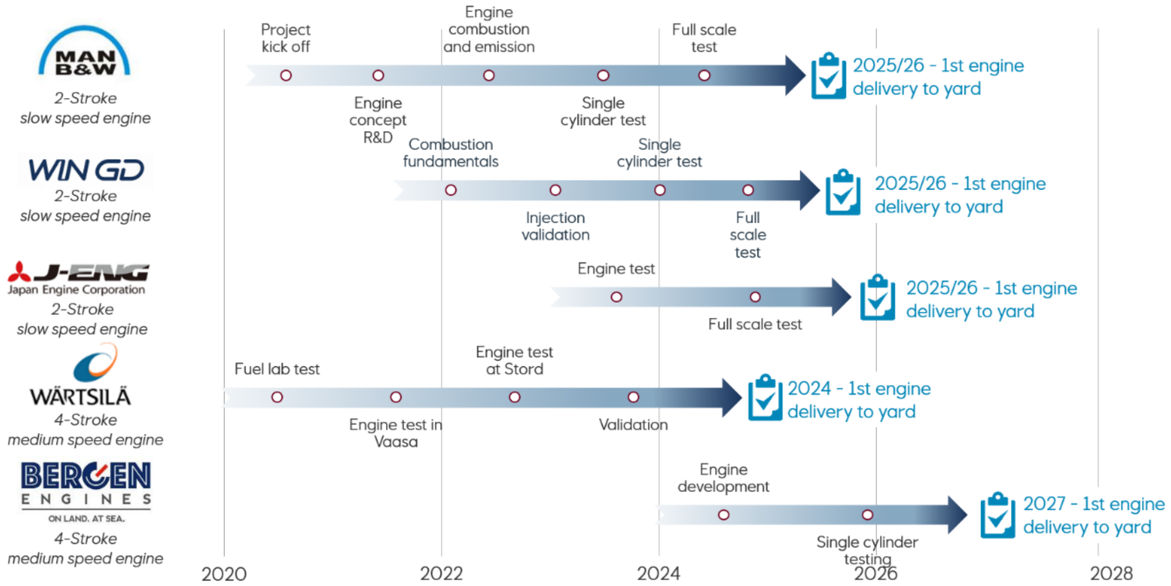


Figure 3-10 – Timeline for technology development of ammonia marine engines

3.5 Boiler and Inert Gas Generator

Till date, ammonia firing boilers has not been applied in maritime industry but in September 2022, Alfa Laval received the approval from Danish authorities for testing with ammonia at its test facility. The setup includes a double-walled ammonia tank at a safe distance from other fuels, as well as double-walled piping with encapsulated welds for all pipes to and from the centre. These barriers reflect the safety measures that will likely be required for ammonia as fuel onboard. As a starting point, ammonia boiler system will be designed based on the well proven dual fuel boiler for liquid fuel and LNG. Alfa Laval has delivered more than 300 DF boilers for the last 15 years.

In this concept design, the ammonia dual fuel boiler system will consist of:

- Boiler body (pressure part)
- Burner assembly
- Oil cabinet
- Gas Valve Unit (GVU)
- Oil supply system (can be common with engines or separate)
- Ammonia supply system (can be common with engines or separate)
- Ammonia leakage handling system for double wall piping (can be nitrogen blanket, under pressure ventilation, etc.)
- Control system
- Other appurtenances

Table 3-9 describes the functions of the boiler. Figure 3-11 shows the layout of an ammonia DF boiler.

Table 3-9 – Ammonia boiler functions

Function	*Description*
Heat (steam) generation	Basic operational mode of boiler. Ammonia as fuel supplied in gaseous state to boiler's GVU. Boiler's performance on ammonia to be verified during upcoming tests.
Boil-off gas management (tank pressure control by thermal oxidation)	Two ways of handling boil-off gas on boiler: BOG compression or free flow to boiler. Additional requirements will be applicable for the use of a boiler for fuel tank pressure conditions maintenance (see chapter 3.3.3.).
Gassing-up and gas freeing operation	This operational mode is related to tank emptying and filling before and after maintenance. Boiler will combust a mixture of ammonia and inert gas from tank. Main flame will be from liquid fuel. Size of boiler and burner capacity will be dependent on the gas flow (ref. Figure 3-12)
Handling of purge/vent gas with ammonia trace	Like gassing up/gas freeing, in purge gas handling, the boiler will combust a mixture of ammonia and inert gas with main flame firing liquid fuel. Gas mixture will likely be with low ammonia contents
Generating inert gas	For crude oil tankers, inert gas system shall be capable of delivering not more than 5% oxygen contents by volume[8]. Therefore, oftentimes flue gas from auxiliary boiler is used for generating inert gas onboard. Flue gas is extracted from the boiler by fans, after which it is drawn through a scrubber, where the gas is cooled and washed before being delivered to the cargo tanks (ref. Figure 3-13)

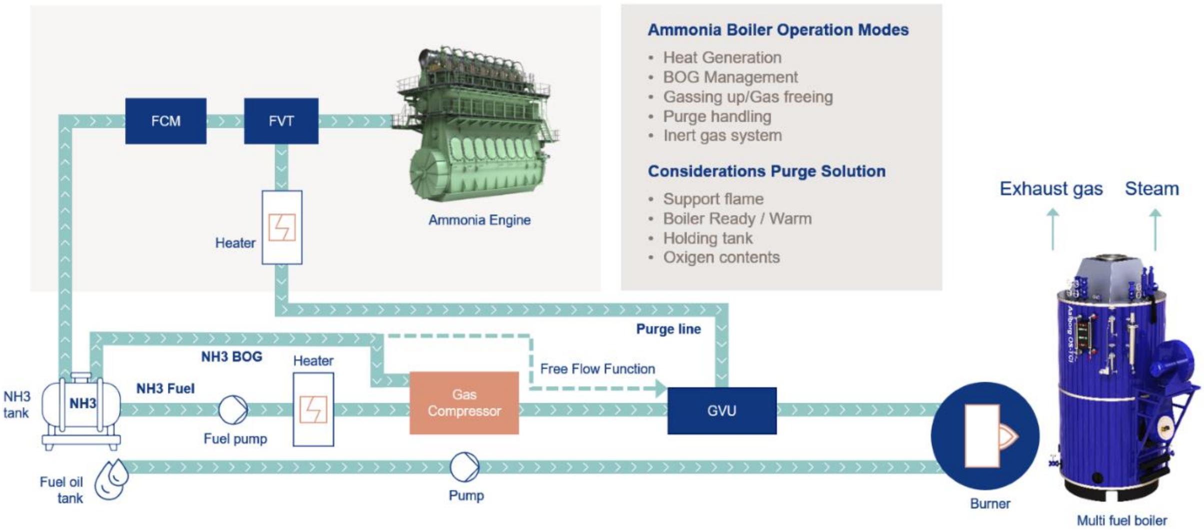


Figure 3-11 Schematic system layout of ammonia DF boiler

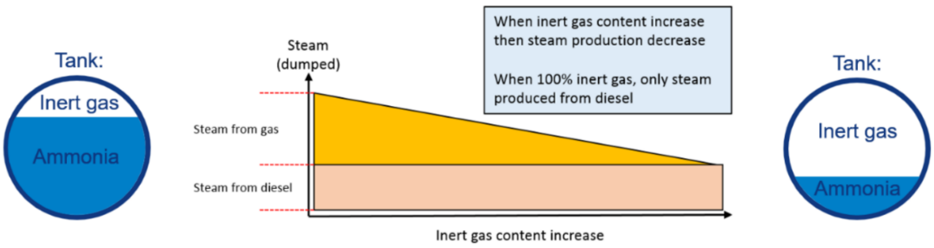


Figure 3-12 Steam output in Gassing up/Gas freeing operation

[8] International Convention for the Safety of Life as Sea (SOLAS 1974), as amended.

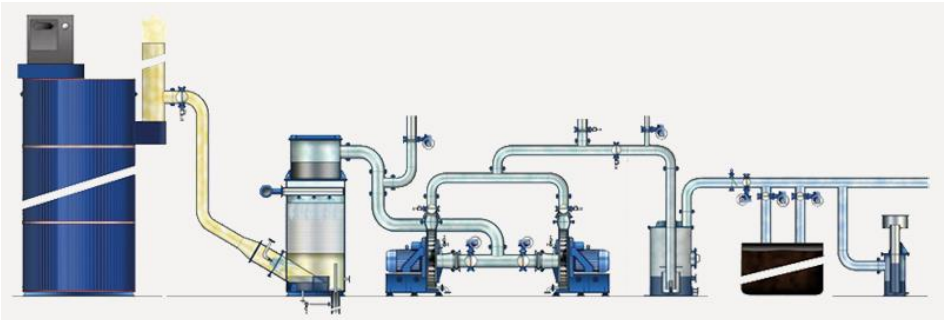


Figure 3-13 Inert gas system utilising boiler flue gas

3.6 Utility and safety arrangements

3.6.1 Piping

Piping containing liquid ammonia shall be protected by a secondary enclosure able to contain leakages, except for piping in enclosures able to contain leakages and fully welded bunkering piping with no fittings on open deck[9]. The material for the secondary enclosure shall be able to handle low temperature effects in case of an ammonia leakage. The secondary enclosure shall be designed according to DNV Rules Ship Pt 6 Ch 2 Sc 14 [5.1.4]. A vent pipe for the secondary enclosure shall be arranged.

The material for the fuel piping and secondary enclosure shall be designed for a minimum temperature of -55°C according DNV Rules Ship Pt 6 Ch 2 Sc 14 [2.1.1].

Piping containing gaseous fuel in enclosed spaces shall have a secondary enclosure to contain leakages. While open ended vent piping on open deck and fully welded bunkering pipes located on open deck may be arranged without secondary enclosures, in accordance with DNV Rules Ship Pt 6 Ch 2 Sc 14 [5.1.4.1].

3.6.2 Engine Exhaust System

The exhaust system shall be designed in accordance with DNV Rules Ship Pt 6 Ch 2 Sc 14 [5.5].

Unless exhaust systems are designed with the strength to withstand the worst case over pressure due to ignited gas leaks, explosion relief systems shall be suitably designed and fitted.

Combustion machinery shall have separate exhaust systems.

3.6.3 Nitrogen

Nitrogen is required for the purging of fuel bunkering and supply lines DNV Rules Ship Pt 6 Ch 2 Sc 14 Section [5.4].

Prior to maintenance, nitrogen shall be used to purge the equipment to be opened. The fuel tank shall be inerted with nitrogen before it is gas-freed for inspection. Where a nitrogen line is permanently connected to the fuel system, it shall be equipped with a double block and bleed arrangement and a closable non-return valve closest to the fuel system.

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[9] Secondary enclosure proposed required also for bunkering pipes from 2023 DNV Rules, aligning with 2024 IGF Code update for LNG.

3.6.4 Gas/ventilation systems for fuel tanks

Vapor return shall be arranged for bunkering operations in accordance with the IGC Code Ch. 5.6.3, and Ch 9.6.

A tank venting and gas freeing system for the fuel tank shall be installed in accordance with IMO IGC Code Ch.9. A vent mast shall be installed, in accordance with DNV Rules Ship Pt 6 Ch 2 Sc 14 [5.2.2] and [9.2.2]. When gas is discharged at the vent mast a visual and audible alarm based on the permanently installed gas detector shall be activated in the open deck area to warn personnel to stay away from the area where gas is discharged DNV Rules Ship Pt 6 Ch 2 Sc 14 [10.1.2] and [10.2.4].

Area classification and toxic zones shall be defined according to DNV Rules Ship Pt 6 Ch 2 Sc 14 [9]. In addition to the area classification required by the standards given in IEC 60079-10-1; 2008 Explosive atmospheres Part 10-1: Classification of areas - Explosive gas atmospheres and guidance, safety distances from toxic zones shall be taken into considerations when defining the layout of the fuel system.

3.6.5 Fire Safety

The overall fire protection system for the fuel and utility systems shall be in accordance with DNV Rules Ship Pt 6 Ch 2 Sc 14 [7]. The requirements listed are like the ones for LNG as a fuel. The fire safety requirements for fuel tanks, bunkering station areas, fuel preparation rooms and ventilation trunks include the installation of water spray and dry chemical powder extinguishing systems, portable fire extinguishers, fail-safe fire dampers, and fixed fire detection and alarm systems with flame or temperature detectors.

3.6.6 Control monitoring and safety systems

Control monitoring and safety systems shall be designed and installed according to DNV Rules Ship Pt 6 Ch 2 Sc 14 [10].

The functional requirements for the Control, monitoring and safety systems are given in the start of this chapter:

- Control, monitoring, and safety systems shall be arranged to ensure safe and reliable operation of the fuel installation.
- Leakages of fuel shall be detected and alarmed.
- A fuel safety system shall be arranged to automatically close down the fuel supply system upon fault conditions which may develop too fast for manual intervention and upon system failures in accordance with these rules and the installations safety philosophy.
- Propulsion shall be maintained upon single failure in control, monitoring, or safety system, taking into consideration that the engine is a dual fuel engine DNV Rules Ship Pt 6 Ch 2 Sc 14 [5.1.2].
- Propulsion shall be restored within 30 seconds (redundancy type 1) upon a fuel safety action and the restored propulsion power shall be in accordance with DNV Rules Ship Pt 6 Ch 2 Sc 14 [5.1.2], taking into consideration that the engine is a dual fuel engine.
- Control, monitoring, and safety systems shall be arranged to avoid spurious shutdowns of the fuel supply system.
- Information and means for manual intervention shall be available for the operator.

3.7 Cost Level of Ammonia Fuel System

Additional cost for ammonia fuel system (Dual Fuel) compared to conventional system is estimated to approximately 12,5M USD ref. Table 3-10.

Table 3-10 – Additional cost for ammonia fuel system compared with conventional system

Item	*Cost (USD)*
Ammonia Fuel Storage Tanks	4,200,000
Fuel Supply System	3,800,000
Ammonia Main Engine	1,500,000
Ammonia System Integration and Testing	1,000,000
Required Utility, Control and Safety Arrangements	2,025,000
Total Estimated Additional Cost	12,525,000

Potential requirements for structural reinforcements in deck for storage tank support and potential additional cost for exhaust system requirements (3.6.2) not included.

3.8 Energy Efficiency measures

3.8.1 Air Lubrication

Air lubrication is a popular method of reducing frictional resistance on vessel hulls. Frictional resistance contributes significantly to a vessel's total resistance and is proportional to the hull's wetted surface area and friction coefficient. Advanced hull coatings and air lubrication are two ways of reducing frictional resistance. Air lubrication systems put and maintain an air layer underneath the hull to reduce frictional resistance. To be successful, air lubrication systems must develop a stable air film resistant to ship motions and require minimal energy to transport air to the boundary layer. The Silverstream system air-film concept, which uses the Kelvin-Helmholtz instability to produce fine air bubbles in an energy-efficient way, was evaluated in the pilot, ref. Table 3-11. Air Release Units (ARUs) supply air to the boundary layer, and specially designed compressors control the air supply. Excess air in engine turbo-charging systems could be an alternative air source to reduce overall cost and energy consumption. To meet the requirements of MARPOL Annex I Regulations 15 and 14, measures to ensure low oil contamination of the air will be necessary.

Table 3-11 - Propulsion power saving (from similar vessel)

Speed (kn)	*Total supply power (kW)*	*Gross savings (kW)*	*Net Savings (kW)*
10	275	320	45
11	300	420	120
12	325	535	210
13	355	675	320
14	430	835	405
15	565	1020	455
16	725	1185	460

3.8.2 Rotor Sails

Norsepower Rotor Sails are modernized versions of Flettner Rotors. The Rotor Sail technology is based on the Magnus effect: wind accelerates on one side of the spinning rotor sail and decelerates on the opposite side. The change in the speed of air flow results in a pressure difference, which creates a lift force that is perpendicular to the wind flow direction. When wind conditions are favourable, the Rotor Sails allow the main engines to be throttled back, saving fuel, and reducing emissions while providing the power needed to maintain speed and voyage time.

The power and fuel saving impact of three 35x5 meter Rotor Sails were studied on three different routes (ref. Table 3-12).

Table 3-12 - Summary of roundtrip results

Route	*Vessel speed [kn]*	*Average Net Saving [kW]*	*Average Net Saving [%]*	*Average fuel saving*[tonnes]*
Roundtrip: New Jersey - Rotterdam	13	1520	19	3357
Roundtrip: Rio Grande - Le Havre	13	673	8	1486
Global Average	13	896	11	1980

*Assuming main engine running fully with ammonia with SFOC=360g/kWh.

3.8.3 Deep well pumps and deck mounted cargo heaters

The use of Framo cargo pumps in combination with submerged ballast pumps eliminates the need for a pump room, increasing cargo carrying capacity and providing more volume for cargo or fuel. This design also results in a reduction in steel weight and a safer environment. By removing steam-driven turbines, the number of boilers can be reduced, and one 30-tonne boiler capacity is sufficient for cargo heating and tank cleaning. One pump in each tank provides full cargo segregation, easy cleaning, and efficient switch between cargoes with less slop and oily water pollution. The Framo system facilitates easier switch between different grades of cargoes and less time in ballast, with built-in stripping devices and effective tank cleaning notation. By switching from steam turbines to electrical driven pumps, the estimated fuel savings during discharge operation is 40 tonnes of LNG which corresponds to 137 tonnes of CO_2 avoided (including methane slip).

The Framo deck-mounted cargo heater is designed for heating all types of cargoes, creating a turbulent flow ensuring an efficient heat transfer. It allows for efficient tank cleaning with no coils inside tanks and reduced the number of tank entries, improving safety and efficiency. The estimated savings with the Framo system are 745 MWh in reduced energy consumption and 64 MT of saved fuel per voyage compared to traditional heating systems.

3.8.4 Steam generation economizer

Waste Heat Recovery (WHR) economizers are an important part of ship design and operation across most vessel segments. WHR economizers can be of smoke-tube or water tube type, ref. Figure 3-14 and Figure 3-15, and is designed to deliver the required steam demand in nominal operating conditions. Water tube type economizers are more efficient in heat exchange, with a boost of 10-20% in steam output compared to smoke tube type. Water tube economizers are also lighter, increasing the ship's payload.

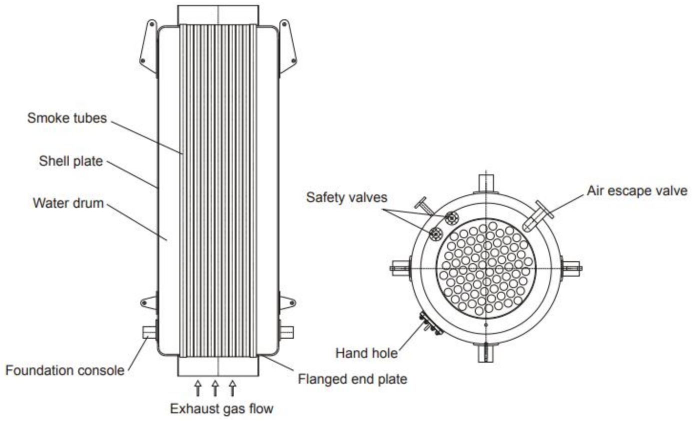


Figure 3-14 Smoke tube type WHR economizer

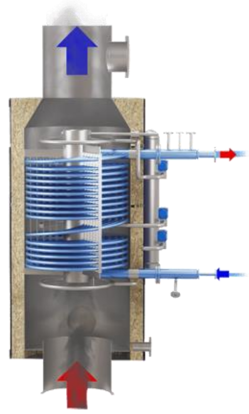


Figure 3-15 Water tube type WHR economizer

However, with the use of low-carbon fuels such as ammonia, it is expected that the required delivery temperature of service steam can be lowered, whilst the steam demand in terms of mass flow will not be significantly altered. Therefore, the operating pressure of the steam system can be set to lower pressure, resulting in up to 30-40% more steam production from the same economizer-engine combination.

In the latest 2-stroke engine models, there is a higher potential that the ship's steam demand may not be fulfilled with the WHR economizer connected to the main engine only, especially in cold environmental conditions. Installing small WHR economizers for auxiliary engines can be an effective solution in this case.

When the steam plant is optimised for best efficiency, the boiler's fuel consumption is minimized, and the steam output in ISO and tropical conditions may exceed the steam demand. Alfa Laval E-PowerPack (ref. Figure 3-16) is a compact and easily installed module that can convert waste heat directly into electrical power. This is achieved through Organic Rankine Cycle (ORC) technology, which is relatively new to the marine market. ORC technology can also be used to take advantage of this heat energy available onboard to reduce the ship's fuel consumption and carbon emissions.

Figure 3-16 - Alfa Leval E-PowerPack

3.9 Technology gaps

ARMS: As outlined in chapter 3.3.5, an ARMS system is deemed required on any ship sailing using ammonia as fuel and therefore identified as an essential technological GAP that has a kind of urgency to be closed. Wärtsilä will have an ARMS system commercially available by end 2023.

Ammonia fuel pumps: long shaft or fully submerged pumps that meets needed capacity and head are already available from several suppliers however fuel needs are on the low end of the capacity range requiring pump recycle in some modes. Heat ingress to the tank system is considered low, even for fully submerged pumps, hence recycling at reduced demand does not cause concerns. However, pump manufacturers should be encouraged to develop a pump range that better meets the demand.

Lube Oil (Cylinder oi–) - (Færder/Equinor)

Engines as outlined in chapter 3.4.

Boilers as outlined in chapter 3.5.

4 Bunkering risks and mitigation for tankers

Large ships in deep-sea segments are critical for achieving IMO goals for GHG emission reductions. Green and blue ammonia are promising fuels for zero-emission ocean transport and there is comprehensive industry experience in handling and transporting ammonia at sea.

This chapter entails a description of the requirements for a bunkering system for an ammonia fuelled tanker. In addition, the safety principles for LNG Bunkering are described, as there are similarities to the design rules and handling systems. Further the concept for MS Green Ammonia is described.

4.1 Bunkering options for Ammonia fuelled tanker

Many low-carbon fuels have chemical and physical properties posing/introducing more severe safety challenge requiring an advanced handling system compared to conventional fuels. To maintain the inherent safety, additional safety barriers are needed. Ammonia and LNG are gases with boiling temperatures that are not compatible with conventional fuel systems. LNG is highly flammable and has a low minimum ignition energy, so it is essential to avoid any leakages. Ammonia is much less flammable and thus constitutes a low explosion risk, but due to toxicity it is also essential to avoid any leakages to ensure the safety of crew and environment.

DNV and other class societies have developed rules for the design of ships fuelled with ammonia. There are many similarities in the design rules for LNG and ammonia ref. Figure 4-1.

Segregation Protect fuel installation from external events	**Double barriers** Protect ship against leakages
Leakage detection Give warning and enable automatic safety actions	**Automatic isolation of leakages** Reduce consequence of a leakage

Figure 4-1 Safety Concept, IGF Code and DNV rules for LNG

Therefore, the bunkering process for ammonia can be based on many of the same safety concepts as for LNG. Ref. Figure 4-2 for a typical LNG bunkering setup.

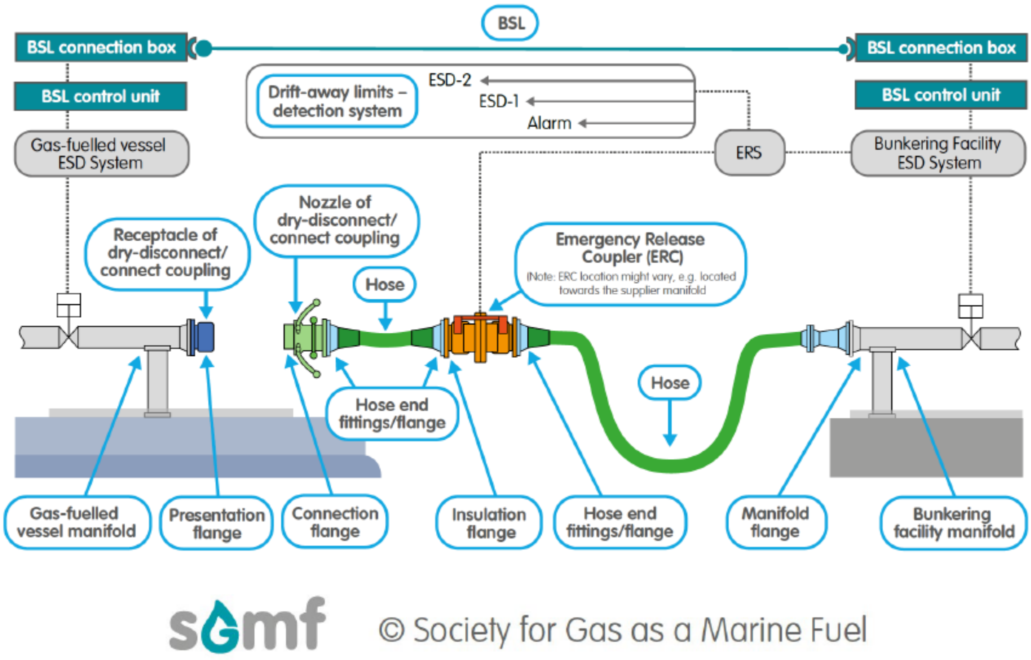


Figure 4-2 – Typical LNG bunkering setup

Given the specification of the Ammonia tanker, ref. chapter 3.1, the fuel requirements for each bunkering operation are:

- Bunkering location at Mongstad Refinery
- 2 x 3000 m^3 NH_3 fuel tanks with maximum 56 number of days between each loading
- Ammonia Fuel Tank at fully refrigerated conditions, -33^{0}C and 1 atm
- Option to permit simultaneous cargo handling (if approved by the relevant authorities)

The basis for the Ammonia bunkering system described in this chapter is based on the Grieg Edge Ammonia Bunkering Ship.

Grieg Edge is developing one of the world's first ammonia powered ammonia tankers. MS Green Ammonia will distribute green ammonia along the coast of Norway, to terminals and via ship-to-ship bunkering. The vessel concept received an Approval in Principle (AiP) from DNV in April 2022. The ship is planned to be ready for operation from 2025/2026. The bunkering vessel will have a total cargo capacity of 7500 m^3 and the ammonia will be stored at -33 degrees and at atmospheric pressure. Ref. Figure 4-3 for a 3D model of the ship.

Figure 4-3 - Stock photo of MS Green Ammonia

The main design particulars for MS Green Ammonia are listed in Figure 4-4. The vessel is designed to offer bunkering operations to various ship types, such as large container vessels, large bulk carriers, very large crude carriers, and cruise vessels. Manifolds have been placed amid ship on port and starboard side at different levels to ensure flexibility on bunkering operations.

DESIGN PARTICULARS

LOA	120.0 m
Breath	19.2 m
Depth	10.2m
Draught	7.0 m
Cargo Capacity	7500 m3
Loading Rate	Up to 2 x 500 m3/h

Figure 4-4 Main design particulars of MS Green Ammonia

4.1.1 Vessel Compatibility

An important step for safe bunkering operations is to verify that the bunker vessel and receiving vessel are compatible. A compatibility assessment should be carried out prior to any ship-to-ship bunkering. A compatibility review can be performed based on a checklist and should include all ship-ship considerations and should address the following:

- Compatibility of vessel dimensions to ensure safe mooring and adequate fendering to prevent damage.
- Conflicts with overhanging equipment, such as lifeboats.
- Relative freeboard to allow hoses and cranes to reach bunkering supply connection, with sufficient slack in case of motions between the vessels.
- Manifold arrangements, spill containment systems and hose connections.
- Capability for emergency release (hose breakaway) with minimal gas release.
- Compatibility in emergency shutdown connections.
- Compatibility with hazardous areas on both supplying and receiving vessels.
- Confirmation that volume, pressure, temperature, and transfer rates are compatible.
- Requirement of vapour return.
- Inert and purging capabilities including ammonia release mitigation system on both vessels.
- Compatibility in communication equipment, monitoring on both sides and capability of emergency shutdown on both vessels.

Both the Equinor tanker and the MS Green Ammonia are at the conceptual design stage, hence all specifications to assess the compatibility are not set. By high level assessment of the two designs, especially focusing on technical feasibility, crane capability, hose lengths, placement of manifold stations and tank systems the two vessels should be a good fit to perform ship-to-ship bunkering operations.

4.1.2 Risk and Safety design during bunkering

Bunkering systems shall prioritize safe operations and limit ammonia release. To achieve this, several safety measures should be implemented. I.e.: Quick Connect Disconnect Couplings to allow for easy and safe connection without bolts and to reduce ammonia release. Dry breakaway couplings installed on manifold stations to minimize spills during large movements.

Emergency shut down (ESD) valve in case of a high tank level, pressure, gas, or fire detection. Hoses used for bunkering supported and secured several places to avoid exceeding the manufacturer's recommended bending limit. Water spray / water curtains to mitigate the dispersion of any ammonia release in addition to collection of liquid spills.

During transfer operations, several potential incidents shall be considered in the safety design and operation. Pressure surges can occur if valves are closed too quickly and can be avoided by adjusting loading rates. In case of an emergency shutdown (ESD2), will initiate the emergency release coupling (ERC) and close valves immediately to prevent liquid spill.

A high liquid-to-gas ratio of ammonia can result in hydraulic shock when cold liquid ammonia is introduced into a piping system that is already filled with warm ammonia vapor. This hydraulic shock has the potential to cause damage to the piping, valves, and other components.

Overall, it is essential to consider these potential incidents and implement the necessary safety measures to ensure safe and effective bunkering operations with minimal ammonia release.

4.1.3 Bunkering Operation

Ammonia ship-to-ship transfer, illustrated in Figure 4-5, will be realized through flexible hoses with 20m length and 8'' diameter. There will be two hoses for liquid connections and one for vapour connection. The vessel will be equipped with a custody transfer system (CTS) for highly accurate metering of both energy content and quantity of transferred ammonia.

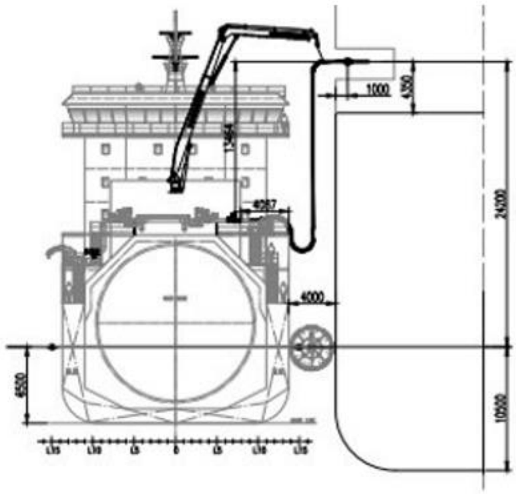


Figure 4-5 Ship-ship bunkering interface

The cargo handling system for the bunkering vessels is described in Table 4-1.

Table 4-1 – Cargo handling system, MS Green Ammonia

Cargo containment system	Two cylindrical Type C tanks 3750m3 per tank
Re-liquefaction plant	Two reliq units to control cargo temperature and pressure
Cargo pumps	Two long-shaft multi-stage centrifugal deep well pumps electrically driven. Nominal capacity 500m3/h @ 129 mlc

Piping	Two manifold/bunker stations each with crossover between PS and SB are set amidship on different levels. Capacity of 100% vapor return during cargo operations. Liquid CO: ANSI 8'' Class 300 RF Vapor CO: ANSI 6'' Class 300 RF
Nitrogen Generator System	Nominal capacity 20-50 Nm3/h @ 97% N2
Cargo Hose Crane	One hose handling crane amidship. Capacity 5 MT (SWL) with outreach 20m

A simplified step by step procedure for ammonia bunkering can be as follows:

Before transfer – for both bunkering and receiving vessel:

1. Function test of bunkering and SIGGTO system
2. Inert liquid and vapour lines

Bunkering operation:

1. Connect bunkering system
2. Connect SIGGTO system
3. Inert bunkering connection
4. Leak test bunkering connection
5. Start bunkering at low rate to cool down piping
6. Increase bunkering to full rate
7. Stop bunkering pump
8. Empty liquid line and bunkering hose with hot ammonia vapour
9. Release ammonia pressure to tank reliquefication plant or ARMS
10. Inert bunkering hose to ARMS with N2
11. Disconnect bunkering hose

4.1.4 Bunkering Operation Checklists

As part of any bunkering operation, a checklist for actions before, during and after bunkering should be performed by the-persons-in-charge. Checklists should be developed for each vessel, in accordance with applicable circumstances, such as type of bunker supply and location. Items to be covered in the checklists are typically:

Before Bunkering: Compatibility with bunkering vessel, notifications and permissions from port authority, establishment of safety zones, hose connections, PPE on onboard personnel, testing of systems (ESD, leak test/pressure test, monitoring and alarm, emergency procedures and response plan, communication).

During Bunkering: Continuous communication, monitoring levels, and pressure, monitoring of safety zones.

After Bunkering: Confirmation of tank levels and custody transfer, draining of hoses, manifolds, and piping, inerting of systems, disconnection, notification of port authority.

4.2 Safety development

Bunkering is critical and operations must be conducted in line with legislation, standards, and best practice guidelines to ensure safety and to protect the environment. Several risks including leakage of ammonia and the associated toxicity and low temperature risks, fire considerations, fuel contamination, layout hazards etc. need to be considered.

Safety related to the bunkering of ammonia is essential. Safety standards and regulations for bunkering of ammonia are yet to be fully established.

Crew on ammonia carriers are already working according to procedures and international safety standards for loading, handling, and discharging ammonia on a vessel. Experience, procedures, and safety standards available today in ammonia cargo operation is the basis for developing safety practices for the bunkering of ammonia as a fuel.

Focus areas for improved Ammonia Bunkering is as follows:

- Use of risk assessment and Quantitative Risk Assessment (QRA) for dispersion analysis.
- Automated operations to minimize human factors during transfer authorization, purging & gas freeing sequences (sequential automated steps, valve position monitoring, interlock, permissive, etc.).
- Interface standardisation to avoid misuse of adaptors.
- Tailor made check list integrated to Standard Operating Procedures for pre/post bunkering steps.
- Proper NH_3 detection technology selection to ensure reliable and early leak detection associated with automatic and quick isolation.
- Ammonia leak consequence mitigation practices, including water curtains and first aid measures "Do's and 'don'ts."
- Provide a working environment for always free of ammonia scent (to keep early warning by smell as efficient as possible).
- Tailor made training program for operators (initial and continuous) including theoretical & practical steps with performance assurance process. (Written exams, certified senior operator as companion for competence final validation).
- Safety leadership program to ensure active supervision of operational discipline.
- It is recommended to include the above focus areas in the bunkering rules to be developed.

5 Well to wake carbon footprint and fuel cost analysis

The well-to-wake CO_2e emissions of blue and green ammonia is estimated with reference to the FuelEU Maritime Initiative's carbon footprint methodology and compared to alternative energy carriers. A cost analysis of the low-carbon fuels blue ammonia, green ammonia, and green methanol, as well as conventional marine fuels, was performed This serves as the basis for the abatement cost calculations. All assumptions are described in the relevant sections.

To frame the analysis and give context, production pathways for blue and green ammonia are presented, as well as a comparison of carbon footprint calculation methodologies. The latter focuses on FuelEU Maritime Initiative's carbon footprint methodology, as well as Equinor's production footprint /11/.

5.1 Production pathways

5.1.1 Blue Ammonia

Blue ammonia refers to ammonia produced from natural gas with CO_2 capture and permanent storage (Figure 5-1). The production process includes a steam methane reformer (SMR) to produce hydrogen, an air separation unit to extract nitrogen from the air and the Haber Bosch process to produce ammonia. CO_2 is captured, compressed, and sent to permanent storage. A new build plant can have a CO_2 capture rate of more than 95%, while 90% is economically achievable for carbon capture retrofit for an existing plant.

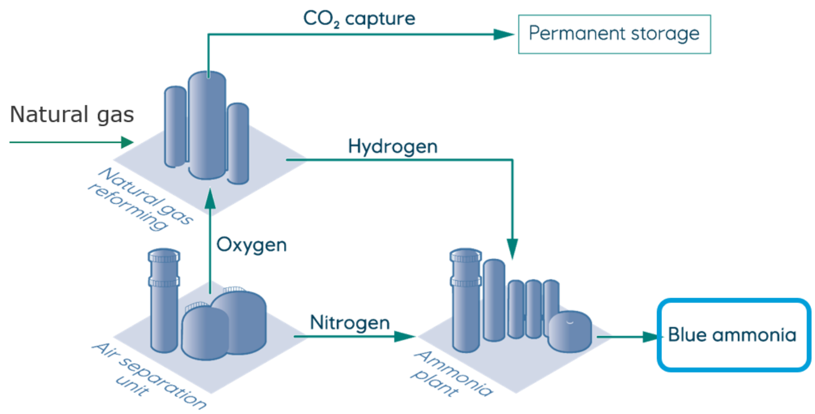


Figure 5-1 Blue Ammonia production

5.1.2 Green Ammonia

Green ammonia production (ref. Figure 5-2) utilises renewable electricity in electrolysers to split water into H_2 and O_2, while N_2 is extracted from the air in an air separation unit. The H_2/N_2 mix is then converted to ammonia in the Haber Bosch process.

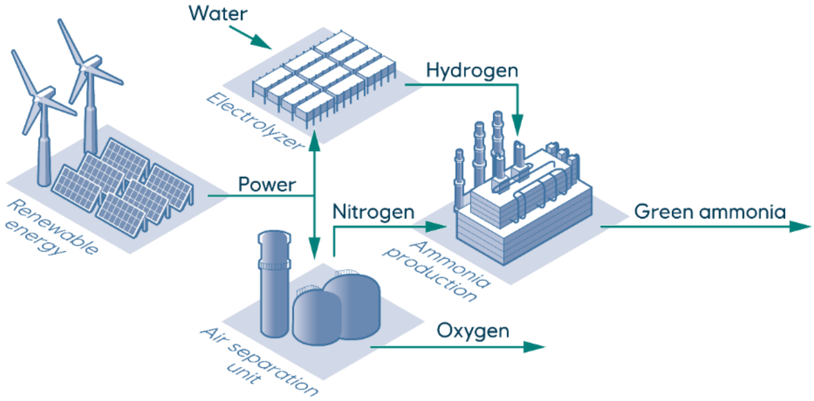


Figure 5-2 Green ammonia production

5.2 Carbon Footprint Analysis

5.2.1 Carbon footprint calculation methodologies

The carbon footprint provides an estimate of the GHG emissions associated with a product or process. When comparing fuels, it is important that the carbon footprint is compared on a like-for-like basis. This is however one of the major challenges for carbon footprint comparisons.

The quantification of GHG emissions and removals across a product's life cycle is complex and the results are highly dependent on the selected methodologies and assumptions. The most widely used carbon footprint standards today, such as the GHG Protocol's Product Standard, are primarily intended to support performance tracking of one product over time. For other product comparisons, additional specifications are needed.

There are a number of important considerations when doing a carbon footprint calculation i.e.., scope boundaries, including exclusion of specific elements, GHGs covered, data sources, data quality and GHG allocation rules. There are several standards for calculating the carbon footprint, and many allow each user the flexibility to tailor-make the assumptions.

In this report, the carbon footprint methodology proposed under the FuelEU Maritime Initiative is used to compare ammonia and green methanol with conventional fuels.

5.2.2 FuelEU Maritime Initiative

The FuelEU Maritime Initiative is one of the proposals aiming to ensure that the European Union achieves the ambition of cutting greenhouse gas emissions by at least 55% by 2030. The purpose is to increase the demand for renewable and low-carbon intensity fuels in shipping.

The GHG methodology for use under the FuelEU Maritime Initiative is described in a proposal document from the European Commission /10/. At the time of writing, any counter proposals from the European Parliament and the European Council were not available.

To provide the full picture of the carbon footprint of the various fuels, a well-to-wake basis is used. This takes into consideration emissions from fuel production, transport, distribution and use on-board. The well-to-wake carbon footprint of fuels is established using either default or actual and certified emission factors. Default emission factors are suggested for fossil fuels.

In the FuelEU Maritime methodology conventional ammonia produced from natural gas has a default well-to-tank (WtT) emission factor of 121 gCO_2e/MJ. However, it is expected that blue ammonia produced from natural gas with carbon capture and storage will be possible to certify and can be considered as a low-carbon shipping fuel going forward in line with certification required for fuels covered in the RED directive like biofuels, RFNBO's and recycled carbon fuels.

5.2.3 Equinor/Norwegian production footprint

As a supplier of fuel to the maritime sector, Equinor has ambitions to escalate the production and use of low-carbon fuels and zero-emission fuels. Extensive focus on decarbonisation results in a portfolio average upstream CO_2 intensity of 7 kg CO_2 per barrel of oil equivalents for Equinor's corporate portfolio of operated assets /11/. This is under half of the industry average intensity reported by the International Oil and Gas Partnership (IOGP).

Equinor offers documented Well-to-Facility-Gate emissions for Equinor-produced products from for instance the Mongstad refinery /11/. The carbon footprint is obtained by allocating Equinor's scope 1, 2 & 3 (transportation and distribution) GHG emissions, as defined by the GHG protocol standard, in grams carbon dioxide equivalents (gCO_2e) per energy content of the product in Megajoules (MJ). Ref. Table 5-1 for a comparison of Equinor Well-to-Facility-Gate footprints and FuelEU Maritime Initiative well-to-tank default values.

Table 5-1 Equinor-footprint compared to FuelEU Maritime Initiative's default values[10]

Fuel	*Equinor (Well-to-Facility-Gate) [gCO_2e/MJ][11]*	*FuelEU Maritime Initiative's default values (Well-to-Tank) [gCO_2e/MJ][12]*
Light fuel oil (LFO)	7,6	13,2
Liquefied petroleum gas (LPG)	2,6	7,8
Liquefied Natural Gas (LNG)	3,8	18,5
Marine diesel oil (MDO)	5,3	14,4
Marine gasoil (MGO)	7,6	14,4
Methanol (from natural gas)	20,9	31,3
Conventional NH3 (from NG)		121
Renewable NH3 (RFNBO)		Certification (70% savings threshold)

Introducing company specific carbon footprints (CSCF) can be a market differentiation tool for fuel consumers in evaluating products based on carbon efficiency. With the proposed use of FuelEU Maritime Initiative default values, CSCF will in contrast open for an additional incentive for both fuel buyers to consume and producers to produce, as carbon efficient conventional fuels as possible in a transition period, while continuing the development of low and zero-carbon fuels.

[10] Refined products produced at Mongstad, methanol produced at Tjeldbergodden, LNG from Hammerfest LNG facility and natural gas from NCS piped to Europe (feedstock for methanol, hydrogen, and ammonia)
[11] Equinor numbers verified by independent third-party assurance companies.
[12] Default value for well-to-facility gate footprint in the EU Renewable Energy Directive Delegated Regulation for calculating the GHG savings of RFNBOs

5.2.4 Certification of fuels

Certification of fuels is essential to guarantee the environmental integrity of renewable and low-carbon fuels. The certification of biofuels, biogas, renewable fuels of non-biological origin and recycled carbon fuel under FuelEU Maritime Initiative relies on the rules established by the EU Renewable Energy Directive (RED). This approach of certification also applies to fuels bunkered outside the EU. When companies intend to deviate from the default values provided by RED for FuelEU Maritime Initiative, the values need to be certified by one of the voluntary schemes recognized under RED (for well-to-tank values) or by laboratory testing or direct emissions measurements (tank-to-wake).

5.2.5 Comparison of well-to wake emissions for different fuels

The calculations for the well-to-tank GHG emissions for different fuels, including different capture rates and electricity footprints, are based on the Equinor value chain model for future energy carriers. The model is developed to enable a comparison of different footprints, using a consistent set of assumptions based on the best available technology (BAT) for each product. Transport emissions are currently modelled using conventional fuels.

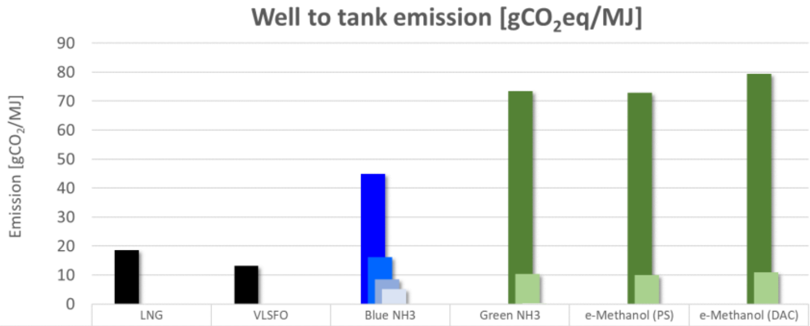
The following assumptions are selected for the base case:

Blue fuels – Ship transport distance: 620 nm
Green fuels – Ship transport distance: 340 nm
Natural gas upstream emission: 1.6 gCO_2eq/MJ /4/
Electricity upstream emission: 17 gCO_2eq/kWh /4/
CO_2 capture rate for blue NH_3: 95%

In addition, sensitivities for capture rate and electricity footprint are as follows:

Blue NH_3: CO_2 capture rate of 60%, 90%, 95%, 98% (CO_2 is permanently stored)
Green products: Electricity footprint 0, 17 and 125 g CO_2e/kWh representing fully renewable, Norway based and EU grid mix with 50% renewable.

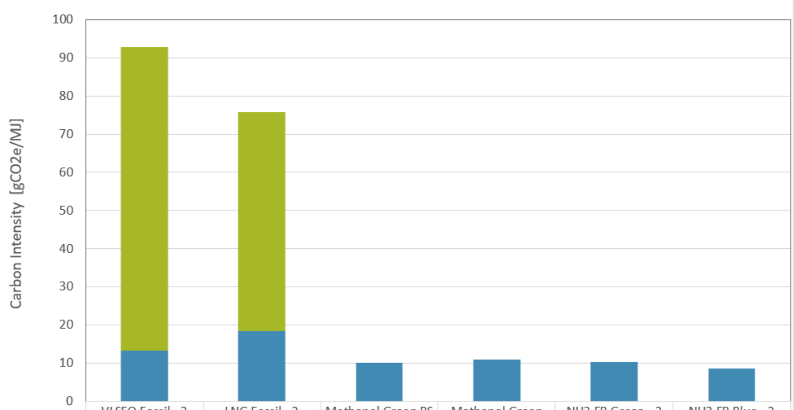
Well-to-wake emission factors for conventional fuels are based on the FuelEU Maritime Initi-ative framework. Tank-to-wake emissions from green and blue fuels are in this context assumed to be 0. Ref. Figure 5-3 and Figure 5-4 for WtT and WtW results, respectively.



	LNG	VLSFO	Blue NH3	Green NH3	e-Methanol (PS)	e-Methanol (DAC)
Conventional fuels	18.5	13.2				
60% capture			44.9			
90% capture			16.2			
95% capture			8.5			
98% capture			5.2			
125 g CO2/kWh				73.3	72.9	79.5
17 g CO2/kWh				10.3	10.0	10.9
0 g CO2/kWh				0.4	0.1	0.1

Figure 5-3 Well-to-tank emissions for a selection of fuels [13]

WtT emissions for new pathways are very dependent on upstream GHG emissions associated with the natural gas, capture rate (and storage) for CO_2 and/or electricity footprint of energy used in the production. Green and blue fuels can both potentially be produced with a very low GHG intensity, even below typical values for fossil fuels (only looking at the upstream footprint). However, development of a methodology to certify products based on actual footprint from production is essential to be able to assess footprint of emerging fuels and the focus should be on lower-carbon products and not on production pathway.



	VLSFO Fossil - 2 Stroke HP	LNG Fossil - 2 Stroke HP	Methanol Green PS - 2 Stroke HP	Methanol Green DAC - 2 Stroke HP	NH3 FR Green - 2 Stroke HP	NH3 FR Blue - 2 Stroke HP
WTW Carbon intensity	93	76	10	11	10	9
TtW Carbon Intensity	80	57	0	0	0	0
WtT Carbon Intensity	13	19	10	11	10	9

Figure 5-4: Well-to-wake carbon intensity[14]

[13] Assuming natural gas upstream emission of 1,6 gCOeq/MJ /4/. CO_2 capture rate and electricity upstream emission is varied as described in the figure. Upstream emissions from VLSFO and LNG from FuelEU Maritime Initiative.

[14] Well-to-wake carbon intensity for VLSFO, LNG, e-Methanol point source capture, e-Methanol direct air capture, blue - and green ammonia. Tank to wake carbon intensity from Equinor ship cost model, see chapter 5.3.4.

The WtW values represent the base case assumptions for the selected fuel types and the TtW contribution from methanol or ammonia is assumed zero in this comparison due to lack of data on combustion products for these fuels. This should be addressed when developing the combustion technology and potential aftertreatment to avoid N_2O formation or CH_4 emissions. Further, the carbon source for the methanol production is assumed certified to zero. To avoid double counting this assumes that the source is either direct air capture (DAC), point source capture of bio/waste flue gas or from an industrial source where the carbon capture does not credit a reduction at the source. However, this needs to be addressed in the detailing of certification methodology for recycled carbon fuels. It is clear from the comparison that, in a WtW perspective, significant reductions in GHG emissions from ships can be achieved by switching to low-carbon energy carriers. From 93 to 10 gCO_2e/MJ going from VLSFO to green ammonia on WtW basis.

5.3 Cost Analysis

The levelised cost of fuels was calculated using the NavigaTE v.1.2 model developed by Maersk Mc-Kinney Møller Center for Zero Carbon Shipping /13/ .

5.3.1 Energy cost

Two different cases were defined to show the sensitivity of the fuel price to the energy prices for fuel production (i.e., gas and electricity cost) using historical values from 2019 pre-covid/Russia-Ukraine war (case 1) and values from 2022 (case 2).

Ref. Figure 5-5 for historical price values of various marine fuels from 2019 until today. Figure 5-6 illustrates the historical electricity prices for the five different price regions in Norway from 2016 until today and Figure 5-7 illustrates the historical Title Transfer Facility (TTF) gas prices from 2016 till today.

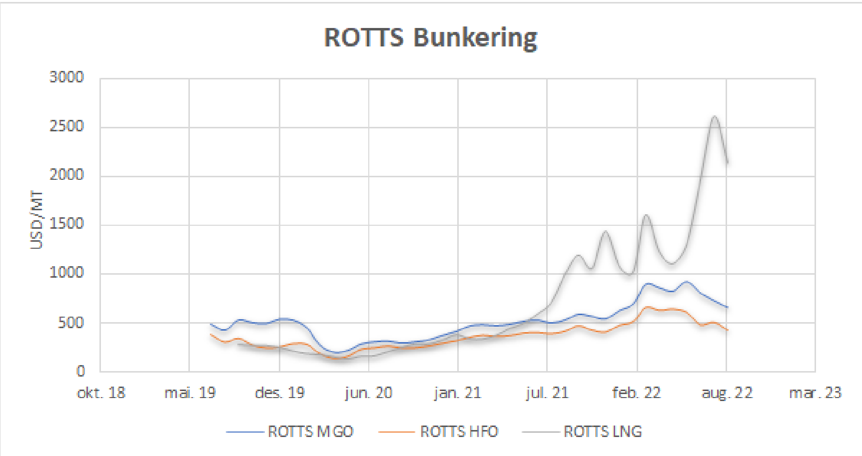


Figure 5-5 Historical fuel cost values for MGO, HFO and LNG bunkered at Port of Rotterdam (ROTTS).

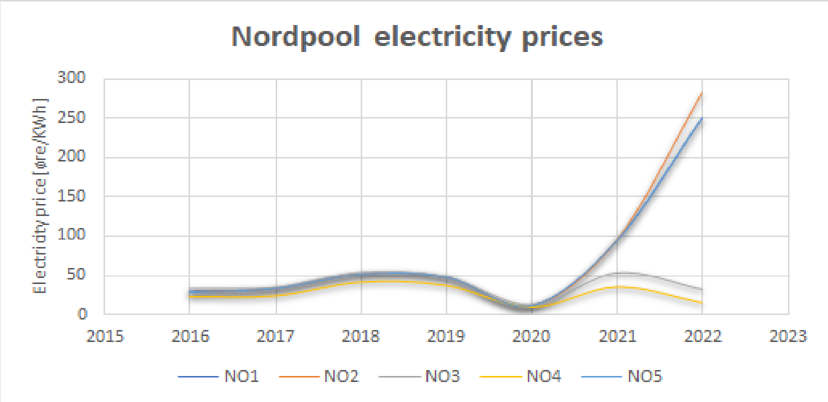


Figure 5-6 Historical electricity prices for the five Norwegian price regions /13/

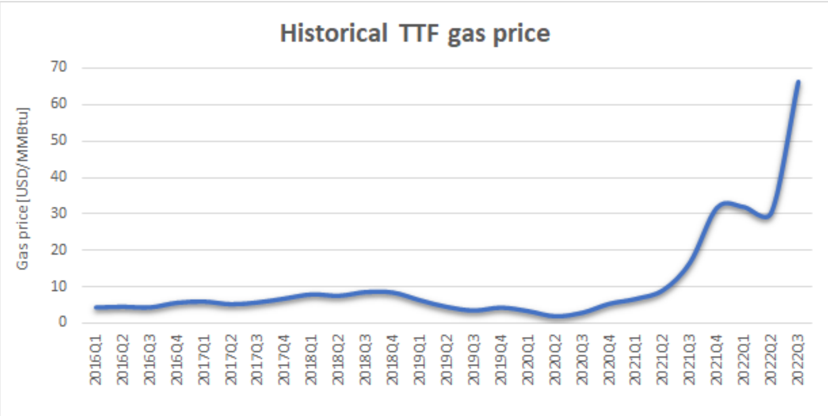


Figure 5-7 Historical TTF gas prices, quarterly average in USD/MMBtu

Based on these numbers, the two cases were defined based on 2019 (case 1) and 2022 (case 2) numbers, ref. Table 5-2. Bunkering prices are not included. The VLSFO price is estimated by using HFO cost with an added 150 USD/tonne (estimated cost difference based on historical data).

Table 5-2 Gas, power and fuel cost for the two different cases.

		Case 1 (2019)	*Case 2 (2022)*
Gas	[USD/MMBtu]	7	30
Electric power	[USD/MWh]	50	250
VLSFO	[USD/tonne]	350	750
MGO	[USD/tonne]	400	800
LNG	[USD/tonne]	300	1250

5.3.2 Fuel cost calculation

The NavigaTE v.1.2 model is used to estimate fuel production cost for blue and green ammonia and methanol for the two cases, ref. Figure 5-8. An important finding is that the MGO and VLSFO cost differentiate with a factor of 2 between the cases, while the low-carbon fuels typically increase with a factor of 2.5 to 3.3. The increase of the LNG cost is about 4 times. Further, of the low-carbon fuels, blue ammonia is less sensitive to the increased energy cost.

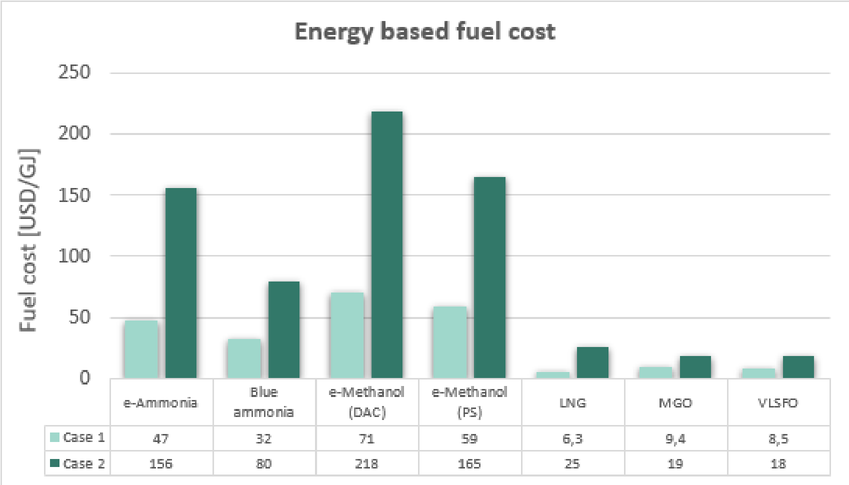


Figure 5-8 Fuel cost comparison, case 1 and case 2. Results from NavigaTE model /13/

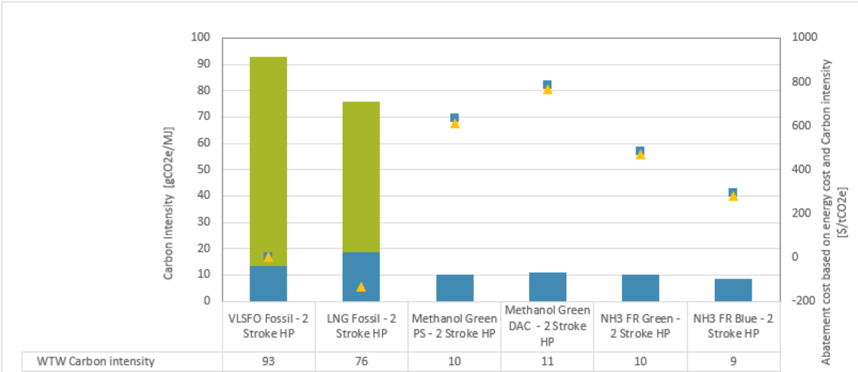
5.3.3 Abatement cost based on fuel cost

Based on the fuel costs and footprint of the fuels, the abatement cost for switching to a low-carbon fuel can be calculated. The abatement cost calculation is not taking the ship modification cost or difference in energy efficiency into account.

The abatement cost is calculated by using difference in emissions and cost between two alternatives. The reference case is the VLSFO, and the low-carbon fuels are compared to the reference case with respect to emission reduction and cost difference. The abatement cost can be calculated based on tank-to-wake or well-to-wake basis. When calculated on a tank-to-wake basis it can be compared with a required carbon tax level like ETS cost to balance the cost difference between the fuels. If the abatement cost is negative, it means that the fuel option is more cost efficient and at the same time have lower emissions.

$$Abatement\ cost\ \left(\frac{USD}{CO2e\ ton}\right) = \frac{(Cost\ of\ alternative - Cost\ of\ reference\ case)[USD]}{(CO2e\ emission\ reduction)[ton]}$$

Figure 5-9 displays abatement cost based on the case 1 (2019 energy prices). The tank to wake abatement cost shows that blue ammonia is the most cost competitive option with abatement cost compared to the reference case of approximately 300 USD/tonne CO_2e saved. Taking the current ETS price into account it shows a gap to be commercially attractive for the 2019 cost level. For these cost levels for energy LNG will have a negative abatement cost with reduction in emissions and energy cost.



	VLSFO Fossil - 2 Stroke HP	LNG Fossil - 2 Stroke HP	Methanol Green PS - 2 Stroke HP	Methanol Green DAC - 2 Stroke HP	NH3 FR Green - 2 Stroke HP	NH3 FR Blue - 2 Stroke HP
WTW Carbon intensity	93	76	10	11	10	9
TtW Carbon Intensity	80	57	0	0	0	0
WtT Carbon Intensity	13	19	10	11	10	9
TtW Abatement cost - Energy cost	0	-103	637	788	486	294
WtW Abatement cost - Energy cost	0	-135	612	766	469	277

Figure 5-9: Carbon intensity and energy-based abatement cost for case 1 (2019 num-bers)[15]

The same analysis for case two illustrates the same overall picture for low-carbon fuels vs VLSFO but with higher abatement cost reflecting the higher spread between low-carbon energy carriers and fossil products.

5.3.4 Ship cost

The Equinor ship cost model is used to compare greenhouse gas (GHG) emission impact and abatement cost for fuel switching and indicate impact on the cargo transport cost.

Reference is made to chapter 3.7 for relevant ship cost parameters, chapter 5.2.5 for WtT GHG emissions and chapter 5.3.2 for fuel cost levels. Table 5-3 shows contract price for conventional Aframax tanker new build, and delta cost for dual fuel LNG, ammonia, and methanol new builds. The newbuild delta cost for LNG is based on inhouse knowledge from Altera an Equinor while DF methanol cost is based on MAN Whitepaper /18/ where a 3 million USD is stated for a LR1 tanker and thus assumed 4 million USD for an Aframax/LR2. Main point is to reflect the expected cost level for the three different DF ships and especially that methanol system is expected to have a lower CAPEX compared LNG and ammonia.

Table 5-3 Contract prices new build, Q4 2024 – Q2 2025.

Ship case	*Contract price / delta cost [MUSD]*
Conventional Aframax VLSFO, 113-115 dwt[16]	68
DF Aframax LNG	+13
DF Aframax NH_3[17]	+13
DF Aframax MeOH[18]	+ 4

[15] Results are from Equinor ship cost model, see chapter 5.3.4. The abatement cost for reduction of CO_2equivialent [$/t$CO_2$e], is based on energy content, carbon intensity and fuel price. Negative results indicate income for reduction. Positive results indicate cost for reduction. Ship costs are not included.

[16] Including shaft generator and hydraulic deep well pump system

[17] Based on cost input detailed in chapter 3.7

[18] Based on information from EMSA /6/ and MAN /18/ additional cost for DF Methanol Aframax is assumed 4 MUSD.

The operational profile used in the analysis is based on average data from representative vessels in the Equinor time charter (TC) fleet, ref. Table 5-4. The case profile is a combined route of three independent round tips, with load port Mongstad, and discharge ports Bayway, Porvoo and Rotterdam. Simultaneous cargo and bunkering operations are presumed.

Table 5-4 Operational profile Aframax for cost analysis

	Nautical miles	Hours	%
Case profile	10 080	1040	
Transit laden	5040	414	40
Transit ballast	5040	469	45
Port stay loading (19 hours each operation)		57	5
Port stay idle		43	4
Port stay discharge (19 hours each operation)		57	5

Transit consumption is obtained for each leg by use of power curves from Figure 3-2.

The engine efficiency is assumed to be the same for all fuel types. Auxiliary engines to operate on MGO. The pilot fuel is MGO for all cases assuming 2% for the LNG, 5% for the methanol, and 10% for the ammonia-cases. Boilers and inert gas generators are assumed to operate on MGO for fossil fuel cases, and main fuel for the ammonia and methanol cases.

The new fuels system on the vessel will result in added weight and increased draft. In this analysis this is assumed by added consumption for LNG, methanol, and ammonia with 1%, 2% and 3% respectively, due to the added mass of fuel and equipment.

Shaft generator with 1MW rating is engaged during transit for all cases, ref. Table 5-5, covering the onboard electricity consumption without the use of auxiliary engines. Cargo heating with deck mounted cargo heaters is applied for laden, see chapter 3.8.3, and associated consumption divided between auxiliary engines and boiler.

Hydraulic deep well pumps and inert gas generator are used for discharge operations, see chapter 3.8.3. Cargo heating during loading operation is disregarded in this analysis.

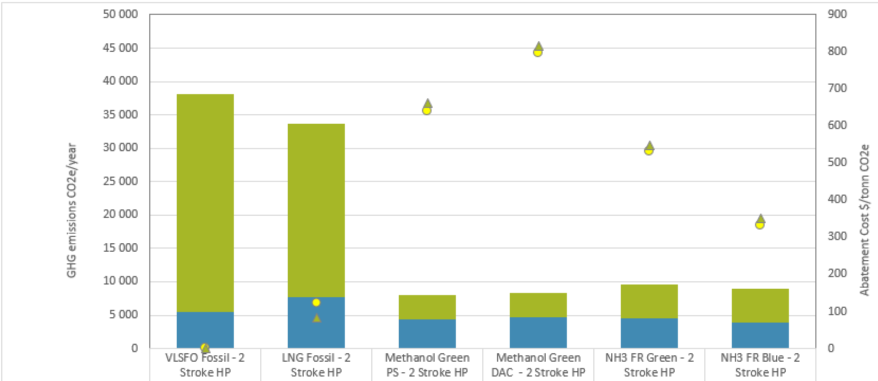
Table 5-5 Machinery and fuel factors input. Non-exhaustive list.

Machinery	*HP Two-stroke MAN B&W 6G60ME-C10.5* [19]
Sea margin [%]	15
Hotel load [kW]	850
ME engine efficiency, 75% MCR [KJ/kWh]	6963
MCR [kW]	11730
Shaft generator rating [MW]	1

5.3.5 Abatement cost including ship cost

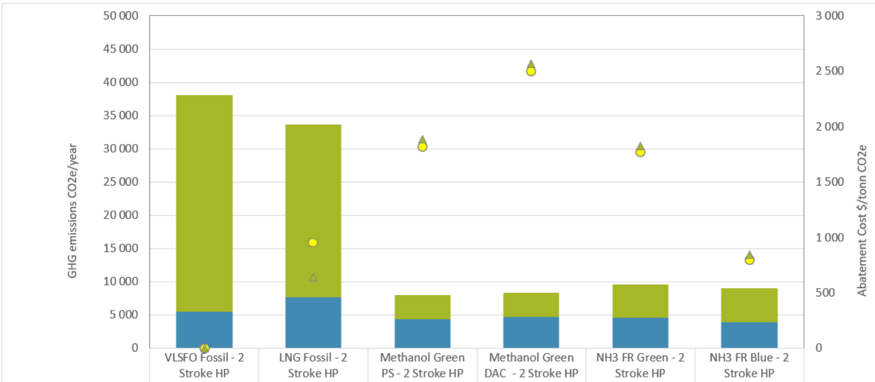
Greenhouse gas emission and the abatement cost for fuel switching for case 1 (2019 cost level) and case 2 (2022 cost level) are presented in Figure 5-10 and Figure 5-11.

[19] Tier II, Scrubber not installed, Fixed Pitch Propeller



	VLSFO Fossil - 2 Stroke HP	LNG Fossil - 2 Stroke HP	Methanol Green PS - 2 Stroke HP	Methanol Green DAC - 2 Stroke HP	NH3 FR Green - 2 Stroke HP	NH3 FR Blue - 2 Stroke HP
WTW	38 050	33 619	7 973	8 301	9 621	8 999
TTW	32 568	25 967	3 587	3 587	5 031	5 031
WTT	5 482	7 651	4 385	4 713	4 590	3 968
Abatement cost WTW	0	122	638	795	530	332
Abatement cost TW	0	82	662	816	547	350

Figure 5-10: Case 1 – Greenhouse gas emissions and abatement cost



	VLSFO Fossil - 2 Stroke HP	LNG Fossil - 2 Stroke HP	Methanol Green PS - 2 Stroke HP	Methanol Green DAC - 2 Stroke HP	NH3 FR Green - 2 Stroke HP	NH3 FR Blue - 2 Stroke HP
WTW	38 050	33 619	7 973	8 301	9 621	8 999
TTW	32 568	25 967	3 587	3 587	5 031	5 031
WTT	5 482	7 651	4 385	4 713	4 590	3 968
Abatement cost WTW	0	951	1 817	2 500	1 769	800
Abatement cost TW	0	638	1 886	2 567	1 826	844

Figure 5-11: Case 2 – Greenhouse gas emissions and abatement cost

Compared to the VLSFO reference case, the total WtW emissions are reduced by approximately 76% for blue ammonia, 75% for green ammonia and 79% for green methanol.

Pilot fuel and auxiliary engines are contributing to the total emissions for the non-fossil fuels, by approximately 56% of the total WtW emissions for blue ammonia, 52% for green ammonia and 45% for e-methanol.

The reduction in both the TtW and WtW emissions are high for all ammonia and methanol cases, even with a conservative assumption on pilot fuel consumption. The reduction in the LNG case is limited, even with low methane slip engine technology, especially in the WtW perspective where the high upstream emissions (WtT) of LNG is substantial.

The analysis shows that the abatement cost for green fuels is higher than for blue ammonia and that ammonia is the most cost efficient of the low-carbon alternatives. For case 1 (2019 cost assumption) the abatement cost of 350 USD/tonne CO_2e on a tank wake basis indicates that further incentives are required to close the cost gap compared to the fossil alternatives in addition to ETS for shipping.

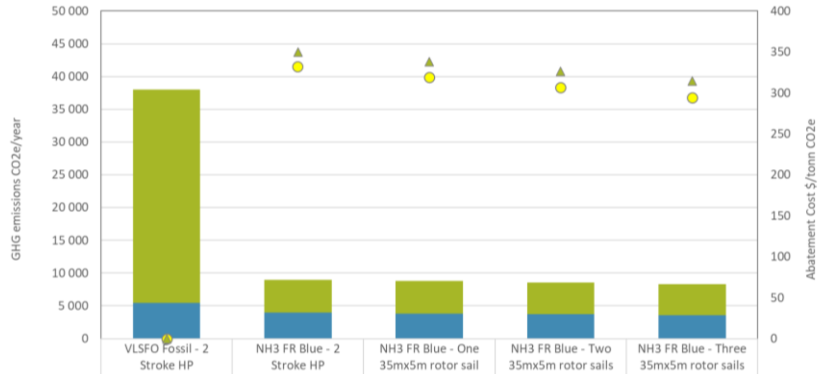
From Figure 5-10 the energy-based abatement cost for LNG was negative and a good business case both from an environmental and commercial perspective, however when the added cost of the ship CAPEX is included in the calculation, Case 1 switches to be an added cost balancing around the current ETS price while for Case 2 the LNG abatement cost is higher in the WtW perspective compared to blue ammonia.

Case 2 with high energy prices especially for natural gas/LNG and electricity illustrates how the picture can change within a short time range. The abatement cost for blue ammonia increases from 350 $/tonne to almost 850 $/tonne, but still it is a significantly lower increase compared to e-methanol Point Source increasing from 660$/tonne to 1890$/tonne. The increase in abatement cost closely corresponds with the increase in the fuel production costs (ref. Figure 5-8).

Case 2 illustrates the benefit of fuel flexibility to enable selection of the right energy source depending on the market. It also rises the importance of knowing the risk of price sensitivity to the energy market of the selected fuel.

5.3.6 Energy efficiency sensitivity analysis

The abatement cost of low-carbon fuels can be reduced by including energy efficiency technology on the vessel to reduce fuel consumption. Due to the higher energy cost of low-carbon fuels, investments in technologies like rotor sails will become more important and attractive. The Equinor ship cost model includes expected performance data and cost for rotor sails and sensitivity cases are calculated to investigate the business case of one to three 35x5 meter rotor sails and the impact on abatement cost.



	VLSFO Fossil - 2 Stroke HP	NH3 FR Blue - 2 Stroke HP	NH3 FR Blue - One 35mx5m rotor sail	NH3 FR Blue - Two 35mx5m rotor sails	NH3 FR Blue - Three 35mx5m rotor sails
WTW	38 050	8 999	8 767	8 535	8 304
TTW	32 568	5 031	4 925	4 820	4 714
WTT	5 482	3 968	3 842	3 716	3 590
Abatement cost WTW	0	332	319	307	294
Abatement cost TW	0	350	338	326	314

Figure 5-12 Case 1 – Flettner Rotor sails sensitivity analysis.

The result as presented in Figure 5-12 is a reduction in abatement cost on a Tank-to-Wake basis from 350 to 314 USD/tonne CO_2e with an estimated reduction in ammonia consumption of more than 10%. The feasibility of installing 3 rotor sails on the pilot vessel is not further investigated, but the positive result on reduced energy consumption and costs points to the importance of energy efficiency and optimised design for vessels going forward.

5.4 Fuel impact on Energy Efficiency Operating Indicator

The Energy Efficiency Operating indicator (EEOI) is the main parameter for emissions performance selected by Equinor and externally by the Sea Cargo Charter. The impact of low-carbon fuels will significantly reduce the carbon intensity of the shipping operation as illustrated in Figure 5-13.

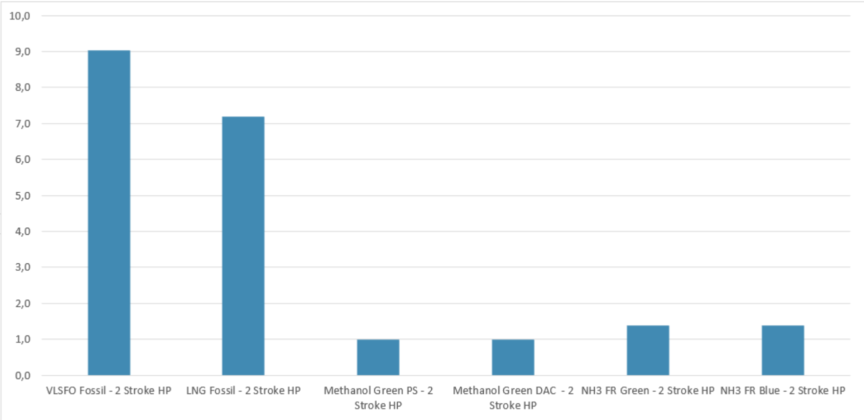


Figure 5-13: Energy Efficiency Operating Indicating [gCO_2e / tonne mile]

6 Key findings

To ensure the uptake of Ammonia as a viable fuel for low-carbon ocean transport, several areas of development need to be addressed. The overall learnings are detailed in the respective chapters. However, a summary of the key/identified technical and operational developments required can be found below. The results should be applicable for a variety of ship segments in addition to crude and product tankers.

What we have learned

- Blue and green ammonia and e-methanol can significantly reduce WtW GHG emissions.
    - Actual GHG intensity in the value chain is key and must be certified.
- Blue and green ammonia gives more cost-efficient decarbonisation than e-methanol.
    - Current carbon pricing (ETS) will not close the gap.
    - Contracts for difference is currently required for economic feasibility.
- Framework for safe design of ammonia fuel systems and bunkering is maturing.
    - Safe ammonia cargo handling is proven technology on gas carriers.
    - Bunkering guidelines should be developed based on LNG bunkering and ammonia cargo handling.
- Technical feasible to integrate a DF ammonia system on an Aframax tanker.
    - CAPEX comparable to LNG
    - Sufficient range for deep sea trade with ammonia fuel
    - Ship to Ship is a flexible bunkering option for first movers.
- Ammonia technology is under development.
- Energy efficiency and reduction of fuel consumption is key in newbuild design utilising low-carbon fuels.
    - Optimised hull design, onboard energy system, energy efficiency devices and wind assisted propulsion.
    - Tanker specific requirements and design optimization including optimised Inert gas system and electrical driven cargo pumps.

Way forward

- Optimised ship concept development
    - Optimise energy efficiency and reduce fuel consumption.
    - Layout and ship arrangement
    - Cargo operations (inert gas and pumps)
    - Shore power
- Ammonia specific equipment development
- Further de-risking of ammonia fuel handling
    - Operators and crew training
    - Water curtain barrier efficiency
    - Liquid spill / spill to sea
    - Risk analysis of bunkering process (StS)
    - Synergy with Equinor ammonia PSV retrofit projects.

Together with the industry - bring the use of ammonia to the required safety levels for cost efficient decarbonisation of shipping!

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