Nordic Innovation

NoGAPS: Nordic Green Ammonia Powered Ship

Project Report

2021

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About Fürstenberg Maritime Advisory

Fürstenberg Maritime Advisory is an independent maritime consultancy, helping all actors across the maritime space to innovate and take the right strategic decisions in a time of unprecedented change.

About Nordic Innovation

Nordic Innovation is an organization under the Nordic Council of Ministers. Nordic Innovation aims to make the Nordics a pioneering region for sustainable growth and works to promote entrepreneurship, innovation and competitiveness in Nordic business.

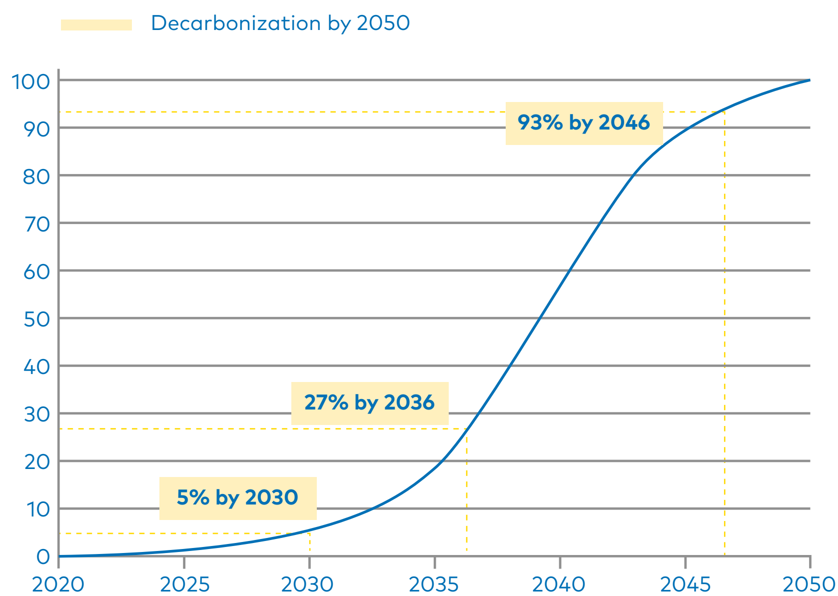
Executive summary

The Nordic Green Ammonia-Powered Ship

Findings from the Nordic Innovation concept study

Why zero-emission shipping?

Decarbonizing the global economy – an urgent priority if the world is to avoid the worst impacts of climate change – cannot be achieved without the decarbonization of global shipping. Momentum is building behind the transition to zero-emission shipping, and there is growing understanding of what needs to be achieved by when. An analysis for the Getting to Zero Coalition estimates that achieving long-term decarbonization objectives would require that zero-emission fuels make up 5% of the international fuel mix by 2030.



Decarbonization by 2050:
Zero emission fuel adoption rate (Source: COP26 Climate Champions, UMAS)

Understanding of the technological solutions needed to deliver that objective is also growing. Increasingly, ammonia-powered shipping is seen as central to achieving these objectives. Among zero-emission fuels, ammonia offers many advantages related to its potential scalability and application on long-distance routes. There is an urgent need to demonstrate the viability of powering ships with green ammonia – demonstrations that will need to encompass the design and construction of new vessels, a sourcing strategy for green ammonia fuel, and the elaboration of credible business and financial models.

Pillar 1
Ships capable of running on zero-emission fuels such as green ammonia must be designed, built, and demonstrated in an operating environment.

Pillar 2
Zero-emission fuels such as green ammonia must be produced at scale, certified as green, and have their costs brought down.

Pillar 3
Infrastructure for bunkering zero-emission fuels such as green ammonia must be developed

Foundation of all 3 pillars: Business models, financing and policy need to be developed to efficiently allocate risk, cost, and benefits across the value chain.

The NoGAPS concept

The Nordic region is in a unique position to pioneer ammonia-powered shipping. Already home to plentiful renewable energy, large-scale ammonia production, and some of the world's leading shipping companies and engine manufacturers, the Nordic region has an opportunity to build the value chain for ammonia-powered shipping on an accelerated timetable.

The NoGAPS project brings together key players in the value chain for a Nordic-based ammonia-powered vessel. Together this consortium has elaborated a concept for an ammonia-powered gas carrier, transporting ammonia as a cargo in Northern Europe and using zero-emission ammonia as a fuel.

In line with the pillars of zero-emission shipping, the consortium investigated the vessel, the fuel and the fueling options, as well as the business and financing considerations. The major conclusions were clear:

1. The potential of ammonia-powered shipping to contribute to the decarbonization of the maritime sector is significant, and ammonia carriers present a logical starting point for demonstrating this potential.
2. Neither the technical considerations nor the associated regulatory approval for an ammonia-powered vessel present major obstacles to putting the M/S NoGAPS on the water.
3. Ammonia synthesized from green hydrogen represents a credible long-term, zero-emission fuel.
4. The most important challenge to be overcome is to develop and demonstrate a business model that is credible in the eyes of investors and operators. Both the vessel design and the fuel sourcing strategy offer opportunities to reduce risks and costs in meaningful ways.
5. Government support and public finance can both accelerate the short-term timetable for investment in demonstration and improve the outlook for long-term deployment of ammonia as a shipping fuel.

The ammonia-powered vessel

Powering a vessel by using ammonia as a fuel is practical and feasible, and engines should be available as early as 2024. These engines will need to minimize the release of unburnt ammonia as well as N_2O and NO_x emissions, but good solutions for doing so look to be available. The expected design pathway for these engines will be dual fuel, which will help mitigate the risks to investors in the ships, as the availability of green ammonia fuel remains to be seen.

New vessel designs will need to accommodate larger fuel tanks, as well as safety considerations to minimize the possibility of leaks, since ammonia is toxic to people and the environment. While the best options for minimizing risks are still being explored, the M/S NoGAPS is designed as a carrier of ammonia cargo, so that relevant routines and protocols for safe handling of ammonia will already be in place and can be adapted for ammonia fuels.

Sourcing green ammonia

The production of green ammonia presents few technical challenges, and while total costs are much higher than for traditional ammonia or fossil fuels, these costs can be expected to come down as production is scaled up and operational efficiency improves. Nonetheless, green ammonia is not widely available today, so pioneering vessels like the M/S NoGAPS will need to put in place a fuel strategy.

In order to prove the concept of ammonia-powered shipping, the M/S NoGAPS can begin its operating life using conventional 'grey' ammonia – produced with fossil fuel inputs – as a fuel. This ammonia is chemically precisely the same as green ammonia, and will allow the vessel operators to test the fuel and develop systems for bunkering and handling safety issues. Over time, green ammonia will become more available to be purchased on a certified mass-balance basis, and policy-based incentives for its production and use such as feebates or Contracts for Difference can be expected to make the transition to green ammonia more economical, a key to making the overall business case for the vessel work.

The business and financing models

Due to the currently high costs of green ammonia relative to conventional shipping fuels, developing a business case that can secure the necessary investment is the biggest challenge facing the NoGAPS consortium. Early action on ammonia-powered shipping is a strategic choice, but to make that action investable, costs, benefits and risks must be distributed efficiently in the value chain and among stakeholders in society.

The project partners have identified a number of measures that can strengthen the business case:

1. Some in-kind contributions/financial concessions to reduce the risks of cost overruns
2. Vessel design optimization to minimize the cost related to ammonia fuel storage
3. A long-term chartering contract or joint venture to decrease the risk of ship ownership
4. Dual fuel capabilities to decrease the exposure to fuel supply risks
5. A transition strategy from grey NH_3 to green NH_3 that is aligned with access to subsidies and premia and reflected in the risk sharing in the chartering contract/joint venture

The following complementary measures by governments will likely be necessary:

1. Grant financing of the "excess" costs of vessel construction relative to conventional ships
2. Loan guarantees
3. Contracts for difference or equivalent for green ammonia production/use
4. Eventual regulations or incentives for CO_2 reductions

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Glossary

Capital Expenditure (CAPEX): Expenses incurred to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology or equipment.

Green Ammonia: Green ammonia is produced through combining green hydrogen with nitrogen separated from the air.

Green Hydrogen: Hydrogen produced through the process of splitting water into hydrogen and oxygen through electrolysis using renewable electricity.

Hazard Identification (HAZID): Evaluation method for identification of potential hazards in design.

Hazard and Operability study (HAZOP): Evaluation method for identification of operability hazards in design.

Heavy Fuel Oil (HFO): A fraction obtained from petroleum distillation, either as a distillate or a residue that is commonly used as primary fuel in large ship engines.

ICE: Internal Combustion Engines.

International Maritime Organization (IMO): A specialized agency of the United Nations responsible for regulating shipping.

Liquefied Natural Gas (LNG): Natural gas (primarily methane) that has been liquefied by reducing its temperature to -162°C at atmospheric pressure.

Operating Expense (OPEX): Segment expenses related both to revenue from sales to unaffiliated customers and revenue from intersegment sales or transfers, excluding loss on disposition of property, plant, and equipment; interest expenses and financial charges; foreign currency translation effects; minority interest; and income taxes.

Scalability: ability to increase production by adding additional resources.

Selective Catalytic Reduction (SCR): a means of converting NOx into N_2 and H_2O by using a catalyst.

1. Introduction

Toward zero emissions: the shipping sector in transition

In April 2018, the International Maritime Organization (IMO) set an objective to reduce absolute GHG emissions from shipping by at least 50% by 2050 compared with a 2008 baseline. To achieve this target and ultimately progress towards carbon neutrality in the sector by mid-century, in line with Intergovernmental Panel on Climate Change (IPCC) scenarios to limit the rise in global temperature to 1.5°C, shipping will need to go beyond operational and energy efficiency and deploy zero-emission fuels and propulsion technologies. Given the 20-30-year lifetime of vessels and other industry assets, the maritime sector must therefore ensure that zero-emission vessels are operating on a commercial scale on deep-sea trade routes by 2030. An analysis for the Getting to Zero Coalition estimated that achieving long-term decarbonization objectives would require that zero-emission fuels make up 5% of the international fuel mix by that point.[1] To reach these objectives, accelerating investments in zero-emission fuels and technologies will be crucial.

The decarbonization of shipping is fundamentally interlinked with the land-based transition to renewable sources of primary energy and particularly to the adoption of hydrogen as an energy carrier. The decarbonization of shipping depends on the availability of green hydrogen; conversely, the scaling up of land-based green hydrogen production will not happen without reliable, large sources of demand and the construction of associated electricity generation and hydrogen production and storage infrastructure. The adoption of green ammonia as a fuel for international shipping may be the most promising route to decarbonizing the most challenging segments of the industry. By accelerating its own deployment of ammonia-powered vessels, shipping can act as enabler for the wider decarbonization of the world's energy usage.

The pillars of zero-emission shipping

Zero-emission shipping must be built on three pillars:

1. **Vessels** capable of running on alternative, zero-emission fuels must be developed, tested, and deployed at scale. While there will also be some potential for retrofitting existing ships, many of the ships likely to run on zero-emission hydrogen-based fuels will be new builds. Changes will need to be made both to engine and vessel design, and safety, reliability and performance proven in operational contexts.
2. **Zero-emission fuels** will need to be produced in large quantities. Producing these fuels using zero-emission hydrogen appears to be the most scalable available solution, though bio-based fuels will have a role to play. Technologies for the production of zero-emission fuels such as green ammonia are well-understood today, but volumes remain miniscule and costs relatively high. Business models that enable efficient and economic fuel production will need to be developed.
3. **Financing and investment** in both existing and new infrastructure is necessary to decarbonize shipping across the value chain.

1 Getting to Zero Coalition, Five percent zero emission fuels by 2030 needed for Paris-aligned shipping decarbonization (2021) https://www.globalmaritimeforum.org/content/2021/03/Getting-to-Zero-Coalition_Five-percent-zero-emission-fuels-by-2030.pdf

None of these pillars requires unknown or immature technological solutions. The main barrier to their construction is the so-called chicken-and-egg problem, whereby the actors responsible for developing and investing in each pillar will hesitate to do so without the other two being in place.

The role of demonstration at scale

Pilot and demonstration schemes will be at the heart of overcoming this chicken-and-egg problem. By demonstrating solutions in each pillar – particularly at full-scale as part of an operational supply chain – these projects will prove the zero-emission shipping concept, build confidence among relevant parties, and move the technologies involved along the S-curve of innovation, in which a slow growth during a development demonstration phase transforms into rapid scale up and rollout via market-based dissemination.

There is considerable activity in the technological development of ammonia-powered vessels and associated propulsion systems. In its *Mapping of Zero Emission Pilots and Demonstration Projects*, the Getting to Zero Coalition identified 14 shipping technology concept studies, pilots, and demonstrations focused on ammonia powered shipping being undertaken in Japan, China, South Korea, Greece, and Northern Europe. Another nine projects on ammonia production and fuelling infrastructure for shipping were identified. Both of the leading global ship engine manufacturers are engaged with the research and development of ammonia engines. At least five shipyards and three classification societies are also involved in progress with ammonia as a ship fuel, as are numerous academic institutions. More often than not, ammonia features in the steady flow of new papers dealing with the transition of maritime fuels, and numerous quantitative modelling exercises have identified ammonia as a high-potential fossil-free fuel alternative for shipping.[2]

The Nordic Green Ammonia Powered Ship

Ammonia offers a number of advantages as an alternative fuel for zero-emission shipping. Just as importantly, ammonia carriers offer an important point of entry for proving ammonia as a shipping fuel, with potential synergies in safety, handling, and fuelling. This report showcases a concept for how this could happen.

Through this concept study, the report identifies existing barriers – technological, regulatory, financial, and commercial – for putting an ocean-going green ammonia-powered vessel in the water through the lens of the three pillars of zero-emission shipping. Options for addressing these barriers in the shipping sector at large will be touched upon. Simultaneously, the report will introduce a specific 'case vessel' – the ammonia-powered ammonia carrier, the *M/S NoGAPS* – to illustrate how barriers could be addressed in a potential joint effort involving the partners of this project, based in Northern Europe. The report views the M/S NoGAPS from a full value chain perspective – introducing concepts for ship design and operation, but also for fuel supply and for the business and investment case.

2 Getting to Zero Coalition, Mapping of Zero Emission Pilots and Demonstration Projects (2021) https://www.globalmaritimeforum.org/news/new-mapping-of-zero-emission-pilots-and-demonstration-projects-shows-an-increasing-focus-on-hydrogen-based-fuels

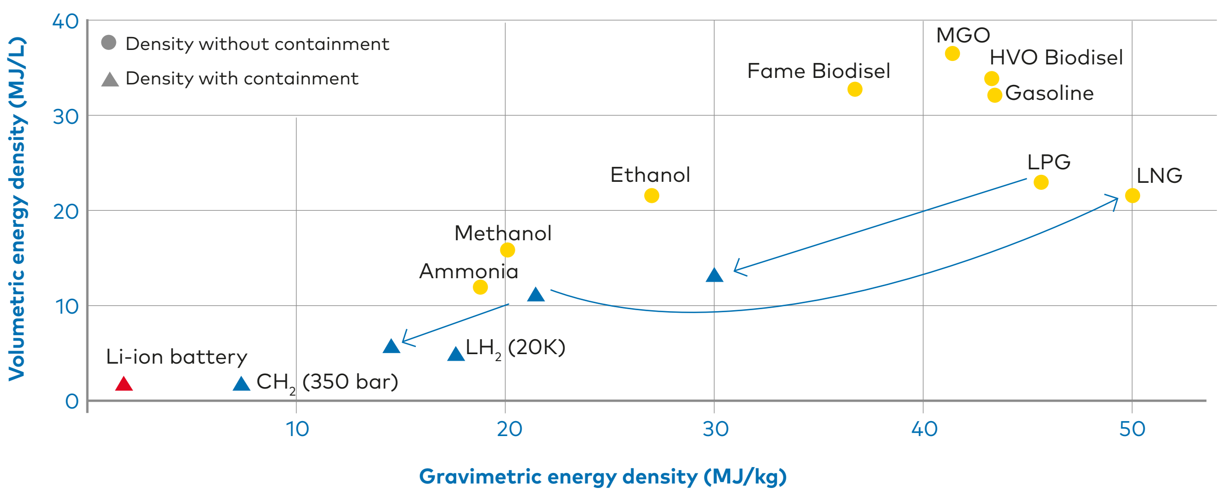
2. The ammonia-powered vessel

This chapter will delve into why the application of ammonia is attractive as a maritime fuel, and the implications ammonia as a fuel has for vessel technology, safety, and environmental impact. Regulatory implications of using ammonia as a fuel will be presented, and proposals for handling key issues in the design and operation of the M/S NoGAPS ship are explored.

2.1. Ammonia as a shipping fuel

As a fuel carried onboard, ammonia comes with a number of advantages and disadvantages. It will impact the design of the engine, the fuel system, and general arrangements on and below deck.

Ammonia has a lower energy density than traditional fossil fuels. Figure 1 illustrates the relative energy densities of the traditional and leading alternative fuel solutions.



Ammonia is easier and less energy intensive to contain in storage compared to hydrogen. The cost of energy storage is cheaper for ammonia than for either hydrogen, electricity in batteries, or liquefied petroleum gas (LPG). Table 1 below compares the different fuel types.

Figure 1: Energy density of fuel types. Energy density of ammonia, LPG, LNG and H_2 is lowered when considering the mass and space requirements of necessary containment structures. (DNV, 2020)

	MDO	LPG	H2 350 bar	H2 liquid	Ammonia	Methanol
Density (t/m3)	0.835	0.49	0.023	0.071	0.68	0.792
LHV (GJ/t)	42.7	46	120	120	18.6	19.9
GJ/m3	35.7	22.6	2.80	8.52	11.4	16
Volume (m3/ GJ) normalized	1	1.58	12.75	4.18	3.14	2.23

Table 1: Comparison of volumes required per energy unit on lower heating value basis for ammonia compared to MDO, LPG, methanol and hydrogen (DNV, 2020)

2.2 Vessel design and operation

Ammonia is a carbon-free fuel that, with the aid of a pilot fuel to help overcome its relatively low explosiveness, can readily be used in an internal combustion engine. Doing so will require some adjustments to the design and operation of the engine and vessel to ensure safety and minimize environmental impact. This work is ongoing in the sector and at present none of the developmental needs appear to present major technical hurdles. The following sections examine some of the options for implementation in the NoGAPS case.

2.3 Safety considerations

Ammonia has implications for the safe operation of a ship. It is toxic to humans and animals, even at low concentrations. Ammonia is also corrosive to certain materials, which must be considered in design and construction. Any leakage of ammonia to the environment will also have a negative impact, and mitigation measures must be put in place. At the same time, ammonia is already carried as maritime cargo, so protocols for handling the substance exist. The following fact box provides information on the safe handling of ammonia.

The cost of handling a toxic fuel depends on both toxicity and flammability/explosiveness, and many measures contribute to mitigating both. In the case of ammonia, the toxicity risks are higher than many other options, but the flammability risks are lower, so that the overall costs are expected to be manageable. While liquid fuels such as methanol or Marine Gas Oil (MGO) may be cheaper to handle, ammonia's handling costs should not differ from those of other gaseous fuels, such as liquefied natural gas (LNG), once First of a Kind (FoaK) technology deviations have been overcome.

The vessel design will need to mitigate the risks of large leaks, especially in confined spaces where the crew could be exposed. Mitigation may affect the location of accommodation to reduce impact from accidental ammonia discharges, or the location of safety equipment such as emergency generators and lifeboats. Prior to final design of the vessel, thorough, in detail HAZIDs and HAZOPs[3] must be completed. These exercises will build upon the safety case work available for existing but traditionally fuelled ammonia carriers. It is a distinct advantage that crews on ammonia carriers already have specialized knowledge and training with regard to the handling of ammonia.

3 Requirements for a safe ammonia fuel system will include so called passive safety measures inherent in the design, as well as active safety measures to assist crew onboard. A safety level equivalent to that of natural gas has to be demonstrated, which means the toxic properties of ammonia must be taken into account in the design and demonstrated not to pose any additional risk to personnel or environment.

SAFE HANDLING OF AMMONIA

Ammonia in liquid or vapour form reacts acutely with water to form ammonium hydroxide, a strong base. When inhaled or coming into contact other moist parts of the body such as the eyes, it causes at least irritation and at worst severe tissue damage, depending upon exposure concentration.

Ammonia is not considered carcinogenic and all impacts upon the body are rooted in the "burn" effect from ammonium hydroxide. There is not a great deal of evidence for the effects from long-term low-level exposure, possibly because its presence is already highly irritating at just 50ppm. However, prolonged exposure can dull sense of smell, so sensor equipment remains highly relevant.

The following should be noted when considering the handling of ammonia:

- When even small leaks occur from an ammonia plant they reveal themselves very clearly by smell and can be dealt with by wearing appropriate equipment to protect the eyes, respiratory system, and moist areas of skin.
- The toxicity of ammonia is such that it irritates a low-levels, demanding immediate action yet at this point presenting no serious health hazard.
- Ammonia thus presents no risk of chronic health impacts from insidious low-level and long-duration exposure as is common with many other toxic compounds.
- Conversely, large leaks of ammonia within confined spaces may, due to the intense acute effects in high concentrations, pose a relatively higher health risk. Mitigations for such events therefore need to be taken at the design stage and by implementing operational contingency solutions.

Table 2: Summary of toxic effects following acute exposure to ammonia by inhalation (Public Health England, Compendium of Chemical Hazards: Ammonia, 2015)

Exposure		Signs and symptoms
mg/m³	ppm	
35	50	Irritation to eyes, nose and throat (2 hours' exposure)
70	100	Rapid eye and respiratory tract irritation
174	250	Tolerable by most people (30–60 minutes' exposure)
488	700	Immediately irritating to eyes and throat
>1,045	>1,500	Pulmonary oedema , coughing, laryngospasm
1,740–3,134	2,500–4,500	Fatal (30 minutes' exposure)
3,480–6,965	5,000–10,000	Rapidly fatal due to airway obstruction, may also cause skin damage

Values in mg/m³ are approximate calculations from ppm, mg/m³ = ppm x gram molecular weight/24.45 (molar volume of air at standard temperature and pressure)

Environmental risks

Ammonia presents risks to the environment that also need to be mitigated. Since the environmental risks of ammonia carried as a cargo are already well regulated, the focus on future investigations will be on any additional risks to the environment from using ammonia as a fuel. Ammonia may, upon combustion, release unburnt ammonia (so-called ammonia slip). Ammonia can be harmful to aquatic organisms even at low concentrations, though variable conditions such as water temperature and pH will impact the actual level of toxicity (see Fact Box – Aquatic Toxicity of Ammonia). If there is a greater risk of ammonia leakage to the environment from fuel operations, additional safety measures will be needed.

The ammonia molecule, composed of one nitrogen atom and three hydrogen atoms (NH_3), is carbon free. Chapter 3 details the various ways to produce ammonia and its environmental profile during the process. The GHG footprint of ammonia will largely depend upon the energy and feedstock used. When combusted in an engine, it may produce another greenhouse gas, nitrous oxide (N_2O). Such emissions must be mitigated for ammonia to have zero GHG impact.

Use of ammonia as a fuel may also lead to emissions of NO_x and N_2O, and ammonia in the exhaust can trigger smog to develop, due to an affinity for pm 2.5 particles. These issues will need to be investigated as part of ongoing research. NO_x emissions will have to meet IMO's existing Tier II or Tier III emission standards, and new regulations are expected to be developed to mitigate N_2O and ammonia slip. A limit of 10 ppm ammonia slip with the exhaust would be in line with standards previously applied to selective catalytic reduction (SCR).

Existing technologies will likely be able to mitigate both slip and NO_x/N_2O emissions, though they will need to be proven effective in shipping. These installations may be large, but the cost penalty for inserting emission abatement systems to the exhaust train is expected to have greater impact on OPEX than CAPEX as catalytic conversion may reduce engine efficiency by up to a few per cent. These costs should be considered in the context of similar costs for managing nitric oxides control in traditional fuel engines. Emission mitigation solutions must be compatible with relevant flows and temperature in the combustion cycle, as well as with the presence of sulphur in pilot- and lubrication fuels.

AQUATIC TOXICITY OF AMMONIA

Ammonia can be toxic to aquatic life at low concentrations*, but in soils and water ammonia will go through many complex biochemical transformations.

Water reacts with ammonia (NH_3) to form ammonium (NH_4) and hydroxide ions. While ammonia is toxic to aquatic organisms, ammonium is non-toxic. The balance between the toxic and non-toxic compounds is affected by the water temperature and pH (acidity) – at higher temperatures and higher pH (lower acidity), the amount of toxic ammonia will increase.

$$\underset{\text{(ammonia in water)}}{NH_3\,(aq) + H_2O\,(l)} \rightleftarrows \underset{\text{(ammonia + water)}}{NH_3 \cdot H_2O\,(aq)} \rightleftarrows \underset{\text{(ammonia in water)}}{NH_4^+\,(aq) + OH^-\,(aq)}$$

*At a concentration of 0.02 mg/L (48 hour LC50) un-ionized ammonia is lethal to some sensitive freshwater fish. This equates to about 3 CL of un-ionized ammonia in one million L of water. Source: https://www.mda.state.mn.us/ecological-effects-ammonia

Fuel storage and cargo carrying capacity

When considering the additional cost of employing alternative fuels, the loss of cargo carrying capacity due to the requirement to carry larger volumes of fuel needs to be considered. Ammonia-fuelled ships will require CAPEX for storage containment installation, but this is unlikely to be prohibitive when considered as a percentage of the far greater eventual OPEX related to fuel costs (see Chapter 3). In comparison, the cost for hydrogen storage installation does present a considerable CAPEX requirement, even in comparison to OPEX.

Propulsion/engine design and operation

Ammonia is not as explosive as carbon-based fuels or hydrogen and will not easily combust on its own in current internal combustion engines. The initiation of ammonia combustion therefore requires the input of additional energy via a small amount of a higher-responding fuel which, when ignited, gets the ammonia combustion underway. The proportion of pilot fuel required is not yet established but it is expected to be well below 30%.

The current development of two-stroke engines for burning ammonia is based upon dual-fuel technology for conventional fuel oil and liquefied petroleum gas (LPG). These engines can be run with traditional fuel only or with LPG, utilizing (as above) a small amount of pilot fuel. The ambition is to re-engineer such engines for dual fuel operation with ammonia instead of LPG. For ammonia engines designed to be dual fuel, Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO) are the likeliest candidates as pilot fuel. This starting point yields considerable cost savings and such a pilot fuel can be interchanged with net zero alternatives such as biodiesel.

Dual fuel engines will allow for some flexibility in fuel usage by shifting to conventional fuel use. This may be especially important for ammonia-powered ships that are not themselves carrying ammonia as a cargo. Flexibility could reduce risks during the early years of operation when ammonia fuel may not be readily available everywhere the vessel would prefer to be employed. For investors, such flexibility would also reduce both the technology risk involved with such a project and the risk of stranded asset.

Regulatory issues and processes

Safety guidelines for ammonia fuel aboard ships are under development, and Class Rules will likely be the earliest regulatory framework in place for using ammonia as a fuel. Until statutory legislation is adopted by the IMO, Flag Administrations and associated Recognized Organizations will need to approve ammonia-powered ships based on Alternative Design Assessments. This is similar to the manner in which many pioneering shipping advancements have previously been launched, with regulatory bodies ready to adapt to the need to facilitate progress.

Regulatory requirements are developed at international and national levels. Acceptance of the vessel by the required regulatory bodies is necessary to be able to trade and to get insurance. Acceptance will progress through the following stages:

- The role of the ***Classification Society*** is to ensure the ship is designed and able to operate according to applicable requirements for safety of the ship, crew, and the environment embedded in their Rules. Based on the concept design, Class may issue an Approval in Principle (AiP) which indicates that the concept has the potential to meet the Rule requirement.
- In addition, the vessel operator is responsible for and must ensure vessel ***compliance with Port State-specific requirements*** (e.g. emission requirements) that may apply for territorial waters of ports where the vessels intends to trade.
- Finally, updates of the ***IGC code at IMO*** level will assist in reducing barriers to adopting implementation of ammonia as fuel on gas carriers on a world-wide scale.

See Table 3 for function and distribution of responsibility between relevant regulatory bodies.

Table 3: Regulatory stakeholders for ship approval

Regulatory Body	Jurisdiction	Function	Term	Rules specifically relevant to project
IMO	International according to internationally agreed conventions as ratified by national government.	To set a baseline set of internationally agreed standards for the safety, security and environmental performance of international shipping.	The IMO	IGC IGF STCW
Flag State, Flag Administration, National Maritime	The ship, national	To enforce Statutory requirements as agreed at the IMO for ships enrolled in the applicable Flag Administration's registry	Flag, Flag State, Flag Adminstration	Statutory requirements and applicable local interpretations/adaptations
Classification Society, Class	The ship	To regulate the design and operation of ships enrolled into Class to ensure the safety for life, environment and property. To perform certain regulatory approvals on behalf of Flag if selected for delegation. Obtaining Class approval is mandatory for vessels on international voyages under IMO requirements.	Class	Class Rules
Port State, National Maritime Authority	Any national waters within their Economic Zone	To ensure that ships visiting their territorial waters comply with international, regional and national regulations.	Port State	Typically, Port States belong to groups which share common enforcement guidelines and vetting information. These groups sign common Memoranda of Understanding (MOA)

The IGC Code and the IGF Code

The IGC code applies to tank ships carrying liquified gases in bunk, and currently contains a provision against the use of toxic cargo as a fuel. This will eventually need to be revised in order to operate an ammonia-powered vessel in accordance with the code. In the interim, operators can apply to a Flag Administration for exemption from such a requirement based on sound technical justification. By demonstrating through an Alternative Design Assessment that an equivalent level of safety is provided, an ammonia-powered vessel may be granted approval.

IGC CODE

The IGC Code is the International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk adopted by IMO resolution MSC.5(48). This Code applies to ships engaged in the carriage of liquefied gases having a vapour pressure exceeding 2.8 bar absolute at a temperature of 37.8°C, and other products covered by this Code, when carried in bulk. Ammonia, which exhibits physical properties within these ranges is also mentioned specifically in the Code's special requirements section. In addition to fire prevention, the special requirements largely deal with prevention of stress corrosion cracking and refer to steel strength and composition design elements which are needed to manage the additional risk posed by ammonia.

In relation to stress corrosion cracking, the Code refers to the need for operational risk reduction by minimizing oxygen content with the cargo. A well-established industry standard (Fertilizers Europe and Yara) ensures minimum 2000 ppm water is added to the traded and shipped ammonia, in order to avoid stress corrosion. The same would appear to apply for ammonia as a fuel. Chapter 16 of the IGC Code includes provisions allowing gas carriers to utilize cargo as a fuel. Natural gas (methane) is the Code reference fuel, however, other cargo gases may be permitted given that the same level of safety as natural gas (methane) is provided (ref. requirements in Ch. 16).

Paragraph 16.9.2 does however not permit toxic cargo as a fuel, which seemingly excludes ammonia as a potential fuel for gas carriers.

To trade internationally, acceptance may also need to be obtained from the intended destination Port and/or maritime authorities.[4] Further to equivalent safety, Flag Administrations may also start to accept ammonia as a fuel, based on a given proposal, as all Flags are free to adopt early implementation internally if they so wish.

Another important regulation for ammonia-powered ships, specifically ships other than gas carriers, will be the IGF Code, primarily developed for the use of natural gas or other low-flashpoint fuels. While this code does not prohibit use of toxic gases as fuels, it requires demonstration of an equivalent level of safety for the alternative fuel compared to a conventional fuel.

IGF CODE

The IGF Code is the International Code for Safety for Ships using Gases or other Low-flashpoint Fuels. Any type of fuel subject to the Code needs to meet the Code's functional requirements and provide an equivalent level of safety as conventional fuels (section 2.3 CHECK SECTION Alternative design).

Potential toxicity, which would be relevant for the application of ammonia, is addressed in paragraphs 3.2.6 and 5.2.1.3. Respectively, the paragraphs require the design not to allow unintended accumulation of i.e. toxic gas, and that access to spaces where toxic gas may be present is arranged such that toxic gas may not escape to spaces that are not designed for the presence of such gas.

4 Domestic ports may have objections to accepting ammonia-powered ships due to the fuel's properties.

It is not anticipated that a revision of the IGF Code is required to allow ammonia carriers to use ammonia as a fuel. Regarding the competence for maintenance and operation, presently the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) does not deal specifically with ammonia. STCW review may therefore be in order if any specific requirements to address the use of ammonia as a fuel are applicable. It is fundamentally important that during the development of new ammonia technologies and practices for its application as a fuel, the required training is built in tandem. In the case of any Flag State implementations which are independent and in advance of industry-wide convention, training must be firmly addressed.

2.4 Approval in Principle

Approval in Principle (AiP) from Class Societies is an early-phase approval scheme allowing new designs to progress and is widely recognized in the industry as an early-phase verification level for new design concepts or for existing designs in new applications. This allows for novel designs and concepts to demonstrate project feasibility to project partners or regulatory bodies at an early stage of development. AiP is usually granted under the condition that functional or safety aspects that are not fully developed are demonstrated for the final design stage, and AiP is as such no guarantee for a full Class or Statutory approval (See Fact Box – Approval in Principle).

APPROVAL IN PRINCIPLE

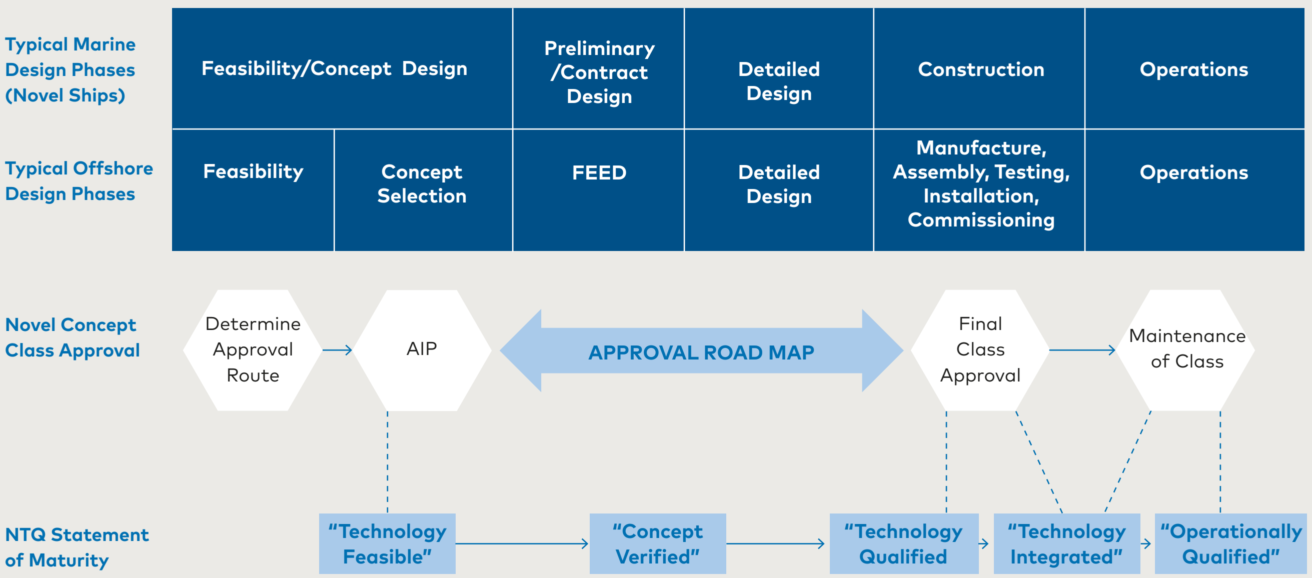


Figure 2: Approval in Principle

An Approval in Principal is an independent assessment of a concept within an agreed framework of requirements for which a Class Society is authorized to carry out third party verification. The AIP review aims to determine the feasibility of the concept according to an agreed scope of documentation where all safety related aspects shall be covered, including functional aspects affecting the evaluation of safety in the design (e.g. assumptions used as basis for justifying safety functions). Extending the scope of documentation beyond minimum requirements of the review will help decrease the uncertainties related to the concept.

The AiP process generates the following output documents:

- Approval in Principle Statement
- Letter of Approval

An AiP Statement confirms compliance with the AiP requirements and is often used as documentation to internal stakeholders, prospective clients and financers that a certain level of confidence has been reached.

The Letter of Approval describes requirements for the AiP in more detail, the reviewed documents, and the conclusions including potential critical issues identified by the review. An Appendix to the Letter may include all comments issued for the documentation during the process.

Figure 2 from ABS, Approval in Principle and Novel Concept Classification (2017) https://ww2.eagle.org/content/dam/eagle/publications/cutsheets/AIP_Novel_Concept_Cutsheet_17099.pdf

2.5 M/S NoGAPS: Handling of key issues in vessel design and operation

The consortium has explored different options for altering of ship and fuel system layouts. In the following sections, the M/S NoGAPS considerations of design, safety, environment, and design approval are presented.

Fuel use and engine design/propulsion

The engine will primarily be designed to operate on industry-grade ammonia, as a dual-fuel option with MDO or low sulphur fuel oils (LSFO). While a pilot fuel percentage cannot be specified at this point, it is *assumed* by the engine manufacturers to amount to 20-30%. Eventual net zero operation will thus necessitate inclusion of a bio-based pilot fuel or one of synthetic origin.

Mitigating safety hazards

Design considerations for M/S NoGAPS include optimizing safety of the crew, vessel, and the environment. For the business case, it is essential that any necessary safety requirements are not prohibitively costly. The consortium has engaged in a high-level HAZID to search for any high magnitude barriers to prevent hazardous events, and which may have major implications for the initial vessel concept. The project has identified some key recommendations for advising the safety of the design. These are detailed in the text box Safe Design Considerations. With regard to the operational safety of personnel, the partners in the project identified a specific opportunity to leverage their perspectives and capabilities from operations further up the ammonia value chain. For example, it was noted that within the shore-based industrial ammonia industry, standalone, self-contained vapour-tight personnel shelters are employed. These are available on the open market and could potentially be employed aboard an ammonia-fuelled tanker where design limitations make risk mitigation challenging. Such measures would build upon extensive existing design regulations for gas and ammonia carriers which have brought about the inclusion of *shelter in place* designs for the bridge and other areas of the vessels.

SAFE DESIGN CONSIDERATIONS

As detailed above, the safety risks of ammonia relate to 1) the formation of the highly basic ammonium hydroxide when ammonia comes in contact with water, 2) leaks, and 3) high levels of exposure due to accumulation in closed spaces. The following design considerations relate to mitigating these three issues.

Considerations related to contact with water:

- Ensure all operational measures particular to the handling of ammonia are thoroughly understood, such as dangers associated with allowing vent hosing to enter the sea.
- Ensure appropriate fire-fighting installations are fitted. In particular ensure that any fire-fighting media are *compatible* with ammonia.

Considerations to prevent ruptures and leaks:

- Consider designing the fuel piping at adequate strength to hold trapped liquid, without relying on venting arrangements. This in order to remove the need for venting pressurized ammonia from the fuel system when, for instance, it is not in use.
- Fuel system piping should be routed in such a way that the risk of mechanical impact or dropped objects is minimized, to reduce the risk of pipe ruptures.

Considerations to avoid accumulation:

- Particularly in areas where a leak from the system could lead to accumulation of fuel, as well as for valves and gaskets, carefully consider the choice of materials to ensure they are suitable for carriage of ammonia, to avoid corrosion.
- Provide an adequate venting system for clearing down the fuel system and machinery during idle time and service. This should include assessment of need for installing liquid collector tanks or ammonia vent scrubber systems. Furthermore consider the installation of a closed purging system to avoid any need for venting.
- Ensure that the engine design includes means of safely clearing vapor from the plant at all times and means of detecting gas accumulation, for example in the crank case. The design must also consider toxicity hazard mitigation, and find venting solutions allowing for 2-stroke propulsion in such an environment.
- Ensure that there is due regard for the risk of leakage from the ammonia fuel system to interfacing systems and that such systems may *benefit* from their own ammonia detection and ventilation arrangements.
- To avoid the hazard of ammonia build-up in enclosed spaces deeper in the vessel, the fuel tanks are located on deck. This design characteristic aligns with the requirements for gas carrier construction. This location of fuel weight higher in the vessel potentially marginalises stability requirements and therefore needs to be carefully managed. Fuel load aspirations should be tested early in a next phase, as fuel tanks located on deck may impact design stability. Tanks need to accommodate for sufficient capacity also during ballast voyages.

Mitigating environmental impact

When operating on ammonia, exhaust from the combustion can include NOx, unburnt ammonia and N_2O. Exhaust after-treatment installations will thus be fitted in order to mitigate emissions of such substances. In order to handle the nitrous oxide emissions, there may be a synergy with the presence of an ammonia fuel feed; fitting an SCR catalyst installation based on ammonia instead of urea may prove to be a superior option for ammonia carriers. This could be looked at in detail for any final design proposal.

Expected approval pathway and design considerations

As detailed above there are various levels of regulatory acceptance to be passed through before the vessel will be considered to be fully approved. However, it should be understood that this is not an unusual situation and need not be a barrier to deployment.

With the expected publishing of DNV Classification rules for ammonia as a fuel in July 2021, the design project will be well placed to advance. The initial objective would be to progress the design to the point of AiP, which could potentially be achieved in Q4 2021. This would address some of the points identified in the safe design considerations mentioned above. Further development of the general safety arrangements would be required, subject to additional risk assessments, in order to properly address risks identified during development. During the AiP period it will also be beneficial to involve an applicable Flag Administration, as well as appropriate authorities in any states at which the vessel is expected to visit. Engagement of the formal approval body to the alternative design assessment as required by the IGC Code will also be pursued. All relevant stakeholders will have the opportunity to contribute, comment and lend provisional agreement to the design principles.

Once AiP is achieved with Class and this acceptance is recognized by the above-mentioned stakeholders, the project will move towards a full construction specification. By this phase, starting perhaps in early 2022, there will be additional clarity on the direction being taken by the IMO with regard to its GHG ambitions. It will therefore be possible to make a reasonable evaluation of the need to additionally futureproof the design for anticipated regulation.

M/S NoGAPS will start its operation (proposed 2024) whilst many regulatory proposals on alternative fuels and their emissions are still undecided, both at regional and international level. It is expected that Class Rules will be in place as a design standard by this time, and that the IGC Code will have provisional guidelines for safety and operation. Operational manuals and procedures must also be in place.

3. Fuel supply & infrastructure

3.1 Ammonia uses and production

Ammonia is an important commodity used as essential feedstock in many industries. While ammonia is not currently used as a marine fuel, it is one of the most widely synthesized natural substances with a global annual production of at 150-180 million tons. Its most common use (about 80%) is for fertilizers. The remaining demand is as feedstock for processes such as chemicals, mining and metallurgy, pulp and paper, fibre and plastics, pharmaceuticals, cleaning agents, explosives, and refrigerants. As a commodity, ammonia is internationally traded and an estimated 20 million tons is carried by ships annually, on general gas tankers as well as dedicated ammonia carriers.

Ammonia is most commonly produced through a century-old process called Haber-Bosch, where atmospheric nitrogen (N_2) reacts with hydrogen (H_2) over an iron-based catalyst under high temperatures and pressures, to produce ammonia (NH_3). The hydrogen source is most commonly methane (CH_4) which is converted to hydrogen and carbon dioxide through a process called steam reforming. In the supply chain, ammonia is typically stored as a liquid, at atmospheric pressure and at -33,6 C, and transported in a semi-pressurized vessel at similar temperatures.

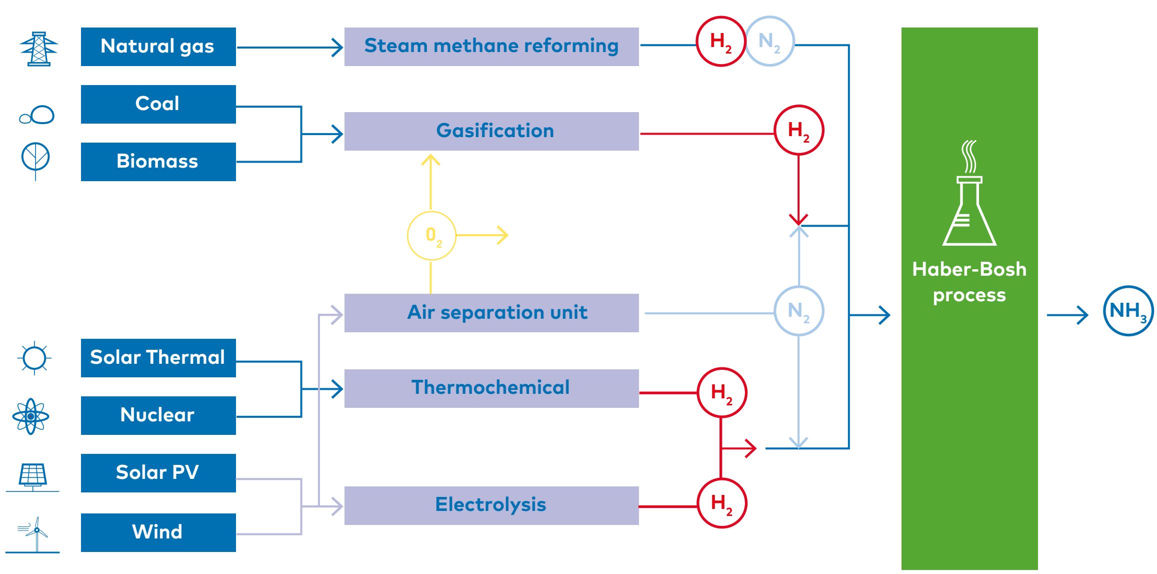


Figure 3: Ammonia production (DNV, 2020)

Like any process dependent on fossil fuels, current ammonia production will have to be shifted to a low- or zero-emission model if climate objectives are to be met. The decarbonization of ammonia production is likely to go hand-in-hand with an increasing overall demand for ammonia as an energy carrier. Interest is already growing in ammonia as an energy carrier or storage medium in industrial and power systems, but the most immediate large-scale use may be as a shipping fuel. The total market for ammonia in these energy applications is potentially several times larger than the total global market for ammonia today.[5]

Ammonia as a fuel

When ammonia is produced through use of low-carbon energy, it can be a promising alternative to fossil fuels. In fact, ammonia can also be used as a hydrogen carrier, as it can be converted back to hydrogen with an acceptable yield ratio and is easier to store and transport. In Saudi Arabia, sustainable city initiative NEOM has announce a 4 GW ammonia plant, with off-taker Air Products intending to convert the ammonia back to hydrogen for use in mobility applications.[6]

Shipping could be a catalyst for scaling demand for green ammonia. As an integrator for trade, shipping can be an important enabler for the shift towards renewables, connecting demand across industries and sectors. While other sectors such as agriculture may also boost demand for green ammonia, buyers are somewhat fragmented. Demand from the maritime industry may have the greatest potential to drive the scale-up in production and distribution infrastructure. Yet if ammonia is to play a large role in decarbonizing shipping, much larger volumes, in the hundreds of millions of tonnes, will be needed. To reach these targets, ammonia plants built for net-zero production need to come on stream. It is therefore particularly promising that Yara recently announced plans to fully electrify its Porsgrunn facility in Norway, producing 500,000 tonnes green ammonia per year by 2026, if sufficient funding can be secured.

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5 IRENA estimates the necessary volumes to decarbonize global shipping with ammonia alone at twice current global production (this does not include other energy applications). IRENA (2019) https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Renewable_Shipping_Sep_2019.pdf

6 Air Products (2021) "Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM Powered by Renewable Energy for Production and Export of Green Hydrogen to Global Markets" [Press Release] https://www.airproducts.com/news-center/2020/07/0707-air-products-agreement-for-green-ammonia-production-facility-for-export-to-hydrogen-market

Certification for use as a fuel

The existing production and trade of ammonia is based upon a high standard of purity. Typically, ammonia is traded in bulk by sea as water conditioned with a certificate of quality specifying composition within the ranges indicated in Table 5 below. Otherwise, ammonia is traded as anhydrous, which usually is carried by specialized road trailers.

Product	Ammonia
Chemical	NH_3
Specification	NH_3 99,7 – 99,8 wt% H_2O 0,2 – 0,3 wt% Oil max 5ppm
	Boiling point –33° C Melting point –78° C Density 0,64 g/cm3 (0° C) Vapor pressure 8,55 bar (20° C) Vapor density 0,6 (air=1)

Table 5: General specification of traded ammonia

Ammonia fuel standards for maritime use in Internal Combustion Engines (ICEs) are under development. While ISO standards are not a requirement for a fuel standard, they will be an enabler for wider uptake of NH3 as a maritime fuel. Sampling and measurement standards will further enable such uptake. MAN Energy Solutions and Wärtsilä have indicated that the first 2-stroke ammonia engine will be available by 2024, and it is expected that fuel standards will be available on roughly the same time scale.[7] While the CO2 footprint of ammonia depends on its feedstock and production efficiency, it averages around 1.6–4 tonnes of CO2 per tonne of ammonia.[8]

7 The estimate includes the total fertilizer production, as well as downstream of ammonia process. (Yara)

8 1.6 t CO2 / t NH_3 estimated BAT plants, and EU ETS benchmark, 2 t CO2 / t NH3 is average for gas-based ammonia plant, and 4 t CO2 / t NH3 for coal-based ammonia plants. (Yara)

EXISTING AMMONIA-RELATED STANDARDS

ISO 3165:1976, Sampling of chemical products for industrial use - Safety in sampling

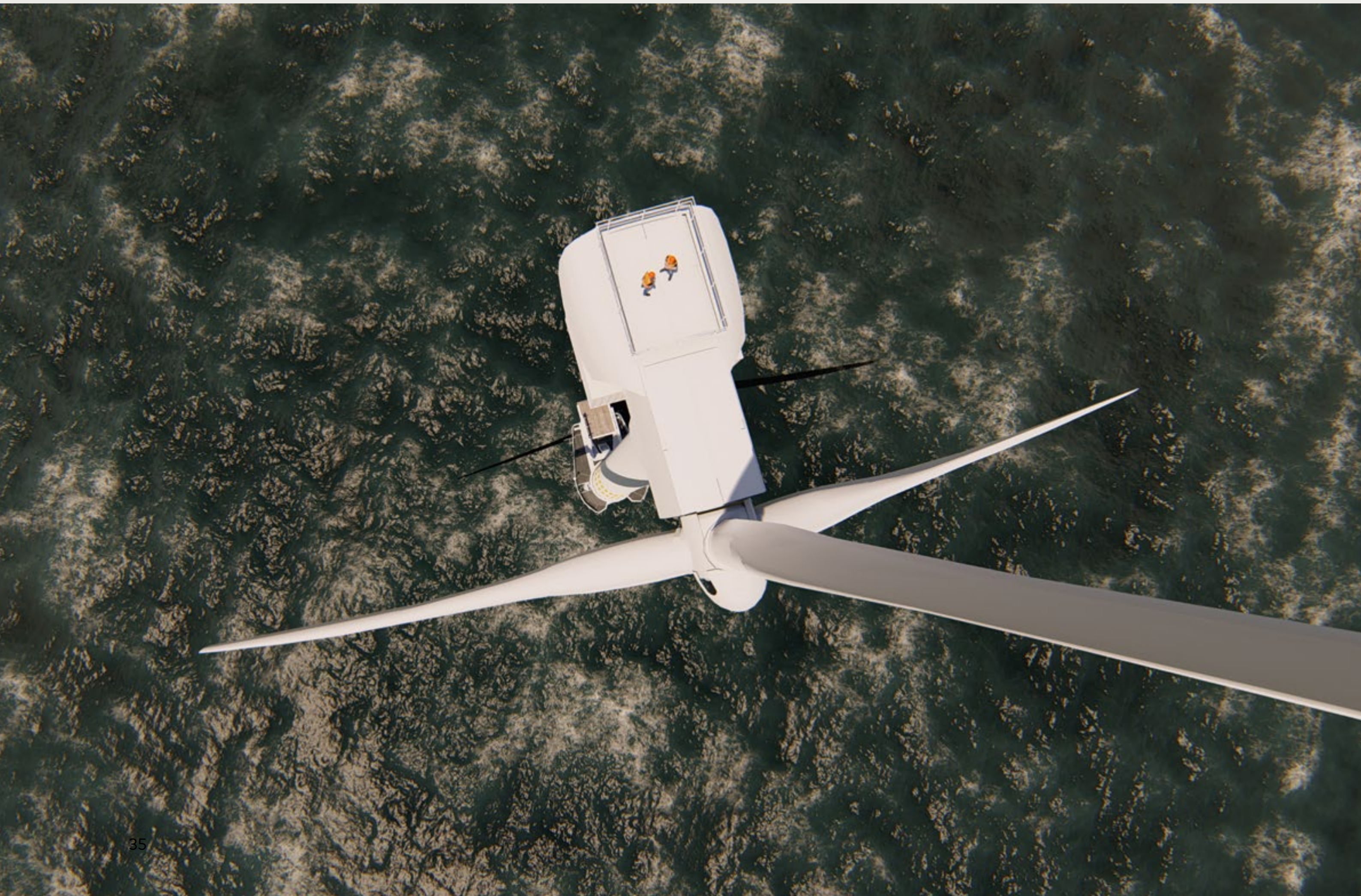
ISO 7103-1982, Liquefied anhydrous ammonia for industrial use – Taking a laboratory sample

ISO 7106-1985, Liquefied anhydrous ammonia for industrial use - Determination of Oil Content - Gravimetric and infra-red spectrometric methods

ISO4276:1978 Anhydrous Ammonia for industrial Use; Evaluation of residue on evaporation: Gravimetric method

MSDS of Anhydrous Ammonia

AOAC Official Methods of Analysis (2000), AOAC Official Method 959.02 – Sampling of Anhydrous Ammonia



3.2 Green ammonia

Green ammonia is the description given to ammonia produced using green hydrogen. In turn, green hydrogen is hydrogen produced using zero-emission electricity to power the electrolysis of water into hydrogen gas and oxygen. This hydrogen gas is then fed into a traditional Haber-Bosch process. The hydrogen and ammonia production processes thus produce no greenhouse gases.

The key step in producing green ammonia from a process perspective is the electrolysis. Electrolysis is a relatively mature technology in use around the world today, though newer system designs technologies are also developing rapidly. The volumes of green hydrogen included in most energy transition scenarios would require electrolysis capacity to expand by many thousand-fold from today's low base.[9] In addition, electrolysis-based hydrogen production is currently much more expensive than steam reforming. The intertwined challenges of scaling up and bringing down costs of electrolysis will be essential to the future economics of green ammonia.

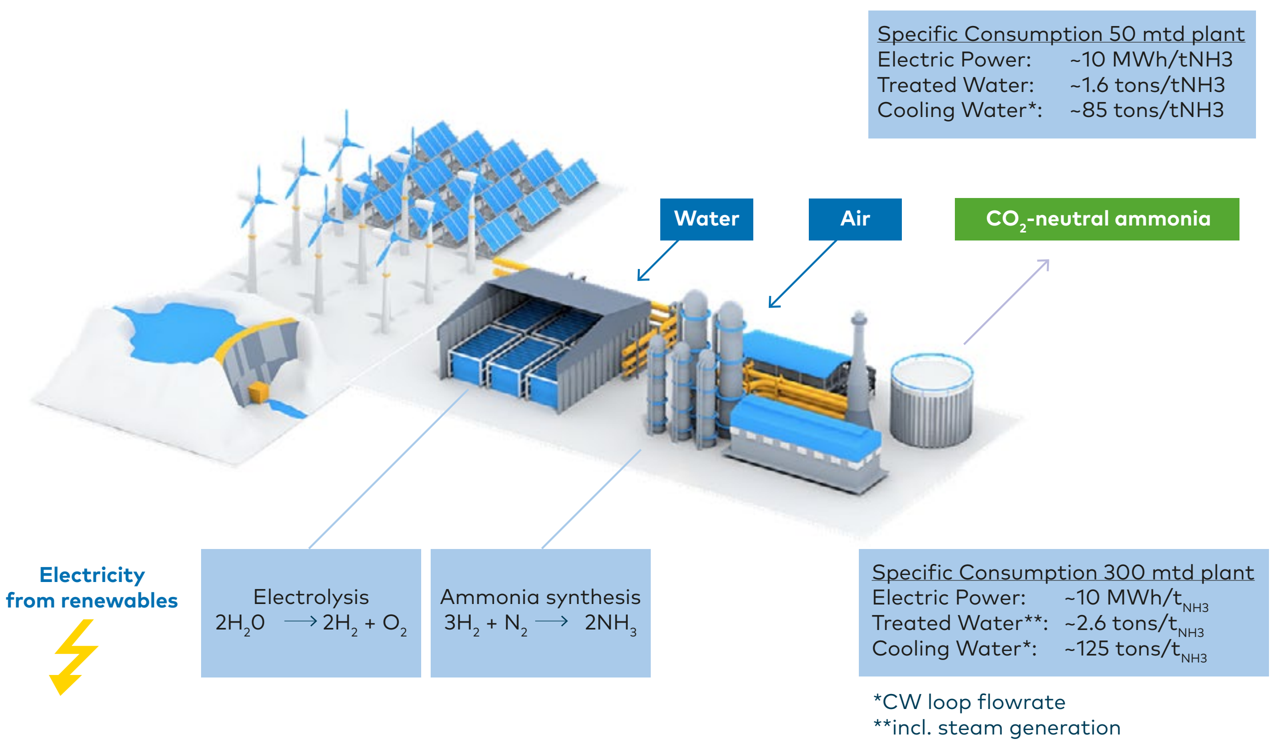


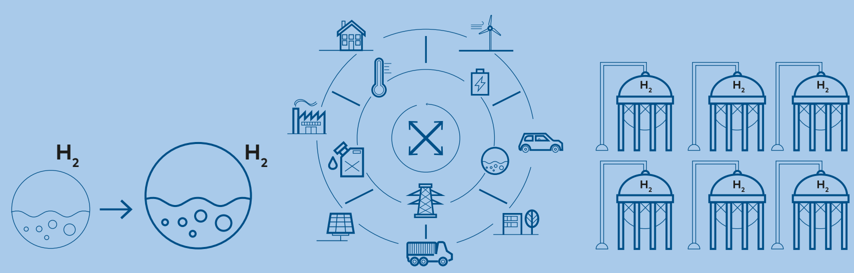
Figure 4: Green ammonia production system by Thyssenkrupp (Will, Lueke, 2nd Power to NH3 conference, 2018)

9 IRENA's Global Renewables Outlook 2020 estimates that an expansion from 2GW in 2020 to 1700 GW to meet just 5-6% of global final energy demand in 2050. Deep decarbonization of hard-to-abate sectors would require much more.

Green hydrogen and the energy transition

There is growing optimism that these challenges can be met and that a reasonable scale and unit cost can be achieved. Green hydrogen is on the rise, in Europe and elsewhere, and this should enable the development of a market for green ammonia. The EU has set a climate ambition of carbon neutrality by 2050. The EU's Hydrogen Strategy is a crucial part of realizing this ambition.

The path towards a European hydrogen eco-system step by step:



Today - 2024

From now to 2024, we will support the **installation of at least 6GW of renewable hydrogen electrolysers in the EU**, and the production of **up to 1 million tonnes** of renewable hydrogen.

2025 - 2030

From 2025 to 2030, hydrogen needs to **become an intrinsic part of our integrated energy system**, with at least 40GW of renewable hydrogen eclectrolysers and the production of **up to 10 million tonnes** of renewable hydrogen in the EU.

2030 -

From 2030 onwards, **renewable hydrogen will be deployed at a large scale** across all hard-to-decarbonise sectors.

Figure 5: EU Hydrogen Strategy (European Commission, 2020)

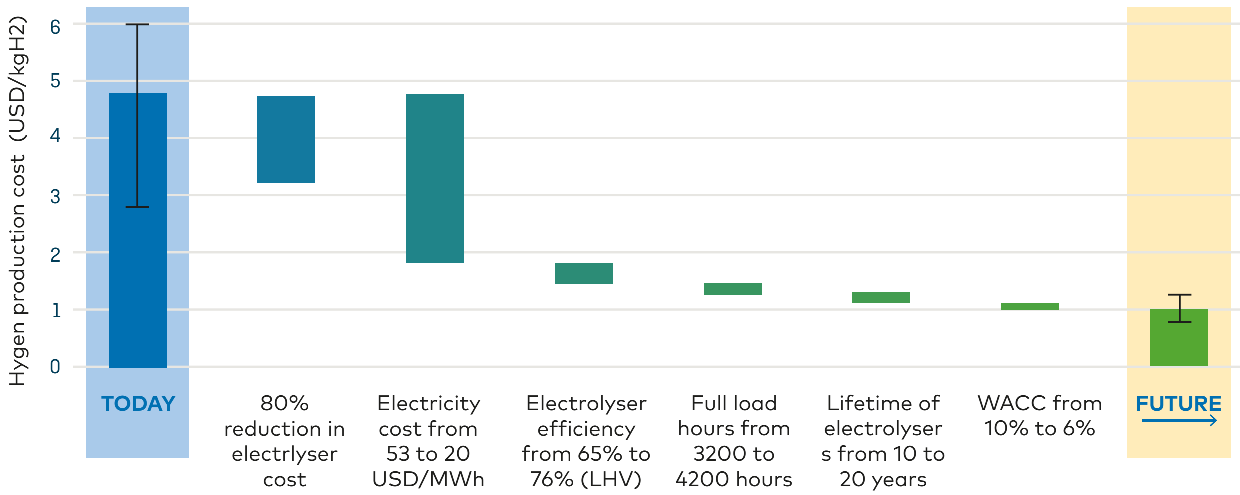
As part of the European Green Deal, the EU Hydrogen Strategy has set a target of 40 GW of electrolyzer capacity by 2030, delivering 140 TWh of work annually. Ten million tonnes of green hydrogen are expected to be produced by that same year. Further, the EU's Wind Strategy targets a five-fold increase of installed offshore wind capacity over the next ten years to reach 60 GW by 2030, and a 30-year target of reaching 300 GW installed capacity by 2050 (+40 GW of installed ocean energy).[10]

As production of green ammonia at scale will require significant expansion of renewable electricity generation and electrolyzer capacity, the capacity targets set by the European Commission send a clear signal that it will be possible to expand the production of green ammonia if the demand is there.

10 European Commission, A hydrogen strategy for a climate-neutral Europe (2020) https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

Challenges in scaling green ammonia production

Ammonia produced through electrolysis from green energy currently costs roughly three times as much as ammonia from steam reforming of fossil gas. As such, mechanisms will be needed to begin production as cheaply as possible and also to bring down costs in the long run.



Note: 'Today' captures best and average conditions, with an average investment of USD 770/kW, efficiency of 65% (LHV), an electricity price of USD 53/MWh, 3 200 full load hours (onshore wind), a WACC of 10% (relatively high risk). Best conditions are USD 130/kW, efficiency at 76% (LHV), electricity price at USD 20/MWh, 4 200 full load hours (onshore wind), and WACC of 6% (similar to renewable electricity today).

Figure 6: Step changes for achieving green hydrogen competitiveness (IRENA, 2020)

In the long run, the main driver of these higher costs will not be ammonia infrastructure, but the very high volumes of electricity consumed by the electrolysis process. While innovations in electrolysis can bring this cost down, access to very cheap electricity will be crucial. This points to likely scenarios of large-scale green ammonia production being placed in regions where renewable energy is more cost-competitive, for instance Morocco, Chile, or Australia.

While bringing down the costs related to electricity inputs will be essential, these steps can be complemented by smaller but important measures such as repurposing infrastructure, process learning in demonstration and commercial environments, and scaling up throughout the value chain.

Green ammonia can be produced by partially converting and even making use of extra capacity at existing plants, which is economically the most viable alternative to start producing at scale. While such conversions will likely only cover about 10% of each plant's total production, this could satisfy the short-term demand for green ammonia.

An important complement to bringing down costs will be capturing more value, potentially in the form of 'green premiums' from final consumers (cargo shippers, the food industry). In order to be able to sell green ammonia at a premium, viable certification needs to be in place. In order to avoid creating barriers to scale-up, certification of green hydrogen on a mass-balance basis will be needed. Similar systems to those currently in use to certify the origin of green electricity will be needed for hydrogen and ammonia.

Blue ammonia

Another alternative approach to producing hydrogen with a low emission profile is to apply carbon capture and storage (CCS) technology at steam reforming plants. Hydrogen and ammonia from these sources are often referred to as blue hydrogen and blue ammonia. While activity related to CCS is increasing, the necessary technical, market and regulatory infrastructure remain underdeveloped.

3.3 GHG footprint of ammonia

Almost all ammonia today is produced from a hydrocarbon source. The global annual carbon footprint from this so-called 'grey' ammonia is estimated to be at around 2% of annual global GHG emissions. While the CO_2 footprint of ammonia depends on its feedstock and production efficiency, it averages around 1.6 – 4- tonnes of CO_2 per tonne of ammonia.

Another alternative approach to producing hydrogen with a low emission profile is to apply carbon capture and storage (CCS) technology at steam reforming plants. Hydrogen and ammonia from these sources are often referred to as blue hydrogen and blue ammonia. While activity related to CCS is increasing, the necessary technical, market and regulatory infrastructure remain underdeveloped.

The use of ammonia as a means of decarbonizing shipping therefore, will therefore only achieve GHG reduction when the ammonia combusted is produced from a renewable source (green), or where its carbon has been captured and sequestered (blue).

Figure 7: Life cycle emissions of different shipping fuels (Lloyd's Register/UMAS 2020)

The first ships pioneering ammonia as a fuel may have to use grey ammonia as a bridge to low-emission operations. Chemically the same substance, this will provide the same basis for knowledge and capabilities development around, for example, bunkering, handling, maintenance, etc. Green ammonia is not likely to be sold as a separate commodity in Europe, with mass-balance certificates used instead to certify green fuels and build up the market.

This means that a transition from grey ammonia to green ammonia could be seamless from the perspective of vessel operation (though not economics).

Grey ammonia will only be used in a transitional phase and thus will thus have a minor impact on the climate footprint of the vessel over its operating life. During the transitional phase the greenhouse gas emissions from the M/S NoGAPS can be expected to be similar to other fossil-fueled vessels, if temporarily slightly higher than some gas carriers.

3.4 Bunkering of ammonia

The fueling of ammonia-powered ships is likely to evolve with the value chain, as the best options for the first demonstration vessels will differ from those serving the more developed market.

Different options for bunkering will have to be evaluated from case to case, but a number of alternatives may be relevant:

a. Direct supply from cargo tank

b. Internal transfer

c. Loading arm

d. Barge

From a cost perspective, the internal transfer option is much preferred, provided the use of cargo as a fuel is permitted. Bunker barge will become a viable option once sufficient demand has been established, and when ammonia starts to be delivered at that scale. Approaches to collaboratively building such demand should be explored, including through collaboration with other projects not carrying ammonia as a cargo.

Safety related to the bunkering of ammonia is essential. While safety standards and regulations for the bunkering of ammonia are yet to be established, the use of an ammonia carrier as a first-mover has a specific advantage in this case. Crew on ammonia carriers are already working according to procedures and international safety standards for loading, handling and discharging ammonia on a vessel. Such procedures and safety standards will very likely be used as the basis for developing safety standards for the bunkering of ammonia as a fuel.

3.5 M/S NoGAPS: Handling key issues in fuel sourcing

The above challenges in producing green ammonia as a shipping fuel will have implications for how the M/S NoGAPS approaches its fuel sourcing. To build the long-term business case, a supply of verified green ammonia will have to be secured at an acceptable price. At the same time, in order to accelerate the proof of concept, a strategy for employing grey ammonia as a transition fuel will have to be adopted. Bunkering arrangements will need to be decided and the supplied ammonia will need to be certified for use as a fuel.

Volumes

Given the proposed operating model (see Chapter 5), the fuel requirements for the M/S NoGAPS can be roughly estimated as equivalent to 7,925 tonnes of MDO per year, or 18,000 tonnes of NH_3. The actual demand for each fuel will depend on optimizing the business model across multiple factors – cost, emission reductions, long-term strategic benefits, etc. These choices will be discussed in the examination of the business case in Chapter 5.

Sourcing green ammonia

While the M/S NoGAPS will have the flexibility to run on a range of fuels, the proof of the overall concept requires that arrangements for green ammonia supply be in place once it is available. Partners in the project are developing green ammonia production capacity. If successful, this capacity could be operational and supplying the M/S NoGAPS with green ammonia in 2026. See Fact Box – Yara and Ørsted Collaboration at Sluiskil.

It is anticipated that the ammonia fuel will be purchased from Yara. The ammonia fuel mix (green + grey) will be produced from the Yara facilities at Sluiskil and Porsgrunn, Norway and certified on a mass-balance basis.

YARA & ØRSTED COLLABORATION AT SLUISKIL

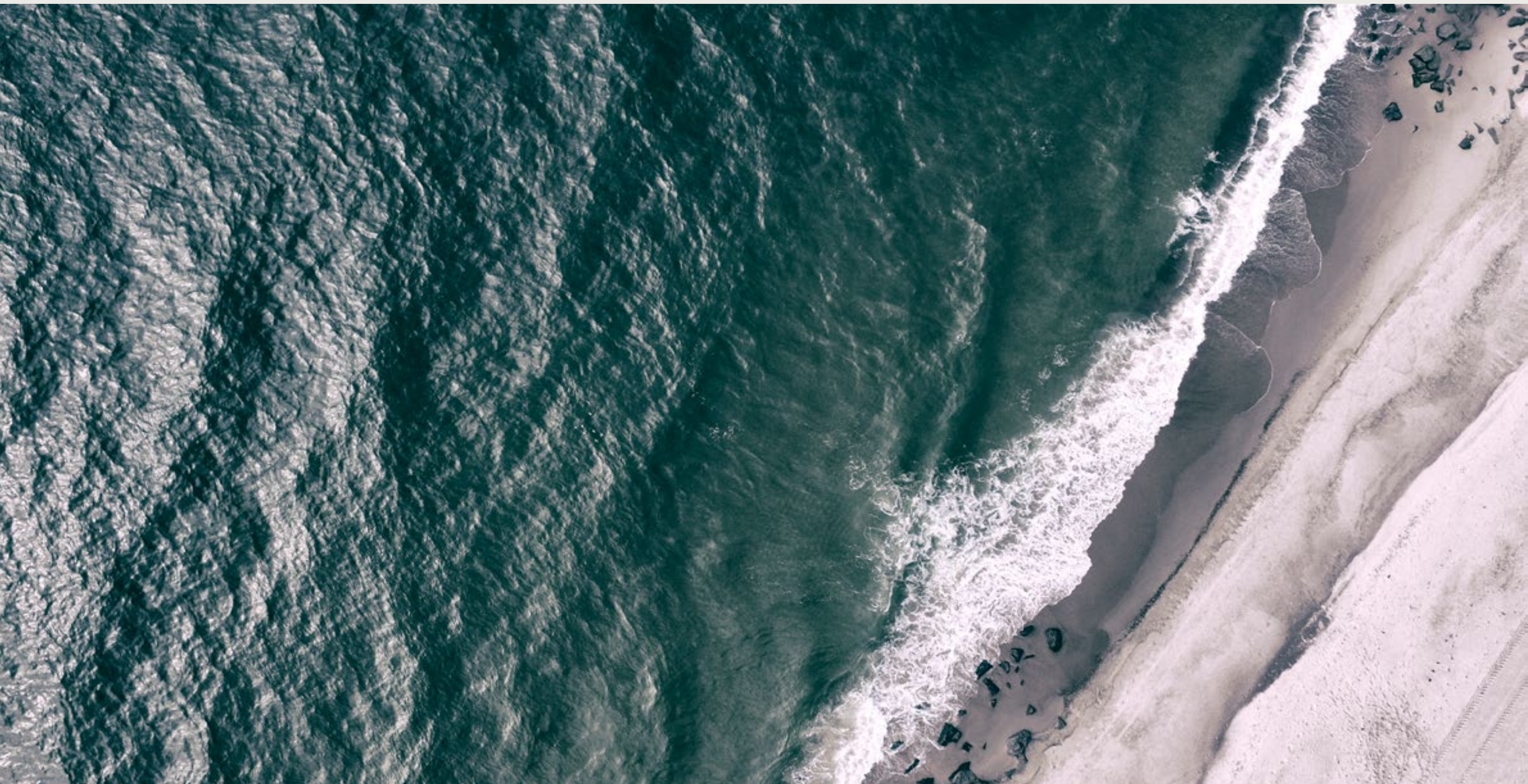
Yara and Ørsted are seeking public co-funding for the development of the Sluiskil project, consisting of a 100 MW electrolyzer plant for green hydrogen production, and a revamp of the existing ammonia plant. Conditional to sufficient co-funding and a confirmed business case, a final investment decision to build the new plant could be taken late 2021 or early 2022. The plant is expected to be operational by 2026.

For large-scale deployment of green hydrogen and ammonia, electrolyzer industrialization and hydrogen infrastructure development will be key. Smaller projects can start on existing ammonia production sites with existing infrastructure. A maximum of 10 to 20% of an existing unit can be converted to green ammonia. Utilizing surplus capacity, the Sluiskil plant opts to revamp 10% of its capacity through a process called hybridization.

In a hybrid revamp, the existing ammonia synthesis plant is used, and an electrolysis front end is added in parallel with the natural gas front end. In such a scenario, the only cost-significant plant modification is the electrolyzer installation. The plant ammonia production is kept unchanged, but 10% of the hydrogen feed to the synthesis is produced by the electrolyzer. The existing synthesis gas front end operation is optimized to this new operating point.

At Yara's Sluiskil plant, revamping 10% of its capacity to green production would generate around 75,000 tonnes of green ammonia per year using hydrogen produced from Ørsted's offshore wind farms. The 10% green capacity is achievable with a limited level of investments, whereas 20% would require significant investments.

(Yara International, 2020)



Bunkering solutions

As neither green nor grey ammonia is currently provided as a ship fuel, the infrastructure for bunkering will have to be selected. Bunkering locations will be developed specifically for M/S NoGAPS, which will during a trialing phase be in the simplest and safest form. Additional bunkering solutions and infrastructure will start to develop as the orderbook for ammonia-driven vessels increases.

As M/S NoGAPS is an ammonia carrier, fuel provision will take place at existing ammonia terminals, making use of existing infrastructure for cargo handling. DNV and Argus have mapped the ammonia terminals worldwide.[11] Yara has also published their ammonia production and terminal infrastructure in relation to major bunkering hubs. Although not in perfect overlap, the existing ammonia infrastructure is within distance to start. Barge-to-ship transfer is also a common practice in ammonia transport/shipping.

Fuel certification

Ammonia as a shipping fuel will be available and according to approved fuel standards. Engines operating on ammonia will be designed so that they can operate on so called "cargo grade" ammonia, which means that ammonia producers can offer a final product directly to the shipping customer, without the need for a separate preparation step.

The introduction of a small quantity of water to the ammonia vastly reduces its tendency to induce stress corrosion cracking in the containment vessels. Fortunately, the presence of water in ammonia is not seen to present any problem for its use in maritime ICEs. Development of ammonia burning ICEs is based on the models and combustion principles already in use which already handle water content in the fuel.

From a vessel operator perspective, it is assumed that these definitions and requirements will be in place and that certified green ammonia can be purchased on a mass-balance basis, where the output of green ammonia is in proportion to the input of green hydrogen.

With a marine fuel standard for ammonia developed, ammonia fuel can be made available at scale. The fuel standard is expected to be finalized during 2021.

Fueling the M/S NoGAPS

To build the long-term business case, a supply of verified green ammonia will have to be secured at an acceptable price. At the same time, in order to accelerate the proof of concept, a strategy for employing grey ammonia as a transition fuel will have to be adopted. Bunkering arrangements will need to be decided and the supplied ammonia will need to be certified for use as a fuel.

11 DNV, Alternative Fuels Insight Platform, https://store.veracity.com/da10a663-a409-4764-be66-e7a55401275a

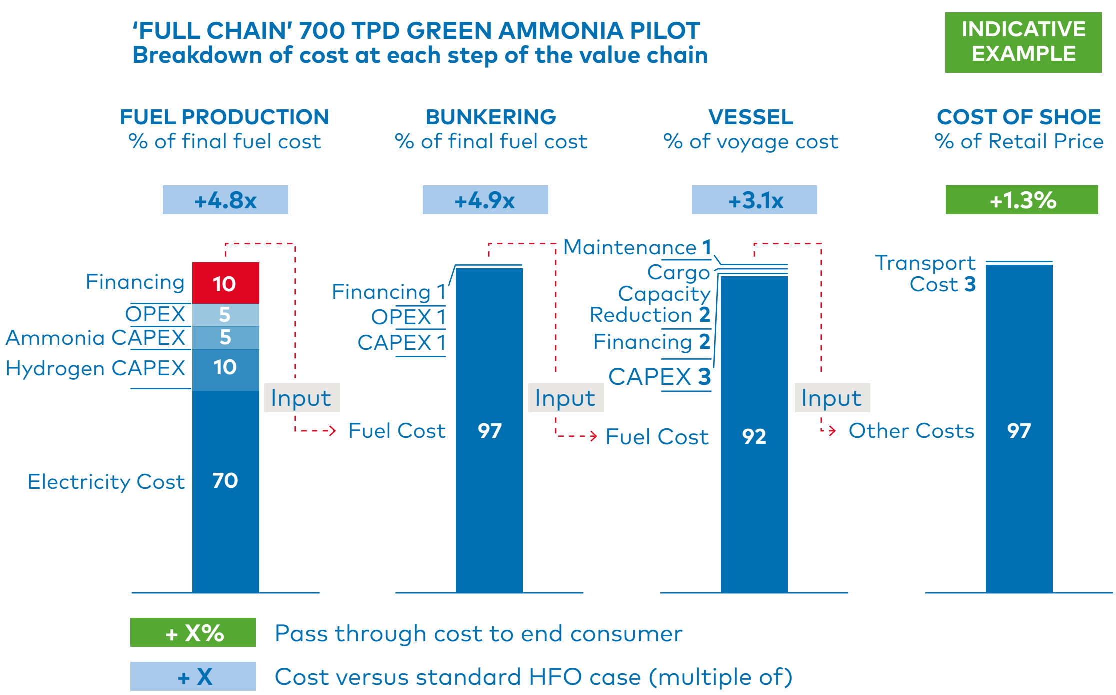
4. Economics and financing of ammonia-powered shipping

Just as zero-emission vessels and fuels need to be demonstrated at scale, so do the financing and business models that will bring these innovations to market. Demonstrations like NoGAPS help to build confidence in technologies and infrastructure, but they can also build confidence in the long-term economic viability of ammonia-powered shipping.

4.1 Elevated costs and risks

The main economic challenge facing companies wanting to transition to zero-emission fuels is to reduce costs and risks. With the industry engaging in ground-breaking technological development and with numerous trials underway, the major obstacles for introducing green ammonia as a fuel are not primarily expected to be technological. Rather, it is the significantly higher cost and limited availability of the fuel and its scarcity compared to HFO that appears to be the greatest barrier.

Based on a high-profile industry report published in 2020 by the Energy Transition Commission,[12] 75-90% of total CAPEX of an end-to-end pilot of green ammonia will be attributable to the land-based fuel production infrastructure, and especially the cost of electrolyzers and equipment for ammonia synthesis. The remainder of the CAPEX relates to fuel bunkering and vessel fuel storage and engine systems. As these costs cascade across the value chain, the resulting fuel cost for a green ammonia first mover is up to five times the cost of HFO, and more than 90% of the pilot's total voyage cost. Figure 8 illustrates the breakdown of cost to ship a consumer product (a shoe) across the value chain from fuel to retail.



Source: ETC analysis (2020)
Key assumptions listed in Appendix

Figure 8: Cost breakdown reference case ammonia pilot (Energy Transition Commission, 2020)

12 Energy Transition Commission, The First Wave – A Blueprint for Commercial Scale Zero Emission Shipping Pilots (2020)

For a newbuild vessel, the initial CAPEX of an ammonia-powered first-of-a-kind project has been calculated to be around 25-30% higher than as for a standard vessel. In addition to the costs for a novel ammonia fuel engine, higher costs are also the consequence of material selection, toxicity safeguards, additional and specialized fuel tanks, and fuel system.

With new and less proven technologies, any first mover will have vessels with higher technology risks, facing possible insurance premiums and contractual limitations on employment. The first-of-a-kind design and approval process in itself presents an elevated cost picture. Meanwhile as the pathways for scaling of ammonia as a maritime fuel will continue to evolve, the risks of stranded assets due to lack of flexibility at the design stage will have to be carefully managed. However, broken down to the level of specific engineering challenges posed by the development of this vessel, these are mostly not firsts of their kind and therefore do have proven solution paths.

The Energy Transition Commission details some key levers for commercial and financial arrangements which can be employed toward de-risking and building a reasonable business case. It distinguishes between three types of measures to reduce CAPEX and OPEX: Game Changers, Quick Wins and High-Hanging Fruits. This approach has been used to suggest ways to reduce fuel production costs, bunkering costs and vessel retrofitting and operation costs. Game Changers include repurposing existing fuel production as well as fuel storage facilities and accessing low-cost electricity, co-investing by parties in the value chain, and investment support.

Cost, competitiveness, and dilution in the value chain

The largest single enabler for piloting alternative maritime fuels may be the mobilization of the full value chain. This holds very strongly for an ammonia-powered ammonia tanker. Green ammonia to be used in the pilot vessel is estimated to be about three times more costly than standard HFO. Should HFO for some reason triple in price overnight, the maritime world would doubtless shudder for a time but, theoretically, in the medium/long term the increase in cost would be borne by freight rates and ultimately the end consumers of cargo. However, a first-of-a-kind vessel running on a fuel at such an inflated cost cannot compete in the current fuel market, all else being equal. While for some cargo owners (as in the example of the shoe above) the share of the final product cost driven by shipping is small, and demand for their product fairly elastic, ammonia is a bulk commodity and as such quite price sensitive. Therefore, the burden needs to be borne not by an end consumer but instead by dilution across as much of the greater value chain as possible.

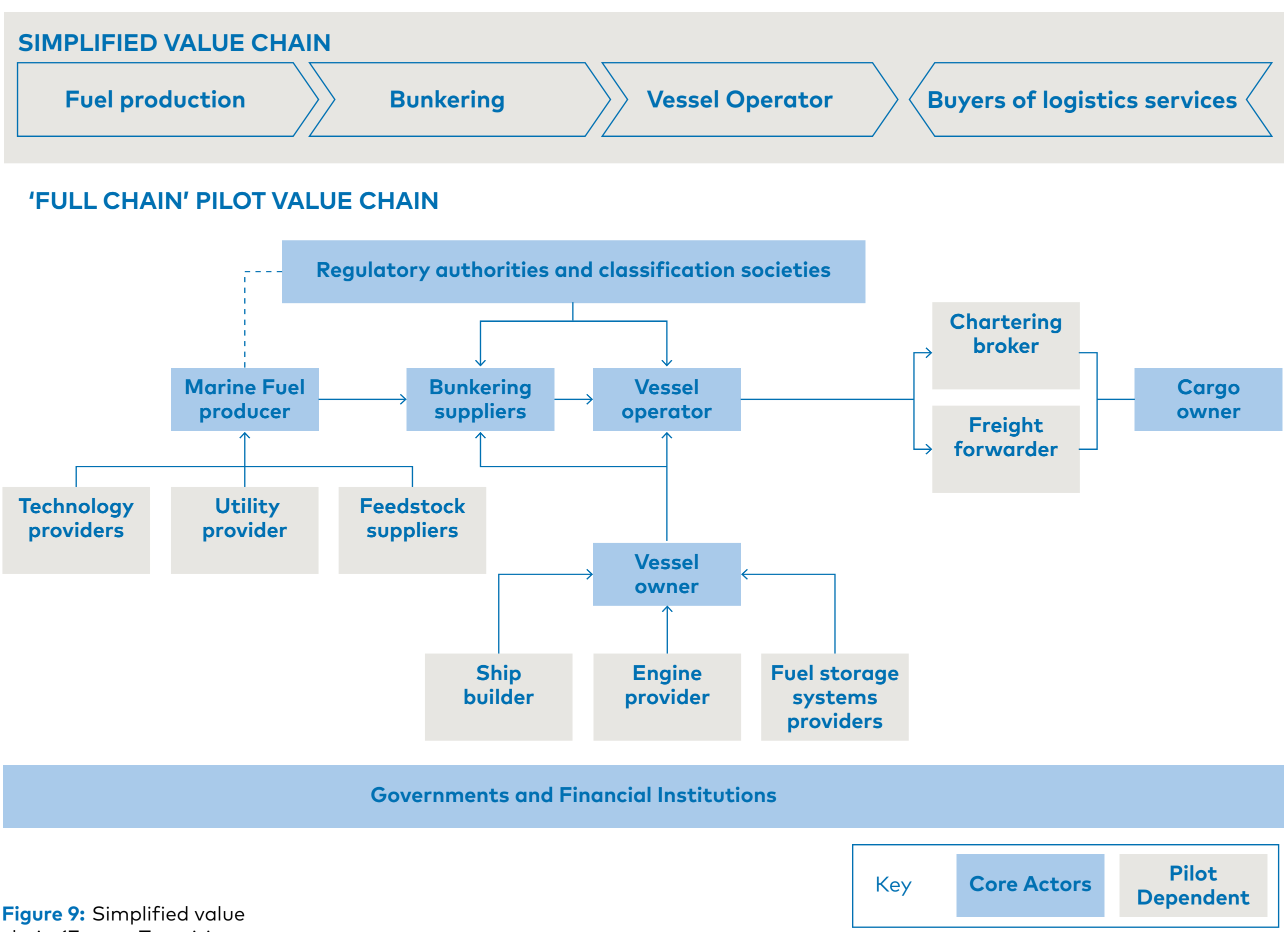


Figure 9: Simplified value chain (Energy Transition Commission, 2020)

Measures to reduce fuel production costs

The cost of green ammonia is largely dependent upon the cost of the green electricity used to produce it. Cost reductions in green electricity supply may be achieved by co-location of green ammonia production with the feedstock elements of green hydrogen and green electricity. There may also be arrangements available for preferential grid supply with waiver of certain charges and access to green supply credits. Such undertakings may be supported by long term purchase agreements. Long-term (10-year) offtake for green hydrogen production can play a role, and there is potential in extended partnerships and co-investment with other actors in hydrogen offtake plans.

1. Repurposing of assets and co-investing across the value chain can reduce infrastructure costs

CAPEX on fuel production can be minimalized by the repurposing of existing infrastructure and initially by the incorporation of green production to existing capacity. Nominally, there is significant spare capacity globally, and production capacity is not expected to be a constraint on the market.[13]

Once green (or blue or grey) ammonia is produced, it needs to be stored and transferred to the user vessels. Although this process represents a relatively small part of the overall cost profile, it is nevertheless an essential part of the supply chain and must be handled as efficiently as possible. Cost efficiency in this area can likewise be improved by repurposing and retrofitting existing infrastructure and vessels where possible. There are again opportunities here for co-investment through the value chain and the sourcing of public investment for the requisite port facilities. Savings of up to 50% may be possible through smart alignment of value.[14]

2. Sector coupling

The prospect of shipping taking an active role in sector coupling[15] in order to share risk and opportunity across potential fuel clusters is becoming ever more prominent. The announcement of the intention to create such a cluster utilizing green electricity for a Power-to-X cluster in Copenhagen is an example.

13 Review of Global Ammonia Supply, Oliver Hatfield, Argus Media, AEA Conference (2020) https://www.ammoniaenergy.org/wp-content/uploads/2020/12/Oliver-Hatfield.pdf

14 Energy Transition Commission, The First Wave – A Blueprint for Commercial Scale Zero Emission Shipping Pilots (2020)

15 *"Sector coupling involves the increased integration of energy end-use and supply sectors with one another. This can improve the efficiency and flexibility of the energy system as well as its reliability and adequacy. Additionally, sector coupling can reduce the costs of decarbonisation. To foster the full potential of sector coupling in several end-use and supply applications, it is important that existing techno-economic, policy and regulatory barriers are removed. Furthermore, a more integrated approach to energy systems planning is needed."* From the European Parliament's Committee on Industry, Research and Energy. Sector Coupling: How can it be enhanced in the EU to foster grid stability and decarbonize (2018)

The participation in such clusters requires longer term and systemic approaches which, despite shipping asset lifecycles, are not actually part of the current paradigm for fuel supply. However, the Energy Transitions Commission estimates that such cluster initiatives represent up to a 20% reduction in fuel cost base as they will reduce offtake risks for fuel providers, enable scale-up and share energy infrastructure costs across ranges of stakeholders. Engagement with such clusters should certainly include long-term agreements which will tend to drive fuel price stability and encourage effective scaling.

Measures to reduce operational costs for vessels

The cost of fuel itself represents most of the operational cost for shipping. Cost increases related to use of the fuel in operations will thus need to be minimized: factors such as crew training and the administration of new regulations may be prioritized should be streamlined as much as possible by administrating authorities.

1. Grey ammonia in the piloting phase

Using grey ammonia until green ammonia volumes are available will allow the vessel technologies and bunkering processes to be piloted and refined. According to reports from the Energy Transitions Commission and research on behalf of Trafigura (a major cargo owner), grey ammonia cost is approximately 40% lower than green ammonia.

2. Design considerations for yard stay and docking periods

Typically, newly designed vessels are built in multiplicity in order to avail of economies of scale. A standardized "off-the-peg" vessel which is designed and built by a shipyard with few special requirements from the owner should be most cost effective. On the other end of the spectrum, a first-of-a-kind construction involving fundamental innovation can generate unexpected costs as multiple stakeholders adjust. Due to the various perspectives of the stakeholders involved, efficiencies are optimized by tighter and earlier co-operation.

Through coordinated planning across original equipment manufacturers, contractors, and yards, it is possible not only to further optimize design, but also to reduce capital expenditures. Designs can be planned so that solutions are easier to build and install, which will be an important driver of cost reductions. Design should also investigate solutions for yard stay during docking intervals. This could for instance include fuel system flexibility allowing ammonia fuel tanks to remain full when entering into dock.

POSSIBLE FUTURE DEVELOPMENTS: SHIPPING AS A SERVICE?

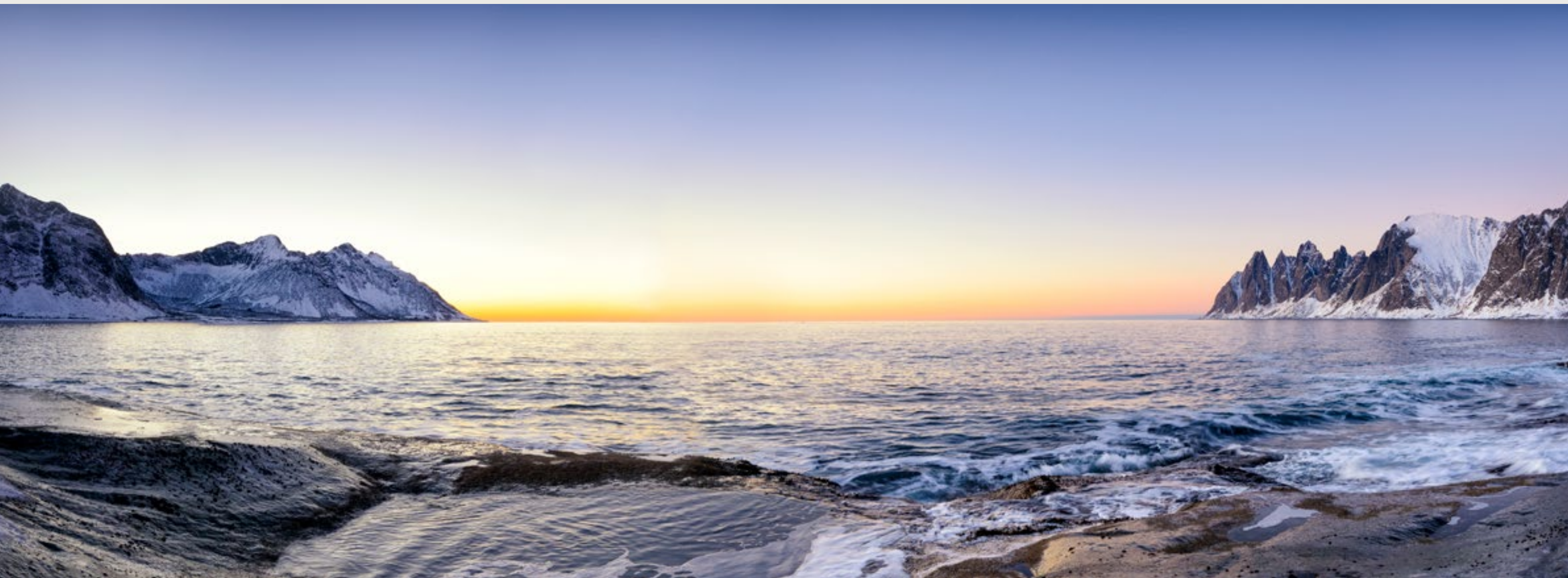
The concept of shipping as a service is increasingly being attached to the discussion around the energy transition and the future of shipping as a whole.

Currently investment in shipping assets is slow, as ROI is poor and the broader investment market is relatively active. The attractiveness of maritime assets can be improved by promoting the creation of barriers to entry in conjunction with the transition to zero-emission fuels.

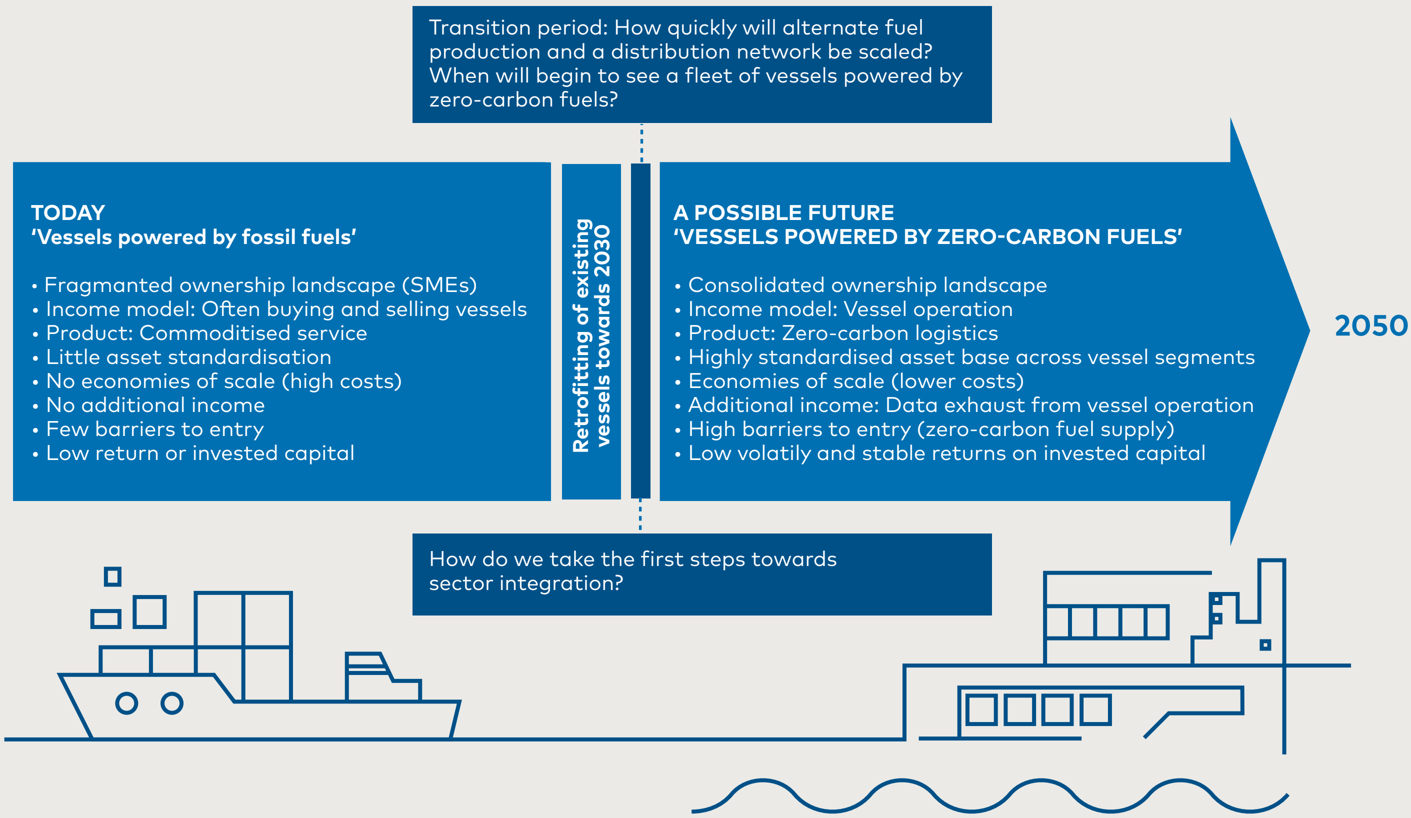
The development needed is one of massive scaling of renewable energy in order to produce sufficient quantities of new fuels, such as ammonia, along with greater standardization of the assets themselves within segments. This could be supported by grand sector coupling between fuel producers and the asset owners for an optimum supply/demand balance at scale, in order to drive down cost to fossil fuel levels. In this suggested model, the transactional, cargo owner-facing element of shipping is entirely carved out from the owning and operation of the asset. Therefore, the ocean element of a logistics chain is a highly commoditized and a lean Ship-As-A-Service solution can be purchased under simple terms from the asset owners or operators.

The bonding of fuel supply to asset owners holds potential for driving considerable asset owning consolidation over time. The effect of such consolidation would be to raise barriers to entry and thus holds potential to in turn attract investment. Such consolidation may not of course be very attractive to many present-day stakeholders but rather a threat. Conversely, for those who recognize this as a future scenario now and become engaged with the fuel transition early, the threat can instead become an opportunity.

Danish Ship Finance discussed such a scenario in their November 2020 paper entitled *A Pathway to Zero Carbon Shipping*, as part of their shipping market review.



A PATHWAY TO ZERO-CARBON SHIPPING
Reaching zero-carbon emissions is technically and economically feasible if we work together across sectors



Although a pilot vessel certainly does not benefit from lower costs through economies of scale, the end-game of driving down the price gap between ammonia and fossil fuels through sector coupling and asset standardization should be kept in mind in developing first-of-a-kind solutions like the M/S NoGAPS.

Figure 10: A pathway to zero-carbon shipping (Danish Ship Finance, 2020)

4.2 Financing

First-of-a-kind projects come with a set of risks which inevitably increase the cost of financing.

The two main barriers of technological risk and cost need to be reduced to an acceptable level to facilitate capital investment for both the vessel and the fuel supply chain. Risk mitigants and a strong equity commitment from an owner with a good balance sheet are important for new projects seeking to attract commercial finance to unproven technologies or unproven markets.

When taking steps to mitigate risk the proportionality must be understood. The CAPEX is heavily biased ashore – with 70-90% associated with fuel production.[16] However, the technology development required primarily relates to onboard technologies, since the component technologies for green ammonia production are well understood. As such the technology risks are not associated with large capital investments, at least from a value chain perspective. On the other hand, the fuel production faces market risks as industrial scale production plants will need to be confident in offtake for green ammonia. This creates a synergistic possibility to share risks and lower financing costs through co-investment along the value chain.

Commercial finance

The broader commercial debt market (e.g. bank and bonds) primarily targets established companies and mature and proven concepts, while first-of-a-kind concepts are normally funded through equity and/or other forms of risk capital. The attractiveness of a project among the former improves when sponsors and offtakers can be brought in via e.g., long-term contracts, guarantees and equity support. As bank financing is most relevant for mature and established companies, having access to finance early in the lifecycle of new and untested concepts usually requires strong corporate support; either directly on the balance sheet or through a tight project financing structure enhancing cash-flow visibility and reducing risks for lenders.

Public finance

The Fact Box on public financing levers below illustrates some examples of where public involvement may assist with reduction of cost and/or risk for the private sector investor and their finance providers. Regardless of the employment of such options it must be remembered that in the final analysis a legitimate business case must emerge.

Public support for investment will be much needed to lower the financial burden for first movers, but also to de-risk private investments, and lower the cost of capital for the first-of-a-kind ammonia-powered vessel and associated infrastructure. With such a large cost differential between green ammonia and conventional fuels, and a high level of technology and commercial risk, public financing can enable a faster uptake of commercial scale projects across a highly complex maritime value chain.

16 Energy Transition Commission, The First Wave – A Blueprint for Commercial Scale Zero Emission Shipping Pilots (2020)

There are a number of financial de-risking mechanisms which could be used to make a project like M/S NoGAPS more attractive to external capital. Governments have a quick-win opportunity to support the significant CAPEX entailed in the setup of green ammonia production and vessel construction. Direct subsidy or support through loan guarantees could help de-risk a first-of-a-kind vessel, making it more palatable to providers of capital from the private sector whether on the equity or debit side.

PUBLIC FINANCING LEVERS

Direct grants: Direct subsidies for equipment purchases are the most obvious mechanism that governments can use to facilitate first mover pilots. For pilots based in Europe, for example, there are several EU funds, such as the EIC Fast Track to Innovation and Connecting Europe Facility, that focus specifically on high-risk sustainability projects. However, direct grants do not allow for any return on investment for taxpayers and limit the potential to crowd in private capital.

Concessional loans: Governments can also facilitate the financing of investments by providing concessional loans to first mover projects through public financial institutions, which enable key stakeholders to access capital at a lower financing cost than what would have been offered by a private debt provider. From a public finance point of view, such a mechanism allows for a regular recycling of taxpayers' money in projects as loans get reimbursed and reinvested.

Loan guarantees: Public finance tools can also unlock the financing of investments by private financial institutions through mechanisms that lower the risk for those investors, therefore creating higher leverage for the same amount of public money invested. Loan guarantees are an example of one such mechanism.

Public-private partnership: Securing co-investment by a public sector entity would lower the amount of investment required from the shipping value chain itself. It might sometimes be preferred by public entities, as it creates an opportunity for the public funder to get potential returns on the funds that have been invested. Public co-investment can also be designed to crowd in private capital by ensuring that the public entity assumes a higher level of risk than private investors.

Investment tax credits: By allowing capital expenditure related to first mover projects to be claimed as tax credit, governments can create an incentive for corporate players to invest in first mover projects using corporate balance sheets.

(Energy Transition Commission, 2020)

Emerging trend: Greening of investment

Across all industrial sectors, sources of finance, from equity investment through asset management, private equity or pure debt provision, are all paying ever greater attention to the effect of climate change on investment. This risk assessment is viewed from both the potential for physical climate risk to assets from serve weather events *and* from loss of market confidence in climate negative products. Investors are increasingly mindful of their own profile from the perspective of Environmental and Social Governance (ESG), and the composition of their products portfolio is undergoing increasing scrutiny. The financial industry is monitoring the effect of the climate change issue upon financial risk through bodies such as the Task Force on Climate-related Financial Disclosures (TCFD), which was established to "develop recommendations for more effective climate-related disclosures that could promote more informed investment, credit, and insurance underwriting decisions and, in turn, enable stakeholders to understand better the concentrations of carbon-related assets in the financial sector and the financial system's exposures to climate-related risks."[17]

To the above can be added the evolving EU Taxonomy, which brings new standards into the financial world. This is quite a significant tool, under which all companies with more than 500 employees will have to report what share of their activities is Taxonomy compliant, i.e. satisfies environmental thresholds. The proposal put forward in April 2021 suggested that companies building or operating vessels dedicated to transporting fossil fuels would be excluded from being able to designate investments as 'green,' even if these ships were running on zero-emission fuels. Beyond this restriction shipping would be considered Taxonomy compliant.[18]

Within the maritime industry the most prominent initiative related to climate risk is the *Poseidon Principles*, to which 26 leading banks, jointly representing approximately USD 185 billion in shipping finance, are signatories. The signatory financial institutions have undertaken to disclose the carbon intensity of the vessels financed under their lending portfolios, comparing these emissions to given abatement trajectories. It is expected that, with time, such transparency is going to translate into external and internal pressures channelling capital towards low emission vessels.

These developments may already be encouraging ship financiers to scrutinize and adjust portfolios. However, any potential for a 'greenium' rebate (lower cost of capital for financing green projects) will not be a game changer, unless the business case is made viable with the help of public support for first movers and changes in costs and prices as the market scales up.

17 TCFD, Status Report (2018) https://ec.europa.eu/info/sites/info/files/business_economy_euro/events/documents/finance-events-181018-presentation-tcfd_en.pdf

18 "Tankers, gas and others to be excluded from EU green finance access", Lloyd's List, 22 April 2021.

Market-based carbon-pricing measures There is growing momentum towards policy measures that impose costs on greenhouse gas emitting fuels in order to promote the transition in shipping. The EU is moving to include shipping under the regional carbon trading system, the EU Emissions Trading System (EU ETS), and has since 2018 been running a mandatory emissions reporting system, the Monitoring Reporting and Verification (MRV).

China has also implemented a mandatory reporting system. At the IMO, which has required fuel consumption reporting since 2019 (IMO Data Collection System) a discussion regarding on the implementation of a carbon levy is ongoing at its Marine Environment Protection Committee (MEPC) meetings.

Although the introduction of a carbon levy or another market-based measure is extremely difficult to agree upon internationally, its prevalence in discussions across a large number of fora is already generating pressure and challenging the status quo. In the short term its potential implementation drives interest in precautionary transitional investment by shipowners and some adjacent stakeholders. Regulators are expected to increase their involvement over time.

4.3 M/S NoGAPS: Handling of key economic and financing issues

While a heightened focus on GHG emissions among financial institutions and regulators is no doubt having an effect, a credible business case is of course a prerequisite for attracting finance of all kinds. The following sections outline how key operational and business model issues might be handled for the M/S NoGAPS.

Basics of the operational model

The project vessel M/S NoGAPS will be a semi-pressurized, medium-sized gas tanker, intended specifically for the trade of ammonia. M/S NoGAPS will primarily use ammonia as a fuel.
The vessel has a commercially best positioned cargo carrying capacity of 21.000 m3 and has the following principal particulars:

Length over all	161.2 m	
Breadth mid	25.3 m	
Service speed	16.00 kn	
Machinery	Main Gen. Sets (4-stroke)	Wartsila 8L34DF (2x3840 kW)

Table 6: Operational data for the M/S NoGAPS

The project vessel will be optimized for commercial operation in North-Western Europe, as it is expected that this will provide an optimal fit between supply infrastructure and customers for cargo.

The consortium agrees that grey ammonia will be essential for building momentum and will add significant value to the technological viability of ammonia as a fuel. The ability to trial ammonia as a ship fuel with a reliable and verified product quality will help build trust in the technology, which is a prerequisite for scaling. As soon as green ammonia becomes commercially available, which will be enabled by increasing market demand from shipping and fertilizers, it can easily be mixed with grey ammonia, as the chemical compositions are the same.

The M/S NoGAPS business model

The business case for the NoGAPS concept relies on balancing the long-term benefits from early action against the short-term additional costs and overall risks. These benefits and risks are distributed unevenly over the value chain and making the NoGAPS project investable requires a business model that reflects this.

1. Benefits and value creation

The long-term benefits of early action are in part strategic, with fuel producers and engine manufacturers promoting the growth of a large potential market while at the same time potentially securing an early stronghold in that market by building technology expertise, establishing contracts, etc.

The long-term benefits can also be expected to be financial, as market-based mechanisms and regulation begin to bite, and reduction of greenhouse gas emissions creates increasing financial value for shippers. Even in the nearer term, the value of subsidies (for example in contracts for difference) can reasonably be expected to be higher for first movers in fuel production, though this will depend on the design of support mechanisms.

There is some limited evidence of a potential green premium for green ammonia, for example from food industry buyers of fertilizer. If this segment emerges, a premium for greening the shipping of this ammonia may also create direct competitive benefits.

2. Costs and risks

The extra costs associated with the NoGAPS concept are significant. A rough calculation based on assumptions provided by the partners estimates the total annualized cost of ownership of a green ammonia-powered ammonia carrier at USD 16.8m (see Table 7 for assumptions used in this rough calculation).

Ammonia Carrier Data	Unit	
Main Engine Capacity	kw	5300
Vessel Useful Life	Years	25,00
Annual Vessel Operating Days	Days	255,00
Annual Hotelling Days	Days	110,00
Consumption - Operatings Days	tonnes/day	30,00
Consumption - Hotelling Days	tonnes/day	2,50
Annual MDO Only Fuel Consumption	tonnes	7925,00
Annual NH_3 Only Fuel Consumption	tonnes/year	17.999,87
30% MDO Fuel Consumption	tonnes/year	2.377,50
70% NH_3 Fuel Consumption	tonnes/year	12.599,91
MDO Fuel Cost	$/tonne	500,00
Nh3 Fuel Cost	$/tonne	1.000,00
Total Annual Fuel Cost	$	13.788.657
Financial Data	**Unit**	
Cost of Debt	%	4%
Debt to Capital Ratio	%	75%
Vessel operating lifespan	Years	16

Table 7: Assumptions for rough business case calculations

The overwhelming driver of the extra cost is the cost of the fuel. In the case examined, fuel costs accounted for 93% of the additional annualized cost compared to a traditional carrier running on MDO.

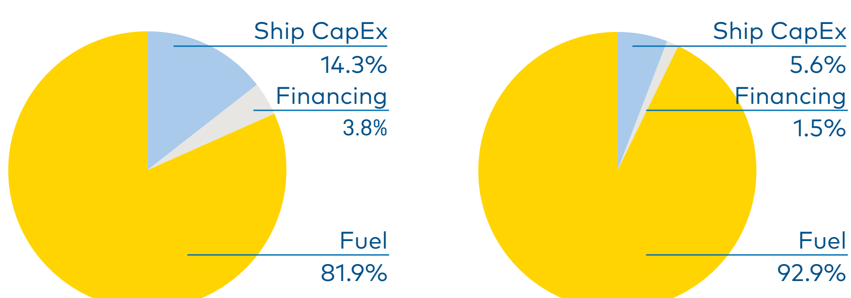


Figure 11: Share of total annual cost (left) and additional annual cost vs. a standard gas carrier and MDO fuel (right)

The additional capital expenditures related to the vessel are significant for the vessel owner (roughly estimated at 25%) though in the overall cost picture they are much smaller than fuels. Nonetheless the extra capital investment represents a significant risk. Should the market for ammonia-powered shipping fail to emerge, the capability to run on ammonia would become devalued and that portion of the capital asset's value stranded.

In addition to these elevated costs and risks, there are smaller but still material risks related to developing a first-of-a-kind vessel, such as delays and cost overruns.

Balancing benefits and costs

While all risk and financial cost cannot be eliminated, the design of the NoGAPS business model must align the strategic and financial benefits with the costs and risks sufficiently to make the project investable.

Table 8 inventories some of the available options for achieving this via the NoGAPS business model.

	Cost/risk driver	Associated benefit /revenue stream: *Why bear the extra cost or share in the risk?*	Size of the cost/risk	Potential mitigant or risk-sharing approach in business model	
				Partners	Governments or customers
CAPEX	Increased costs (engine and vessel modifications, storage tanks etc)	Development of strategic technology advantages and/or market position	Medium	• In-kind coverage of some extra costs from partners • Design optimization of fuel tanks to leverage fuel flexibility (e.g. NH_3 for regional trade, MDO for rarer long journeys; option to fit additional NH_3 tanks later; ability to top up from cargo mid-journey) • Financing discounts to reduce capital costs	• Grant financing of extra cost • Concessionary finance (public) e.g. loan guarantees
CAPEX	Risk of delays/ overruns		Low	• In-kind coverage of some extra costs from partners	
CAPEX	Risk of stranded asset if market does not emerge		High	• Dual fuel capabilities • Long-term (15+ years) chartering agreement • Joint venture/co-ownership with cargo owner	
OPEX	Fuel cost gap MDO-Grey NH_3	Prove NH_3 shipping concept: develop market, infrastructure and operations	Medium	• Dual fuel capability • Cost coverage by fuel producer as part of charter arrangement	• Acceptance of Grey NH_3 in publicly-supported projects
OPEX	Fuel cost gap MDO-Green NH_3	• Capture subsidies and incentives for green fuel production • Avoid costs for GHG emissions • Capture green premium from end consumers	High	• Favorable long-term electricity off-take • Reduce NH_3 production cost through scale effects and technology learning • Scale the proportion of green ammonia in use according to availability of subsidies and green premie	• Contracts for difference or other subsidization of Green NH_3 (e.g. concessional finance for investments in production) • Carbon price or fuel mandates that incentivize the use of zero emission fuels • Green premie from customers

Table 8: Risks, costs, and measures in the business model

5. The M/S NoGAPS at sea

There are a number of mechanisms that should be in place to take this concept study forward and lead to M/S NoGAPS to sea. The basic building blocks of the NoGAPS business model are likely to be:

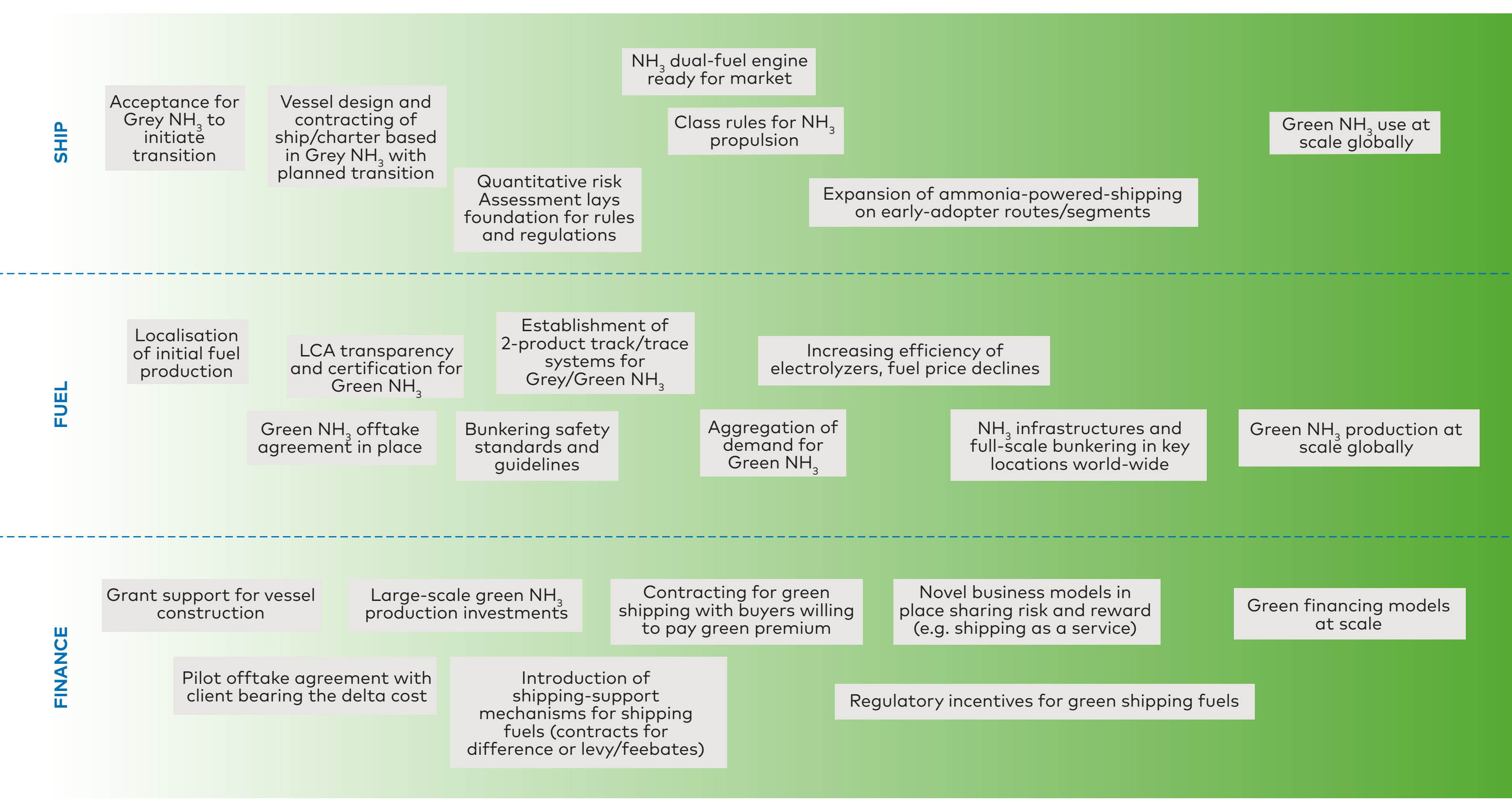
1. Some in-kind contributions/financial concessions to reduce the risks of cost overruns
2. Design optimization in accordance with a regional business model to minimize the cost related to NH3 fuel storage
3. Long-term chartering contract or joint venture to decrease the risk of ship ownership
4. Dual fuel capabilities to decrease the exposure to fuel supply risks
5. A transition strategy from grey NH3 to green NH3 that is aligned with access to subsidies and premiums and reflected in the risk sharing in the chartering contract/joint venture

The following complementary measures by governments will likely be necessary:

1. Grant financing of additional CAPEX
2. Loan guarantees
3. Contracts for difference or equivalent for green NH_3 production
4. Eventual regulations or incentives

With these elements in place, the M/S NoGAPS could be a viable proposition. Figure 12 illustrates how these and other elements might usefully fall into place over time.

Figure 12: Key milestones in the shift from grey to green operations for M/S NoGAPS



Conclusions

The potential of ammonia-powered shipping to contribute to the decarbonization of the maritime sector is significant, and ammonia-powered ammonia carriers present a logical starting point for demonstrating this potential. This project's elaboration of the M/S NoGAPS concept points to a number of key conclusions for the path forward:

1. Neither the technical considerations nor the associated regulatory approval for an ammonia-powered vessel present major obstacles to putting the M/S NoGAPS on the water.
2. Ammonia synthesized from green hydrogen represents a credible long-term, zero-emission fuel.
3. The most important challenge to be overcome is to develop and demonstrate a business model that is credible in the eyes of investors and operators. Both the vessel design and the fuel sourcing strategy offer opportunities to reduce risks and costs in meaningful ways.

Government support and public finance can both accelerate the short-term timetable for investment in demonstration and the improve the outlook for long-term deployment of ammonia as a shipping fuel.

Appendices

Appendix 1 - List of figures & tables

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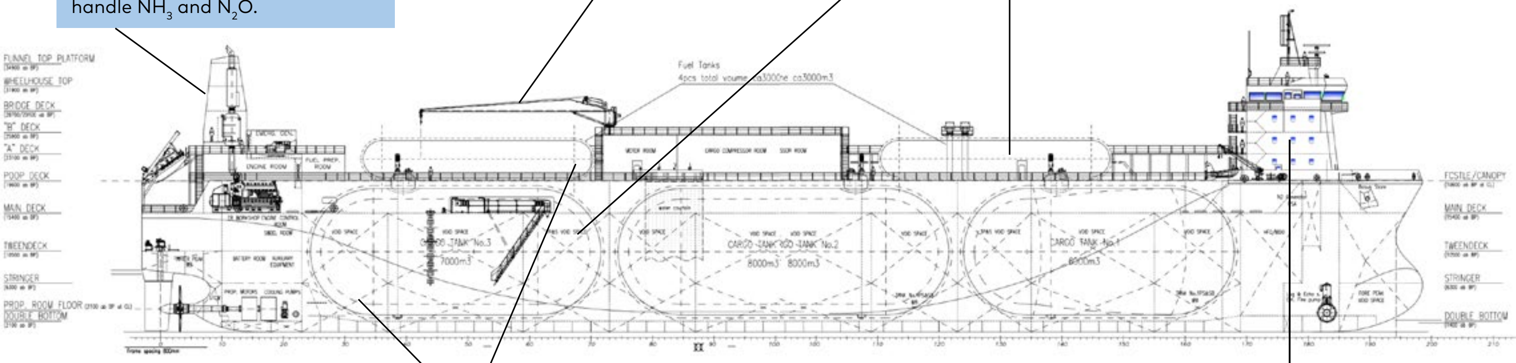
Appendix 2 – Vessel design

Ammonia fuel operation may require specific exceptions to typical ship designs, e.g. the placement of accommodation. The consortium has explored different options for altering of ship and fuel system layouts, suggesting the following key considerations. (Figure 13 and Figure 14)

Exhaust gas treatment: The exhaust train will likely need to include a scrubber installation to handle NH_3 and N_2O.

Bunkering: Bunkering of ammonia fuel could be either done through a dedicated bunker skid, or by including a dedicated fuel connection to the cargo manifold. If vessel is carrying ammonia as cargo, the option of direct transfer of cargo to the fuel tanks should be explored.

Positioning of fuel tanks: Location above weather deck. Current size/capacity allows for Pacific voyage. Later design evaluations may suggest fuel tanks below deck may be a better option, in which case potential risk variation should be separately assessed.



Fuel supply: A submerged low-pressure pump supplies the ammonia through the tank connections to the Liquid Fuel Supply System (LFSS) which will be located in an enclosure on deck (Fuel preparation room) together with the Fuel Valve Train (FVT), which will enable isolation of the system when the engines are not running on ammonia, and to control the engine recirculation pressure.

Life boat arrangement: Free-fall life boats in the aft of the ship. An alternative location is in the vicinity of the accommodation, with two side-ways launched free-fall lifeboats. Subject to exemption approval.

Accommodation: To reduce the risk of ammonia leakage reaching the accommodation, the vessel concept has been designed with forward accommodation. This in turn will necessitate design alterations to improve sailing conditions in harsh weather. Accommodation forward will also give noise reduction from machinery, and better light-weight distribution which will reduce amount of ballast water needed.

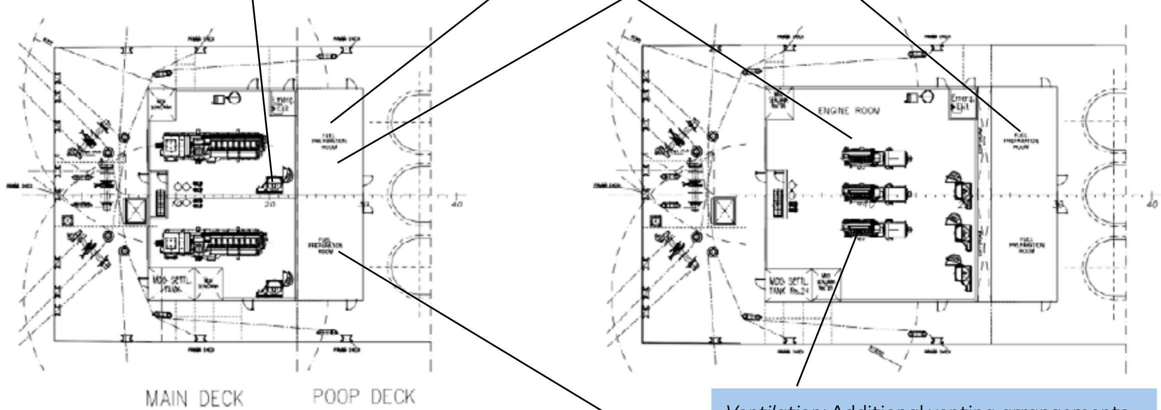
Figure 13

Engine room: The design of the engine room is presented as two different options, one with 2-stroke main propulsor and one with 4-stroke plus gensets. Both options are proposed within an enclosed machinery space. No tank connection rooms as tanks are placed on deck.

Emergency generators are placed within this space too. For 2-stroke option, it is assumed that cofferdams can be used for the routing of double-wall piping to the engine.

Engine room: The engine room and ammonia fuel preparation room is located within the cargo area in the aft part of the vessel. These cannot be adjacent to engine room Class A, unless separated by A60 bulkhead or a cofferdam.

Fuel system: Accounts for both 2-stroke and 4-stroke operation, and will likely store ammonia fuel semi-refrigerated at intermediate pressure, with lower point of -33C and ambient pressure, and higher point at around 5 bar.



Ventilation: Additional venting arrangements are expected needed to handle controlled and uncontrolled venting from the fuel system. The 2-stroke solution has option of being fully ventilated. 4-stroke solution keeps all machinery and NH_3 fuel systems on main deck which allows ventilation easier to arrange and control.

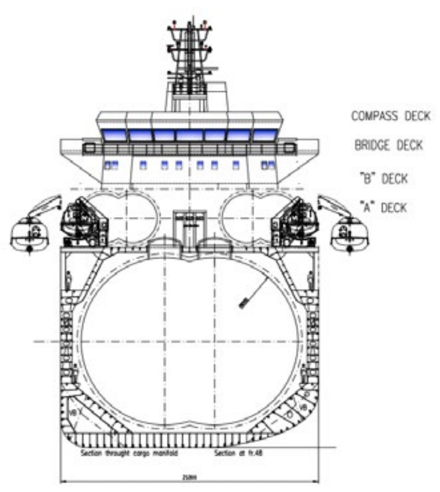


Figure 14

Appendix 3 – Select ammonia-related maritime projects

Ammonia-related projects from the Getting to Zero Mapping of Zero Emission Pilots and Demonstration Projects:

1. 13 50,000 dwt MR ammonia tanker design
2. Ammonia fuelled VLCC concept design
3. Ammonia-fueled Chittagongmax container
4. Avin International orders landmark ammonia-ready suezmax series
5. Dalian Shipbuilding Industry Ammonia Concept Study
6. Joint Agreement Reached for GHG Zero-Emission Ship
7. Joint Development Project for DSME NH3 fueled Container Ship
8. LR and SHI ammonia-fuelled tanker design
9. Mejillones ammonia plant
10. Memorandum of Understanding to study ammonia marine fuel supply chain in Singapore
11. NoGAPS
12. NYK ammonia-fueled ammonia gas carrier and Ammonia Floating Storage and Regasification Barge
13. NYK ammonia-fueled tugboat
14. SDARI ammonia-fueled Bulk Carrier
15. SOC4NH3
16. The ShipFC project - Viking Energy Ship
17. The world's first green ammonia fueled tanker: MS Green Ammonia
18. Zeeds (Zero Emission Energy Distribution at Sea initiative)
19. Pilbara Ammonia Plant
20. Porsgrunn Plant Project
21. SOFC4Maritime