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ALTERNATIVE FUELS IN SHIPPING

DIPLOMA THESIS

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Introduction

In the contemporary landscape of global trade and transportation, the maritime industry stands as a backbone, facilitating the movement of goods and commodities across continents. However, this pivotal sector faces a pressing challenge: the imperative to decarbonize in the face of escalating climate change concerns. The maritime community, acknowledging its contribution to greenhouse gas emissions, is actively exploring transformative pathways toward sustainability. At the forefront of this evolution are the alternative fuels, heralding a new era of environmental-friendly shipping practices.

The present thesis delves deep into the options of alternative fuels, a critical domain in the pursuit of a greener maritime industry. The exploration unfolds through a multifaceted lens, encompassing legislative frameworks, market drivers, and a comprehensive analysis of both bridging and future alternative fuels, including Liquified Petroleum Gas (LPG), Liquified Natural Gas (LNG), Methanol, Biofuels, Batteries, Ammonia, Hydrogen and Fuel Cells. Furthermore, the thesis investigates a spectrum of technical and operational energy efficiency measures that play a significant role towards decarbonization.

The legislative framework forms the foundation upon which the transition to alternative fuels rests. Understanding the international and regional regulations governing emissions in the maritime sector is essential to discern the mandatory directives and incentives that steer shipowners and operators toward sustainable choices. Not only regulations but other market drivers also force propelling the maritime industry toward the adoption of alternative fuels, including expectations of cargo owners, consumers and access to investors and capital.

Shipping emissions are a multifaceted challenge that requires a comprehensive and collaborative approach to mitigate their impacts. These challenges shall be addressed by ship owners and operators at the most viable way, by either approaching technical and operational measures or/and by employing alternative fuels engines.

The present thesis consists of two main aspects. The first one is the Legislative Framework that currently underlies the maritime sector including also the Market Drivers forcing shipping towards decarbonization. The second one, which is also the most extensive, is the Study of the pathways to achieve zero-carbon emissions until 2050, including, from the one hand, technical and operational measures and from the other, the use of alternative fuels.

Abstract

The main objective of the present thesis is the study for the use of alternative fuels in shipping. This study investigates the fuel options that will be available on the upcoming years and will be in compliance with the regulations in force.

To this purpose, the current and the future Legislative Framework were examined at both International and Regional stage, exploring International Maritime Organization's – IMO's measures, such as Green House Gas – GHG Strategy, Energy Efficiency Indexes (EEDI, EEXI), Ship Energy Efficiency Management Plan (SEEMP), Fuel Oil Consumption Data Collection System (DCS) and Carbon Intensity Indicator (CII), as well as regional schemes, such us those of European Union, Asia Pacific Region and United States.

The main objective was accompanied by study of other Market Drivers such us Cargo Owners and Consumers and Investors/Financial Factors. These impose a significant role as Cargo owners are increasingly facing customer and investor expectations to decarbonize their operations. This is taking place at every stage of the supply chain, all the way to the public. In response, practices such us ESG framework (Environmental, Social and Governance), Green Finance and Poseidon Principles are being followed up by various organizations to monitor their sustainability.

Policy developments and stakeholder engagement over the next decades are driving shipowners to identify, evaluate, and use technologies, fuels, and solutions that help decarbonize ships, cut energy consumption, and meet other environmental requirements. The expected adoption of energy-saving technologies and logistics and carbon-neutral fuels may fundamentally change how ships are designed and operated. Applying operational and technical efficiency measures could be sufficient to achieve shorter-term compliance with GHG regulations while in a longer term the use of green fuels seems to be the most widely used choice.

Fuel choice will be determined by ship type, operational profile, fuel availability, owner preferences and business strategy. Short sea vessels and ferries operating on fixed routes may opt for low or zero emission fuels (hydrogen, methanol, electricity) if there is supply in place locally. While for the deep-sea trades, LNG and LPG are currently the most widely used alternatives, although some owners are evaluating the viability of green methanol and ammonia. Liquified Natural Gas (LNG) emerges as a trailblazer in the realm of alternative marine fuels. A critical assessment of LNG's environmental impact and economic feasibility forms the cornerstone of this exploration. Ammonia stands as a potent contender in the pursuit of decarbonization and it is characterized as a frontrunner in the race toward sustainable maritime propulsion despite the fact that some safety concerns exist. Hydrogen, hailed as the fuel of the future, holds great potential for the maritime industry, ranging from green and blue hydrogen to bio.

As we evaluate these future marine fuels through the lenses of environmental impact, energy efficiency, availability, and economic feasibility, it becomes evident that no single fuel emerges as the silver bullet for the maritime industry. Instead, the most promising path forward involves a nuanced approach that recognizes the unique advantages and limitations of each fuel type.

Περίληψη

Στόχος της παρούσας διπλωματικής είναι η μελέτη για τη χρήση εναλλακτικών καυσίμων στη ναυτιλία. Αυτή η μελέτη διερευνά τις επιλογές καυσίμων που θα είναι διαθέσιμες τα επόμενα χρόνια και θα είναι σύμφωνες με τους ισχύοντες κανονισμούς.

Για το σκοπό αυτό, εξετάστηκε το τρέχον και το μελλοντικό Νομοθετικό Πλαίσιο τόσο σε διεθνές όσο και σε ηπειρωτικό επίπεδο, διερευνώντας τα μέτρα του Διεθνούς Ναυτιλιακού Οργανισμού – IMO, όπως η στρατηγική για το αέριο θερμοκηπίου – GHG Strategy, οι δείκτες ενεργειακής απόδοσης (EEDI, EEXI), η Διαχείριση Ενεργειακής Απόδοσης Πλοίων (SEEMP), Σύστημα συλλογής δεδομένων κατανάλωσης καυσίμου (DCS) και δείκτης άνθρακα (CII), καθώς και τοπικοί κανονισμοί, όπως αυτοί της Ευρωπαϊκής Ένωσης, της περιοχής Ασίας-Ειρηνικού και των Ηνωμένων Πολιτειών.

Ο κύριος στόχος συνοδεύτηκε από μελέτη άλλων παραγόντων της αγοράς, όπως οι ναυλωτές, οι καταναλωτές και οι επενδυτές. Αυτά επιβάλλουν σημαντικό ρόλο καθώς οι πλοιοκτήτες αντιμετωπίζουν ολοένα και περισσότερο τις προσδοκίες των πελατών και των επενδυτών για απαλλαγή από τις εκπομπές άνθρακα, που λαμβάνουν χώρα σε κάθε στάδιο της εφοδιαστικής αλυσίδα.

Εξελίξεις στην αγορά και τη νομοθεσία ωθούν τους πλοιοκτήτες να εντοπίσουν, να αξιολογήσουν και να χρησιμοποιήσουν νέες τεχνολογίες, εναλλακτικά καύσιμα και λύσεις που βοηθούν στην μείωση των ρύπων και της κατανάλωσης ενέργειας. Η εφαρμογή μέτρων επιχειρησιακής και τεχνικής απόδοσης θα μπορούσε να είναι επαρκής για την επίτευξη βραχυπρόθεσμης συμμόρφωσης με τους κανονισμούς, ενώ μακροπρόθεσμα η χρήση πράσινων καυσίμων φαίνεται πως θα είναι η πιο ευρέως χρησιμοποιούμενη επιλογή.

Η επιλογή καυσίμου θα καθοριστεί από τον τύπο του πλοίου, το λειτουργικό προφίλ, τη διαθεσιμότητα καυσίμων, τις προτιμήσεις του ιδιοκτήτη και την επιχειρηματική στρατηγική. Τα πλοία μικρών αποστάσεων και σταθερών διαδρομών θα επιλέξουν καύσιμα χαμηλών ή μηδενικών εκπομπών (υδρογόνο, μεθανόλη, ηλεκτρική ενέργεια) εάν υπάρχει τοπικός εφοδιασμός. Ενώ για το εμπόριο μεγάλων αποστάσεων, το LNG και το LPG είναι επί του παρόντος οι πιο ευρέως χρησιμοποιούμενες εναλλακτικές λύσεις, αν και ορισμένοι ιδιοκτήτες αξιολογούν τη βιωσιμότητα της πράσινης μεθανόλης και αμμωνίας.

Το Υγροποιημένο Φυσικό Αέριο (LNG) αναδεικνύεται ως πρωτοπόρος στη σφαίρα των εναλλακτικών καυσίμων πλοίων. Μια κριτική αξιολόγηση των περιβαλλοντικών επιπτώσεων του LNG και της οικονομικής σκοπιμότητας αποτελεί τον ακρογωνιαίο λίθο αυτής της εξερεύνησης. Η αμμωνία είναι ένας ισχυρός διεκδικητής στην επιδίωξη της απανθρακοποίηση, ενώ χαρακτηρίζεται ως πρωτοπόρος για τη βιώσιμη θαλάσσια πρόωση, παρά το γεγονός ότι υπάρχουν ορισμένες ανησυχίες για την ασφάλεια. Το υδρογόνο, που χαρακτηρίζεται ως το καύσιμο του μέλλοντος, έχει μεγάλες δυνατότητες για τη ναυτιλιακή βιομηχανία.

Καθώς αξιολογούμε αυτά τα μελλοντικά καύσιμα υπό το φάσμα των περιβαλλοντικών επιπτώσεων, της ενεργειακής απόδοσης, της διαθεσιμότητας και της οικονομικής σκοπιμότητας, γίνεται προφανές ότι κανένα καύσιμο δεν αποτελεί τη χρυσή τομή για τη ναυτιλιακή βιομηχανία. Αντίθετα, η πιο πολλά υποσχόμενη προσέγγιση περιλαμβάνει μια διαφοροποιημένη οπτική που αναγνωρίζει τα μοναδικά πλεονεκτήματα και περιορισμούς κάθε τύπου καυσίμου.

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CHAPTER 1

Legislative Framework & Market Drivers

Introduction

Shipping is a vital component of global trade, responsible for transporting around 80% of the world's goods by volume. As world trade continues to grow, there is an increasing number of ships crossing the oceans. Ships currently use 300 million tons of fossil fuel a year. According to the International Maritime Organization (IMO), maritime transport accounts for 2.5% of global greenhouse gas (GHG) emissions, but without further action, shipping emissions are expected to grow by 50-250% until 2050.

The IMO has set a target for cutting CO_2 emissions by 50% by 2050. Under this spectrum, on June 2021, the IMO adopted amendments to **MARPOL Annex VI at MEPC 76**, introducing regulations of the **EEXI** - Efficiency Existing Ship Index and **CII** - Carbon Intensity Indicator in order to reduce the Operational Carbon Intensity.

The decarbonization of shipping requires a massive shift to additional energy saving measures and renewable energy sources. A fundamental factor to achieve it is the modernization of ship design and the scaling up of the use of alternative low and zero carbon fuels.

These changes are being driven by IMO's initial greenhouse gas strategy and regulations that have been adopted by IMO to propel energy efficiency in shipping. IMO is further developing its regulatory framework to promote the global availability, affordability and uptake of alternative marine fuels, taking into account developing countries specific needs.

Decarbonizing the shipping sector demands international cooperation between countries via IMO and bilaterally with Renewable Energy Producers, Port Authorities and between Public and Private Sectors.

This chapter of the present thesis analyzes the Key Drivers making the pathway to alternative fuels compulsory, starting from the regulatory framework and leading to commercial pressure applied by cargo owners, the public, and the tightening requirements of investors.

1.1. Impact of Maritime Transport Emissions

Shipping is a vital component of the global economy, enabling the transportation of goods and commodities across vast distances. However, shipping emissions are currently increasing and will most likely continue to do so in the future due to the increase of global-scale trade. Ship emissions have the potential to contribute to air quality degradation in coastal areas, in addition to contributing to global air pollution.

The primary sources of these emissions are ship engines, fuel combustion, and exhaust gases. Heavy fuel oil (HFO) has been traditionally used by ships, but it contains high levels of sulfur and other pollutants. In recent years, cleaner alternatives like marine gas oil (MGO), liquefied natural gas (LNG), and even hydrogen fuel cells are gaining traction to reduce emissions.

This section explores the role of emissions in shipping, which primarily consist of greenhouse gases (GHGs), including Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O), and other air pollutants, such as Sulfur Oxides (SOx), Nitrogen Oxides (NOx) and Particulate Matter (PM), their sources, and their effects on the environment and human health.

1.1.1. Greenhouse Gases (GHG)

Greenhouse gases (GHGs) are a group of gases that trap heat in the Earth's atmosphere, leading to global warming and climate change. While naturally occurring, human activities, including shipping, have significantly increased the concentrations of these gases, intensifying their impact on the environment. Several greenhouse gases are emitted by ships during their operations, including:

1. **Carbon Dioxide (CO_2):** The primary greenhouse gas emitted from burning fossil fuels in ship engines. It is a major contributor to the enhanced greenhouse effect and global warming.
2. **Methane (CH_4):** Released during the incomplete combustion of hydrocarbon fuels, methane is a potent but relatively short-lived greenhouse gas with a higher heat-trapping potential than CO_2.
3. **Nitrous Oxide (N_2O):** Emitted from the combustion of fossil fuels, as well as from various industrial processes, N_2O is a greenhouse gas with a long atmospheric lifetime.
4. **Fluorinated Gases:** Used in refrigeration, air conditioning, and other industrial applications on some ships, these gases can have high global warming potentials but are usually emitted in smaller quantities compared to CO_2, CH_4, and N_2O.

1.1.1.1. Sources of Greenhouse Gas Emissions in Shipping

Shipping emissions primarily originate from the combustion of fossil fuels for propulsion, power generation, and onboard operations. These emissions are released into the atmosphere from exhaust systems and other equipment. The main sources include:

1. **Main Engines:** The primary engines used for propulsion, typically powered by heavy fuel oil, diesel, or alternative fuels like LNG.
2. **Auxiliary Engines:** Smaller engines used to generate electricity for lighting, heating, air conditioning, and other onboard systems.
3. **Boilers:** Used for steam propulsion and heating purposes on certain types of ships.
4. **Ventilation Systems:** Equipment used to manage the airflow in the ship's enclosed spaces can release GHGs from within the ship.

1.1.1.2. Environmental Impact of Greenhouse Gas Emissions

The accumulation of greenhouse gases in the atmosphere leads to global warming, causing a range of environmental and health impacts:

1. **Global Warming:** The primary consequence of greenhouse gas emissions is global warming. Elevated concentrations of these gases trap heat in the Earth's atmosphere, leading to higher average temperatures worldwide. This warming affects various aspects of the environment:
   - **Melting Ice:** Rising temperatures cause glaciers and ice sheets to melt, contributing to rising sea levels and increased risk of coastal flooding.
   - **Sea Level Rise:** Melting ice and the expansion of seawater due to higher temperatures contribute to sea level rise, threatening coastal communities and ecosystems.
2. **Ecosystem Disruption:** Climate change disrupts ecosystems by altering temperature and precipitation patterns. This can lead to:
   - **Shifts in Habitats:** Species that are adapted to specific temperature ranges may be forced to migrate or face extinction as their habitats change.
   - **Loss of Biodiversity:** Climate change can affect the breeding and migration patterns of animals, leading to reduced biodiversity and imbalanced ecosystems.
   - **Coral Bleaching:** Higher ocean temperatures cause coral reefs to expel the symbiotic algae that provide them with nutrients, resulting in coral bleaching and ecosystem degradation.
3. **Extreme Weather Events:** Greenhouse gas emissions contribute to the frequency and intensity of extreme weather events:
   - **Hurricanes and Cyclones:** Warmer Ocean temperatures fuel the intensity of hurricanes and cyclones, leading to more destructive storms.
   - **Droughts:** Altered precipitation patterns can lead to prolonged droughts in some regions, affecting agriculture, water supply, and ecosystems.
   - **Heatwaves:** Rising temperatures increase the frequency and severity of heatwaves, posing health risks to vulnerable populations.
4. **Health Impact:** Greenhouse gas emissions contribute to a wide range of impacts in human well-being.

- **Respiratory and Cardiovascular Diseases:** Increased concentrations of greenhouse gases lead to poor air quality, which can exacerbate respiratory and cardiovascular conditions, such as asthma, chronic obstructive pulmonary disease (COPD), and heart disease.
- **Vector-Borne Diseases:** Altered temperature and humidity patterns can influence the distribution of disease-carrying vectors like mosquitoes and ticks, leading to the expansion of diseases like malaria, dengue fever, and Lyme disease.
- **Mental Health:** The stressors associated with climate change, such as extreme weather events and displacement, can contribute to mental health issues, including anxiety, depression, and post-traumatic stress disorder (PTSD).
- **Food Security:** Climate change affects crop yields and food production. Altered growing seasons and extreme weather events can lead to crop failures, affecting food supply and prices, while disrupted food production can exacerbate malnutrition and food insecurity, especially in vulnerable populations.

1.1.2. SOx emissions

Sulfur oxides (SOx) are a group of air pollutants that include sulfur dioxide (SO_2) and other related compounds. These emissions are a byproduct of burning fossil fuels, particularly those with high sulfur content, and can have detrimental effects on both the environment and human health. In the context of shipping, SOx emissions are a significant concern due to their impact on air quality and the marine ecosystem.

1.1.2.1. Sources of Sulfur Oxide Emissions in Shipping

SOx emissions from shipping predominantly originate from the combustion of sulfur-containing fuels, primarily heavy fuel oil (HFO). HFO has been a traditional choice for marine engines due to its affordability; however, it contains significant amounts of sulfur. When burned, sulfur in the fuel reacts with oxygen to form sulfur dioxide (SO_2), which is released into the atmosphere through ship stacks and exhaust systems. SOx emissions can also occur from the use of lower-quality fuels that may contain sulfur compounds.

Recognizing the environmental and health impacts of sulfur oxide emissions, the International Maritime Organization (IMO) has introduced regulations to control these emissions:

1. **MARPOL Annex VI:** The International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI sets limits on the sulfur content of marine fuels. The regulation has established designated emission control areas (ECAs) with stricter sulfur limits, driving the use of cleaner fuels in these regions.
2. **Global Sulfur Cap:** In January 2020, the IMO implemented a global sulfur cap, limiting the sulfur content of marine fuels to 0.5% for ships operating outside ECAs. This significantly reduced sulfur oxide emissions from ships worldwide.

To comply with sulfur oxide regulations and reduce emissions, the maritime industry has adopted several strategies:

1. **Low-Sulfur Fuels:** Ships are transitioning from high-sulfur fuels to low-sulfur alternatives like marine gas oil (MGO) or compliant fuel blends to meet the sulfur content requirements.
2. **Exhaust Gas Cleaning Systems (Scrubbers):** These systems remove sulfur oxides from exhaust gases, enabling ships to continue using higher-sulfur fuels while reducing emissions.
3. **Alternative Fuels:** Some shipowners are exploring alternative fuels like liquefied natural gas (LNG) that inherently have lower sulfur content and emissions.

1.1.2.2. Environmental and Health Impact of Sulfur Oxide

Sulfur dioxide (SO_2), a key component of SOx emissions, has various negative effects on the environment and human health:

1. **Air Quality:** SO_2 contributes to the formation of fine particulate matter (PM2.5) and can lead to the formation of acid rain. These pollutants can degrade air quality, impair visibility, and damage ecosystems.
2. **Acid Rain:** SO_2 emissions can react with other compounds in the atmosphere to form acid rain. Acid rain has corrosive effects on buildings, soil, and aquatic ecosystems, leading to environmental degradation.
3. **Human Health:** Inhalation of SO_2 can cause respiratory issues, exacerbate asthma symptoms, and contribute to cardiovascular diseases. It can also irritate the eyes and throat.
4. **Marine Ecosystem:** SOx emissions can deposit sulfur compounds into marine environments, affecting coastal waters and marine life. Acidification of oceans due to SO_2 emissions can harm coral reefs and shellfish populations.

1.1.3. NOx emissions

Nitrogen oxides (NOx) are a group of reactive gases that include nitrogen dioxide (NO_2) and nitric oxide (NO). These gases are produced through various combustion processes, including those occurring in vehicle engines, power plants, and industrial facilities. In the context of shipping, NOx emissions are a significant concern due to their contribution to air pollution, smog formation, and their role as a precursor to other environmental and health issues.

1.1.3.1. Sources of Nitrogen Oxides Emissions in Shipping

NOx emissions in shipping primarily originate from the combustion of fossil fuels, particularly in ship engines. The high temperatures and pressures in engines cause nitrogen in the air to react with oxygen, forming nitrogen oxides. These emissions are then released into the atmosphere through ship stacks and exhaust systems.

Recognizing the environmental and health impacts of sulfur oxide emissions, the International Maritime Organization (IMO) has set limits on NOx emissions from ship engines through the International Convention for the Prevention of Pollution from Ships (MARPOL). These regulations establish Tier I, II, and III emission standards based on the ship's engine type, size, and operation. Maritime industry is investing in research and development to design more fuel-efficient and low-emission engines that can help reduce NOx emissions, while Selective Catalytic Reduction (SCR) systems can be installed in ship engines to reduce NOx emissions. These systems use a catalyst to convert NOx into harmless nitrogen and water vapor. Some alternative fuels, such as liquefied natural gas (LNG), inherently produce lower NOx emissions compared to traditional fuels like heavy fuel oil.

1.1.3.2. Environmental and Health Impact of Nitrogen Oxides

Nitrogen oxides (NOx) have various negative effects on the environment and human health:

1. **Air Quality:** NOx emissions contribute to poor air quality, leading to the formation of ground-level ozone and smog. Ground-level ozone can cause respiratory problems, especially in children, the elderly, and individuals with pre-existing respiratory conditions.

2. **Acid Rain Formation:** Nitrogen oxides can combine with other air pollutants to form nitric acid, which contributes to acid rain. Acid rain can harm aquatic ecosystems, damage crops, and erode buildings and infrastructure.

3. **Eutrophication:** NOx emissions can lead to the deposition of nitrogen compounds in water bodies, causing eutrophication. This process promotes excessive growth of algae, which depletes oxygen levels in the water and can harm aquatic life.

4. **Health Impact:** Nitrogen oxides (NOx) contribute to a wide range of impacts in human well-being.
   - **Respiratory Issues:** Nitrogen dioxide (NO2), a major component of NOx emissions, can irritate the respiratory system, worsen asthma symptoms, and increase the risk of respiratory infections.

   - **Cardiovascular Effects:** Long-term exposure to NO_2 has been associated with an increased risk of cardiovascular diseases, including heart attacks and strokes.

1.1.4. PM emissions

Particulate Matter (PM) refers to tiny solid particles and liquid droplets suspended in the air. These particles vary in size and composition, and they can originate from various sources, including combustion processes. In the shipping industry, PM emissions are a significant concern due to their adverse effects on air quality, human health, and the environment.

1.1.4.1. Sources of Particulate Matter Emissions in Shipping

PM emissions in shipping arise from various sources, primarily associated with the combustion of fossil fuels in ship engines, including heavy fuel oil (HFO), marine gas oil (MGO), and other fuel types. The combustion process, particularly in diesel engines, generates fine particles that can vary in size from a few nanometers to micrometers, occurred as a result of incomplete combustion. These particles can include elemental carbon, organic carbon, sulfates, nitrates, metals, and other compounds.

The International Maritime Organization (IMO) addresses PM emissions through regulations like the MARPOL Annex VI, which sets limits on the sulfur content of marine fuels. By reducing sulfur emissions, the formation of sulfate particles is also minimized. Using lower-sulfur fuels and cleaner alternatives like liquefied natural gas (LNG) can lead to reduced PM emissions from ship engines, while scrubbers can help remove particulate matter from exhaust gases, reducing the emissions of both PM and sulfur oxides (SOx). Incorporating advanced engine technologies, such as improved fuel injection and combustion processes, can lead to more efficient combustion and reduced PM emissions.

1.1.4.2. Environmental and Health Impact of Particulate Matter

1. **Air Quality:** PM emissions contribute to air pollution, affecting air quality in port areas and along shipping routes. Fine particulate matter (PM2.5) can be especially concerning as it can penetrate deep into the respiratory system and even enter the bloodstream.
2. **Climate Effects:** Some PM particles can have a cooling effect on the atmosphere by reflecting sunlight back into space. This is known as the aerosol effect, which interacts with greenhouse gases and contributes to complex climate dynamics.
3. **Environmental Impact:** Deposition of PM particles can affect terrestrial and aquatic ecosystems, leading to soil and water contamination. In marine environments, PM deposition can impact water quality and marine life.
4. **Respiratory and Cardiovascular Health:** Exposure to PM can lead to respiratory problems, exacerbate asthma, and increase the risk of cardiovascular diseases. Fine particles, in particular, are linked to more severe health effects due to their ability to penetrate deep into the lungs.

Shipping emissions are a multifaceted challenge that requires a comprehensive and collaborative approach to mitigate their impacts. As the world continues to rely on maritime transport, the need to address the environmental consequences of shipping becomes more pressing. Through a combination of stringent regulations, innovative technologies, and industry-wide commitment, it is possible to navigate towards a cleaner and more sustainable future for global shipping.

1.2. Shipping Decarbonization Key Drivers

Shipping decarbonization is a pressing and intricate challenge that has gained significant attention on the global stage. The shipping industry, a backbone of international trade and commerce, is responsible for a substantial portion of the world's greenhouse gas emissions. As societies and industries increasingly recognize the urgent need to mitigate climate change, the imperative to decarbonize shipping has emerged as a critical frontier in the broader battle against environmental degradation.

Decarbonization is a complex and multifaceted challenge that requires the collective effort of various stakeholders, including governments, industry players, technology developers, and research institutions. Shipping companies need to adapt to a changing business environment with ever stricter emissions regulations, pressure from cargo owners, the public, and the tightening requirements of investors.

The initial IMO GHG Strategy and the first wave of regulations are already impacting the design and operations of all ships, as latest shall fulfil the minimum requirements. However, commercial pressure may incentivize shipowners to aim higher. Especially if poor performers become less attractive on the charter market, and struggle to access capital.

The dynamics of ship decarbonization are underpinned by three fundamental pillars that are anticipated to shape the course of this transformation throughout the 2020s and beyond. These pillars– **regulations and policies**, **access to investors and capital**, and **cargo-owner and consumer expectations** – converge to propel the shipping industry toward a more sustainable and environmentally responsible future (DNV, 2022).

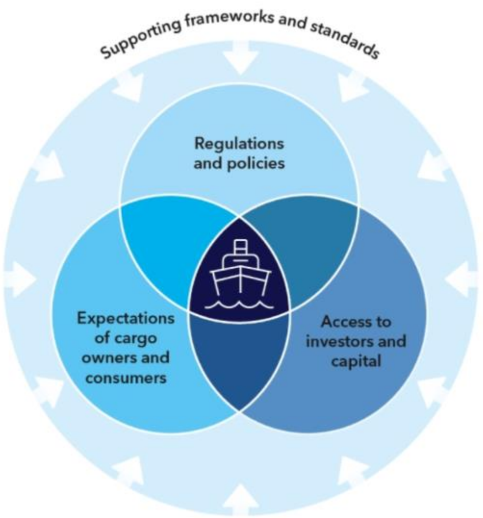

Figure 1-1: Three Key Fundamental Drivers of shipping decarbonization.

Subject section of present thesis analyses the main key drivers pushing the shipping industry toward decarbonization.

1.2.1. Regulations and Policies

The decarbonization targets pose challenges for a range of stakeholders, from ship owners, charterers and cargo owners to ship builders, designers, engine manufacturers, fuel suppliers' financiers and policy makers. Reaching these targets will require the application of new and existing technologies, lowering speed and the deployment of large volumes of sustainable zero-carbon or carbon-neutral fuels.

The key to achieving reduction of emission is developing, maturing and scaling up solutions to a level where the cost is acceptable. Regulations should be supplemented by other policy measures and incentives to drive technology development and emission reductions, while at the same time ensuring the shipping activity is not restricted.

With the **6th IPCC Assessment Report**[1] on climate change urging rapid action on climate change, owners and operators can expect increasingly strict limits on carbon emissions to come into force over the next decade (IMO). From sweeping global regulations to restrictions enforced by local port authorities, shipowners must not only comply with existing regulations but prepare for a future likely to include carbon taxes or regionally enforced emissions trading schemes. Business-critical decisions are increasingly shaped by new environmental requirements.

1.2.1.1. IMO Regulations

IMO – the International Maritime Organization – is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. IMO's work supports the UN sustainable development goals (**UN SDGs**). IMO contributes to the global fight against climate change, in support of the UN Sustainable Development Goal 13, to take urgent action to combat climate change and its impacts.

The IMO Convention for the Prevention of Pollution from Ships (**MARPOL**) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes. The Convention includes regulations aimed at preventing and minimizing pollution from ships and currently includes six technical Annexes.

In **1997**, a new annex was added to MARPOL Convention. The "Regulations for the prevention of air pollution from ships" (**Annex VI**) seek to **minimize airborne emissions** from ships and the **carbon intensity** of global shipping in order to annihilate its contribution to local and global air pollution and environmental problems.

MARPOL Annex VI entered into force on 19 May **2005** and since then it has been continuously evolving in line with the commitments that Member States make within IMO to

[1] The Sixth Assessment Report (AR6) of the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) is the sixth in a series of reports which assess scientific, technical, and socio-economic information concerning climate change. Three Working Groups (WGI, II, and III) covered the following topics: The Physical Science Basis (WGI); Impacts, Adaptation and Vulnerability (WGII); Mitigation of Climate Change (WGIII). Of these, the first study was published in 2021, the second report February 2022, and the third in April 2022. The final synthesis report was finished in March 2023.

limit the harmful effects of air pollution and GHG emissions from international shipping on human health and the environment.

In **2011**, IMO adopted amendments to MARPOL Annex VI to mandate technical and operational energy efficiency measures to reduce emissions of greenhouse gases from international shipping, the Energy Efficiency Design Index (EEDI) mandatory for new ships, and the Ship Energy Efficiency Management Plan (SEEMP).

In **2018**, IMO adopted an initial strategy on the reduction of GHG emissions from ships, setting out a vision which confirms IMO's commitment to reducing GHG emissions from international shipping and to phasing them out as soon as possible.

A. IMO GHG Strategy

The IMO's Marine Environment Protection Committee (MEPC), on their 72nd session (**MEPC 72**) in April 2018, adopted the resolution MEPC.304(72) with an ambitious **GHG Reduction Strategy** with a vision to decarbonize shipping.

Subject to amendment depending on reviews to be conducted by the Organization, the Initial Strategy identifies levels of ambition for the international shipping sector noting that technological innovation and the global introduction of alternative fuels and/or energy sources for international shipping will be integral to achieve the overall ambition. The reviews should take into account updated emission estimates, emissions reduction options for international shipping, and the reports of the Intergovernmental Panel on Climate Change (IPCC), as relevant. Levels of ambition directing the Initial Strategy are as follows:

1. **Carbon Intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships**
   to review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate;

2. **Carbon Intensity of international shipping to decline**
   to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and

3. **GHG emissions from international shipping to peak and decline**
   to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO2 emissions reduction consistent with the Paris Agreement temperature goals.

Candidate measures set out in this Initial Strategy should be consistent with the following timelines:

I. possible **short-term measures** could be measures finalized and agreed by the Committee between 2018 and 2023.

II. possible **mid-term measures** could be measures finalized and agreed by the Committee between 2023 and 2030.

III. possible **long-term measures** could be measures finalized and agreed by the Committee beyond 2030.

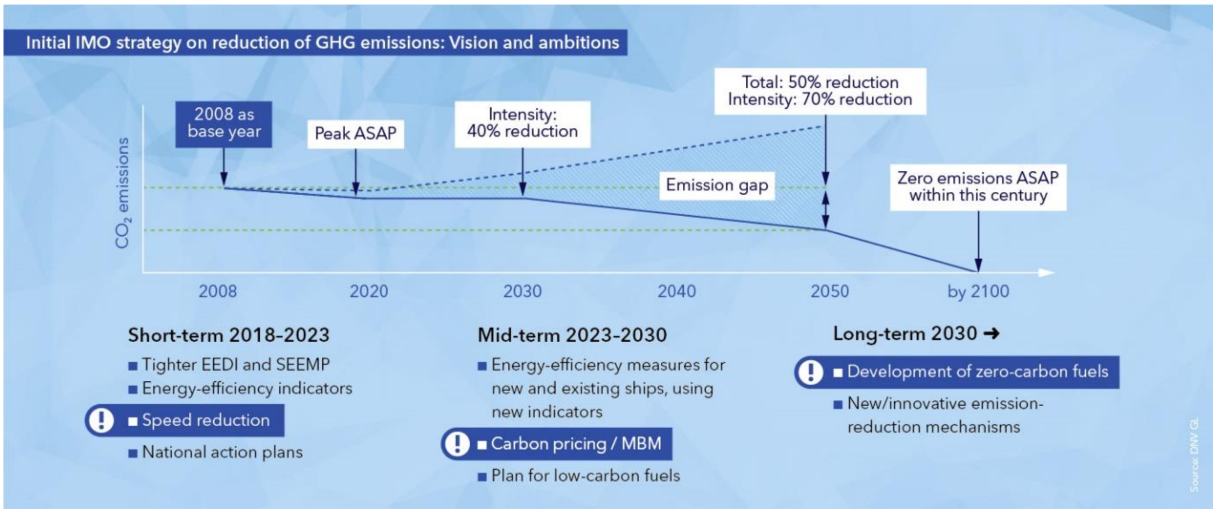

Figure 1-2: Initial IMO GHG Reduction Strategy timeline

The Third IMO GHG Study 2014 has estimated that GHG emissions from international shipping in **2012** accounted for some **2.2%** of the total anthropogenic CO_2 emissions, while the Fourth IMO GHG Study 2020 has estimated that shipping in **2018** emitted 1,056 million tonnes of CO_2, accounting for about **2.9%** of the anthropogenic CO_2 emissions for that year. In 2050, shipping emissions could be between 90 and 130% of 2008 emissions, according to a series of long-term business-as-usual scenarios (IMO, 2021).

On **July 2023**, Member States of IMO, meeting at the 80th Marine Environment Protection Committee (**MEPC 80**), have adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, with enhanced targets to tackle harmful emissions.

The revised IMO GHG Strategy includes an enhanced common ambition to reach net-zero GHG emissions from international shipping close to 2050, a commitment to ensure an uptake of alternative zero and near-zero GHG fuels by 2030, as well as indicative check-points for 2030 and 2040. Levels of ambition directing the 2023 IMO GHG Strategy are as follows:

1. **carbon intensity of the ship to decline through further improvement of the energy efficiency for new ships**
   to review with the aim of strengthening the energy efficiency design requirements for ships;

2. **carbon intensity of international shipping to decline**
   to reduce CO2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, compared to 2008;

3. **Uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to increase**
   uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030; and

4. **GHG emissions from international shipping to reach net zero**
   to peak GHG emissions from international shipping as soon as possible and to reach net-zero GHG emissions by or around, i.e. close to 2050, taking into account different national circumstances, whilst pursuing efforts towards phasing them out as called for in the Vision consistent with the long-term temperature goal set out in Article 2 of the Paris Agreement.

Indicative checkpoints to reach net-zero GHG emissions from international shipping:

- to reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008; and
- to reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040, compared to 2008.

B. Energy Efficiency of Ships

In order to reduce shipping's impact on climate change, IMO has started in the early 2000s to consider **technical and operational measures** to improve the energy efficiency of ships (IMO). In 2011, IMO adopted amendments to MARPOL Annex VI to mandate technical and operational energy efficiency measures to reduce the amount of CO_2 emissions from international shipping. The Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) entered into force on 1 January 2013.

IMO adopted further energy efficiency measures for continuous improvements in the energy efficiency of shipping which remains crucial (IMO). These measures includes:

- Energy Efficiency Design Index (**EEDI**): New ships must be built and designed to be more energy efficient.
- Energy Efficiency Existing Ship Index (**EEXI**): Set to enter into force in 2023, EEXI applies many of the same design requirements as the EEDI, with some adaptations regarding limited access to design data.
- Ship Energy Efficiency Management Plan (**SEEMP**): A practical tool for helping shipowners manage their environmental performance and improve operational efficiency.
- The Fuel Oil Consumption Data Collection System (**DCS**): Mandates annual reporting of CO_2 emissions and other activity data and ship particulars for all ships above 5,000 GT.
- Carbon Intensity Indicator (**CII**) is a rating scheme (A-E) developed by the IMO to measure the annual performance of all ships above 5,000 GT in terms of CO2 per DWT and distance covered.

EEDI & EEXI: Energy Efficiency Indexes

The **Energy Efficiency Design Index (EEDI)** is an important technical measure aiming at promoting the use of more energy efficient equipment and engines for the design of new ships in order to make them less polluting. It was set into force on 1 January 2013, following a two-year transitional phase.

The EEDI requires a minimum energy efficiency level for different ship type and size segments and provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO_2) per ship's capacity-mile (the smaller the EEDI, the more energy efficient the ship design) and is calculated by a formula based on the technical design parameters for a given ship.

The EEDI is a non-prescriptive, performance-based mechanism. As long as the required energy efficiency level is attained, ship designers and builders are free to use the most cost-efficient solutions for the ship to comply with the regulations. Typical efficiency measures include the following:

- Propulsion optimization (e.g. ducted propellers, improved hull design)
- Engine optimization (e.g. hybrids)
- Energy efficient technologies (e.g. waste heat recovery)

The **Energy Efficiency Existing Ship Index (EEXI)** requirements were adopted in June 2021 as a short-term measure under the Initial IMO GHG Strategy framework for implementation before 1 January 2023.

Under the EEXI framework, all existing ships of 400 GT and above are required to calculate their **attained EEXI**, which reflects the "technical" or "design" efficiency of the ship. Ships then have to reach a "**required EEXI**", equivalent to Required EEDI levels for 2022, with intention to bring existing vessels to a similar efficiency standard as the most recent ones.

The EEXI framework is technology neutral, and the shipowner or charterer can choose the most appropriate means to achieve the goals set by IMO regulations. Existing technologies available to comply with the Required EEXI are engine/shaft power limitation, waste heat recovery, wind assisted propulsion, etc.

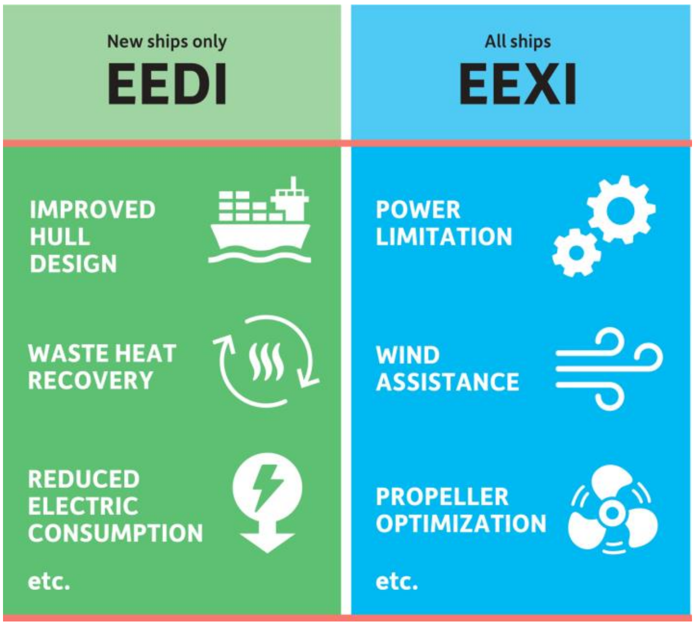

Figure 1-3: EEDI in contrast to EEXI. (IMO)

CII: Carbon Intensity Indicator

The **Carbon Intensity Indicator (CII)** requirements, as well as the EEXI, were adopted in June 2021 as a short-term measure under the Initial IMO GHG Strategy framework for implementation before 1 January 2023.

The CII measures how efficiently a vessel above 5,000 GT transports goods or passengers and is given in grams of CO_2 emitted per cargo-carrying capacity and nautical mile.

The first reporting of the CII based on 2023 data is due no later than 31 March 2024. Vessels will receive a rating of A (major superior), B (minor superior), C (moderate), D (minor inferior) or E (inferior performance level). The rating thresholds will become increasingly stringent towards 2030. A vessel rated D for three consecutive years or rated as E, shall develop a "Plan of corrective actions".

The CII framework provides tools for Administrations, ports and other stakeholders, including the financial sector, to provide incentives to most energy efficient ships.

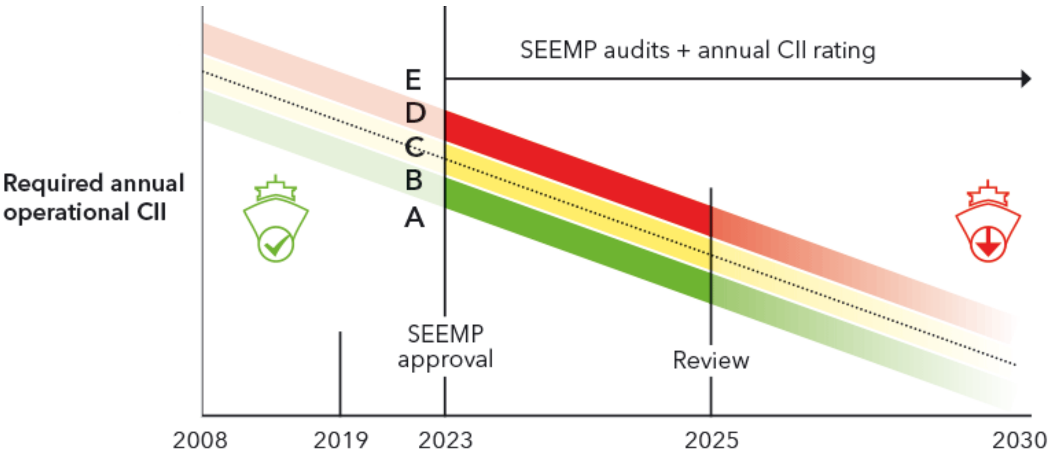

Figure 1-4: CII rating stringent towards 2030.

The CII unit is “grams of CO_2 emitted per cargo-carrying capacity and nautical mile”, whereby cargo capacity is either deadweight or gross tons depending on ship type. In addition, to cater for special design and operational circumstances, the correction factors and voyage adjustments can be applied to the basic CII calculations for the purposes of determining the rating.

<u>Ship Energy Efficiency Management Plan (SEEMP)</u>

Introduced in 2013 by the IMO, and further enhanced in 2023, the Ship Energy Efficiency Management Plan (SEEMP) is an operational mechanism to improve the energy efficiency of a ship in a cost-effective manner. The SEEMP consists of three parts:

- Part I: Ship management plan to improve energy efficiency
- Part II: Ship fuel oil consumption data collection plan
- Part III: Ship operational carbon intensity plan

Part I of the SEEMP is mandatory and must be kept on board all ships above 400 GT. A verified. **Part II** is mandatory for all ships above 5,000 GT as part of the Data Collection System. A verified **Part III** is required for all ships subject to the Carbon Intensity Indicator (CII). SEEMP Parts I and III are generally divided into the following sections: Goals, Planning and implementation of measures, Monitoring and Self-evaluation/improvement.

The SEEMP urges the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimize the operational performance of a ship. The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time using recognized monitoring tools. Typical examples of improving operational efficiency and carbon intensity include:

- Speed optimization
- Weather routing
- Hull monitoring and maintenance
- Installation of heat recovery systems

<u>IMO DCS – Data Collection System</u>

In October 2016, MEPC 70 adopted, by resolution MEPC.278(70), mandatory MARPOL Annex VI requirements for ships to record and report their fuel oil consumption in order to have the necessary data to make decisions on further measures to improve the energy efficiency of ships.

Starting from 1 January 2019, ships of 5,000 GT and above (which produce approximately 85% of the total CO_2 emissions from international shipping) are required to collect data, such as fuel consumption, distance travelled and hours underway, for each type of fuel oil they use.

The aggregated DCS data forms the basis for the CII rating and the SEEMP Part III. From 1 January 2023 the SEEMP Part III must be verified and onboard ships of 5,000 GT and above to document their plans to achieve their CII targets. The intention of the enhanced SEEMP is to ensure continuous improvement, and its implementation will be subject to company audits.

Starting in 2024, the CII shall be calculated based on the DCS data of the previous year, and then reported to the DCS verifier to be verified together with the aggregated DCS data. The attained CII and the environmental rating (A to E) will then be noted on the DCS Statement of Compliance (SoC), which will be required to be kept on board for five years.

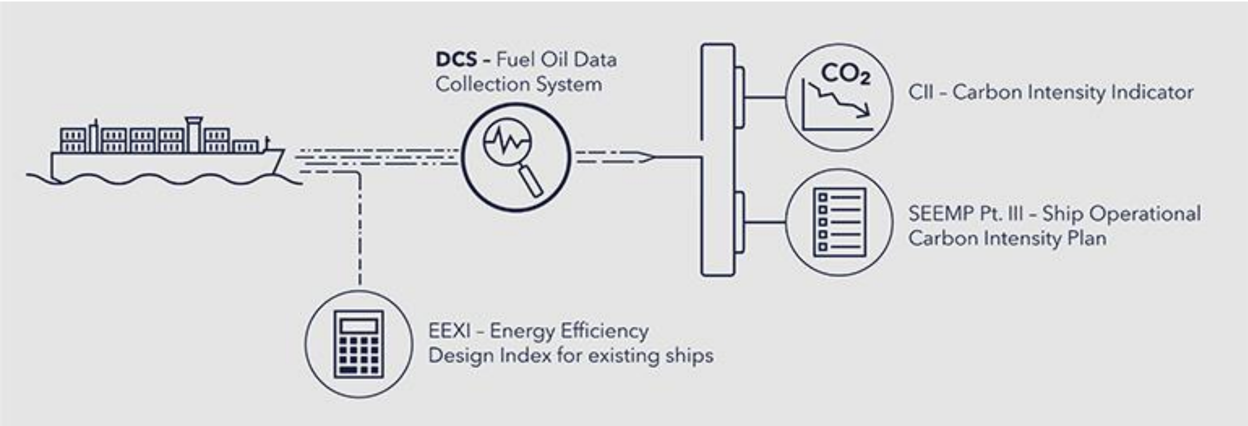

Figure 1-5: Connection between the DCS, CII and SEEMP Part III. (DNV)

1.2.1.2. *Regional Developments*

Coordinated global action will be required to lower emissions from ships. However, except of the aforementioned International Regulations and Standards set by IMO, ship owners and managers must also consider regulations implemented and enforced by regional, state, and local authorities.

Many state actors have developed and implemented their own regulations to lower emissions from ships. While operators would be wise to become familiar with steps smaller maritime countries or ports in the Middle East, South East Asia, South America and the Pacific have taken to lower GHGs, ambitious actions planned or taken by leading maritime nations such as China, the EU, Japan, South Korea and the United States will shape the industry’s future in the years ahead.

A. European Union (EU)

The EU accounts for around 15% of world's trade in goods. As a result, EU regulations on emissions can have a significant impact on global shipping.

Emissions control

In 2007, Sulphur Emissions Control Areas (SECAs) were established in the Baltic and North Seas, and from 1 May 2025 the Mediterranean Sea is also included, requiring that ships must use marine fuels with a sulphur content not exceeding 0.10 per cent. The EU Sulphur Directive mandates a similar requirement for ships that berth in EU ports, regardless of the area. The Baltic and North Seas are also designated NOx Emission Control Areas (NECAs), and all ships constructed after 1 January 2021 need to comply with NOx Tier III requirements when sailing in these areas.

The EU, through the European Climate Law, has set legally binding targets to reduce emissions by 55% in 2030 (relative to 1990) and to become climate-neutral by 2050. The Green Deal is a blueprint of the change required to reach these ambitions, and a key part of this plan is the “**Fit for 55**” legislative package which was proposed in 2021. Two of these legislations, the **EU ETS** and the **FuelEU** Maritime, set specific requirements on ships.

EU Emissions Trading Scheme (ETS)

First introduced in 2005 for some land-based industries and aviation, the **EU Emissions Trading Scheme** (**EU ETS**) is an emissions cap-and-trade system whereby a limited number of emissions allowances – the cap – is put on the market and can be traded. In 2020, the European Parliament has adopted a resolution to include shipping in Europe’s (ETS) from 2023, with a target to achieve a 40 per cent reduction in CO_2 emissions by 2030. Despite some resistance from shipowners, final amendments to the legislation are expected shortly.

The cap is reduced each year, ensuring the EU’s emissions target of a 55 per cent reduction by 2030 (relative to 1990) can be met while becoming climate-neutral by 2050. Ships above 5,000 GT transporting cargo or passengers for commercial purposes in the EU will be required to acquire and surrender emissions allowances for its GHG emissions from 2024 as reported through the **Monitoring, Reporting** and **Verification** (**MRV**) system.

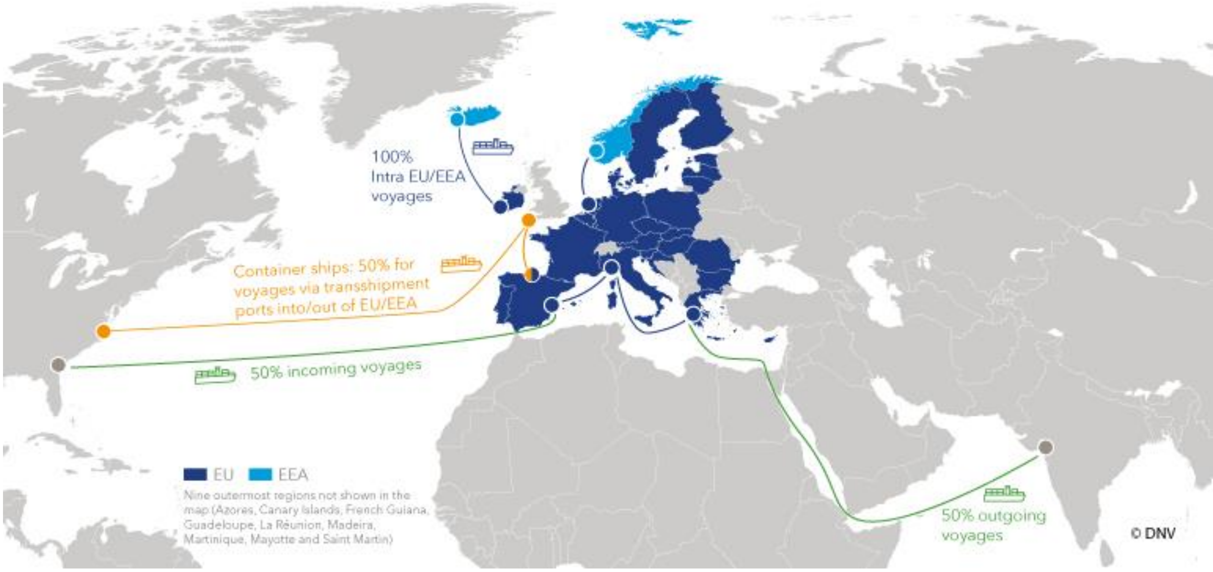

Figure 1-6: EU ETS based on percentage of emissions on voyages. (DNV)

The **FuelEU Maritime** regulations set well-to-wake GHG emissions requirements per unit of energy used by the ship. The requirements take effect from 2025, and over time more stringent limits will be set on well-to-wake GHG emissions. The reduction requirement is set relative to the average well-to-wake fuel GHG intensity of the fleet in 2020, starting at a 2 per cent reduction in 2025, increasing to 6 per cent in 2030, and accelerating from 2035 to reach an 80 per cent reduction by 2050. The regulation also allows for compliance across a group of ships, meaning that one ship in the group can over-achieve on the well-to-wake GHG intensity, allowing for the other ships to continue to use fossil fuels.

Port and bunkering infrastructure

To improve local air quality and reduce GHG emissions, many ports are working to offer shore power, and as part of FuelEU Maritime, container and passenger ship are required to use shore power when at berth in European ports from 2030. The revised Alternative Fuels Infrastructure Regulation requires the main EU ports (TEN-T ports) to provide a minimum shore-side electricity supply for oceangoing container ships and oceangoing passenger ships as of January 2030. Member states are also required to provide refuelling points for liquefied methane and develop plans for hydrogen, ammonia and methanol.

EU and IMO

The EU plans to introduce regulations to reduce GHG emissions that exceed IMO requirements in European waters. While some argue that the EU's proactive approach to combatting climate change will push the IMO to move more decisively, others worry that regionalizing regulations will slow global action. The revised EU ETS includes a clause requiring a review of the EU ETS directive in case the IMO adopts a market-based measure, and in case the IMO has not adopted any measure by 2028, the EU ETS for shipping may be strengthened further.

B. Asia Pacific Region

Home to some of the world's busiest ports, shipping companies, sea-lanes and shipyards, countries in the Asia Pacific region will play a critical role in the industry's efforts to decarbonize. While leading maritime nations like China, Japan and Korea work together with the IMO on global solutions, each country also has their own decarbonization strategies which are likely to impact the industry going forward.

❖ CHINA

Public pressure to act on improving air quality and fighting climate change has pushed the Chinese government to announce ambitious GHG reduction targets. Some have called for China to move more quickly, and the government has shown that when political and economic forces align, it can move speedily to manage any challenge.

Emissions control

The Ministry of Ecology and Environment (MEE) acts as the national authority with joint oversight of trading activities with other national regulators. In September 2015, China designated its own Domestic ECAs (extending 12km from the coast in select areas) and announced a gradual implementation of requirements covering emissions of air pollutants SOx and NOx from ships. China's DECAs do not apply to GHGs at present but establish a framework for future action. China is also in dialogue with the IMO to establish an ECA that would extend 200 km off the coast.

China's Emissions Trading Scheme

In 2020, the Chinese government announced ambitious plans to become carbon-neutral by 2060. This was followed up in October 2021 with the Action Plan for Carbon Dioxide Peaking Before 2030. Regarding the shipping sector, China has committed to work faster to upgrade old ships, develop ships fueled by electric power and LNG, further promote the use of shore power by ships while in port, and make in-depth efforts to advance demonstration and utilization of green, smart ships along coastline and inland waterways according to local conditions. China's national ETS started operating in 2021 and does not yet include the shipping sector (as of April 2023). But the national market has been built on the successful experience of local pilot markets. The Shanghai ETS market already included local shipping companies and ports into its carbon emissions allowance management unit list in 2021, indicating that the national ETS could be further expanded as well.

❖ SOUTH KOREA

The year 2020 was an important one for climate ambitions in South Korea, with the government announcing a Green New Deal and a net-zero target for 2050 tied to a commitment to speed up investment in clean technologies across the economy. In January 2021, the government announced plans to reduce particulate matter (PM) in ports by 60 per cent in 2025 (compared to 2017).

Emissions control

In September 2020, the South Korean Ministry of Maritime Affairs and Fisheries (MOF) introduced an air quality control programme that defines selected South Korean ports and areas as Emission Control Areas (ECAs). From 1 September 2020, speed limits were introduced and vessels at berth or quay had to comply with a maximum sulphur limit of 0.1 per cent. From 1 January 2022, all vessels operating within these ECAs will have to comply with sulphur limits and limits on speed. The programme does not yet apply directly to GHGs but establishes a framework for future action.

South Korea's Emissions Trading

Launched on 1 January 2015, South Korea's ETS was East Asia's first nationwide mandatory ETS. The system covers 685 of the country's largest emitters, accounting for about 73.5% of national GHG emissions. It not only includes direct emissions of six GHGs but also covers indirect emissions from electricity consumption. At present (as of April 2023), the ETS does not apply to shipping, but the ETS will play a critical role in meeting South Korea's 2030 NDC target of a 24.4 per cent reduction (from 2017 emissions).

- **JAPAN**

As the world's third-largest ship-owning nation and a leader in maritime technologies, Japan's actions on emissions reductions will be watched closely. In addition to setting ambitious national targets, Japan has played an important role in establishing global mechanisms, such as providing technical support to the IMO's EEXI regulation, among other initiatives.

Emissions control

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Japan's Emissions Trading Scheme

While Japan pioneered cap-and-trade schemes in Tokyo (2010) and the nearby Saitama Prefecture (2011), these programs do not yet apply to the country's shipping industry. It should also be noted that the government of Japan has expressed concerns over the extension of EU ETS to international shipping, preferring a global approach rather than a regional approach.

C. United States (US)

In US territorial waters, regulations on emissions from ships are managed by the Environmental Protection Agency (EPA).

The EPA manages regulations on emissions from ships in accordance with the “Clean Air Act”, a federal law that regulates air emissions from stationary and mobile sources. The law authorizes the EPA to establish National Ambient Air Quality Standards (NAAQS) to protect public health and regulate emissions of hazardous air pollutants, but do not yet include caps on GHGs.

The EPA, and other departments within the US Government, work with the IMO to help draft, amend and enforce international regulations on emissions. For example, the U.S. successfully petitioned the IMO to designate the North American Emission Control Area (including the Hawaiian Islands) in 2010 and the U.S. Caribbean Sea Emission Control Area in 2014. While these ECAs do not apply to GHG emissions, they provide a framework for future action on decarbonization.

Engine certification and reporting

The EPA issues the Engine International Air Pollution Prevention (EIAPP) certificate to document that the engine meets MARPOL Annex VI NOx standards for US flagged vessels. The US Coast Guard issues International Air Pollution Prevention (IAPP) certificates and makes sure operators maintain records regarding their compliance with emission standards, fuels requirements and other provisions of MARPOL Annex VI.

Port authorities Port emissions are managed by local authorities, with policies that vary from state to state. For example, in 2020, Port Houston became the first in the world to power all terminals and public facilities with renewable electricity from a solar farm in West Texas. And in 2021, California’s State Office of Administrative Law tightened emissions regulations defined by “the Control Measure for Ocean-Going Vessels at Berth”, which include limits on GHGs. Many other ports in the US offer shore power, which supplies vessels in port with electricity from existing grids.

The politics of climate change

Fractious electoral politics in the US has slowed efforts to combat climate change in the world’s largest economy. For example, in 2015, the US signed the Paris Agreement (COP 21) but withdrew in 2020, then rejoined in in 2021. More recently, the US has pledged to work with the IMO to cut GHG reductions from ships by 2050. While policies may shift again in future, growing public pressure on politicians to act on climate change may signal a more consistent approach going forward.

1.2.2. Cargo Owners and Consumers

Cargo owners are increasingly facing customer and investor expectations to decarbonize their operations. This is taking place at every stage of the supply chain, all the way to the public. In response, many cargo owners have announced that they are building decarbonization targets into their business strategy. Some are aiming for carbon-neutral or carbon-positive impact by 2040, or even by 2030.This is likely to increase expectations on the shipping industry to be more transparent, as part of increased GHG emissions reporting requirements throughout the supply chain.

1.2.2.1. ESG: Environmental, Social and Governance

Environmental, Social and Governance (ESG) is a framework used to assess an organization's business practices and performance on various sustainability and ethical issues. It also provides a way to measure business risks and opportunities in those areas.

Comprehensive ESG reporting is becoming a 'must have' for shipping companies. Financial institutions have for some time required ESG reporting from their customers. This trend is driven by requirements related to the offering of financial instruments such as green and sustainability-linked bonds and low-carbon funds, and through direct disclosure regulations such as the **EU Sustainable Finance Disclosure Regulation** (SFDR).

In the maritime world, similar to other industries, ESG reporting covers topics such as recycling, greenhouse gas emissions, other pollutants to air, ecological impacts, business ethics, employee health and safety, as well as accident and safety management.

ESG reports and sustainability reports aim to disclose performance on parameters within all three areas that are important for the company’s operation. The reporting serves to satisfy stakeholders’ demands for transparency on corporate responsibility issues. It also conveys that the company has policies, initiatives and strategies in place to manage the ESG risks and opportunities.

Figure 1-7: ESG Pillars.

1.2.2.2. Sea Cargo Charter

In the fall of 2020, leading cargo owners, including Anglo American, Cargill, Dow, Total, and Trafigura, together with shipowners Euronav, Norden, Stena Bulk and other stakeholders, launched the Sea Cargo Charter, which establishes a framework for assessing and disclosing the climate alignment of ship chartering activities around the globe (DNV).

The Sea Cargo Charter goals are consistent with the policies of the IMO, including ambitions to reduce shipping's total annual GHG emissions by at least 50 per cent by 2050. In addition, the Sea Cargo Charter will enable cargo-owners and shipowners to align their chartering activities with responsible environmental behavior and incentivize the decarbonization of international shipping.

The Sea Cargo Charter is aligned with the **Poseidon Principles**:

- **Assessment of climate alignment**
  Signatories are to calculate the 'GHG emission intensity' and 'total GHG emissions' of their chartering activities on an annual basis. They are to then assess the results and their 'climate alignment' against IMO ambitions.
- **Accountability**
  To ensure impartiality in the data assessment, the Sea Cargo Charter identifies the preferred method of performing the requisite calculations by third parties acting on behalf of the signatories.
- **Enforcement**
  Signatories will agree to work with owners, and business partners to collect and process the information necessary to calculate carbon intensity and total GHG emissions and assess climate alignment.
- **Transparency**
  Each signatory will report its climate alignment results annually and send all supporting information to the Charter Secretariat.

The Sea Cargo Charter relies specifically on the IMO's Energy Efficiency Operational Indicator (EEOI) a tool created by the IMO to track fuel efficiency for ships in operation over time and to gauge the effect of any changes during operation.

Regulations, banks and cargo owners

While most owners recognize the need to reduce GHGs, coordination between regulators, ship finance and cargo owners creates powerful incentives for the industry to change. Alignment between the Poseidon Principles and the Sea Cargo Charter, based on standardized IMO methodologies to calculate ship efficiency and carbon emissions, provides a strong platform for measuring performance and a basis to reward owners who act. The industry will need more collaboration among other stakeholders to achieve the IMO's target for GHG reductions. However, both the Poseidon Principles and the Sea Cargo Charter represent good models.

1.2.3. Investors and Finance

Financial institutions and institutional investors have recently increased their focus on green and ESG related activities and are aiming to reduce their exposure to non-sustainable businesses and contribute positively to mitigating climate change. This 'green drive' could make access to capital more dependent on environmental credentials and meeting expected decarbonization trajectories throughout the lifetime of ships.

1.2.3.1. Green Finance

Sustainable finance in growing exponentially across industries. Institutional investors and banks have earmarked hundreds of billions of dollars for ESG compliant investment and lending. In the maritime industry, many ship owners, yards and terminal operators have already secured or issued – green, sustainability-linked or transition – loans and bonds. They can benefit from a broader lender base, slightly better financing conditions and positive public perception.

Green finance is designed as asset finance with a defined use of proceeds. Vessels need to meet specific criteria outlined by organizations or standards like the Climate Bonds Initiative, the EU Taxonomy or the Green Shipping Program. That typically means that the AER (Annual Efficiency Ratio) or the EEOI (Energy Efficiency Operational Index) need to be below defined decarbonization trajectories. The EU Taxonomy, however, also allows use of the EEDI (Energy Efficiency Design Index) and defines specific requirements for vessels retrofitting. In addition to the technical criteria for the vessel, the ship owner must also prepare a green finance framework that meets the requirements of relevant bodies such as the LMA (Loan Markets Association, for loans) and the ICMA (International Capital Market Association, for bonds).

Sustainability-linked finance is designed as corporate finance but can also be used for financing specific assets. The borrower or issuer of a bond commits to achieving a substantial improvement in one or more sustainability-related key performance indicators (KPI) over the short to medium term. The interest rate of the finance instrument is linked to whether or not the KPI are met. For example, a KPI might be an AER reduction of 60% between 2008 and 2030. Periodical reporting of verified performance is required.

Transition finance is designed as corporate finance but can also be used for financing specific assets. To be eligible, companies need a credible corporate decarbonization strategy that addresses climate risks in line with the Paris Agreement and achieves net zero in 2050, with tangible measures and milestones in the short and medium term. The Climate Transition Finance Handbook of the ICMA is often used as a reference.

1.2.3.2. Poseidon Principles

Launched in June 2019, the Poseidon Principles is an agreement between banks to assess the environmental footprint of their investment portfolios in shipping and monitor performance on an annual basis (Poseidon Principles).

The targets are consistent (if not identical) with IMO's GHG Strategy. By 2021, 27 banks, representing about USD 185 billion in shipping finance, are acknowledged signatories.

The four Poseidon Principles provide a benchmarking tool by which leading institutions can demonstrate their commitment to reducing the impact of GHGs of the fleets they finance.

- **Assessment of climate alignment** Signatories will measure the carbon intensity of their shipping portfolios on an annual basis and assess their climate alignment relative to established decarbonization trajectories.

- **Accountability** Signatories commit to using data types, sources, standards and service providers established by the IMO to calculate their shipping portfolio's climate alignment.
- **Enforcement** Signatories commit to making compliance with the Poseidon Principles contractual in their new business activities. They will use standardized covenant clauses and work together with their clients and partners to meet this requirement.
- **Transparency** Signatories are required to report their portfolio alignment score on an annual basis. All signatories' scores will be published annually by the Secretariat of the Poseidon Principles.

Standardized reporting

The Poseidon Principles are based on the IMO's Fuel Oil Consumption Data Collection System (DCS), which mandates annual reporting of CO_2 emissions, among other information. This provides a common platform to measure GHGs emitted by ships, allowing owners and banks to benchmark performance.

1.3. Pathways Towards Decarbonization

Policy developments and stakeholder engagement over the next decades will drive shipowners to identify, evaluate, and use technologies, fuels, and solutions that help decarbonize ships, cut energy consumption, and meet other environmental requirements. The expected adoption of energy-saving technologies and logistics, carbon-neutral fuels, and exhaust cleaning (following Figure) may fundamentally change how ships are designed and operated. Applying operational and technical efficiency measures could be sufficient to achieve shorter-term compliance with GHG regulations and thereby reduce the need for consumption of more expensive fuels.

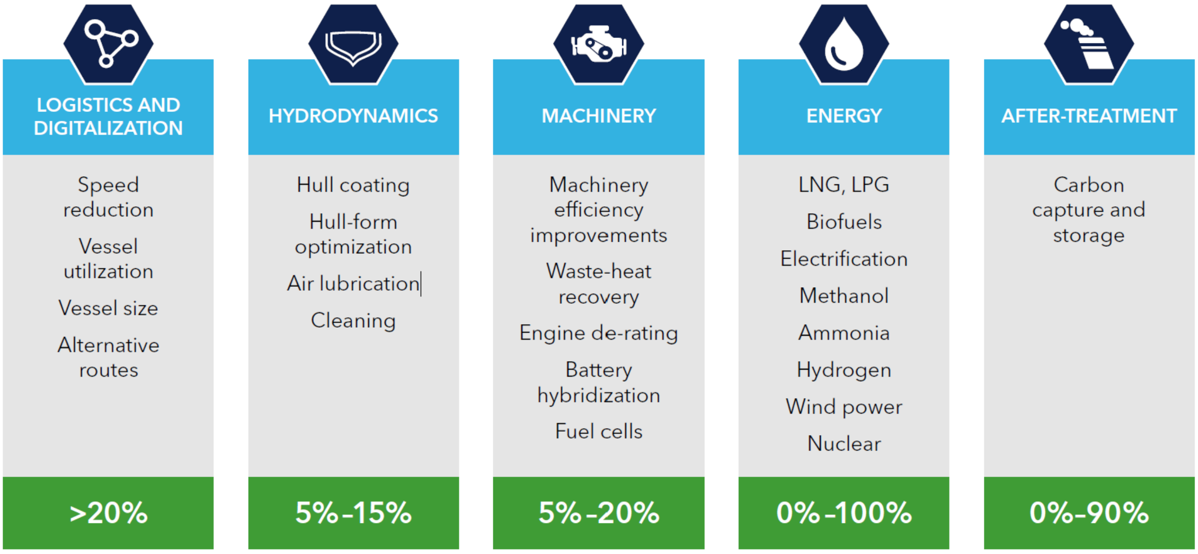

Figure 1-8: Solutions that can contribute to decarbonize shipping, and their GHG reduction potential. (DNV)

Finding the right pathway towards decarbonization will be the key to sustained success for shipowners and operators. While the biggest impact on decarbonization will be the choice of fuel and energy converter, these fuel and technology shifts must go together with greater energy efficiency of ships, requiring intensified uptake of both technical and operational energy-efficiency measures.

While all vessels can make some use of efficiency technologies and explore alternative fuels, individual strategies must be shaped based on the **type of vessels** they operate, the **cargo**, and the **route**. Decarbonization will also drive logistics optimization, including the use of measures such as increased fleet utilization and speed reductions – facilitated by digitalization.

It is worth stressing that the fuel technology transition is already in progress. For ships in operation, 6.52% of tonnage can operate on alternative fuels. Dozens of large vessels have wind-assisted propulsion systems. Air lubrication systems are installed or ordered for hundreds of ships.

Driven by the tightening regulations and commercial drivers described on the previous section, the increased cost of operating on carbon-neutral fuels will strengthen the drive for more efficient operation of the vessel fleet and simultaneously improve the business case for implementing energy-efficiency measures. **Operational efficiency measures** relate to the way in which the ship is maintained and operated, and therefore generally have low investment costs and moderate operating costs. They include measures such as optimized trim and ballasting, hull and propeller cleaning, improved engine maintenance, and optimized weather routing, scheduling, and vessel utilization. Operational measures do not require significant investment in hardware or equipment. Implementation of many of these measures will require execution of programs involving changes in management and training.

Technical efficiency measures generally aim at either **reducing** the propulsion and auxiliary engine **energy demand** (e.g. increasing hull and propeller efficiency, reducing hotel load, shore power) or **improving the energy production** (e.g. waste-heat recovery, battery hybrid systems, and machinery-system optimization). There is potential for improvement in the areas of greatest energy loss; for example, by reducing hull friction and recovering energy from the engine exhaust and cooling water. These measures generally have a substantial investment cost and potentially significant emission-reduction effects. Many technical measures are limited to application on new ships, due to the difficulties or high costs of retrofitting existing ships. With the increased system complexity and the need for partially automated operation of several of these technologies, software and controls are becoming ever more important aspects of ship operation and design.

Newbuilds will, of course, have more available options than ships in operation. Abatement measures such as wind power, air lubrication systems, and hull and machinery measures, are now emerging - some almost as standard features.

For retrofits, there are inherent limitations that will rule out some measures and make a cost benefit analysis even more critical. Even so, because a vessel's largest operational cost is fuel, well planned abatement measures can have a negative cost over the lifetime of the vessel – all while helping to ensure GHG emission compliance.

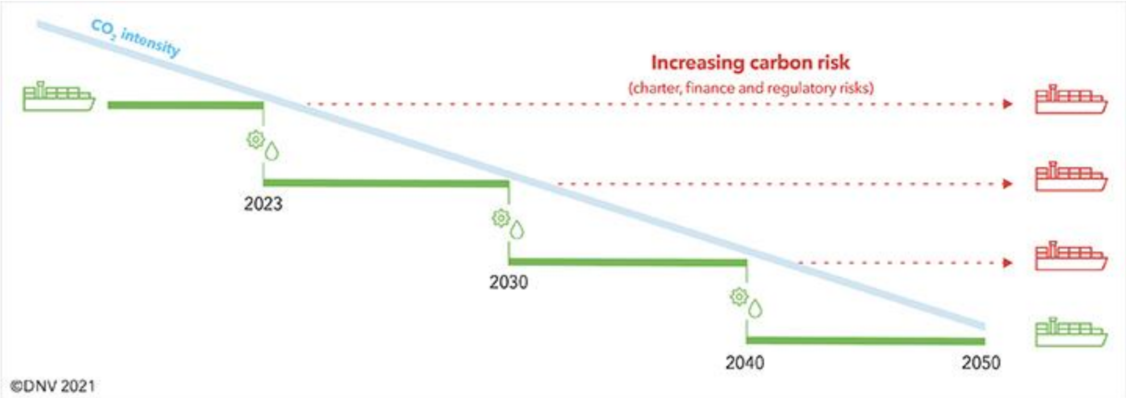

Figure 1-9: The decarbonization stairway and potential exposure to carbon risk

A vessel's age, drydocking schedule, and the overall cost benefit analysis will all impact the decision to investment in keeping a ship in operation – especially under tightening GHG regulations. In some cases, opting for a newbuilding may be the right decision, based on the cost and complexity of a retrofit or conversion. However, if the numbers add up, there are a number of options to lower an existing ship's carbon intensity.

1.3.1. Existing Tonnage

This section will explore the best options for existing tonnage to meet the regulations while maintaining economic viability, as carbon trajectories tighten.

1.3.3.1. Operational Changes

Owners of existing tonnage can make operational changes that can have a significant impact on carbon emissions. The choices for compliance while maintaining the existing equipment are presented below:

Slow steaming: A vessel's fuel consumption for propulsion is a function of the energy needed to push a vessel through water at a given speed. The faster a vessel travels, the more fuel is required. However, by maintaining a constant, slower speed, vessels can both reduce fuels costs and corresponding emissions. While effective, it should be noted that reducing speed may have commercial implications that will impact charter agreements.

Voyage optimization: Because more fuel is required to navigate strong currents, heavy wave forces and high winds, voyage planning can impact fuel consumption. By leveraging real-time information on sea conditions and weather data, owners can choose the best possible routes to avoid suboptimal conditions, thus reducing emissions.

Trim optimization: Trim optimization (or how the disposition of cargo impacts hull hydrodynamics), can reduce emissions and fuel consumption by up to six per cent. While the impact may vary, trim and draft optimization is applicable to all vessel types.

1.3.3.2. Retrofits

Retrofitting vessels to accommodate new fuels is a possibility, but there are also many energy efficiency measures, both technological and operational changes that could keep a vessel in the water with good ROI (Return On Investment) or even negative abatement costs.

Ship design: Changes to the hull design, to improve hydrodynamics and reduce drag, could be explored (e.g. bulbous bow retrofit, vessel widening, rudder and propellor redesign)

Hull coatings/Air lubrication: Using compressed air evenly distributed along a ship's hull, owners can reduce the friction between the ship's hull and seawater creating energy-saving effects. Also, advanced hull coatings and new technologies, such as remotely operated robotic hull cleaning systems, can significantly improve hull performance.

Wake-equalizing ducts: A wake equalizing duct is a ship hull appendage mounted in the inflow region of a screw propeller, increasing efficiency, thus reducing fuel consumption and GHG emissions.

Waste heat recovery systems: Systems developed specifically for marine use have been developed to take waste heat from the engines to heat the vessel and/or generate clean electricity, thus reducing emissions.

Electrification: While batteries do not yet generate enough power for deep sea shipping, they can be used for onboard supplementary or auxiliary power, thus reducing emissions. Electricity can also be generated from installed solar panels to power some onboard systems.

Wind assisted propulsion: Advances in aerodynamics in combination with computer technology has produced a number of exciting wind-assisted technologies that can cut fuel consumption by up to 30%.

1.3.2. New-Buildings

The key considerations for newbuilding is to stay competitive and compliant over a long term. The often-significant gap between ordering and delivery means shipowners are forced to make investment decisions without knowing how conditions might change while the vessel is under construction. Making the right choices at the start can help not only to achieve compliance but help access green financing products, with more favorable terms, and can ensure increased competitiveness.

There are a broad range of systems available today to help owners reduce fuel consumption and corresponding emissions that owners should consider when ordering a vessel. While many of the examples below can make a difference on their own, owners should also consider how different systems may work together. Operational related choices, such as Slow steaming, Voyage and Trim optimization, as mentioned above, may also apply in new buildings and can serve great advantages related to ship's energy efficiency. Below are some of the key technologies and choices for new buildings.

Ship design: In anticipation of wider availability of low emissions alternative fuels, owners are encouraged to design vessels to accommodate emerging fuel types. For example, vessels can be equipped with multifuel engines, specialized tanks and related hardware to enable a seamless switch from FO to ammonia. In addition, the introduction of innovative hull designs, which improve hydrodynamics to reduce drag, and high tensile steels, which reduce the structure's weight, should be explored.

Hull coatings/Air lubrication, Wake-equalizing ducts, Waste heat recovery systems, Electrification and Wind assisted propulsion, as mentioned above, could also apply to new buildings projects.

Fuel choice: Fuel choice will be determined by ship type, operational profile, fuel availability, owner preferences and business strategy. Short sea vessels and ferries operating on fixed routes may opt for low or zero emission fuels (hydrogen, methanol, electricity) if there is supply in place locally. While for the deep-sea trades, LNG and LPG are currently the most widely used alternatives, although some owners are evaluating the viability of green methanol and ammonia. In addition, drop in fuels (e.g. biofuels), could be used as a substitute for FO to lower emissions.

Energy Efficiency (EE) Measures are described in detail in Appendix A, while on the next chapters the available fuel types for compliance, which is the main target of subject diploma thesis, will be analyzed furtherly.

CHAPTER 2

Alternative Fuels in Shipping

Introduction

The decarbonization of shipping requires a massive shift to additional energy saving measures and renewable energy sources. A fundamental factor to achieve it is the modernization of ship design and the scaling up of the use of alternative low and zero carbon fuels. Fuel choice will be the most significant factor in decarbonizing shipping. The industry is in a transition phase, with many potential options emerging alongside conventional fuels.

Even though the world fleet is still mainly powered by diesel engines running on marine fuel oils, there is an increasing number of LNG-fueled vessels, ships utilizing batteries, and vessels fueled with liquefied petroleum gas (LPG) and methanol. The first hydrogen - and ammonia - fueled vessels will also soon come into operation.

The viability of alternative fuels varies greatly for different ship types and trades. Deep-sea vessels need to store very large amounts of energy keeping the ship at steady speed over long distances. While for short sea, the options are more diverse, including the possible use of electric or hybrid-electric power and propulsion systems.

This increasingly diverse fuel and technology environment means that engine and fuel choice now represent potential risks. Factoring in the impacts of availability, price and policy on different fuels, makes the choice even more complex. A ship should be designed to allow for the needed upgrades or fuel changes later in its lifetime.

In this chapter of the thesis, the focus is on examining the role of "Bridging and Future Fuels" in the maritime industry's transition to sustainability. It explores the main characteristics of transitional fuels like LNG in bridging the gap between conventional and sustainable options. The chapter also discusses the potential of future fuels such as Ammonia and Hydrogen in achieving long-term carbon reduction goals.

2.1. Bridging Fuels

As the industry moves away from carbon-intensive heating oil (FO) to reduce greenhouse gas emissions, there are several alternative fuel options to choose from.

Not all alternatives are optimized for all owners or trades but represent promising short and medium-term "bridge fuels" to comply with tightening IMO mandates on GHG emissions until zero-emissions solutions can be developed (DNV).

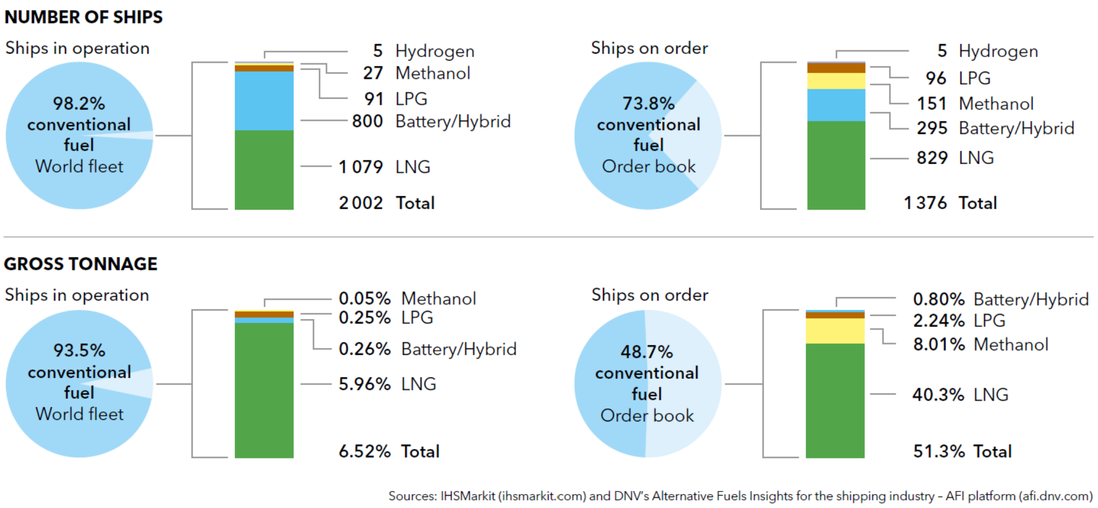

Figure 2-1: Alternative fuel uptake in the world fleet in number of ships (upper) and gross tonnage (lower), as of July 2023. (DNV)

As Bridging Fuels are defined those of the below figure, which will be further analysed on the following sections:

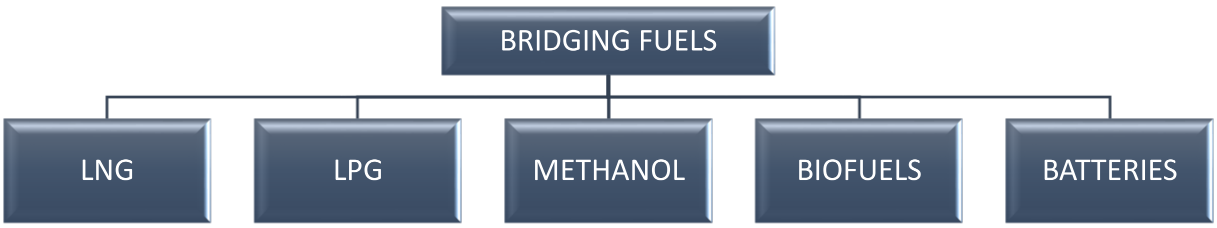

Figure 2-2: Bridging Fuels.

2.1.1. LNG – Liquified Natural Gas

LNG stands for liquefied natural gas, natural gas transformed into a liquid state through a cooling process. In its liquid form, natural gas has a significantly smaller volume for export, shipping, and storage. It is a low-emission, clean-burning fossil fuel that can be used for marine propulsion and transportation and regasified after delivery to a terminal.

LNG is considered a mature alternative fuel option. However, there are some technology choices that need to be made depending on specific vessel design and operational requirements.

The following table illustrates the key characteristics of LNG, including calorific value, exhaust emissions and applicability on 2-stroke and 4-stroke marine engines/vessel type.

Table 2-1: Key characteristics of LNG.

	CALORIFIC VALUE	EMMISIONS	2-STROKE	4-STROKE
LNG	45-50 MJ/kg	Produces significantly lower SOx, CO2, NOx and particulate matter emissions compared to fuel oils. LNG is considered to be an excellent bridging fuel during the ongoing energy transition.	Two-stroke dual fuel engines: Container vessels, Tankers, LNG carriers, Bulk carriers, RoRo vessels	Four-stroke dual fuel engines: Container vessels, Tankers, LNG carriers, Bulk carriers, Ferries, RoRo, Cruise and Fishing vessels

Benefits of LNG as marine fuel

- LNG-fueled vessels can reduce a vessel's EEDI rating by 20% and the corresponding Carbon Intensity Indicator CII rating by approximately the same amount.
- At the same time, improved vessel design and engine technologies can reduce GHGs by up to 25 per cent. LNG bunkering facilities are now widely available and others planned, LNG represents a good, medium-term option to reach compliance.
- An LNG fueled vessel can use lower/zero carbon fuel options like SNG, or biogas with minimal conversion – offering a potential path to decarbonized operations. (MAN)

Technical considerations

- Because LNG has a lower volumetric energy density than fuel oil, onboard gas storage requires larger tanks than conventional fuel oil storage to provide the same operational range.
- And due to the low temperature of LNG, the tank insulation and required gas handling systems additional space and equipment is required.
- Depending on their preferences and priorities, owners can choose between two main types of engine technologies with different characteristics that are now available to the market. (MAN)

On the following diagrams, the increasing number of the existing and on order LNG vessels are depicted, by delivery year and vessel type (DNV).

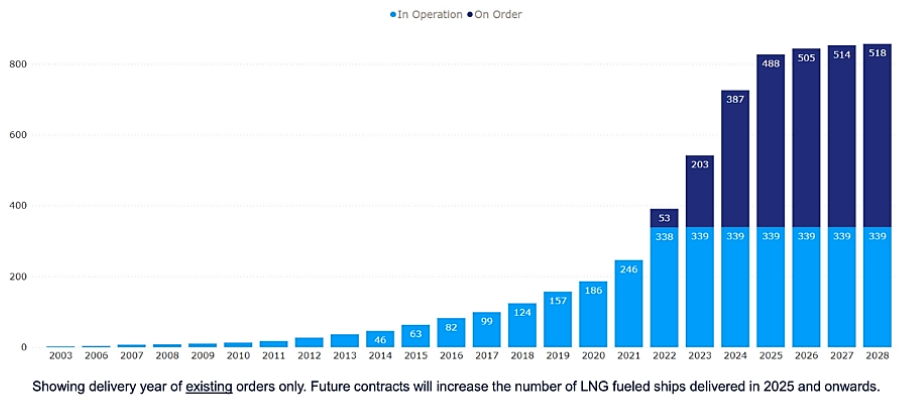

Figure 2-3: Growth of LNG-fuelled fleet. (DNV)

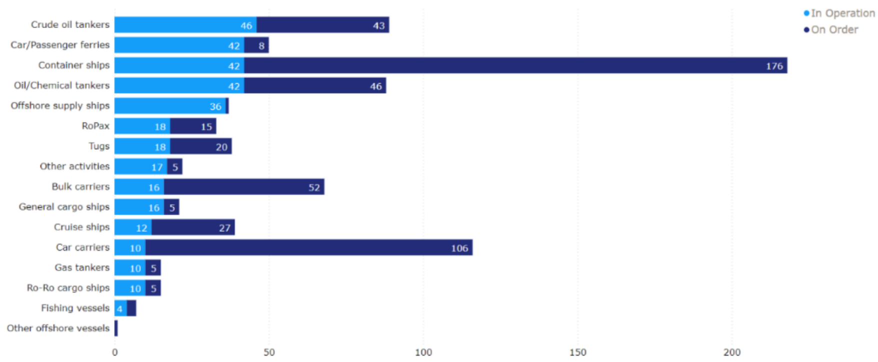

Figure 2-4: LNG-fuelled vessels fleet by ship type. (DNV)

2.1.2. LPG – Liquefied Petroleum Gas

LPG stands for liquefied petroleum gas. It is extracted from natural gas by absorption and, unlike diesel, can be stored almost infinitely without any degradation. Known to the wide public and commonly used as a domestic gas for cooking and also heating, it’s largest proportion is used for commercial and industrial applications.

The following table illustrates the key characteristics of LPG, including calorific value, exhaust emissions and applicability on 2-stroke and 4-stroke marine engines/vessel type.

Table 2-2: Key characteristic of LPG.

	CALORIFIC VALUE	EMMISIONS	2-STROKE	4-STROKE
LPG	55 MJ/kg	LPG can contain close to zero sulfur and meets the requirements for Sulfur Emission Control Areas, while CO_2 and particulate matter emissions are lowered significantly at the same time.	Two-stroke LPG & dual fuel engines: Ideal for LPG carriers and shuttle tankers	Dual-fuel LPG conversions, PVU: Container vessels, Tankers, LPG carriers, Bulk carriers, RoRo vessels

Benefits of LPG as marine fuel

- LPG combustion results in CO_2 emissions that are approximately 15% lower than those of Fuel Oil.
- When accounting for the complete life cycle, including fuel production, the CO_2 savings amount to roughly 17%.
- The cost of installing LPG systems on board a vessel is roughly half that of an LNG system. This is because there is no need for special materials for handling cryogenic temperatures.
- LPG tanks can also be suitable for ammonia, so long as their pressure rating is appropriate. Engine technology is also quite similar, making LPG designs the easiest to retrofit to utilize ammonia as fuel at a later stage. (MAN)

Technical considerations

- Currently only two-stroke diesel engines are commercially available for using LPG as a ship fuel.
- Four-stroke engines have also been developed but so far are only used for power generation on shore, not for marine applications.
- LPG fueled vessels often install shaft generators to take advantage of LPG for auxiliary engines.
- LPG can be stored under pressure or refrigerated, but bunkering options may not always be available in the temperature and pressure range a ship can handle. Therefore, pressurized tanks are typically selected.
- The bunkering source and the ship must carry the necessary equipment and installations for safe bunkering. (MAN)

On the following diagram, the number of the existing and on order LPG fueled vessels are shown by delivery year (DNV).

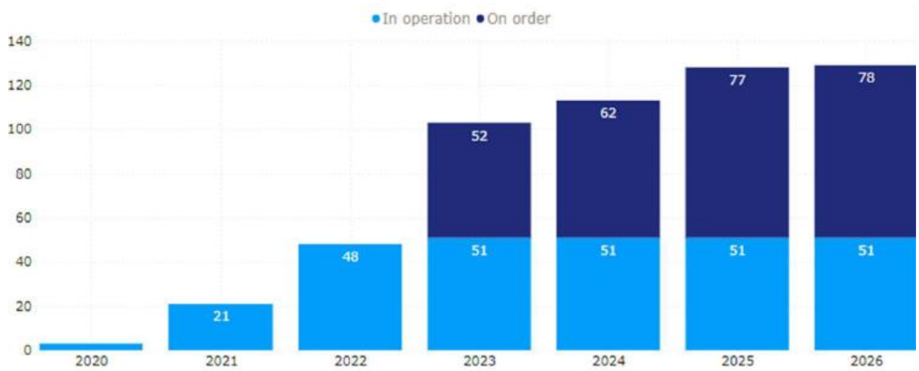

Figure 2-5: Growth of LPG-fuelled fleet. (DNV)

2.1.3. Methanol

Methanol is a biodegradable, clean-burning fuel type that significantly reduces emissions such as particulate matter, sulfur oxides and nitrogen oxides. In the past, it was mainly used as a chemical base for the production of various products, such as building materials but also healthcare and medical products. For some time now, methanol has started to become a more and more attractive alternative used for heating, cooking, and also powering vessels.

Methanol is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. Methanol can be made available through existing infrastructure in more than 100 ports globally.

The following table illustrates the key characteristics of Methanol, including calorific value, exhaust emissions and applicability on 2-stroke and 4-stroke marine engines/vessel type.

Table 2-3: Key characteristics of Methanol.

	CALORIFIC VALUE	EMMISIONS	2-STROKE	4-STROKE
METHANOL	19,7 MJ/kg	Methanol is a clean-burning liquid that can be produced from renewables.	Two-stroke dual fuel engines: Ideal for tankers carrying methanol as cargo. Increasing interest for all other ship applications.	Four-Stroke engines, integrated propulsion systems and retrofit solutions for existing engines, future-proof for adoption of upcoming methanol operation requirement.

Benefits of methanol as ship fuel

- Methanol combustion in an internal combustion engine reduces CO_2 emissions by approximately 10% compared to FO.
- When considering the complete life cycle, including the production of the fuel from natural gas, the total CO_2 emissions are equivalent to or slightly higher (ca. 5%) than the corresponding emissions of petroleum-based fuels.
- In the future, “green methanol” is likely to become available, with the potential for significantly lower GHG emissions. (MAN)

Technical considerations

- There are two main options for using methanol as fuel in conventional ship engines: A two-stroke diesel-cycle engine or in a four-stroke, lean-burn Otto-cycle engine.
- Methanol is a liquid fuel and can be stored in standard fuel tanks, but modifications are required to accommodate its low-flashpoint properties to comply with the IMO's IGF Code. (MAN)

On the following diagrams, the increasing number of the existing and on order Methanol-fueled vessels are depicted, by delivery year and vessel type (DNV).

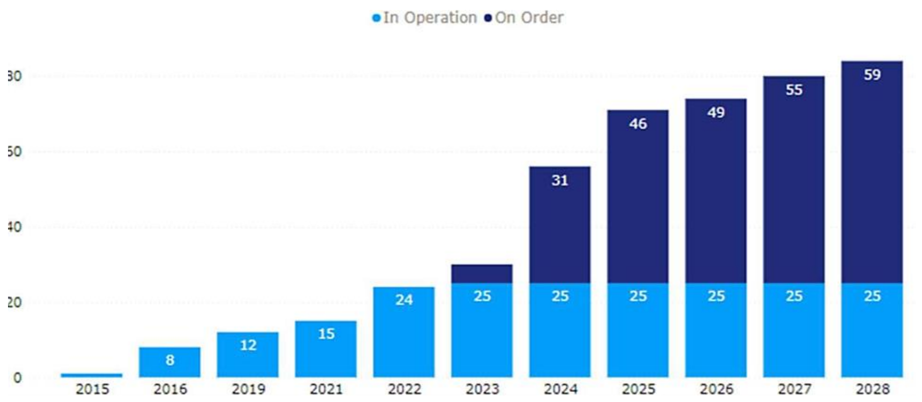

Figure 2-6: Growth of methanol-fuelled fleet. (DNV)

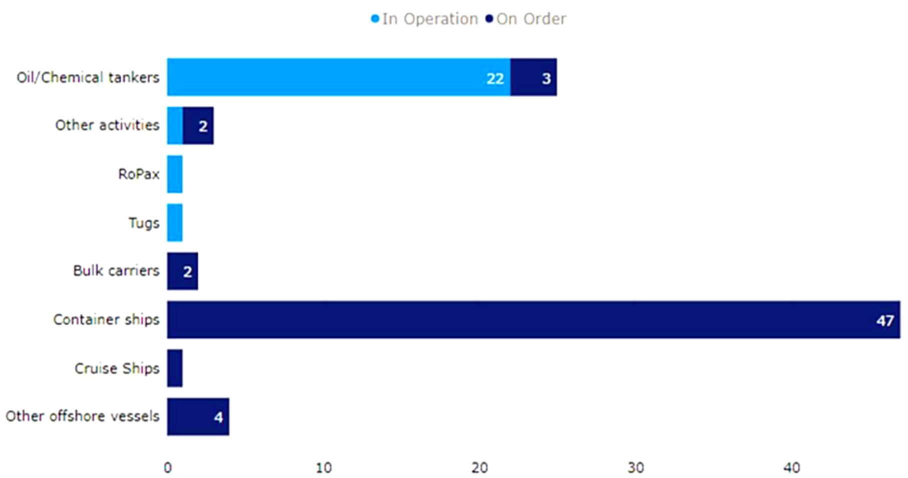

Figure 2-7: Methanol-fuelled fleet by ship type. (DNV)

2.1.4. Biofuels

Biofuels are produced from biomass and cover a range of fuels such as bioethanol and biodiesel. Three types of biofuels are relevant for maritime shipping (DNV, 2023):

- **FAME (Fatty acid methyl ester)** is produced from vegetable oils, animal fats or waste cooking oils by transesterification, where various oils (triglycerides) are converted to methyl esters. This is the most widely available type of biodiesel in the industry and is often blended with regular marine diesel. International standards: ISO 8217:2017, EN 14214, ASTM D6751, EN 590

- **BTL (Biomass to liquid)** fuels are synthetic fuels that are produced from biomass by means of thermo-chemical conversion using the Fischer-Tropsch process or the methanolto-gasoline process. The final product can be fuels that are chemically different from conventional fuels such as gasoline or diesel but can also be used in diesel engines. International standards: EN 16709, EN 15940
- **HVO/HDRD (Hydrogen vegetable oil / Hydrogenation derived renewable diesel)** is the product of fats or vegetable oils – alone or blended with petroleum – refined by a hydrotreating process known as fatty acids-to-hydrocarbon hydrotreatment. Diesel produced using this process is often called renewable diesel to differentiate it from FAME biodiesel. HVO/HDRD can be directly introduced in distribution and refueling facilities as well as existing diesel engines without any further modification. International standards: ASTM D 975

Currently, FAME is the most prominently used biofuel in marine applications. It is either used in blends with traditional petroleum fuels or as 100% biofuel.

While the number of vessels running on biofuels today is relatively small, sustainable biofuels have been identified as one of few options available for deep-sea shipping, especially for existing vessels, to achieve the IMO targets.

The following table illustrates the key characteristics of Biofuels, including calorific value, exhaust emissions and applicability on 2-stroke and 4-stroke marine engines/vessel type.

Table 2-4: Key characteristics of Biofuels.

	CALORIFIC VALUE	EMMISIONS	2-STROKE	4-STROKE
BIOFUELS	36-42 MJ/kg	Biofuels can be fully renewable and nearly 100% CO_2 neutral	Two-stroke engines, including all dual-fuel engines: Tankers, container vessels, bulk carriers, RoRo vessels	Four-stroke engines with exhaust gas after-treatment systems: Container vessels and dredgers are being tested and operated with biofuels at present.

Benefits of using biofuels

- Biofuels from advanced processes derived from sustainable feedstocks can achieve substantial GHG reductions while minimizing other effects.
- Biofuels can be blended with conventional fuels or used as drop-in fuels as substitutes for conventional fossil fuels.
- A drop-in fuel can directly be used in existing installations without major technical modifications, making them very attractive for existing tonnage. (MAN)

Technical considerations

- Because biofuels are derived from organic materials, fuel quality can be compromised by microbial growth and oxygen degradation.
- Some liquid biofuels can have poor flow properties in low temperatures.
- Biofuels are solvents, so during conversions, operators must flush the fuel system when switching from diesel to biofuel to avoid deposits or clogged filters. Managing these challenges is important to ensure trouble-free operations. (MAN)

2.1.5. Batteries

Batteries (and hybrid power plants) represent a transformation in the way energy is used and distributed on board vessels. While not yet a viable replacement to FO for deep sea transportation, batteries are increasingly being used for ferries and short sea shipping.

Benefits of using batteries

- In addition to being emissions free, electric power systems using batteries are more controllable and easier to optimize in terms of performance, safety and efficiency.
- As ship power systems become increasingly electrified and battery technology improves and becomes more affordable, new opportunities emerge. (MAN)

Technical considerations

- Batteries produced by different manufacturers use different chemistries, resulting in significant differences in performance. Depending on the vendor, even batteries with the same nameplate chemistry can have very different properties.
- Developments in battery technologies are expected to be the result of incremental improvements in terms of cost and performance.
- New battery technologies, which would represent a disruptive change for deep sea shipping, may be as much as ten years away. (MAN)

2.2. Future Fuels

To fulfil the IMO goals and take the maritime industry to zero-emissions, a new generation of fuels is needed, fuels that result in vessels producing very low or no GHG emissions from well to wake. In general, this means moving from fossil to non-fossil fuels, produced with renewable or zero carbon energy sources. These fall into roughly three broad categories, as depicted also in the following picture:

- "**Blue**" fuels from reformed natural gas with CCS – Carbon Capture and Storage,
- "**Electro**" fuels from renewable electricity, with non-fossil carbon, or nitrogen (SNG, e-ammonia, e-methanol),
- "**Bio**" fuels from sustainable bioenergy sources (Bio-gas, bio-diesel).

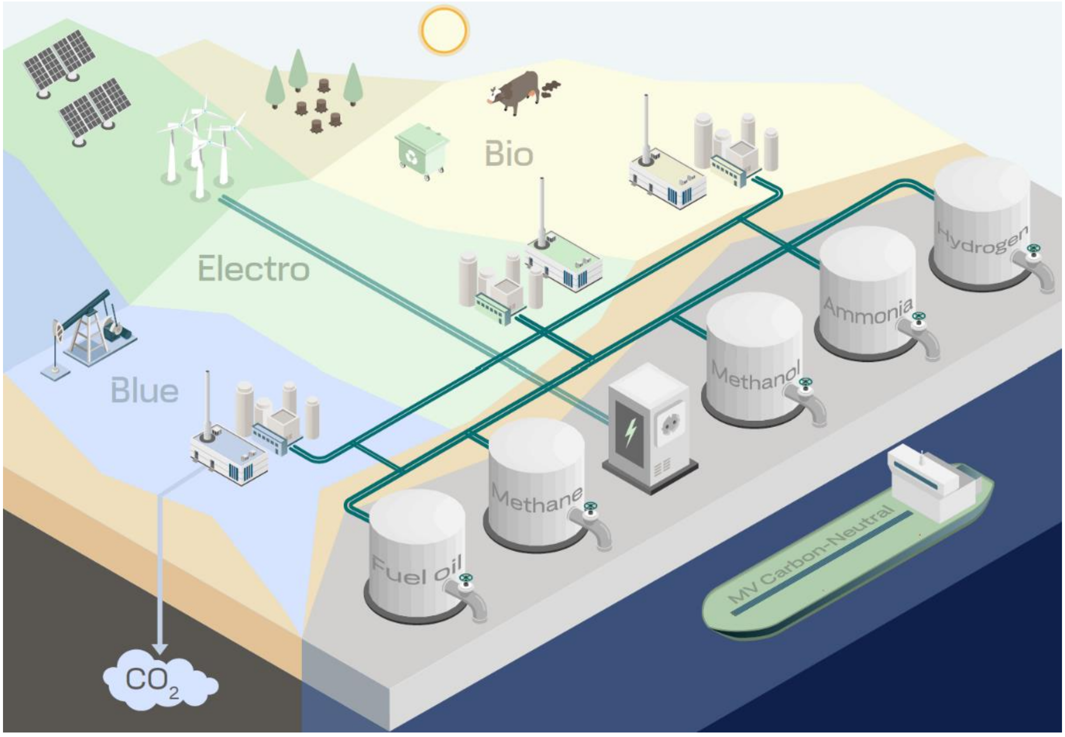

Figure 2-8: Production pathways for carbon-neutral fuels

The future fuel supply for shipping will rely on availability and price of these energy sources. Some of these types of fuels, biogas for example, are already in use, for others primarily non-zero carbon options are in testing or soon to be operational in demonstration projects. The world's first liquid hydrogen-powered ferry has been delivered.

Significant investment is needed in coming decades to enable the transition to carbon-neutral shipping. Current IMO regulations only address onboard tank-to-propeller CO_2 emissions from fossil fuels. However, the IMO is working on guidelines to determine lifecycle CO_2 and GHG emission factors for all types of fuels, including biofuels and electrofuels.

The transition from fossil fuels to carbon-neutral fuels, will have to coincide with a corresponding development in onboard fuel technology, while onboard CCS technology enabling continued use of fossil fuels may become an alternative for some ships.

The below figure depicts the timeline / best estimate according to DNV research for when the onboard engine and fuel systems can be expected to be available for use on board (actual availability of fuel is not included as a limitation in the shown timeline).

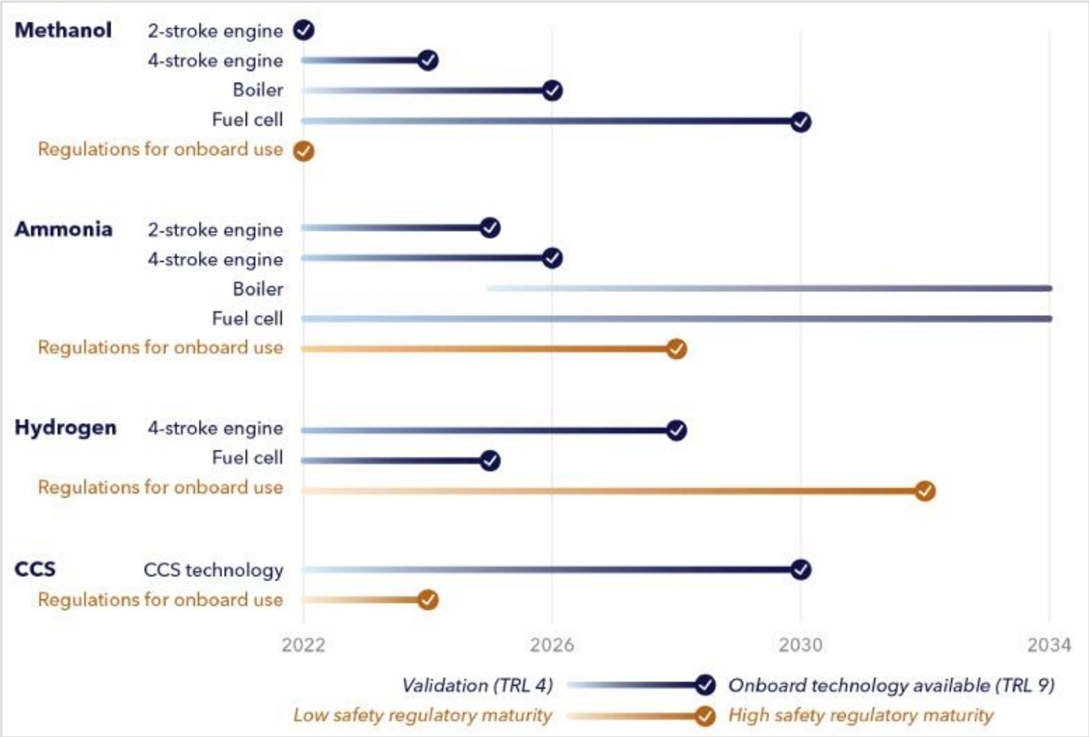

Figure 2-9: Estimated maturation timelines for energy converters, onboard CCS technologies, and corresponding safety regulations for onboard use. (DNV)

As Future Fuels are defined those of the below figure, which will be further analysed on the following sections:

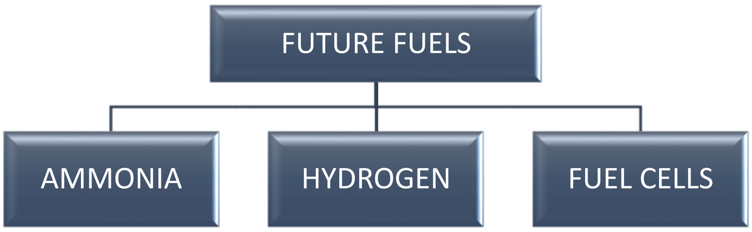

Figure 2-10: Future Fuels.

2.2.1. Ammonia

Ammonia is a synthetic product obtained from fossil fuels, biomass or renewable sources (wind, solar, hydro or thermal). **Green ammonia** (produced by electrolysis powered by renewables), or **blue ammonia**, (produced from byproducts of current fossil fuel production) are promising sources of zero-carbon fuel but will require significant investments in production capacity from renewables and bunkering infrastructure to replace FO.

The following table illustrates the key characteristics of Ammonia, including calorific value, exhaust emissions and applicability on 2-stroke and 4-stroke marine engines/vessel type.

Table 2-5: Key characteristics of Ammonia.

	CALORIFIC VALUE	EMMISIONS	2-STROKE	4-STROKE
AMMONIA	18.8 MJ/kg	Zero CO2 emissions released during combustion. Significantly lowers SOx and particulate matters emissions.	1st Two-stroke Ammonia engine to be delivered in 2024 by MAN.	1st Four-stroke Ammonia engine to be delivered in 2025 by WinGD.

Benefits of ammonia as fuel

- Apart from being a potential zero-carbon fuel, ammonia is cheaper that batteries and easier to store than hydrogen or LNG, and is nearly identical to LPG at low pressure under ambient conditions. (MAN)

Technical considerations

- Ammonia is a toxic and corrosive substance, and emissions from combusted ammonia may contain a high amount of nitrous oxide (N_2O), a powerful greenhouse gas.
- At present, the technology to clean ammonia exhaust is still being refined and the use of this fuel on existing ships will require engine modifications and the installation of new fuel tanks and safety systems. Such engines are expected to be commercially available in 2024.
- However, some owners are already building ships that are “ammonia ready”, equipped with stainless steel tanks to manage corrosion and engines that can handle ammonia as a ‘drop in’ fuel.
- Ammonia-fueled engines will require a certain amount conventional pilot fuel.
- Due to the low volumetric energy of ammonia, it may be more practical in many cases to use a combination of ammonia and fuel oil. (MAN)

2.2.2. Hydrogen

Hydrogen is the simplest and most basic renewable fuel generated by electrolysis, and is carbon-free with the potential for the lowest emissions from the combustion process. Furthermore, hydrogen from electrolysis and renewable energy is the basic building block for a range of fuels. Hydrogen can be used directly as compressed or liquefied gas. Other technologies for storing hydrogen are also being developed.

The following table illustrates the key characteristics of Hydrogen, including calorific value, exhaust emissions and applicability on 2-stroke and 4-stroke marine engines/vessel type.

Table 2-6: Key characteristics of Hydrogen.

	CALORIFIC VALUE	EMMISIONS	2-STROKE	4-STROKE
HYDROGEN	120 MJ/kg	Combustion of hydrogen produces no GHG emissions	Dual-fuel capability by 2030	Four-stroke engine concepts

Benefits of hydrogen as fuel

- If produced using renewable energy, hydrogen does not result in any CO_2 emissions, making it one of the cleanest alternative fuel options.
- While fuel cells are considered the key technology for hydrogen, other applications are being studied such as internal combustion engines that have promising marine applications. (MAN)

Technical considerations

- Storage of hydrogen requires approximately six to ten times more space than conventional FO, depending on the technology selected.
- Liquefied hydrogen is at the lower end of this range, at the expense of very low temperatures (-253°C), which requires appropriate materials.
- Cost of the storage systems is another limiting factor, combined with the lack of infrastructure for supplying hydrogen to shipping.
- Therefore, in the short- to medium-term future, hydrogen is mainly a viable option for coastal vessels that can secure local fuel supply, especially if supported by government financing. (MAN)

On the following diagrams, the increasing number of the existing and on order Methanol-fueled vessels are depicted, by delivery year and vessel type (DNV).

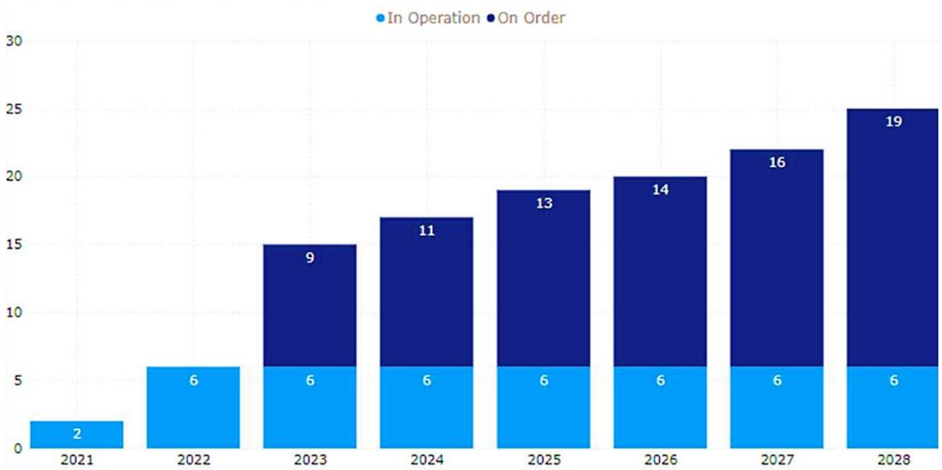

Figure 2-11: Growth of Hydrogen fleet. (DNV)

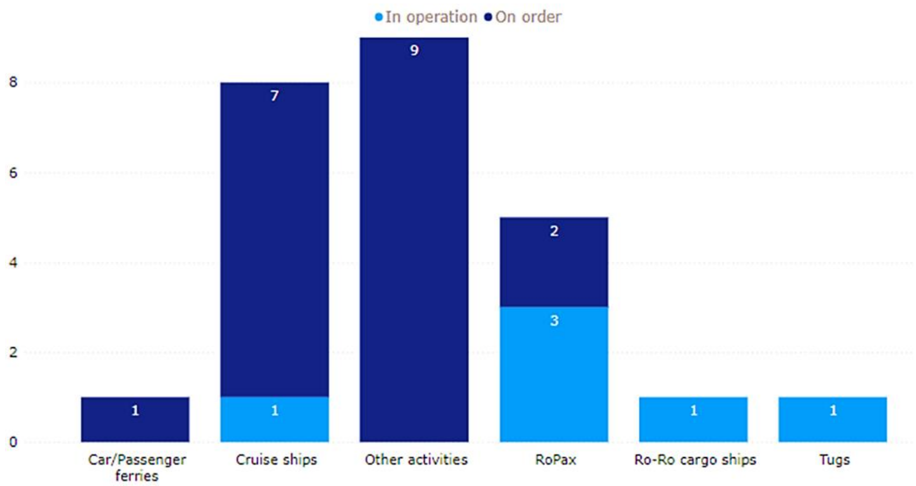

Figure 2-12: Hydrogen ships by ship type. (DNV)

2.2.3. Fuel cells

Fuel cells convert the chemical energy contained in a fuel directly into electrical and thermal energy through electrochemical oxidation, enabling efficiencies of up to 60%, depending on the type of fuel cell and fuel used.

Benefits of Fuel cells

- Due to the high efficiency of fuel cells, a further reduction of CO_2 emissions is possible when using hydrocarbon-based fuels like natural gas or methanol.
- Fuel cells minimize vibration and noise emissions, a major drawback of combustion engines, and may require less maintenance than conventional combustion engines and turbines. (MAN)

Technical considerations

- The main components of a fuel cell power system are the fuel cells themselves, so it should be noted that the lifetime of fuel cell systems and reformer units has not yet been shown to be satisfactory.
- Also, it will be necessary to integrate additional safety and interface components to build a complete ship system that meets regulatory requirements.
- Finally, fuel cells perform better under constant loads, so may require supplemental batteries to even out consumption. (MAN)

2.3. Infrastructure for carbon-neutral fuels

It is essential to have sufficient infrastructure in place for distribution and bunkering. Some biofuels and electrofuels can use existing fuel oil infrastructure (bio-MGO, e-MGO) while carbon neutral liquefied methane (bio-LNG, e-LNG) can use existing LNG infrastructure. Assuming availability for such fuels, the bunkering infrastructure, distribution, and storage capabilities must be prepared for further expansion in line with demand development.

In addition, there is already a significant shipping network for the transport of ammonia and methanol, annually transporting in the order of 50 million tons (Mt) in total. About 18 Mt to 20 Mt of ammonia are transported annually by ship, and about 170 ammonia carriers are in operation, of which 40 ships carry ammonia on a continuous basis. The seaborne transport of methanol was about 30 Mt in 2018, and methanol is already available in more than 100 major ports today, where 47 of those ports have storage facilities in excess of 50,000 tons. The map in the following figure shows the locations of ammonia and methanol terminals globally, where the clusters indicate number of terminals in that area. In total there are around 210 existing ammonia terminals and around 130 existing methanol terminals with storage infrastructure. This infrastructure can possibly serve as a starting point for a distribution network for the use of ammonia and methanol as fuels for shipping, bringing down the 'last-mile' distribution cost. (IRENA and AEA, 2022)

Figure 2-13: Map of geographical distribution of existing ammonia and methanol terminals. (AFI, 2023)

To take advantage of the existing infrastructure, carbon-neutral methanol and ammonia could be mixed with the fossil variants. Certification schemes should be in place enabling selling and using the carbon-neutral variants from the storage even if the physical products are mixed; for example, the Green Gas Certification Scheme.

For hydrogen, the distribution network is not developed, only small-scale transportation of hydrogen exists today. However, liquefied hydrogen has been transported at sea as a test and several projects are in the pipeline for transporting compressed hydrogen, either in bulk, or in pressurized containers.

In 2021, the world's first ship-to-ship methanol bunkering took place in the Port of Rotterdam, and another ship-to-ship bunkering operation was completed in the Port of Gothenburg in January 2023.

2.4. Safety Challenges

Decarbonization will involve a significant increase in the use of alternative fuels. Alternative fuels possess properties that pose new, specific safety challenges when compared with conventional ones, which means that a new understanding and different safety systems and operations are necessary. Transforming the Shipping industry requires a collective ongoing effort – with safety as its foundation.

There are three main safety hurdles associated with the development of alternative fuels.

- Firstly, stakeholders may be working in functional silos focused on subsystems.
- Secondly, regulatory frameworks cannot keep up with technological development.
- Finally, suppliers and end users may lack marine and fuel-specific knowledge/experience.

Holistic risk management, including a systemic perspective on safety, will be the key to managing these safety risks on the pathway to a carbon-neutral industry.

2.4.1. Carriage and Handling

Decarbonization involves alternative fuels and operations with new safety-related risks. After all, the safe and timely transition towards a digitally smart and carbon-neutral future may be compromised if the safety-related risks that these transitions bring about are not accounted for. A successful uptake of alternative fuels depends on the development of efficient safety regulations and the ability to implement a safety culture where all stakeholders take the responsibility to handle the new challenges introduced with the new fuels.

The gradual introduction of **<u>LNG</u>** as a fuel, examples set by first movers, and the experience of decades of carriage and consumption of boil-off on gas carriers have been important for the wider uptake for deep-sea shipping we see indications of today. The entry into force of the IGF Code, 17 years after the launch of a Norwegian LNG-fueled ferry, Glutra, provided an international regulatory framework to handle gases and other low flashpoint fuels, and is a result of 20 years of learnings and experiences of designers, shipowners, manufacturers, yards, flag states and classification societies in how to safely integrate onboard LNG fuel systems. Based on these experiences and the carriage on board gas carriers, rules for the other relevant hydrocarbon gas, LPG, were also developed applying the same safety principles. (DNV, 2023)

To a lesser degree, similar experiences have been gained for **<u>Methanol</u>** through carriage and use as fuel on chemical carriers and as a common cargo on offshore supply vessels. An IMO interim guideline for methyl/ethyl alcohols as fuel is in place, providing guidance and support for the integration of the onboard fuel system. (DNV, 2023)

For **<u>Ammonia</u>** the picture is different. The maritime industry has experience with carriage of ammonia in gas carriers and as a refrigerant in refrigeration plants, but not as a fuel. Due to its toxicity, the introduction of ammonia as fuel creates new challenges related to safe bunkering, storage, supply and consumption. Available energy converters could be 3-4 years away, and regulatory developments in IMO are not yet initiated. Considering the urgency to decarbonize shipping, major deployment of ammonia as fuel may happen faster than for LNG, LPG, and methanol, which means additional focus should be on the installation and safe operational practices. DNV published the first classification society's rules for ammonia as fuel in July 2021 to accommodate owners, shipyards, and designers considering ammonia as fuel. (DNV, 2023)

Hydrogen is not transported as a marine cargo, and the experiences as a marine fuel are currently limited to small-scale R&D projects. The safety implications of storing and distributing hydrogen on board ships are not clear. The general understanding of hazards and risk associated with hydrogen, and particularly liquefied hydrogen (LH_2), is limited. Consequently, no class rules or prescriptive international regulations have yet been developed. Several R&D initiatives are currently ongoing to improve the understanding of LH_2 and associated hazards. The entry into service of a ferry powered by proton-exchange membrane (PEM) fuel cells fueled by liquid hydrogen in March 2023 marked a significant advance for what remains a largely untried technology. The safety implications of storing and distributing hydrogen on ships are unclear. The general understanding of hazards and risks associated with hydrogen as a marine fuel, and particularly liquefied hydrogen, is limited (MTF, 2022). For hydrogen the potential explosion risk related to the low ignition energy and the wide flammability range requires special attention. The very low boiling temperature for hydrogen makes it more challenging to store in its liquefied form.

It is sometimes argued that experience from land-based installations proves that a technology can be safely used on board ships. There are however principal differences to be considered. It is a well-established principle in the IMO and class rules that the level of safety requirements is increased when land-based technology is applied to ships. This relates to a variety of conditions:

- A ship operating out in the **open seas is self-reliant** and can in most instances not rely on help from outside.
- Crew and passengers **cannot escape** to safety in the same way as from a car or within a building on shore.
- Due to space constraint, the **safety distances** are much smaller on ship than a comparable installation on shore.
- The **environmental conditions** are challenging on board ships with humidity, sea spray, vibrations and inclinations.
- The **power demand** for a ship is in a different order of magnitude compared to other applications (for instance automotive) considering similar fuel technology.
- Low temperature **materials** are a necessity for many fuels. As opposed to supporting structures for onshore facilities, ship steel is not resistant to low temperatures.

For the above reasons, land-based solutions are not directly transferable to ships. The qualification of land-based technologies for maritime use adds time and cost. (DNV, 2021)

2.4.2. Bunkering

The introduction of new fuel technologies is expected to have a significant impact on maritime operations on ships and will require that practices are established to ensure continued safe and efficient operations during bunkering, onboard fuel storage, fuel distribution, and maintenance. This includes both normal operational procedures and emergency procedures in case of accidental fuel release.

Bunkering without interrupting other ship and cargo operations is the norm for conventional oil-fueled ships with short port stays. It is also being established as the default bunkering mode for LNG-fueled ships in these segments. It is reasonable to assume that there will also be a commercial and operational drive towards continuing this practice for fuels like methanol, ammonia, and hydrogen.

The practice of refueling while simultaneously performing other operations (simultaneous operations, SIMOPs) is typically reviewed on a case-by-case basis by ship operator towards local stakeholders. The purpose is to identify potential hazardous interactions between bunkering and other activities, regarding the receiving ship and the surrounding area, and to determine if any additional safety measures need to be implemented before the activity can proceed.

Performing SIMOPs safely requires co-ordination between the competent authority, terminal operator, fuel supplier, bunkering infrastructure owner, and receiving ship. The Society for Gas as a Marine Fuel (SGMF) is one organization providing guidance on how to determine which other ship and port operations may be conducted safely while an LNG-fueled ship is being bunkered (SGMF, 2018). Similar guidance is relevant and needed for bunkering of methanol, ammonia, and hydrogen to evaluate the feasibility of performing other operations, such as loading and unloading cargo or having passengers on board, while bunkering these fuels. Depending on factors like proximity to populated areas, type of fuel to be bunkered, and type of bunkering facility, the risk may be considered too high to accept bunkering in certain locations or in parallel with other operations.

In interviews with Nordic ports regarding their views on barriers against supplying zero-carbon fuels, nearly all reported safety and regulatory issues as key barriers against supplying hydrogen, ammonia, and methanol (Menon, 2022). The safety aspects are perceived as more critical for ammonia than for hydrogen and methanol, illustrating the need for training for ports as well. Their concerns include, among others, how port operations may pose a threat or affect people living nearby, how to handle potential leakages, the additional space demand related to required safety zones, the lack of a regulatory framework, and uncertainty related to lengthy regulatory processes with authorities.

Safety studies examining the potential ramifications of large ammonia leaks indicate how key operational parameters, such as ammonia storage conditions, transfer flow rate, and release duration, can significantly affect the dispersion of ammonia, and the degree of reduction in affected area that can potentially be achieved by changing parameters (DNV, 2021). An important additional issue with ammonia, however, is that some leaks may be small enough not to be harmful, yet still be perceived as very dangerous (due to the potent ammonia smell) in surrounding areas, leading to potential major responses in public.

Irrespective of risk studies, it is clear that from a bunkering safety point of view, performing ship-to-ship ammonia bunkering at sea/anchorage would have a lower risk than refueling while simultaneously performing other operations in port. Alternatively, shore-to-ship ammonia bunkering could be performed in designated areas where SIMOPS are not common practice, similar to how cargo is transferred between gas carriers and onshore gas terminals today. For ship types with short port stays, the need for performing bunkering operations at sea/anchorage or in designated areas without SIMOPs would have significant implications for operations, causing delays and additional costs.

2.4.3. Human Factor

A technology change driven by transition to carbon-neutral fuels will have to coincide with a corresponding development of the fuel-specific knowledge in terms of seafarer and onshore organization competence, and in the maritime industry in general. Compared with conventional fuels, the safety risks arising from the properties of the alternative fuels – the **gaseous nature** of hydrogen, ammonia, and methane; the **toxicity** of ammonia and methanol; the **low-temperature risks** associated with methane, hydrogen, and ammonia; and the **flammability** of methanol, methane, and hydrogen – bring a new complexity to <u>bunkering operations</u>, <u>onboard fuel storage</u>, <u>fuel distribution</u> and <u>maintenance</u>. (DNV, 2022)

The availability of seafarers with fuel-specific competence will be a critical factor when fuels presenting new operational safety challenges are introduced. Having a clear understanding of the hazards involved in fuel operations and during maintenance will be essential to be able to control and mitigate the risks.

While fuel-relevant competencies gained through decades of operating gas carriers and chemical carriers will be valuable in upskilling other shipping segments, this is a very limited resource considering the limited number of ships and seafarers in these segments compared to the world fleet.

No matter which fuels and technologies are ultimately being used, additional training for seafarers is essential to ensure their safety and that of the environment and local communities. This upskilling needs to be mirrored in the onshore organization.

A recent DNV study for the Maritime Just Transition Task Force points towards an immediate need to train seafarers (DNV, 2022). The increase in newbuild orders for alternative fuels will increase the demand for seafarers with the required competence, challenging their availability in the near term. The number of seafarers expected to work on ships fueled by LNG/LPG could increase by nearly 200,000 within the next five years. As many as 800,000 seafarers may require additional training by the mid-2030s to enable the fuel transition in shipping. However, the timing and type of training provided will depend on the ambition of decarbonization trajectories and the future fuel mix.

The ability to build up sufficient training capacity is currently subject to several constraints including:

- the lack of clarity surrounding alternative fuel options and decarbonization trajectories, along with slow regulatory development, making investment in seafarer training challenging
- the need to invest in training facilities and up-to-date equipment (e.g. simulators providing opportunities for hands-on learning experiences)
- the lack of qualified trainers
- the shortage of experienced seafarers.

The Maritime Technologies Forum (MTF) identifies potential gaps for future safe use of alternative fuels within three existing Conventions/Codes in a recent study:

- The International Safety Management (**ISM**) Code,
- International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (**STCW**) and
- The Maritime Labour Convention (**MLC**).

MTF makes recommendations on how to close the gaps related to safety management, crew training and safety culture (MTF, 2023).

IGF Code (International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels)

In 2004, Norway proposed the development of an international code for gas-fueled ships at the IMO. In response to this proposal and the growing market for LNG-fueled vessels, interim guidelines on safety for natural gas fueled engine installations in ships were introduced and adopted on 1 June 2009 as an intermediate step. After 2009, the IMO proceeded to develop the IGF Code, which it adopted in 2015 at its 95th MSC Session and which came into force on 1 January 2017.

The purpose of the IGF Code is to provide an international standard for ships operating with gas or low-flashpoint liquids as fuel; vessels other than those covered by the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). The IGF Code provides mandatory requirements for the arrangement and installation of machinery, equipment and systems for vessels operating with gas or low-flashpoint liquids as fuel. The IGF Code was developed using goal-based standards and functional requirements in order to form the basis for the design, construction and operation of such vessels.

Application of IGF Code

- Ships for which the building contract was placed on or after 1 January 2017
- Ships without a building contract, the keels of which were laid, or which were at similar construction stage, on or after 1 July 2017
- Ships which were delivered on or after 1 January 2021

- Ships, irrespective of the date of construction, which converted to using low-flashpoint fuels on or after 1 January 2017

The IGF Code provides the goal and the functional requirements for training of seafarers. Companies shall ensure that seafarers on board ships to which the IGF Code applies have completed training to attain the competencies to perform duties and responsibilities on board ships considering the provisions given in the STCW Code (Seafarers' Training, Certification and Watchkeeping Code), as amended. The STCW Code states mandatory training requirements and is divided into two parts: basic training and advanced training.

Basic training is required for seafarers responsible for designated safety duties. The following competencies are achieved after successful completion of basic training:

- Contribute to the safe operation of the ship,
- Precautions to prevent hazards on a ship and to prevent pollution of the environment from the release of fuels found on ships,
- Carry out firefighting operations on a ship.

Advanced training is required for masters, engineer officers, and all personnel with immediate responsibility for the care and use of fuels and fuel systems on board. The following competencies are achieved after successful completion of advanced training:

- Familiarization with the physical and chemical properties of fuels on board,
- Competence to safely perform and monitor all operations related to fuel on board,
- Operate controls of fuel related to propulsion plant and engineering systems and services and safety devices,
- Plan and monitor safe bunkering, stowage and securing of the fuel,
- Precautions to prevent hazards on a ship and to prevent pollution of the environment from the release of fuels found on ships,
- Gain knowledge of the prevention, control, and firefighting and extinguishing systems.

Interim Guidelines for the Safety of Ships Using Methyl/ Ethyl Alcohol as Fuel

The purpose of these Interim Guidelines (MSC.1/Circ.1621) is to provide an international standard for ships using methyl/ethyl alcohol as fuel. The basic philosophy of these Interim Guidelines is to provide provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using methyl/ethyl alcohol as fuel to minimize the risk to the ship, its crew and the environment, having regard to the nature of the fuels involved.

These Interim Guidelines address all areas that need special consideration for the use of methyl/ethyl alcohol as fuel. These Interim Guidelines follow the goal-based approach

(MSC.1/Circ.1394/Rev.2) by specifying goals and functional requirements for each section forming the basis for the design, construction and operation of ships using methyl/ethyl alcohol as fuel.

Crew and other stakeholders need to be vigilant, proactive, and well-trained to identify and address potential safety risks. Most of the global fleet of ships will continue to be operated by seafarers even if some vessels become fully autonomous over the next 10 or 20 years. Advances made in vessel operations technology over the past decade have already seen routine activity shifted from ship to shore. For this ship-shore partnership to work as it should, safety and security training of both seafarers and shoreside teams must be reassessed to ensure that safety will be in focus in all parts of the organization.

CHAPTER 3

LNG – Liquified Natural Gas

Introduction

As already mentioned on the previous chapter, the Maritime industry is under high pressure to improve its sustainability – especially its emissions to air. In terms of greenhouse gas emissions (GHG), the industry needs to take advantage of improvements today – to minimize the long-term impact on the planet.

The uptake of LNG has been very strong in recent years, especially in newbuildings. This has been driven by a combination of the environmental benefits and attractive fuel prices, and the trend is accelerating. LNG bunkering infrastructure is continually improving, with fuel already available in most major shipping hubs.

Switching to LNG as a fuel can provide significant advantages, by meeting regulatory requirements, offering enhanced competitiveness, as well as improving overall air quality, and reducing GHG emissions.

3.1. Definition and Production

Liquefied Natural Gas – LNG – is a mixture of several gases, in liquid form, principally composed of methane (CH_4), with a concentration that can vary from 70 to 99 percent by mass, depending on the origin of the natural gas. Other hydrocarbon constituents commonly found in LNG are ethane (C_2H_5), propane (C_3H_8), and butane (C_4H_{10}). Small amounts of other gases, such as nitrogen (N_2), may also be present. In its liquid form, natural gas has a significantly smaller volume, about 1/600th, than in the gaseous state at Standard conditions for Temperature and Pressure - STP, which is defined as a temperature of 0 °C and an absolute pressure of 1 bar. Natural gas reserves are significant; with the International Energy Agency (IEA) estimating reserves at current usage rates (January 2011) are over 250 years.

LNG is odorless, colorless, non-toxic and non-corrosive. Hazards include **flammability** after vaporization into a gaseous state, **freezing** and **asphyxia**. The liquefaction process involves removal of certain components, such as dust, acid gases, helium, water, and heavy hydrocarbons, which could cause difficulty downstream. The natural gas is then condensed into a liquid at close to atmospheric pressure by cooling it to approximately −162 °C (−260 °F); maximum transport pressure is set at around 25 kPa (4 psi) (gauge pressure), which is about 1.25 times atmospheric pressure at sea level.

The "acidic" elements such as hydrogen sulphide (H_2S) and carbon dioxide (CO_2), together with oil, mud, water, and mercury, are removed from the gas to deliver a clean sweetened[2] stream of gas. Failure to remove much or all of such acidic molecules, mercury, and other impurities could result in damage to the equipment. Corrosion of steel pipes and amalgamation of mercury to aluminum within cryogenic heat exchangers could cause expensive damage.

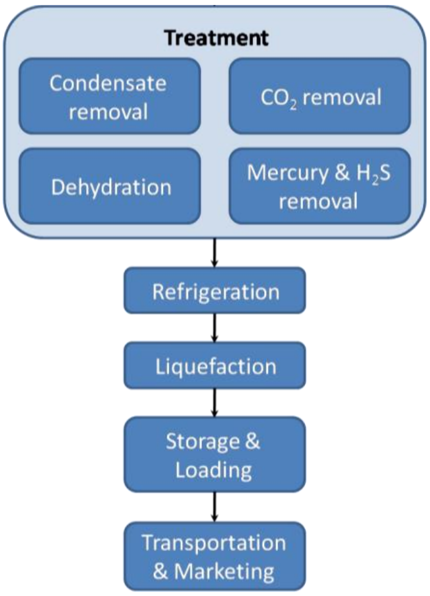

Figure 3-1: Typical treatment of underground hydrocarbon deposits to form LNG.

[2] Processes within oil refineries or chemical processing plants that remove hydrogen sulfide are referred to as "sweetening" processes because the odor of the processed products is improved by the absence of hydrogen sulfide.

The gas stream is typically separated into the liquefied petroleum fractions (butane and propane), which can be stored in liquid form at relatively low pressure, and the lighter ethane and methane fractions. These lighter fractions of methane and ethane are then liquefied to make up the bulk of LNG that is shipped.

Specific energy content and energy density

The heating value depends on the source of gas that is used and the process that is used to liquefy the gas. A typical value of the higher heating value of LNG is approximately 50 MJ/kg. A typical value of the lower heating value of LNG is 45 MJ/kg.

The volumetric energy density of LNG is approximately 2.4 times that of compressed natural gas (CNG), which makes it economical to transport natural gas by ship in the form of LNG. The energy density of LNG is comparable to propane and ethanol but is only 60 percent that of diesel and 70 percent that of gasoline.

History of LNG use

Natural gas was considered during the 20th century to be economically unimportant wherever gas-producing oil or gas fields were distant from gas pipelines or located in offshore locations where pipelines were not viable. In the past this usually meant that natural gas produced was typically flared, especially since unlike oil, no viable method for natural gas storage or transport existed other than compressed gas pipelines to end users of the same gas. This meant that natural gas markets were historically entirely local, and any production had to be consumed within the local or regional network.

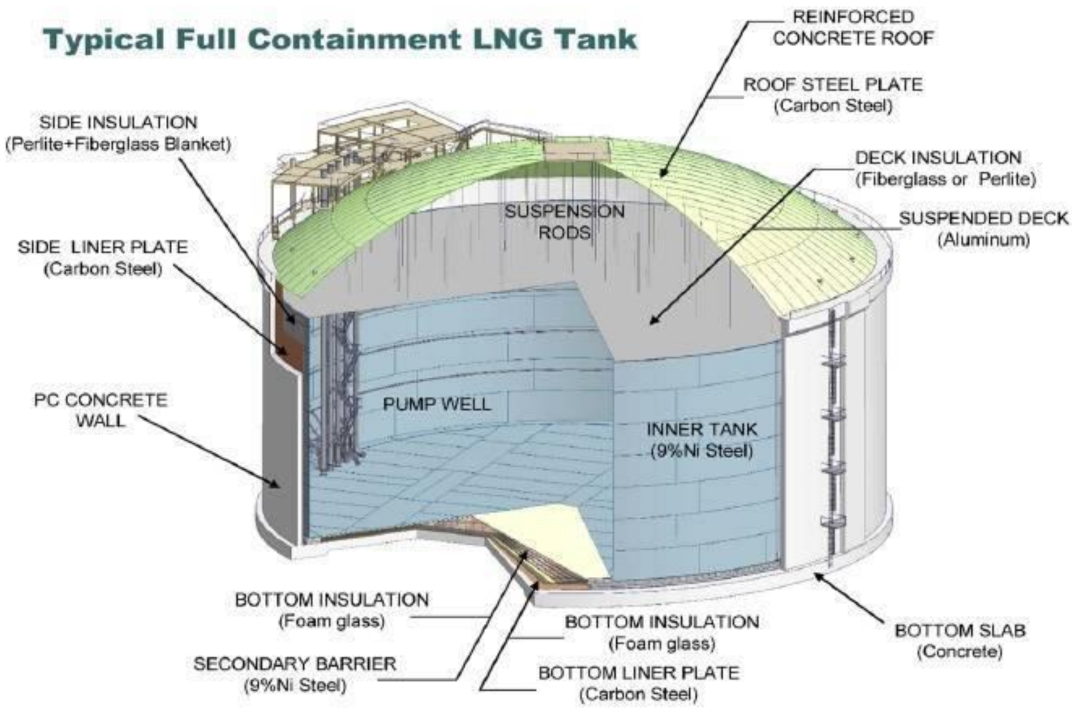

Figure 3-2: LNG cryogenic storage at shore.

Developments of production processes, cryogenic storage, and transportation effectively created the tools required to commercialize natural gas into a global market which now competes with other fuels. Furthermore, the development of LNG storage also introduced a reliability in networks which was previously thought impossible. Given that storage of other fuels is relatively easily secured using simple tanks, a supply for several months could be kept in storage. With the advent of large-scale cryogenic storage, it became possible to create long term gas storage reserves. These reserves of liquefied gas could be deployed at a moment's notice through regasification processes, and today are the main means for networks to handle local peak shaving requirements.

LNG fueled vessels – Market

LNG has been a fuel option for a long time – with the first trials reaching back to the 1970's. However, up until a few years ago, as a ship fuel LNG has been confined to LNG carriers – utilizing the boil of gas from their cargo - and smaller vessels like ferries, OSVs and other coastal tonnage. LNG is now considered a mature alternative fuel option.

Figure 3-3: A typical LNG carrier.

Recently, LNG orders for large vessels have started to take off first in the cruise and container segment and later followed by all other segments including tankers and bulk carriers. In 2020 and 2021, orders from LNG fueled tonnage represented a significant share of newbuilding gross tonnage for the first time. This surge in the number of larger vessels ordered could spark a real step change for the industry by providing the levels of bunker demand that to support and expand the development of LNG bunkering infrastructure around the world.

Larger newbuildings will support the bunker demand needed to roll-out infrastructure in major ports and around the world. LNG is now easily available along most major trade routes – with more than 100 LNG bunkering solutions in operation globally. And with the same number in development and discussion this will develop alongside the fleet. However, there are many technology choices that need to be made depending on specific vessel design and operational requirements.

Supply Chain

Fuel availability is one of the challenges to widespread take-up; however, there are initiatives underway to develop new marine fuel supply chains. In all cases, the three basic routes to supply are truck-to-ship, ship-to-ship and tank-to-ship.

Truck-to-ship is usually the first bunkering method applied but is only suitable for delivering small quantities. Truck-to ship provides most versatility as observed with ferries. They can be driven on board the vessel to provide bunker operations similar to existing conventional fuel bunkering operations. Capacities/transfer rates can be increased by introducing loading manifolds/skids.

Land-based tank infrastructure can require significant investment and take many years to develop and obtain the necessary approvals. However, examples of land-based tank infrastructure exist. For instance, Harvey Gulf International Marine (HGIM) Port Fourchon facility and Eagle LNG facility in Jacksonville, Florida.

The use of dedicated bunker vessels is expected to be a preferred option for many operators. However, the most viable option depends on the GFS operating profile and the regional LNG supply infrastructure where bunker may occur.

Environmental performance

LNG as fuel can significantly improve the environmental footprint of a vessel:

- LNG-fuelled vessels can reduce their EEDI rating by 20%, while their Carbon Intensity Indicator will be reduced by approximately the same amount.
- Competitive vessel design ensures upcoming compliance some ten years longer than conventional designs.
- Up to 23% reduction in GHG emissions, both CO_2 and CH_4 (methane), depending on the type of engine selected
- Almost eliminates SOx, particulate matter (PM)
- NOx emissions are reduced by 20-80%, depending on the engine technology, and with the use of EGR (Exhaust Gas Recirculation) or SCR (Selective Catalytic Reactor) systems NOx Tier III levels can be achieved for all engine types.

Methane slip is higher for 4-stroke engines than for 2-stroke engines and also depends on whether the engines are low or high pressure. High pressure engines typically have considerably lower methane emissions than low pressure designs.

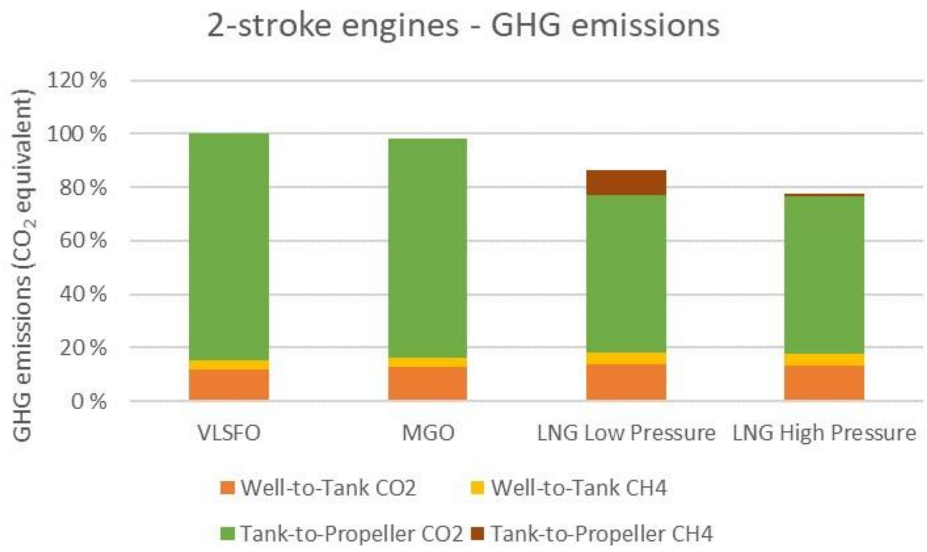

Figure 3-4: GHG emissions in 2-stroke engines burning: VLSFO, MGO, LNG of Low and High pressure.(MAN)

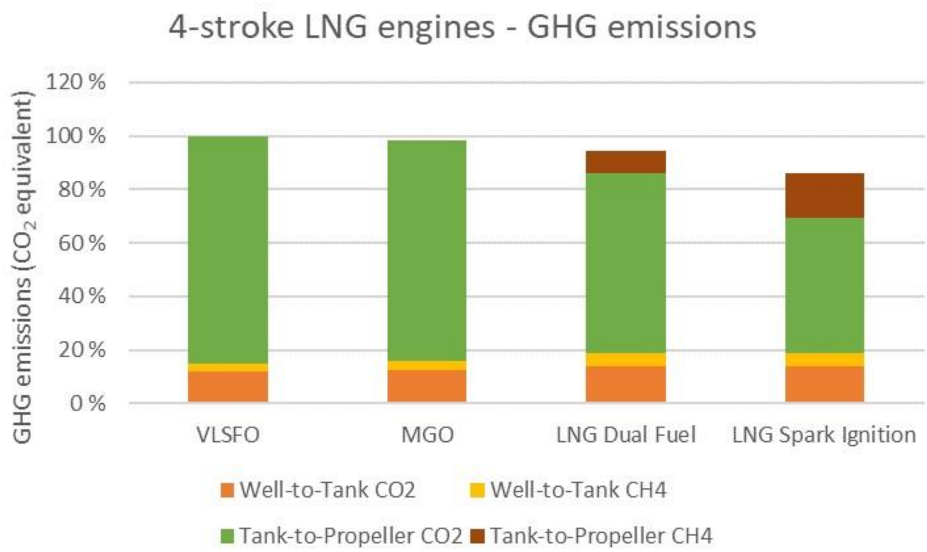

Figure 3-5: GHG emissions in 2-stroke engines burning: VLSFO, MGO, LNG of Low and High pressure.(MAN)

3.1.1 Pros and Cons of LNG as a Marine Fuel

With the IMO 's tightening of SOx (sulfur oxides) regulations introduced in January 2020 (SOx emission regulations); most ocean-going vessels now use low-sulfur heavy oil. However, the use of low sulfur heavy oil does not change CO2 emissions, it is clear that the fuel is inadequate in achieving the IMO goal of reducing CO2 emissions by more than 40% in 2030 compared to 2008.

For this reason, the introduction of LNG-fueled vessels which do not use heavy oil is drawing attention in the long term. LNG is said to have a low environmental impact because it removes sulfur in the pre-liquefaction process, so it emits almost no Sulfur Oxides (SOx) or

Particulate Matter (PM) when burned and emits less NOx (nitrogen oxides) and CO2 than other fossil fuels. It is also relatively safe because its specific gravity is lighter than that of air and it is easy to diffuse, so there is less risk of explosion. In addition, its proven reserves surpass that of oil and its ability to provide a stable long-term supply for more than 50 years is a key advantage.

Globally, the number of LNG-fueled vessels has increased. Most of the vessels in service are operated in Europe and it is expected that the shift from heavy oil to LNG or other alternative fuels will be further accelerated as a result of the strengthening of SOx regulations in January 2020. In Japan, Mitsui O.S.K. Lines, Ltd.(MOL) and Nippon Yusen Kaisha(NYK) have launched Japan's first LNG-fueled tugboats, and plans to build LNG-fueled vessels are continuing. MOL's LNG-fueled tugboat “Ishin” was carried out LNG-bunkering in Kobe as well as in Nagoya.

IMO is limiting the sulfur content of bunker fuel to reduce vessel exhaust emissions of SOx and prevent air pollution. The current limit of 3.5% sulfur content in bunker fuel is being reduced to 0.5% as of January 2020. Main measures include installation of onboard scrubbers, use of complied fuel, and transition to LNG as fuel.

LNG fuel has a low environmental impact, but there are three general disadvantages to using it as a ships fuel:

1. Installation of engines that can use LNG fuel;
2. Capital investment is also required in equipment other than engines, such as fuel tanks 2 to 3 times larger than conventional ones and re-liquefaction equipment and
3. Cost at the time of new construction is 15 ~ 30% higher compared to conventional fueled vessels.

However, as environmental regulations become increasingly stringent, LNG-fueled vessels are expected to continue to grow in market share because of their advantages, such as "zero sulfur content, about 25% reduction in CO2 emissions, and overwhelmingly low nitrogen compound emissions," and "LNG is more competitively priced than expensive low-sulfur heavy oil.

3.2. LNG bunkering, safety, and design

3.2.1 LNG bunkering and supply

Bunkering is to be considered at the beginning of a design project to ensure optimum design. If during the design stage the trading route is known and the potential bunker supplier along the route identified, measures/ contracts can be established to ensure the parameters of the LNG vessel during bunkering and the supplier/ bunker vessel are aligned and procedures of bunkering standardized. If trading routes and suppliers are unknown during design stage, then it might be beneficial to increase the equipment limits on the ship to ensure issues arising from bunkering are handled correctly.

Temperature of bunkers and pressure control are two issues of concern:

- The colder the LNG from the LNG supplier the better it is for the GFS. This means there is more time to manage pressure control in the tanks. If the bunker vessel supplies warm LNG, this might result in handling increased boil-off/pressure which may lead to an increase in fuel consumption just to handle pressure.
- Linked to temperature, an additional concern is understanding if the LNG gas carriers/bunker vessels' vapor return system has been evaluated for conducting vapor balancing in a compatibility study/assessment with the gas fueled vessel. Vapor balancing design compatibility between supplier and receiver is to be verified. As we look at larger bunker tanks, an owner needs to consider what happens during the cool down of the bunker tank prior to full rate loading and how to handle the associated flash gas that will be generated If this is not considered, then this will impact the duration of the bunkering operation evolution, which in results may impact on the expected operating profile.

In addition to verifying the vapor balancing design compatibility between supplier and receiver, there could be challenges with documenting custody transfers. In addition to measuring quantities of LNG supplied to the GFS, the amount of vapor returned may need to be measured. Credits for gas vapor return need to be included into the overall price during custody transfer. Other areas such as bunker station location and bunker vessel compatibility are to be considered.

Supply Chain

Fuel availability is one of the challenges to widespread take-up; however, there are initiatives underway to develop new marine fuel supply chains. In all cases, the three basic routes to supply are truck-to-ship, ship-to-ship and tank-to-ship.

Truck-to-ship is usually the first bunkering method applied but is only suitable for delivering small quantities. Truck-to ship provides most versatility as observed with ferries. They can be driven on board the vessel to provide bunker operations similar to existing conventional fuel bunkering operations. Capacities/transfer rates can be increased by introducing loading manifolds/skids.

Land-based tank infrastructure can require significant investment and take many years to develop and obtain the necessary approvals. However, examples of land-based tank infrastructure exist. For instance, Harvey Gulf International Marine (HGIM) Port Fourchon facility and Eagle LNG facility in Jacksonville, Florida.

The use of dedicated bunker vessels is expected to be a preferred option for many operators. However, the most viable option depends on the GFS operating profile and the regional LNG supply infrastructure where bunker may occur.

3.2.2 Design Considerations

For liquefied natural gas (LNG) fueled ships, the main systems to be accommodated in a design concept that are different, or additional, to conventional ship designs are the LNG fuel containment system, associated LNG bunker station and transfer piping, a Fuel Gas Supply System [FGSS], the double-wall fuel gas distribution piping, gas valve unit (which may be located in a Gas Valve Unit [GVU] room), gas consumers, nitrogen generating plant, vent piping systems and mast(s), and for some LNG tank types, additional equipment for managing tank temperatures and pressure.

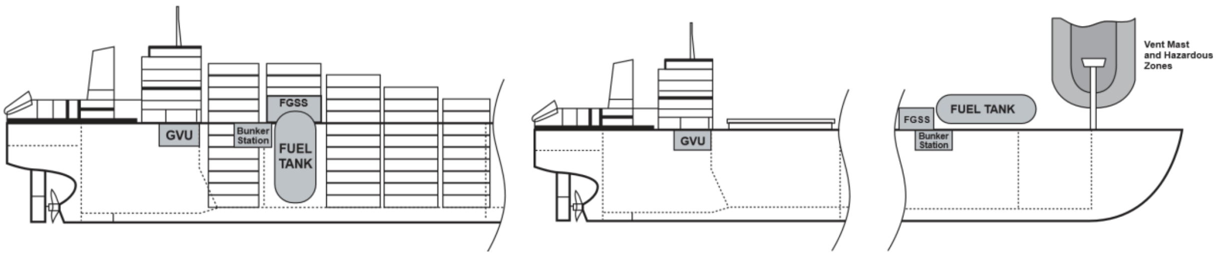

Figure 3-6: Typical Examples for the location of LNG tanks and main equipment

The protective LNG tank location criteria can be based on a deterministic approach considering tank volume or a probabilistic method. The International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) provides a third alternative, where the ship’s hull is specifically designed and reinforced in the way of the LNG tank, therefore minimizing the impact from a collision and so allowing the tank located closer to the ship’s side shell. Figure 1 shows some typical examples for the location of the LNG tanks and main equipment.

The “Emergency Shutdown (ESD)-Protected machinery space” concept introduces additional measures to provide an equivalent level of safety to the conventional non-hazardous machinery space. Application of the ESD-Protected machinery space has been limited so far because of the growing availability of engines that can be supplied meeting the double barrier criteria and perhaps because of the additional vessel complexity and cost that meeting the ESD machinery space concept brings. The non-hazardous machinery space concept is based on the use of double barriers for all gas-containing components such that a failure in a single barrier cannot lead to a fuel gas release into the space. The main differences between the two machinery space concepts are shown in the below figures. The non- hazardous machinery space also shows the GVU room. This may be a separate space outside of the machinery space, or may be a GVU unit, which is a self-contained unit that is essentially an extension of the double barrier piping system and may be located within the non-hazardous machinery space.

Vessels also have to find practical locations that meet the prescriptive requirements for the fuel preparation room, vent mast, and the nitrogen generating equipment, as per the ABS Guide for LNG Fuel Ready Vessels. The LNG fuel containment system vent mast location can be a particular challenge because of the requirements on hazardous area zones around the vent mast exit and the physical location criteria for the LNG tank pressure relief valve vents. These need to be at least 10 meters (m) from any air intake, air outlet or opening to accommodation, service and control spaces or other non-hazardous area and any exhaust system outlet. Vent heights shall normally not be less than B/3 or 6 m. Hazardous areas are also a challenge with location of tanks, fuel gas piping systems, fuel gas supply system (FGSS) and gas consumers.

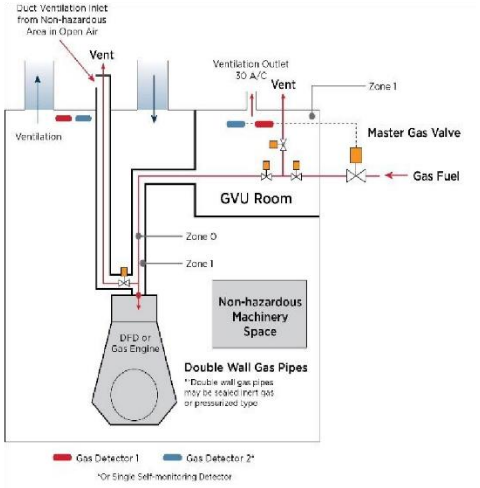

Figure 3-7: IGF Non-Hazardous Machinery Space Concept.

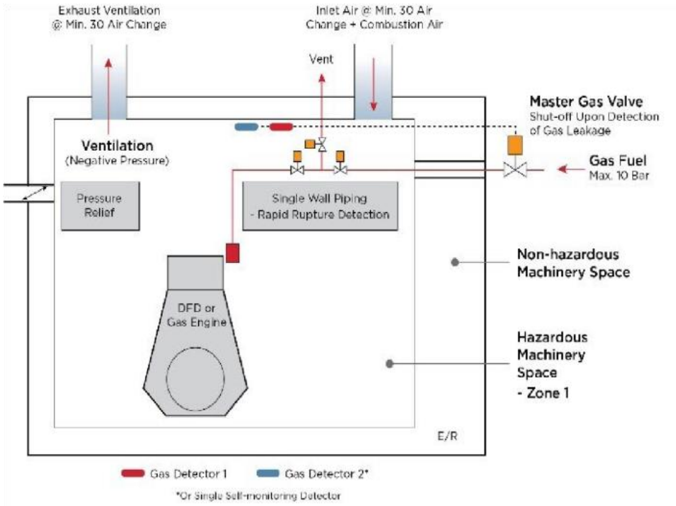

Figure 3-8: IGF ESD Machinery Space Concept.

3.3. Regulatory Compliance

Regulatory and classification requirements are in place for the use of natural gas fuel in marine applications. The specific gas fueled ship (GFS) arrangements depend on the fuel containment, the fuel gas supply system (FGSS), and selected prime mover technologies. The link between fuel storage, fuel preparation and gas consumer is much more interdependent as compared to conventional fuels. Critical equipment and system design decisions cannot be made in isolation. The following sections are to be considered for the use of liquefied natural gas (LNG) as a marine fuel.

3.3.1 IMO Regulations

The adoption of the Initial International Maritime Organization Strategy on Reduction of Greenhouse Gas Emissions from Ships by the Resolution MEPC.304(72) in April 2018 demonstrates the IMO's commitment to support the Paris Agreement. It includes a vision to phase out GHG emissions from international shipping within the century and may be an active driver for member States to initiate decarbonization and reduction of GHGs using policies and procedures.

The IMO's International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) applies to ships to which the SOLAS Part G Chapter II-1 applies and contains only detailed prescriptive requirements for LNG under Part A-1 of the Code. Other low-flashpoint fuels may also be used as marine fuels on ships falling under the scope of the IGF Code, provided they meet the intent of the goals and functional requirements of the IGF Code and provide an equivalent level of safety. This equivalency is to be demonstrated by applying the Alternative Design risk assessment process and SOLAS novel concepts approval procedure of SOLAS regulationII-1/55, and as required by 2.3 of the IGF Code.

3.3.2 Risk Assessment

The following basic operations and routing items are to be considered:

- Type of vessel and associated cargo operations (e.g., offshore support vessel (OSV), tug, container carrier, bulk carrier)
- Expected trade route (including roundtrip or one way).
- Where to bunker the vessel, how often to bunker, bunker providers, bunkering time duration.
- Vessel bunker tank sizes have increased considerably. Larger tank sizes require careful planning for cargo transfer operations as the operation might take weeks in port.
- Vessel build location and maintenance/ repair locations which might influence scheduled and unscheduled delays. Choice of fuel between these locations and plan to manage operating expenditure (OPEX) costs.

These basic considerations can impact on choices and selections for a vessel and in determining engine choice, gas fuel handling system and amount of redundancy needed.

Contingency planning is necessary to account for unexpected vessel repairs (emergency drydocking, hull inspection, engine repair, major damage) to accommodate tank emptying, gas freeing and subsequent return to service.

Extensive prior planning for integration of LNG fuel, methods and procedures with crews, fuel suppliers, transporters, port authorities and regulators is necessary.

3.4. Storage of LNG onboard ships

One of the biggest challenges for LNG fueled vessels is finding the most efficient use of a vessel's available space for the fuel tank and the associated systems. LNG storage on board requires more space than conventional fuel oil storage. This is primarily because LNG has a lower energy density than fuel oil and therefore requires a larger tank to provide the same operational range. In addition, due to the low temperature of LNG, the tank insulation and required gas handling systems additional space is needed

The IMO has defined three basic, independent LNG tank types: Type A, Type B and Type C. In addition, there are membrane tanks which are fully integrated into the ship structure. The main differences between the tank systems are:

- design pressure,
- design of the secondary barrier,
- shape of the tank,
- tank size

An important requirement of the IGF Code is for the system to avoid venting natural gas to atmosphere for a period of 15 days. Various methods for tank pressure control are available:

- Energy consumption by the ship (engines, gas turbines, boilers etc.)
- Re-liquefaction
- Thermal oxidation of vapours (gas combustion unit)
- Pressure accumulation

Types A, B and membrane are low pressure, nominally “atmospheric” tanks, whereas Type C are pressurized tanks.

Type A, B and membrane tanks require a secondary barrier to protect in case of leak from the primary barrier. Type A and membrane systems require a full secondary barrier. Type B requires a partial secondary barrier since these are designed using advanced fatigue analysis tools and a “leak before failure” concept, for which small leaks can be managed with partial cryogenic barrier protection and inert gas management of the interbarrier space. Type C tanks are designed using pressure vessel code criteria and conservative stress limits; therefore, they do not require a secondary barrier.

Most gas fueled ships (GFS) in operation at present have the International Maritime Organization (IMO) Type C pressurized fuel tanks. This is because these are relatively inexpensive to manufacture and simple compared to the other fuel containment types, particularly in the smaller sizes required by the current gas fueled fleet. Type C tanks can also simplify the required boil-off gas (BOG) management equipment because of their pressure accumulation capability; however, these tanks might not be the most space-efficient option.

Large deep-sea vessels would likely specify membrane fuel containment systems to limit the loss of cargo space compared to conventional fueled ships. Sloshing can be an issue that requires special consideration for membrane tanks. LNG membrane tanks for GFS need to be designed to accommodate all LNG liquid levels as in service. Therefore, the tanks will be designed with higher density insulation materials and membrane reinforcement in critical areas.

Table 3-1: IMO LNG Fuel Containment System Comparison

ITEM	TYPE B	MEMBRANE	TYPE C
Secondary Barrier	Partial secondary barrier required	Complete secondary barrier required	No secondary barrier required
Volume Efficiency	Medium as it can follow the compartment shape, however space for inspection to be provided around the tank	Maximum effectiveness as the whole hold is utilized	Least space efficient. Independent tanks, simple cylindrical shape, frequently located on deck. / Bi-lobe and tri-lobe give improved space efficiency
Fabrication	Similar to ship normal structures (skilled welders)	Requires high skills and accuracy (special licenses provided by the designer)	Pressure vessel construction (skilled welders)
Inerting Requirements	Hold can be filled with dry air, but sufficient inert system should be available onboard	Additional systems for pressurizing and inerting the interbarrier spaces are necessary	Hold can be filled with dry air if condensation and icing is an issue (nonvacuum tanks)
Sloshing	In general, it is not an issue due to tank internal structure	May be a serious issue, in particular for large tanks, but specially designed	In general, it is not an issue

		reinforcements are used	
Capability to Retain Boil-off Inside the Tank	Design pressure not higher than 0 .7 bar according to the Codes, therefore they cannot withstand the pressure developed by the boil-off for a long time	Design pressure not higher than 0 .7 bar according to the Codes, therefore they cannot withstand the pressure developed by the boil-off for a long time	High pressure accumulation capability; e.g. LNG tanks 10 bar and LPG 18 bar
Inspections	Inspection relatively easy as the tanks are fully accessible on both sides	Inspections may be difficult as certain parts are not accessible and require special testing or inspection procedures	Inspection relatively easy as the tanks are fully accessible on both sides, smaller tanks through man or remote access holes
Maintenance and Repairs	Similar to normal ship structures, though insulation can restrict access	Specialized workers required and usually time-consuming	Similar to normal ship structures, though insulation can restrict access

3.5. Engine types for using LNG as a fuel

Engine selection is also a key consideration. Currently, the two different gas mode combustion concepts for two-stroke engines are **low-pressure (LP) gas engines using the Otto cycle** and **high-pressure (HP) gas engines using the Diesel cycle**. High-pressure engines offer lower fuel consumption and practically eliminate methane emissions, while low-pressure engines offer simpler designs at a somewhat lower investment cost.

Smaller 4-stroke engines are also available, both of dual-fuel and spark-ignition (gas only) type. LNG engine design has been steadily improving as the technology becomes more widely adopted, with increases in efficiency and reductions in methane slip emissions.

Both marine slow-speed two-stroke engine manufacturers, MAN Energy Solutions and Winterthur Gas & Diesel (WinGD), offer DF internal combustion engines. However, each manufacturer has selected a completely different combustion process for when the engine operates in gas mode.

- The WinGD LP DF engines (X-DF) utilize the Otto process in gas mode and the conventional Diesel process when in oil mode.
- The MAN HP DF engines (ME-GI) use the Diesel combustion process in both oil and gas modes.

For both concepts, the gas is ignited by a pilot injection of liquid fuel from the conventional fuel injection system, or a dedicated pilot fuel system. The point during the combustion cycle where the gas is injected dictates the required gas supply pressure.

The WinGD X-DF is designed to operate at a gas supply pressure of up to 13 bar, and the high-pressure MAN ME-GI uses gas delivered by a direct injection system at approximately 300 bar. The two different designs lead to different combustion concepts, Otto cycle for the X-DF and Diesel cycle for the ME-GI, and therefore have different performance and emissions characteristics. A recent announcement by MAN involved the development of their low-pressure DF engine, ME-GA.

Table 2 highlights some of the key similarities and differences between the slow speed DF concepts. The similarities are limited to, the pilot fuel oil quantities required to start the gas combustion process, the minimum engine load that the engine can achieve when operating in gas mode, and the fact that both concepts are sulfur oxides (SOx) compliant when using sulfur compliant fuel for the pilot fuel.

Overall, the suitability of a specific concept, or engine type, to a ship is very much a case-specific decision. For some, it may simply be that they are not comfortable with HP gas or the increased complexity and cost associated with HP fuel gas supply systems. For others, it may be the concerns with Otto cycle being sensitive to a number of operating parameters (Methane Number, Ambient Conditions), or the GHG impact of methane slip.

Table 3-2: Otto vs Diesel Slow Speed 2-Stroke DF Engine Comparison

	WinGD X-DF	MAN ME-GI
Cycle Type (in Gas Mode)	Otto	Diesel
Gas Supply Pressure [bar]	< 13	300
BMEP [bar]	17.3	19.0 - 21.5
IMO NOx Compliance (in Gas Mode)	Tier III	Tier II
Liquid pilot % @ 30% MCR	~1.0	3.0 - 5.0
Methane Number Sensitive	< 80	No
Knock/Misfire Sensitive	Yes	No
Methane Slip	Yes	Not significant
Development Status [Type (Year)]	XDF 2 .0 (2020)	Mk 2 .0 (2019)

Note: All Figures are approximations, based on Manufacturers' updates, and may change

Boil-Off Gas

LNG has a density of around 430 kg/m³ to 480 kg/m³ and a gross calorific value of around 54 MJ/kg to 56 MJ/kg depending on the composition. When liquefied at approximately -162° C, the volume required for natural gas is reduced to about 1/600th of that required when in the gaseous state. In this condition, LNG is stored in tanks where the heat ingress leads to the generation of boil-off gas (BOG). The BOG is consumed by the engines or is re-liquified in order to maintain the LNG tank pressure within acceptable limits.

For Gas Fueled Ship [GFS], the amount of BOG available in certain instances might not be sufficient to sustain the ship's power demands at maximum continuous rating, so the fuel gas supply systems need to force vaporize the LNG into conditions suitable for the engines. In some cases, the designers may prefer to force vaporize LNG and send it to the main engines because it might be cheaper and more efficient to boost pressure on LNG and vaporize it on a high-pressure vaporizer rather than use a compressor. But the ship will still need to manage the BOG and LNG tank pressures at all times, including times where there is no gas consumption by propulsion related consumers, which can lead to many potential combinations for fuel supply and BOG management equipment.

Vapor returns need to be considered during design when the bunker supplier has the capability of receiving and handling vapor returns. Vapor return does assist with reducing heat transfer while loading the LNG tank with liquid from the bottom in lieu of using top spray to manage pressure accumulation while loading. Vapor return also assists with reducing the duration of the bunker evolution since liquid can be filled in the bottom of the tank and any vapor pressure accumulated during loading can be returned to the supplier.

The LNG fuel containment system selected will influence the installed equipment for BOG management and also have an operational impact on tank filling levels and how bunkering (tank pressure and vapor return) is managed in service. The complexity of LNG bunker vessels is greater than conventional fuel oil bunker vessels and introduces specific compatibility challenges.

The IGF Code permits a number of ways to manage the BOG, including consumption, reliquefication, cooling and pressure accumulation. The IGF Code sets criteria for controlling tank pressure and temperature at all times and for maintaining tank pressure below the relief valve setting for 15 days when the vessel is idle with domestic load only. The 15-day criteria may be difficult for atmospheric tanks to achieve on domestic (hotel) load only and may therefore necessitate the fitting of additional BOG management equipment, such as reliquefication systems.

Fuel Gas Supply Systems

The purpose of the FGSS is to deliver fuel to the engine or consumer at the required temperature and pressure. For gaseous fuels using cryogenic/pressurized liquefied storage, the fuel may be pumped or pressure fed, directly in liquid form, such as LNG, from the tank and vaporized to a gaseous state for the consumer, or supplied in combination with the use of compressed gas from the natural tank BOG.

For dual-fuel (DF) engines, typically there is no requirement for FGSS redundancy since the basic safety concept is that the primary fuel remains the fuel oil and seamless transition back to oil mode is required in the event of a safety system trip of the gas fuel system. In those cases where gas is the means of Tier III NOx compliance, MARPOL Annex VI/ NOx Technical Code (NTC) permits transit to the next port in Tier II mode. However, for practical reasons, duplication of rotating and reciprocating FGSS equipment, such as submerged LNG pumps or high-pressure cryogenic pumps, is often specified by ship owners and operators for redundancy, reliability and maintenance purposes.

Two common engine and FGSS options are:

I. **MAN's ME-GI High-Pressure DF Engine**, operating on Diesel cycle where the gas is supplied to this engine at high pressure (300bar) therefore the FGSS involves high-pressure pumps, evaporators and high-pressure compressors, and

II. **WinGD's X-DF Low-Pressure Engine**, operating on Otto and Diesel cycle where the gas is supplied to this engine at low pressure (13bar), therefore the FGSS involves low-pressure pumps, evaporators and low-pressure compressors.

Common issues reported so far involve the main engines and the relevant FGSS. However, this was expected as these technologies are relatively new to the marine industry. The problems reported on both types of main engines involve mainly the components related to gas mode operation. Based on the service experience being collected, engine designers have improved their designs to minimize operational issues. Problems were initially reported with FGSS operation. However, the suppliers of this equipment have also developed and improved the designs further to eliminate issues during operation. Overall, the development process of DF engines and FGSS is still ongoing. Yanmar produces auxiliary LNG DF generators in its EY35 series lineup which operates at a mean effective pressure of 20 bar. Wartsila's 20DF (21 bar) and 31DF (27 bar) genset series can also be used as LNG auxiliary generators.

Methane Slip

Methane slip is the escape of methane gas from production, processing, transport, operation or combustion. In terms of internal combustion (IC) engines, "methane slip" refers to the unburned methane present in IC engine exhaust emissions. The amount of methane contained in the IC engine exhaust varies greatly between engine combustion types (Otto or Diesel), specific engine designs and engine loads.

Methane is of primary concern due to its increased Global Warming Potential (GWP) over other greenhouse gases (GHGs). There are various studies on the life-cycle GHG emissions, the results of which are typically shown on a 100-year or 20-year GWP basis. It is known that methane emissions in the atmosphere can trap solar radiation more than carbon dioxide (CO_2). Methane emissions are estimated to be 84 times more severe than CO_2 on a 20-year basis and 28 times more severe than CO_2 over the 100-year basis by the IPCC AR5 report.

There are three primary causes of methane slip:

- Scavenging leakage;
- Incomplete combustion and
- Trapped methane in the combustion chamber crevices.

Scavenging leakage occurs when the methane and air mixture pass directly to the exhaust, for example when gas injection to the cylinder occurs prior to closing the exhaust valve.

Incomplete combustion occurs in all IC engine types but is primarily an issue for lean burn Otto process gas engines. Incomplete combustion can occur for many reasons (including trapped methane, detailed below) but it is typically due to flame quenching close to the cylinder walls and extinguishing of the combustion flame at low pressure and temperature. This is effectively fuel quenching at the coldest part of the combustion chamber while the engine is running. This results in increased methane emissions during transient operation and operation at low engine loads. To keep combustion stable and reduce methane slip, lean burn Otto engines need to accurately control combustion between knock and misfire conditions.

Dead volumes, or crevices, within an IC engine cylinder and combustion chamber are also a source for incomplete combustion and an opportunity for methane to leak directly to the exhaust. The amount of methane slip emitted is highly dependent on the installed engine technology. For example, high-pressure gas injection engines using the diesel combustion process in gas mode can reduce levels of methane slip to the engine exhaust more so than low-pressure engines applying the Otto combustion process in gas mode. A two-stroke engine, when compared to a four-stroke engine, is also typically more effective at reducing methane slip due to the reduced quantities of geometric gas traps.

Methane slip can be reduced by running engines at higher power output. While this is not possible in all ship propulsion and power generation arrangements, it can be used in power generation load sharing to optimize power plant operation to reduce methane emissions.

The IMO’s Intersessional Working Group on Reduction of GHG Emissions from Ships continues to consider approaches to control methane slip, which is part of the 37 Candidate Measure Proposals submitted to IMO for adoption. Options to address methane slip include direct methane emission controls or indirect means through fuel carbon factors. The engine manufacturers’ latest specifications and latest updates on the dual-fuel (DF) engine concepts regarding possible primary reductions of methane slip, should be referenced.

CHAPTER 4

Ammonia

Introduction

Ammonia has emerged as a promising marine alternative fuel, revolutionizing the maritime industry's approach to propulsion systems. As the maritime sector seeks cleaner and greener energy sources to reduce greenhouse gas emissions and comply with stringent environmental regulations, the industry strives for sustainable solutions and the use of ammonia (NH_3) as a marine fuel has gained attention due to its potential as a low-carbon and zero-emission alternative.

This chapter explores the attributes that make NH_3 a compelling choice for marine applications, the challenges that need to be overcome, and future prospects.

4.1. Definition and Production

Ammonia is a compound of nitrogen and hydrogen with the formula NH_3. It has about half the energy density of bunker fuels and takes on a liquid form at -33C, so it does not have to be stored in high-pressure or cryogenic tanks. Ammonia is difficult to burn, so specialised internal combustion engines are currently being developed, which are expected to come to market in 2024. Green and blue hydrogen are potential feedstocks to produce zero carbon ammonia that can be bunkered both onshore and offshore before being combusted by onboard engines.

When produced using renewable energy, ammonia becomes “green ammonia,” a zero-carbon fuel from production to use. This provides shipowners a fuel option that could have no well-to-wake CO2 emissions, which will assist in meeting International Maritime Organization’s (IMO) 2050 emissions reduction targets.

However, ammonia also presents challenges: it is toxic at low concentrations, presenting health and safety concerns for crew members. To use ammonia onboard, shipowners must ensure it is handled safely in compliance with applicable requirements.

Fuel properties of ammonia

Ammonia has a relatively low calorific value, and on top of that, characteristics like low cetane number and low flame speed make it difficult to apply in combustion engines. Ammonias fuel properties are are challenging when used in internal combustion engines (Table 1). Note, Table 1 is for comparison purposes only– not all values are obtained from experimental studies. (IEA-AMF, 2023)

Table 4-1: Comparison of fuel properties (IEA-AMF, 2023)

	Energy content (LHV) [MJ/Kg]	Energy content (LHV) [MJ/L]	Density [kg/m3]	Octane [RON]	Flame-velocity [m/s]	Flammability- limits [vol/%]	Minimum Ignition Energy [mJ]
Cooled Ammonia (Liquefied)	18.6	12.69 (1 atm, -33℃)	682	>130	0.067	15-28	680
Compressed Ammonia (Liquefied)	18.6	11.65 (300 bar ,25℃)	626.	>130	0.067	15-28	680
Cooled Hydrogen (Liquefied)	120	8.5 (1atm, -253℃)	70.85	>130	3.25	4.7-75	~0.016
Compressed Hydrogen (gaseous)	120	2.46 (300 bar, 25℃)	20.54	>130	3.25	4.7-75	~0.016
Diesel (n-dodecane)	44.11	32.89 (1 atm, 25℃)	745.7[12]	<20	~0.80	0.43-0.6	~0.23
Gasoline (iso-octane)	44.34	(n-octane) 30.93 (1 atm,25℃)	(n-octane) 697.6	100	0.41 ~0.58 (RON 90-98)	0.95-6 / 0.6-8 (RON 90-98)	1.35 ~0.14 (RON 90-98)
Methanol	19.90	15.65 (1 atm,25℃)	786.3	108.7	0.56	6.7-36	~0.14
Ethanol	26.84	21.07 (1 atm,25℃)	785.1	108.6	0.58	3.3-19	0.6

Ammonia can be a zero-carbon fuel from a well-to-wake perspective if it is produced from air and water using renewable energy. This is then known as "green ammonia." Brown ammonia is produced using fossil fuels and is therefore not a zero-carbon fuel from a well-to-wake perspective. (MAN, 2020)

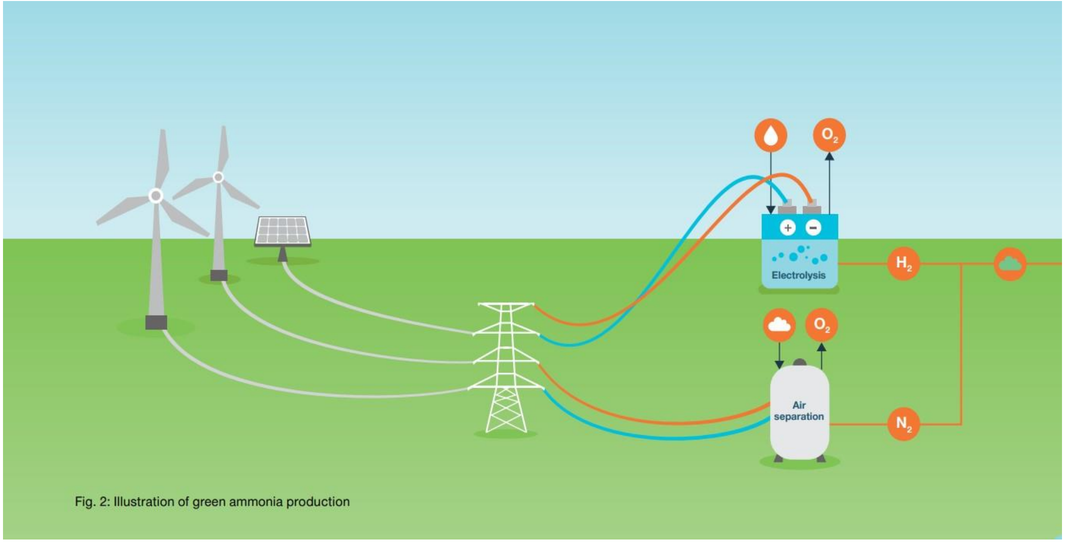

Figure 4-1: Green ammonia production.

Green ammonia is also known as e-ammonia. It is produced via the Haber-Bosch process, which converts green hydrogen and nitrogen into ammonia. Other methods for producing green ammonia – such as electrochemical nitrogen reduction – are under development, but will take time to mature and become industrialized. (MAN, 2020)

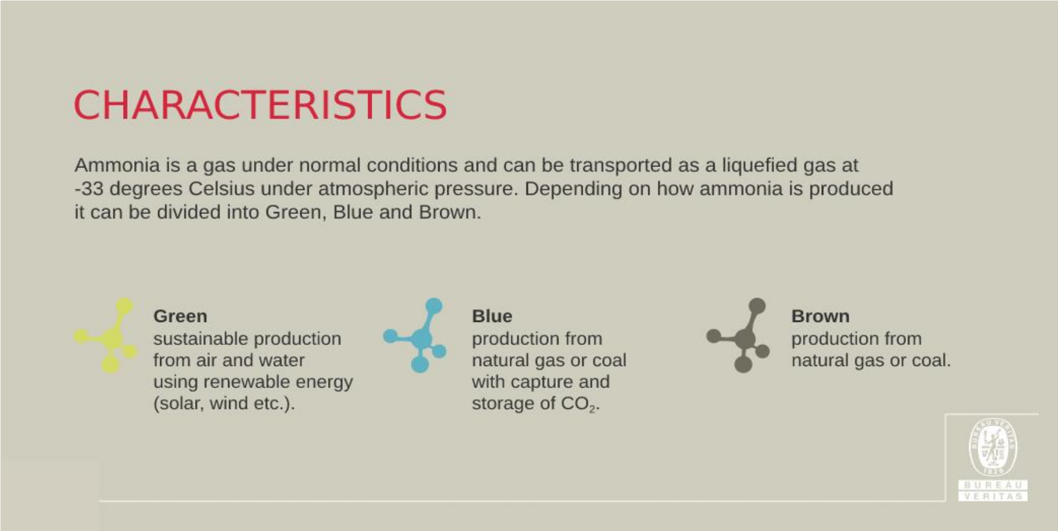

Figure 4-2: Types of ammonia fuel according to production process. (MAN, 2020)

Haber-Bosch process:

In 1909, Fritz Haber and Carl Bosch developed an artificial nitrogen fixation process (the so-called Haber–Bosch process) which enabled the large-scale production of ammonia and with that, the transformation of our society and lives through the first chemical global revolution. Since then, ammonia has been extensively used in the manufacture of fertilisers enabling the expansion of the population from two to over seven billion people during the last century. Its use in explosives has also been decisive in setting the current geo-political borders. The estimated global production of ammonia is approximately 150 million metric tonnes and is projected to increase by 2.3% per year.1 In addition to these established uses, ammonia is currently being explored as a portable long-term (days to months) energy storage vector, whose deployment would increase its future demand by at least an order of magnitude considering the global energy demands and current and projected production of renewable energy. The use of ammonia as energy storage would enable its second revolution as an attractive alternative to the short-term storage (seconds to hours) offered by electrochemical storage (i.e. batteries). (Smith, Hill and Torrente-Murciano, 2019)

Energy storage in the ammonia chemical bonds would enable a much greater uptake of intermittent renewable power sources such as solar, tidal and wind, helping to balance the seasonal energy demands in a carbon-free society.2–10 Energy can be delivered to the end-users by on-demand hydrogen production from ammonia (17.6 wt% hydrogen) in combination with fuel cells.11–14 Other molecules such as alcohol, formic acid and hydrides15 have been also suggested in this context, however, ammonia is the only carbon-free compound which fulfils the requirements of high energy density. (Smith, Hill and Torrente-Murciano, 2019)

Despite the exciting potential of ammonia to contribute to the second chemical revolution, its production through the Haber–Bosch process (>96% of ammonia is currently produced through this route) using fossil fuels as feedstock (natural gas, oil and coal) leads to a number of unanswered questions with regard to its sustainability. The Haber–Bosch process is currently one of the largest global energy consumers and greenhouse gas emitters, responsible for 1.2% of the global anthropogenic CO2 emissions, leading researchers to recommend alternative production methods.16 It is important to highlight though that the current Haber–Bosch process evolved in the context of fossil fuels as the only feasible energy source, which led to its false optimization to accommodate the inefficiencies in hydrogen production from fossil fuels (e.g. methane). Indeed, the process is not optimised to reduce carbon emissions beyond reducing the methane feed and fuel requirement. (Smith, Hill and Torrente-Murciano, 2019)

Therefore, it is a false minima. Through a collection of historic data, evaluation of the CO2 emissions, energy losses and exergy destruction, we critically explore the future role of the world's oldest chemical manufacturing process (Haber Bosch) in the new landscape of energy production away from fossil fuels (i.e. through renewable energy) and identify the technological challenges to make it a reality. We show that a new process optimization results in increased efficiencies and a substantial decrease in CO2 emissions. Indeed, we demonstrate that the traditional Haber–Bosch process, as defined by the ammonia synthesis loop only, can indeed enable the carbon-free ammonia production if: (i) it is decoupled from methane reforming, (ii) electric compressors replace condensing steam turbine compressors and (iii) alternative ammonia separation techniques are adopted to decrease the operating pressure. (Smith, Hill and Torrente-Murciano, 2019)

Further improvements to the process are also suggested to significantly decrease capital costs to establish small-scale production systems which aligns with the intermittency and geographic isolation of renewable energy generation. Indeed, the question of whether the Haber–Bosch process will enable carbon-free ammonia hinges on (i) enhanced water electrolysis efficiency and (ii) a simpler Haber–Bosch process that requires less capital and is more agile (i.e. faster response time). Success in one or both of these areas would lead to exciting opportunities in the deployment of ammonia in conjunction with renewable energy both to reinvent its 20th century role as a fertilizer and to pioneer its 21st century role as a hydrogen and energy storage vector. Such progress needs to be supplemented with further trends in the decreasing cost of renewable energy and the implementation of environmental policies to move away from fossil fuels. This current work focuses only on the technological aspects. (Smith, Hill and Torrente-Murciano, 2019)

Methane-fed and electrically-driven high pressure Haber Bosch processes:

Nowadays, conventional Haber Bosch plants produce ammonia using natural gas (50%), oil (31%) or coal (19%) as feedstock. The methane-fed processes represent the best available technique (BAT) given its higher energy efficiency and lower carbon emissions and thus it will be the benchmark used to compare alternative technologies. (Smith, Hill and Torrente-Murciano, 2019)

A simplified schematic of the methane-fed Haber–Bosch process is depicted in the following Figure (A). A modern ammonia manufacturing process is highly integrated but can be broken down into two main functional steps: the first is hydrogen production from methane and the second is ammonia synthesis by the Haber–Bosch reaction. Hydrogen is produced by primary and secondary steam methane reforming reactors (SMR), followed by a two-stage water–gas shift reactor, CO2 removal and methanation. The first SMR reactor operates in allothermal conditions at around 850–900 °C and 25–35 bar and the energy required for the endothermic reaction is provided by external combustion of methane fuel through furnace tubes that run through the catalyst bed. The second SMR reactor is autothermal, air is compressed and fed to the reactor to provide heat of reaction by partial oxidation of the reagents at 900–1000 °C. The addition of air also provides the stoichiometric nitrogen required for the downstream Haber–Bosch reaction. The SMR process exports steam to be used elsewhere, mostly for compression energy. The SMR outlet mixture of carbon monoxide, hydrogen, and unreacted steam and methane are introduced into the two-stage water–gas shift (WGS) reactor to maximize CO conversion to hydrogen. The WGS reaction is exothermic and heat must be removed to minimize CO concentration at equilibrium. Then, CO_2 is removed through the Benfield or Selexol process and finally a methanation reactor converts any remaining carbon monoxide back into methane to minimize the poisoning of the Haber–Bosch catalyst. Argon and methane present accumulate as inerts in the downstream synthesis loop. (Smith, Hill and Torrente-Murciano, 2019)

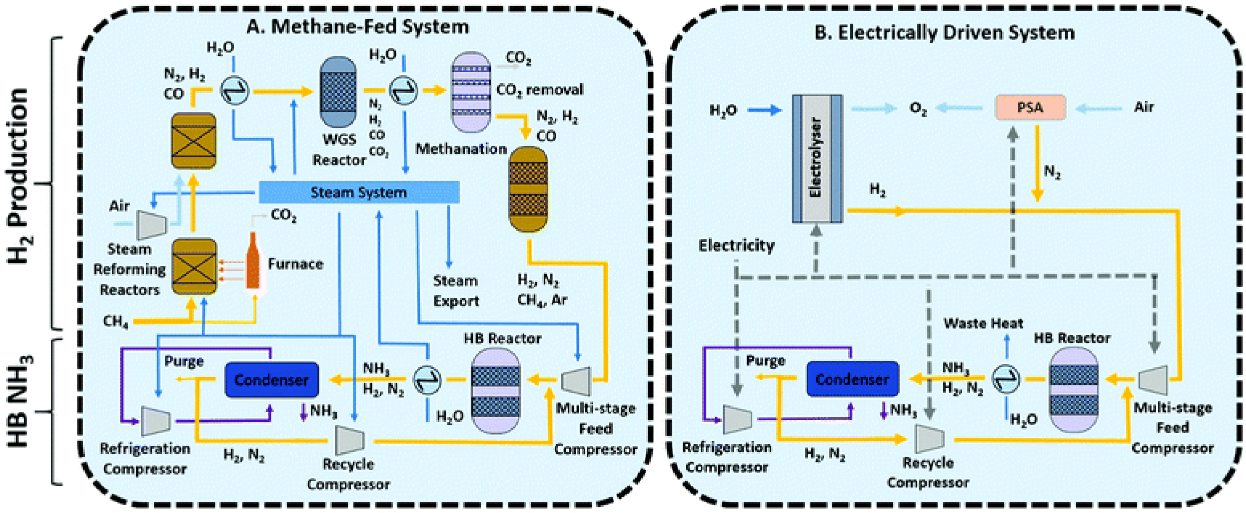

Figure 4-3: Schematic diagram of (A) a typical conventional methane-fed Haber Bosch process and (B) an electrically powered alternative. Hydrogen and ammonia production stages are separated for illustration purposes to identify similitudes and differences between both technologies. Yellow lines are process gas, dark blue lines are water/steam, light blue lines are air, purple lines are ammonia, and dashed lines are electricity. (Smith, Hill and Torrente-Murciano, 2019)

Although the steam methane reforming reactions are endothermic, the high reaction temperature and the need to cool substantially for the water gas shift reaction means that there is substantial waste heat available. This heat is used for raising of high-pressure steam which is expanded in steam turbines for compression, mainly used for compression of the feed in the Haber Bosch loop and the reformer combustion air compressor which are the largest two energy users. The use of methane as feedstock inevitably leads to significant CO_2 emissions from the process and this is further compounded by the use of methane as fuel for the primary reformer furnace. (Smith, Hill and Torrente-Murciano, 2019)

In comparison to the conventional ammonia process, the sustainable future of the Haber Bosch process (and the chemical industry in general) relies on the use of renewable energy as part of what is generally called electrification of the chemical industry. (Smith, Hill and Torrente-Murciano, 2019)

In this particular case, renewable energy has the potential to provide all the energy requirements, replacing methane as both feedstock and fuel. Hydrogen is produced by the electrolysis of water and is converted to ammonia using a Haber–Bosch reactor similar to the conventional process described above. Figure 3 (B) depicts a general process where N2 is delivered through pressure swing adsorption (PSA), suitable for small systems, serving as a starting point for process development. Alternatives such cryogenic distillation (suitable for large scale processes) and membrane separations (assuming that the desired N2 purity can be achieved) should also be considered in future developments. (Smith, Hill and Torrente-Murciano, 2019)

The ammonia production stage consists mainly of the Haber–Bosch (HB) reactor where hydrogen and nitrogen react at 15–25 MPa and 400–450 °C using an iron-based catalyst (either magnetite or wustite). Low equilibrium single-pass conversion (~15%) necessitates the use of a gas recycle. Prior to that, ammonia product is removed by condensation and the build-up of inerts (chiefly methane and argon) is purged and recycled to the SMR furnace. Although the system sometimes uses small electrical motors to drive small compressors and pumps, as mentioned before, large compressors associated to the SMR process air, the Haber–Bosch synthesis feed, the refrigeration cycle and the synthesis loop recycle are driven by steam turbines utilising waste heat from the SMR reactors. Both processes, (methane-fed and electrically driven) share the main concepts in the Haber Bosch synthesis loop, but there are important differences for material and energy integration that need to be considered separately in each case for their independent optimisation as demonstrated below. (Smith, Hill and Torrente-Murciano, 2019)

The concept of electrically driven ammonia synthesis is not a new idea, but it never gained widespread adoption over coal or methane fed processes because the vast majority of electricity was already derived from fossil fuels, with hydroelectric power being a notable exception. For example, Grundt & Christensen evaluated a 1970's design using hydroelectric power where hydrogen was obtained via alkaline electrolysis with a peak efficiency greater than 60% operating at 80 °C. Even though this approach was abandoned due to their lack of competitiveness with the advent of abundant and cheap natural gas, it has recently regained attention because of changes in the energy landscape as well as the environmental pressures to move away from fossil fuels. Recent studies have examined ammonia as an energy storage molecule and have ranged in focus from electrical energy transport in ammonia, to a comparison of hydrogen sources,20 to the implementation with actually renewable energy grid– including islanded grid systems. (Smith, Hill and Torrente-Murciano, 2019)

Can the Haber Bosch process enable a carbon-free ammonia production?

A modern, optimized and highly efficient methane-fed Haber Bosch process emits 1.5–1.6 tCO_2-eq tNH_3^{-1},24 making the global manufacturing of ammonia accounting for 1.2% of anthropogenic CO_2 emissions. (Smith, Hill and Torrente-Murciano, 2019)

This value would further increase if CO_2-equivalent emissions associated to the extraction and transport of natural gas are included. The vast bulk of direct CO_2 emissions from the methane-fed Haber Bosch process are a direct result of the use of methane as feedstock rather than its use as a fuel as depicted in the Sankey diagram in Fig. 2. This is commensurate with the lifecycle studies from Bicer et al.24 who demonstrated that switching the hydrogen production method from methane to hydropower-electrolysis reduces the CO_2 emissions from 1.5 to 0.38 tCO_2-eq tNH_3^{-1} (∼75% decrease). Indeed, an estimated 76% of the methane consumed in the process is associated with the production of hydrogen via the SMR reaction and yields a stoichiometric quantity of CO_2 of 1.22 tCO_2-eq tNH_3^{-1}. The remaining 24% of the methane is consumed as fuel to provide heat of reaction for the endothermic reforming reaction and to raise the necessary process steam, as shown in the following Figure. (Smith, Hill and Torrente-Murciano, 2019)

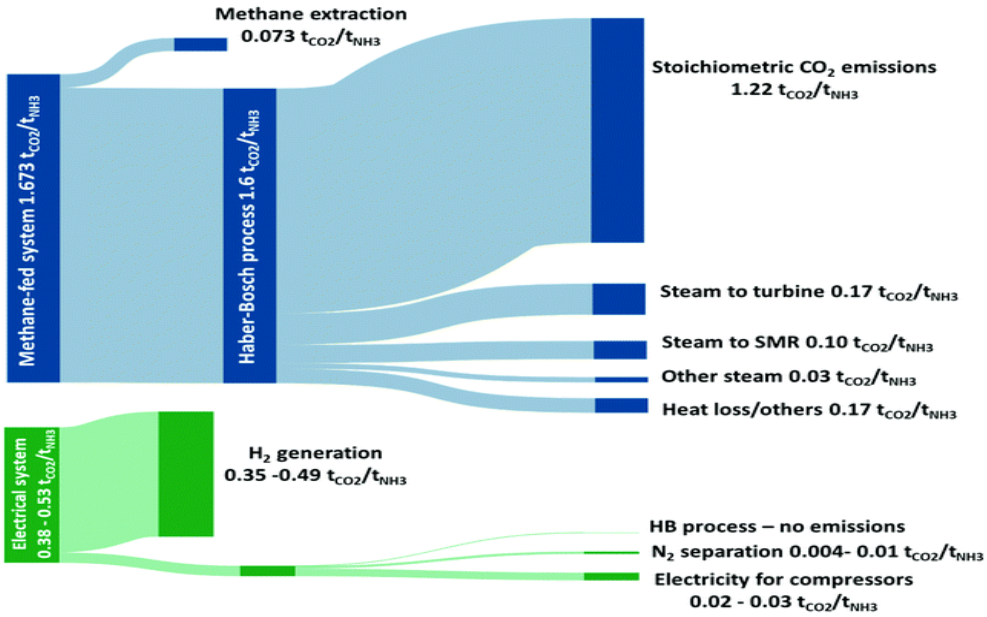

Figure 4-4: Sankey drawing comparing the attributions of direct CO2-eq emissions arising from the methane-fed and the electrically driven Haber–Bosch processes (range of values depend on size of wind turbines). The stoichiometric CO2 emissions are shown to highlight the minimum level of direct CO2 emissions that can be achieved by the methane-fed system without carbon capture. The additional CO2 emissions are allocated proportionally to the significant energy consumers. (Smith, Hill and Torrente-Murciano, 2019)

<u>Advantages of NH3 as a Marine Fuel:</u>

➢ **Environmental Benefits:**

- Low Carbon: NH3 produces no carbon dioxide (CO2) emissions during combustion, making it a promising option to address greenhouse gas emissions.
- Zero Sulfur: NH3 is a sulfur-free fuel, reducing emissions of sulfur oxides (SOx) that contribute to air pollution and acid rain.
- Ammonia Slip: NH3 combustion typically produces lower nitrogen oxides (NOx) emissions compared to traditional marine fuels, contributing to improved air quality. (BV, 2023)

➢ **Energy Density:**

- High Energy Content: NH3 has a high energy density, making it a potential alternative to conventional marine fuels and enabling longer voyages without significant fuel storage constraints.
- Existing Infrastructure: NH3 infrastructure for production, storage, and transportation already exists, facilitating its adoption as a marine fuel. (BV, 2023)

➢ **Cost and Availability:**

- Potential Cost Competitiveness: With increasing global demand and advancements in NH3 production technologies, the cost of NH3 as a marine fuel could become more competitive in the future.

- Diverse Feedstock Sources: NH3 can be produced from various sources, including renewable energy, natural gas, and biomass, providing flexibility and reducing dependence on a single feedstock. (BV, 2023)

Challenges and Considerations:

- **Safety:** NH3 is toxic and requires proper handling and storage measures to ensure the safety of crew members, ship systems, and the environment. Robust safety protocols and training are crucial.
- **Infrastructure:** Although NH3 infrastructure exists for industrial purposes, developing a dedicated marine infrastructure, including bunkering facilities and storage tanks, poses a significant challenge. Investment and collaboration among stakeholders are necessary.
- **Technological Advancements:** The maritime industry must develop NH3-compatible engines and retrofit existing vessels or design new ships with NH3 as the primary fuel. R&D efforts are required to optimize engine performance and ensure operational reliability.
- **Regulation and Standards:** Comprehensive regulations and standards need to be established to address safety, storage, bunkering, and emissions control for NH3 as a marine fuel. International cooperation is crucial for harmonized implementation. (BV, 2023)

4.2. Ammonia bunkering, safety and design

4.2.1. Ammonia bunkering and supply

Currently, the use of fuels is regulated by the International Maritime Organization (IMO) through the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL). From a technological and operational perspective, loading and unloading ammonia as a commodity at the terminal is similar to bunkering ammonia as a fuel. However, the option of bunkering ammonia from cargo terminals will not be a viable solution. In such a case, terminal accessibility for large cargo could be limited and will require a high amount of time. (Global Maritime Forum, 2022)

For handling ammonia, there is a high need to encourage a concept of universal seafarers and onshore workers that are capable of handling all kinds of engines and bunkering. In the longer term, marine bunkering infrastructure should consist of bunkering from bunker ships and bunkering from onshore storage. (Global Maritime Forum, 2022)

4.2.2. The implications of ship design and layout for safety

One of the primary drivers of vessel design is the need to figure out how to reduce the risk of exposure to crew in case of a leak. Mark Darley, Marine and Offshore Director, Lloyd's Register, explained that this is why design and layout must be treated with a high level of safety, from concept to material selection (protecting the structures from corrosive exposure of ammonia) and finally operational measures. Many relevant technologies and design concepts already exist in the market to handle ammonia. (Global Maritime Forum, 2022)

At the top of the agenda, special considerations should be made to risk assessment to prevent accidents. This would take into consideration the probability of leakage, gas detection systems, and certification along the supply chain. Also, new regulations and rules development are needed and could be extended and fortified from existing rules. (Global Maritime Forum, 2022)

Ammonia is highly toxic – more so than traditional fuels. At ambient temperature and pressure, it is a corrosive and flammable gas and there is a high risk for human exposure through inhalation and skin contact with long-lasting effects. It can have similar impacts on aquatic life. According to Sørensen of MAN, a general good practice would be that “onboard and onshore staff must have appropriate personal protection equipment. In addition, all the tanks must be in good condition, leaks prevented, and ensuring gas cannot be released to a confined place”. (Global Maritime Forum, 2022)

4.3. Government action and investments are needed to scale the use of ammonia

4.3.1. The role of collaboration

Governments have a role to play to overcome high costs and other stumbling blocks to take ammonia to a greater scale, and building trust within the industry necessitates public-private collaboration. Clear directions and guidelines are needed as a common framework for engine specifications, ship design, handling operations and infrastructure for bunkering, and sustainable production. This process could encourage realistic technical solutions as proof to convince others. The leadership of the IMO and collaboration among governments is needed to set global rules and standards. (Global Maritime Forum, 2022)

There is a need to move from conventional ammonia – made from fossil fuels – to scalable green or blue ammonia, synthesised from renewable hydrogen or fossil fuels and CCS, respectively. Therefore, involving the private sector in designing regulations and procedures will enable deeper engagement of the maritime sector and allow for feedback from the field. (Global Maritime Forum, 2022)

Statutory requirements:

According to IGC Code regulation 16.9.2, liquefied gas carriers carrying ammonia are not allowed to use ammonia as fuel due to its toxicity. The Flag Administration of the ship is to be consulted to consider the possibility of using ammonia as fuel and the approval process to be followed. (Global Maritime Forum, 2022)

For ships other than liquefied gas carriers intended to use ammonia as fuel, reference is made to the requirements of IGF Code, Part A, which requires an alternative design approach to be performed. The Flag Administration of the ship is to be consulted to define the approval process and the conditions in which the use of ammonia as fuel may be envisaged. In this respect, the Society considers that a ship design complying with the provisions of the present Rule Note and taking into account the outcome of the HAZID and HAZOP studies (see Sec 2, [2.3]) may be used as a basis for the engineering analysis required by SOLAS II-1 / reg. 55.3.

The equivalence of the alternative design is to be demonstrated to and approved by the Flag Administration. (Global Maritime Forum, 2022)

Note: *When a ship is intended to use ammonia as fuel, the concerned Port Administrations need to be contacted to define the conditions in which the ship may operate in the area under their jurisdiction, in particular when the ship is at berth and during bunkering operations. Specific assessment, including dispersal analysis, may be required in this respect. This assessment is to cover the whole bunkering system, including the bunkering source and is to allow the definition of the dangerous areas around the bunkering connections.*

4.3.2. The need for investment

For shipping's decarbonization to be in line with the Paris Agreement temperature goal, we must reach at least five percent zero-emission fuels in international shipping by 2030. A study conducted by The University Maritime Advisory Services (UMAS) and the Energy Transitions Commission (ETC) showed that if shipping is to be fully decarbonized by 2050, the scale of cumulative investment needed between 2030 and 2050 to achieve the IMO target is approximately USD 1-1.4 trillion. This study considered ammonia as being the primary and least-cost zero carbon fuel choice adopted by the shipping industry, and feedstock will be green and blue hydrogen. In this case, the major need for investments is upstream and land-based. Indeed, production, storage and bunkering represent 87% of investment while only 13% of investments are related to vessels – including machineries and onboard storage for new and retrofitted vessels. (Global Maritime Forum, 2022)

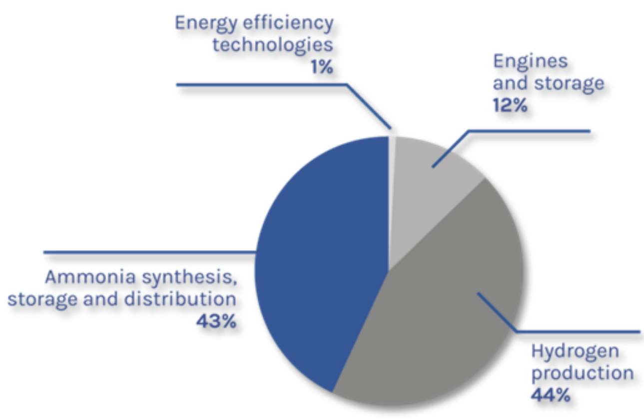

Figure 4-5: Investment breakdown across vessels and land-based infrastructure. (Global Maritime Forum, 2022)

Rob Stevens, Vice President Ammonia Energy and Shipping Fuel at Yara, has highlighted the need for first movers to get assistance through a cost differentiation between conventional and green ammonia to close the competitiveness gap in order for ammonia to become cheaper in the near-term. In addition to policy measures, the "**Getting to Zero Coalition**" has recently highlighted, market-based-measures (MBMs) to support the decarbonization of shipping by closing the competitiveness gap between fossil fuels and zero-emission fuels. Those MBMs aim at increasing the costs of using fossil fuels through setting a price on carbon, and/or reducing the costs of zero-emission alternatives, through tax breaks, RD&D funds, subsidies, or a combination of these. (Global Maritime Forum, 2022)

According to a recent **Getting to Zero** report, in order to achieve 50% GHG emissions reduction by 2050 compared to 2008 (-50% scenario), the carbon price level averages US$173/tonne CO2. For a 2050 target of full decarbonisation (-100% scenario), the average carbon price would only need to be slightly higher: around US$191/tonne CO2. In both scenarios, according to the model, the price level begins at US$11/tonne CO2 when introduced in 2025 and is ramped up to around US$100/tonne CO2 in the early 2030s at which point emissions start to decline. The carbon price then further increases to US$264 /tonne CO2 in the -50% scenario, and to US$360/tonne CO2 in the -100% scenario. (Global Maritime Forum, 2022)

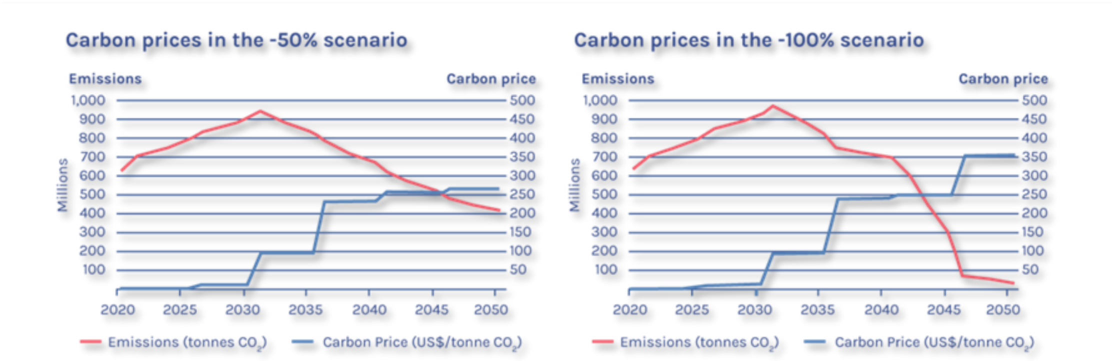

Figure 4-6: Carbon prices in the -50% scenario VS in the -100% scenario. (Global Maritime Forum, 2022)

4.4. Storage of Ammonia onboard Ships

Fuel storage solutions for ammonia already exist. Wärtsilä's LNGPac fuel gas supply and storage system can be readily adapted for ammonia by using stainless steel tanks as opposed to the nickel alloys more often used to house LNG. However, there remain some uncertainties about handling ammonia and the design requirements from classification societies. (Hellenic Shipping News, 2020)

Figure 4-7: Wärtsilä's LNGPac fuel gas supply and storage system. (Hellenic Shipping News, 2020)

One unknown is the impact of the increased weight of fuel storage. Combined with the low energy density and the lower allowed loading limit compared to current fuels, this has a significant impact on the operating range of ammonia-fuelled vessels. So, while it may be easy to prepare LNG-fuelled vessels for a switch to take ammonia fuel, preparing for the operational implications are more challenging. (Hellenic Shipping News, 2020)

The second element is that regulations have not yet specified the pressure and temperature at which ammonia needs to be stored on-board a vessel. Ammonia can either be pressurized or kept in cryogenic liquid form close to ambient pressure. According to Matthias Jansson, General Manager, Fuel Gas Supply Systems, Wärtsilä Marine Power, there are strong signals that cryogenic storage will be considered safer when analyzing the consequences of a potential leak. (Hellenic Shipping News, 2020)

“This would imply that some kind of refrigeration needs to be added to the processing system,” says Jansson. “That could be a challenge for smaller vessels or those that don’t already use LNG. But what that refrigeration would look like and what size it will have to be, we can’t tell yet.” (Hellenic Shipping News, 2020)

What is already clear is that ammonia readiness is not just about the steel tank; it also means looking at the process equipment and all the consequences around a leak of ammonia. (Hellenic Shipping News, 2020)

“LNG is ‘easy’ in that aspect,” adds Jansson. “All you need is a material that can withstand cryogenic temperatures, intrinsically safe electrical equipment and a place to ventilate out the evaporated gas. With ammonia, the toxicity adds a new dimension to handling of leaks – you cannot simply dump it into the water or ventilate it without looking at the toxicity risks.” (Hellenic Shipping News, 2020)

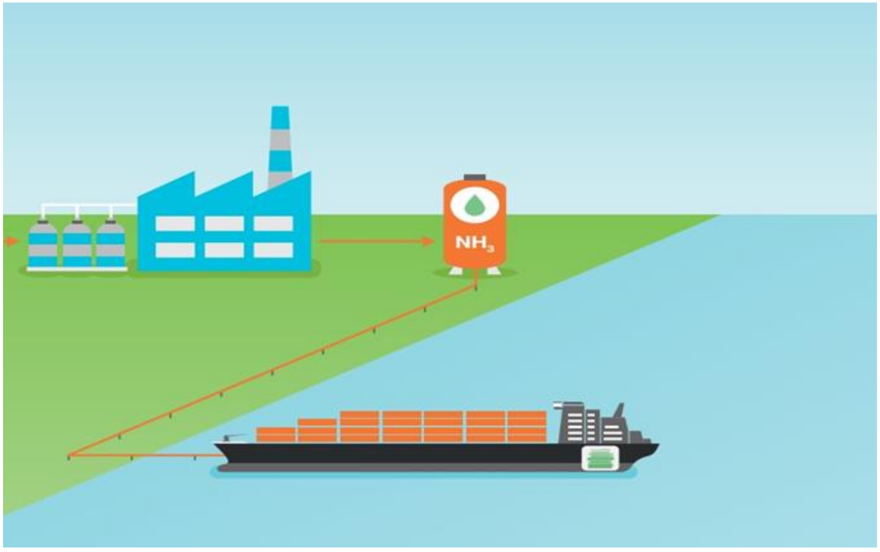

Figure 4-8: Ammonia bunkering. (MAN, 2020)

Finally, the transition to deploying ammonia as fuel will have a significant impact on fuel handling on board. For example, if ammonia is used first as a drop-in fuel alongside a dual-fuel LNG vessel configuration, there will need to be three different types of fuel tanks and fuel handling systems onboard for LNG, diesel and ammonia. Wärtsilä is investigating whether fuel mixing systems are feasible – potentially based on its existing technology for mixing LNG and volatile organic compounds as fuel. Whatever the solution will be, striking the balance between fuel flexibility and operational simplicity will be a critical consideration for shipowners. (Hellenic Shipping News, 2020)

Emissions abatement and regulation

An ammonia-ready vessel will also have to abate the increased NOx that is likely to come with the fuel. Wärtsilä will be exploring this aspect in particular as it embarks on its first full engine tests. Some form of aftertreatment is likely to be needed to bring NOx down to IMO’s Tier II or Tier III limits, and shipowners will need to account for this cost and space. (Hellenic Shipping News, 2020)

The cost of planning for ammonia-fuelled vessels should be reduced when the fuel is included in the IGF Code governing the low-flashpoint fuels, providing more clarity on regulatory requirements. At present the code only covers LNG and methanol. Several of the projects in which Wärtsilä is now participating will feed into the development of IGF Code regulations for ammonia. But to date there is no official timeframe for ammonia to be included. (Hellenic Shipping News, 2020)

Once ammonia is included, shipowners wishing to use the fuel will have more certainty on costs, says Matthias Jansson. “It can be done by following the alternative design approach of the IGF code, but you need to do a lot more on the safety analysis side and you are less sure of costs when you start the project, because you don’t know upfront what the flag state and class will require. It’s where LNG-fuelled vessels were more than a decade ago.” (Hellenic Shipping News, 2020)

4.5. Two-stroke, dual-fueled engine for ammonia

One of the characteristics describing the two-stroke engine portfolio of MAN ES is the fuel diversity. The development of the MAN B&W two-stroke engine has since the beginning been adapted to combust diverse fuel types. (MAN, 2020)

In 2019, the journey towards a two-stroke engine operating on ammonia began, as illustrated in Fig. 4. MAN started a pre-study of the fuel supply and injection concept and conducted several hazard identification, and hazard and operability studies (hazid/hazop) together with classification societies, shipowners, yards and system suppliers. (MAN, 2020)

Presently, we are working on verifying the development concept of the injection system and the engine design in general. We will finalize the development process of the ammonia engine in 2021 and the commercial design verification is scheduled for 2023. When the engine design is released, the first engine can be prepared for test bed. The ammonia development project reaches a major milestone when the first ammonia engine is installed in a vessel during the first six months of 2024. (MAN, 2020)

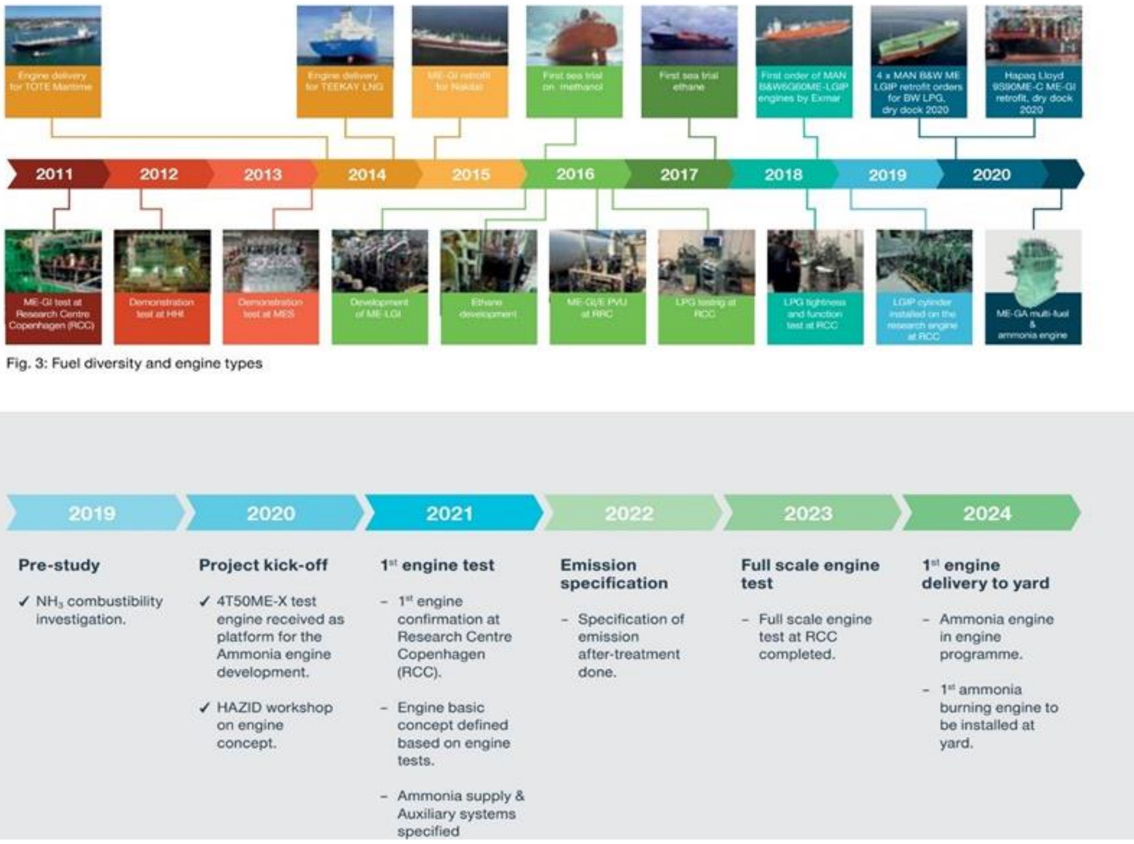

Figure 4-9: Fuel diversity and engine types. (MAN, 2023))

4.5.1. Engine foundation

When designing an engine governed by altered combustion physics due to the chemical composition of a new fuel, it requires thorough research of the influence on all conceivable engine design parameters to provide an efficient and safe engine and fuel supply system to the customers. (MAN, 2020)

Currently, MAN ES carries out research in the Research Centre Copenhagen (RCC) and in different partnerships to assess combustion and heat release characteristics of ammonia. The findings of the research will guide the development of the specific fuel injection properties and clarify the nature of two-stroke emissions, when operating on ammonia. (MAN, 2020)

Ammonia is a toxic substance, and proper safety measures must be in place to safeguard the ship's crew and the surrounding environment. In addition to catering for these requirements, MAN ES brings technology to the market that is engineered to adapt to the skills and work routines of the engineering crew and the resources onboard. This is achieved without fundamentally changing the ship operation. An advantage of the ammonia-fueled low-speed two-stroke engine is that it will not fundamentally change merchant shipbuilding or operation, and thus a simple and well-engineered solution is in place to cater for the requirements of this novel fuel. (MAN, 2020)

The findings will also govern the FSS configuration. Although the first tests of the engine will be concluded in 2021, and the FSS design must be adapted to the outcome, we assume that the configuration for ammonia will inherit main features from the well-known LGP supply system for liquid injection. (MAN, 2020)

The ultimate design of the FSS requires final confirmation, but we have started the development to have a supply system ready for the engine. The fuel supply system for the ME-LGIP engine being the starting point. As for the engine, development of an FSS calls for a safe and reliable design based on the outcome of hazid and hazop investigations. Currently, we have performed three hazid investigations observed by representatives from the classification societies, shipowners, yards and suppliers of components for the FSS. (MAN, 2020)

In principle, the main differences between the fuel characteristics governing the ME-LGIP and the ammonia engine designs are related to heating values, the foul odor, and the corrosive nature of ammonia:

– lower calorific values (LCV) of the fuels

– 46.4 MJ/kg for propane (LPG)

– 18.6 MJ/kg for ammonia

– ammonia is corrosive to copper, copper alloys, alloys with a nickel concentration larger than 6%, and plastic. (MAN, 2020)

The ideal solution is to reuse part of the dual-fuel LPG injection system on the ammonia engine and part of the LPG fuel supply system from tank to engine. Again, an affirmative engine test in 2021 is required, but in the following, the design has been based on the fuel supply system for the ME-LGIP engine. (MAN, 2020)

4.5.2. Fuel supply system and Principles of dual-fuel operation

The below figure and the following sections highlight the main principles of the fuel supply system for the ammonia engine and dual-fuel operation. (MAN, 2020)

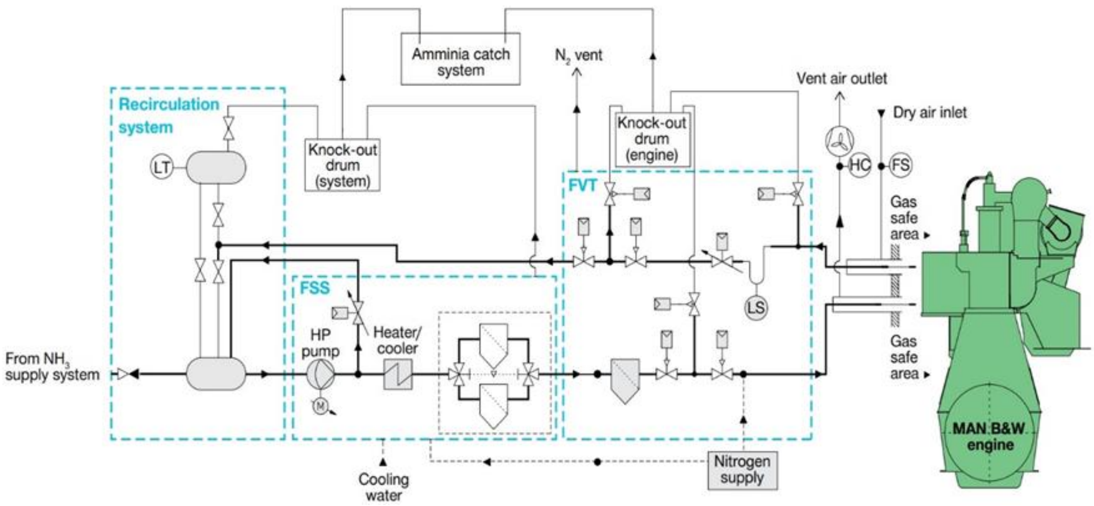

Figure 4-10: Ammonia fuel supply system. (MAN, 2020)

During dual-fuel operation, the ammonia fuel supply to the engine comes from the storage tanks via the fuel supply system. To maintain the required fuel conditions at the engine, a small portion of the ammonia fuel continuously recirculates to the FSS via the recirculation system. (MAN, 2020)

When the engine is not in dual-fuel mode, the double block-and-bleed arrangements of the FVT depressurise and completely isolate the ammonia fuel systems inside the engine room from the ammonia fuel supply and return systems. Before every start, the systems are pressurised with nitrogen to verify the tightness of the system. (MAN, 2020)

When dual-fuel operation stops, the nitrogen pressure pushes back the ammonia fuel from the engine to the recirculation system. When the purging sequence is complete, the FVT will once again ensure the isolation of engine room systems from the supply and return systems. (MAN, 2020)

Throughout the entire operation, the double-walled ventilation system from existing MAN ES dual-fuel engines detects any ammonia fuel leakage and directs it away from the engine room to a separate ammonia trapping system. (MAN, 2020)

Recirculation system: The recirculated ammonia fuel will heat up in the engine during operation. To avoid two-phase conditions, a certain amount of the ammonia fuel is recirculated to a dedicated recirculation line. The same recirculation line recovers the ammonia fuel from the engine whenever dual-fuel operation is stopped. The recirculated fuel may contain traces of sealing oil from the injection valves. The recirculation line eliminates the risk of contaminating fuel storage tanks with oil. The recirculation line also separates and bleeds off nitrogen from the recovered ammonia fuel. (MAN, 2020)

Fuel supply system: The FSS contains the equipment necessary to ensure that ammonia fuel is delivered to the engine at the required temperature, pressure and quality. In most cases, the FSS has a high-pressure pump, a heater, filters, valves and control systems to maintain the ammonia fuel pressure and temperature at varying engine consumptions. (MAN, 2020)

Fuel valve train: The fuel valve train (FVT) is the interface between the engine and the auxiliary systems. The purpose of the FVT is to ensure a safe isolation of the engine during shutdown and maintenance, and to provide a nitrogen-purging functionality. This functionality ensures a safe environment on the engine after shutdown. (MAN, 2020)

Nitrogen system: Nitrogen must be available for purging the engine after dual-fuel operation, for gas freeing prior to maintenance and for tightness testing after maintenance. The capacity of the nitrogen system must be large enough to deliver a certain flow at a pressure higher than the service tank pressure. (MAN, 2020)

Double-walled ventilation system: To maintain a safe engine room, it is vital to detect any leakages from the ammonia fuel system and direct these to a safe location. This has led to the double-walled design of ammonia fuel systems and piping inside the engine room. A constant flow of ventilation air is kept in the outer pipe in accordance with IMO requirements. The system is already part of other MAN B&W dual-fuel engine designs. (MAN, 2020)

Ammonia capture system: The ammonia systems must be designed with an ammonia capture system to prevent release of ammonia to the surroundings. (MAN, 2020)

CHAPTER 5

Hydrogen

Introduction

Hydrogen has been used for decades in a variety of different industrial processes. Oil refining relies on hydrogen to remove sulphur from fuels, it is used as a reducing and oxidising reagent in metallurgical processes, and it is a vital part of the production of two of the other future fuels – ammonia and methanol.

However, there is the issue that almost all the Hydrogen used today is so-called “Grey Hydrogen” and is produced using Fossil Fuels, typically Natural Gas, in a process known as steam reforming. Moving along the colour spectrum we have black or brown Hydrogen, produced using Coal. Blue Hydrogen is Hydrogen that has been produced in a process where the Carbon generated during steam reforming is captured and stored, while green Hydrogen production uses clean renewable energy to split water into Hydrogen and Oxygen in a process known as electrolysis.

5.1. Definition and Production

In recent years Hydrogen has emerged as a potential future-fuel candidate to support the decarbonization of the transport sector, while vehicle manufacturers investigating the possibility of using it to power their vehicles. (Wartsila, 2022)

Global hydrogen production was around 70 million tons in 2018. Currently, almost all hydrogen is produced at or very close to where it is needed, and directed to industrial processes, so it is not transported by ships in the same way as LNG. (Wartsila, 2022)

However, in February 2022 the world's first liquefied Hydrogen cargo transported between Australia and Japan aboard the Suiso Frontier, which is a significant step forward. Unlike an LNG carrier, this vessel doesn't use its cargo as fuel. (Wartsila, 2022)

From a regulatory perspective, the biggest challenge is that there simply are no rules concerning the use of Hydrogen as a fuel for shipping. The IGF Code provides high-level requirements for using low-flashpoint fuels like Hydrogen in maritime applications but to date it has mostly been applied for projects involving LNG. There is work ongoing at the IMO to add hydrogen to the code but it is still at the very early stages, with draft proposals expected later this or next year at the earliest." (Wartsila, 2022)

As it stands today new Hydrogen applications have to follow the Alternative Design approval process, which is a risk-based process for designs that cannot be approved with current regulations. There are several pilot projects in the pipeline that will provide benchmarks, but it's still very early days. (Wartsila, 2022)

5.1.1. Fuel properties of Hydrogen

If Hydrogen is burned in the air, heat is generated due to the chemical conversion with the oxygen from the air. It is therefore considered a fuel – and, because of its suitability for use in engines, also a fuel. Due to this type of combustion – unlike that by which engines generate energy – is based only on an electrochemical reaction, it is also known as "cold combustion." Fuel cell technology takes advantage of this principle: In the Hydrogen fuel cell or direct methanol fuel cell, hydrogen reacts with atmospheric oxygen to form water again. Water, electricity and heat are generated simultaneously. The big advantage is that no harmful byproducts are produced when hydrogen reacts with atmospheric oxygen in the fuel cell. (SFC Energy, 2023)

The heating value of hydrogen, but also its calorific value, are used to quantify its energy content. In most cases, the calorific value is somewhat higher than the heating value. The calorific value of a fuel indicates how much energy (i.e. heat) can be obtained during its combustion. (SFC Energy, 2023)

Unlike the heating value of hydrogen, the calorific value assumes that the water vapor contained in the combustion gases condenses completely, i.e. is liquefied. (SFC Energy, 2023)

In the case of the heating value of hydrogen, on the other hand, it is assumed that the water vapor does not condense despite the cooling of the combustion gases to 25 degrees Celsius, but leaves the plant in gaseous form. The difference is that the heating value of hydrogen does not include the heat of condensation and is therefore generally lower than the calorific value. In other words, the heating value of hydrogen quantifies how much energy becomes usable as heat by simply burning hydrogen. (SFC Energy, 2023)

The calorific value of hydrogen, on the other hand, describes how much energy is recovered in the form of heat if energy is also extracted from the combustion exhaust gases. The heating value of hydrogen is used when the reaction product, water, is gaseous. If it is liquid, we are talking about the calorific value. For example, most internal combustion engines emit the resulting water in gaseous form, which is why no condensation heat can be obtained. (SFC Energy, 2023)

Table 5-1: Comparison with other Marine Fuels (IEA-AMF, 2023)

	UNIT	HYDROGEN	MGO	HEAVY FUEL OIL (HFO)	METHANE (LNG)	ETHANE	PROPANE	BUTANE	DIMETHYL-ETHER (DME)	METHANOL	ETHANOL	AMMONIA
Boiling Point	° C	-253	180-360	180-360	-161	-89	-43	-1	-25	65	78	-33
Density	kg/m³	70.8	900	991	430	570	500	600	670	790	790	696
Lower Heating Value	MJ/kg	120.2	42.7	40.2	48	47.8	46.3	45.7	28.7	19.9	26.8	22.5
Auto Ignition Temp	° C	585	250	250	537	515	470	365	350	450	420	630
Flashpoint	° C	-	> 60	> 60	-188	-135	-104	-60	-41	11	16	132
Energy Density Liquid (H_2 Gas at 700 bar)	MJ/L	8.51 (4.8)	38.4	39.8	20.6	27.2	23.2	27.4	19.2	15.7	21.2	15.7
Compared Volume to MGO (H_2 Gas at 700 bar)		4.51 (7.98)	1.00	0.96	1.86	1.41	1.66	1.40	2.00	2.45	1.81	2.45

5.1.2. Properties of Hydrogen Compared to Other Marine Fuels

Hydrogen is characterized by having the highest energy content per mass of all chemical fuels at 120.2 MJ/kg, as shown in above Table compared to other marine fuels. In terms of mass energy, it exceeds MGO by 2.8 times, and alcohols by five to six times. Therefore, hydrogen fuel can increase the effective efficiency of an engine and help reduce specific fuel consumption. (Maritime Cyprus, 2021)

However, on a volumetric basis, due to its lower volumetric energy density, liquid hydrogen may require four times more space than MGO or about two times more space than liquefied natural gas (LNG) for an equivalent amount of carried energy. Also, important to consider when comparing fuel energy and required volumes are the energy efficiencies of the consumer, or electrical energy losses in fuel cells. True for all marine fuels, additional volumes of fuel may be required to account for efficiency losses between the tank to the output shaft power. Hydrogen requires low temperatures below -253° C (-423.4° F) to liquefy. Due to this very low temperature, the required volume to store liquid hydrogen could be even higher when considering the necessary layers of materials or vacuum insulation for cryogenic storage and other structural arrangements. (Maritime Cyprus, 2021)

5.1.3. Hydrogen Production

Emissions from the production of hydrogen compose the majority of the WtW pollutants. There are four types of Hydrogen in terms of the emissions released during production:

- **Brown Hydrogen**, produced from the processing of coal.
- **Grey Hydrogen**, produced from the processing of other fossil fuels or natural gas.
- **Blue Hydrogen**, produced from the processing of fossil fuels accompanied with emission control technologies, including carbon capture, utilization and storage (CCUS) methods.
- **Green hydrogen**, produced from renewable energy sources, typically via electrolysis using water. Sources of electricity can include solar or wind power to provide net-zero carbon hydrogen production. (DNV, 2021)

Grey hydrogen produced from natural gas is the primary hydrogen production method, as shown in the following Figure, accounting for 75 percent of global hydrogen production. Brown hydrogen is the second largest source of hydrogen production, primarily in China. Green Hydrogen production contributes only two percent of global hydrogen supply, while blue Hydrogen production is not yet widespread. (DNV, 2021)

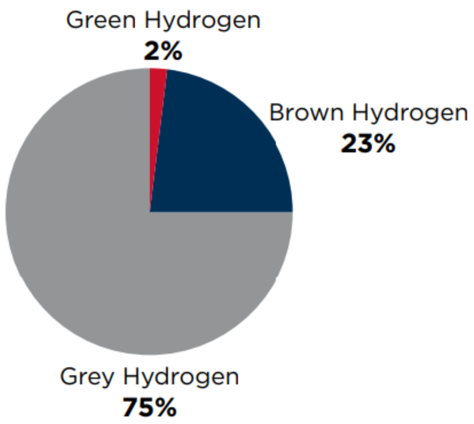

Figure 5-1: Production Sources of Hydrogen (ABS, 2021)

Carbon capture, utilization and storage (CCUS) involves the collection, transportation, reuse and storage of CO2 emissions that are separated from other combustion or processing substances originating from fossil-based fuels. In general, hydrogen production is a high energy consumption process. Currently, the energy used worldwide to produce hydrogen is about 275 Mtoe (million tons of oil equivalent), which corresponds to two percent of the world's energy demand. (ABS, 2021)

Most of the demand is driven by fossil fuel refineries and the production of ammonia for fertilizer. Grey hydrogen production is very carbon intensive, ranging between 71 kg CO2 /MJ H2 for natural gas to 166 kg CO2 /MJ H2 for coal, but these emissions can be reduced or eliminated by implementing CCUS technology. (ABS, 2021)

The below figure shows the WTT amount of CO2 generated for one megajoule of contained energy. The graph shows the variation of possible emissions from several types of hydrogen production, as high as 325 kg CO2 /MJ H2 and as low as zero for renewable energy or nuclear generation. These values are compared to the typical estimated CO2 generated during WTT production of marine gas oil (MGO), 14.2 kg CO2 /MJ MGO. (ABS, 2021)

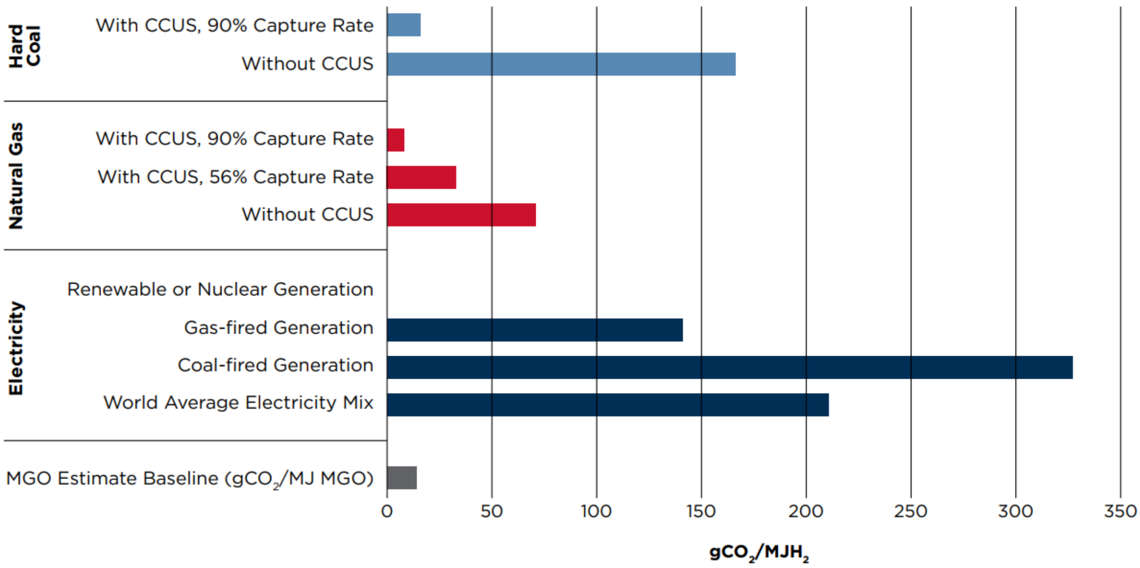

Figure 5-2: Carbon Release from Hydrogen Production With and Without Using CCUS Compared to Marine Gas Oil (MGO) as Baseline (ABS, 2021).

Alternatively, electricity can be used to electrolyze water. Electrolysers work essentially as reversed fuel cells, by taking in water and electricity, and producing hydrogen and oxygen gas. Renewable energy sources such as wind, solar or nuclear electricity generation can be used to produce green hydrogen from this process. (ABS, 2021)

In this case, Hydrogen can be considered an electro-fuel with zero-carbon impact from production. Other Hydrogen production processes include high temperature water splitting, photobiological water splitting and photoelectrochemical water splitting, but these methods are not yet employed in large-scale Hydrogen production. It may be useful to note when considering alternatives to electrolysis hydrogen production that the high purification required to meet the grade 4.5 purity standard (i.e., 99.995 percent pure) for proton exchange membrane (PEM) fuel cells may add to the costs of production. Conversely, mono-fuel and dual-fuel combustion engines do not require this level of purification, and indeed can handle diluents (e.g., methane, carbon dioxide or carbon monoxide) that would otherwise cause significant degradation to a PEM fuel cell. (ABS, 2021)

However, this purity standard may not be a problem in other fuel cells, such as solid-oxide fuel cells (SOFC), although these may have tradeoffs related to emissions, lower operating efficiencies and high temperatures. When hydrogen production and consumption are zero-emission processes, the only life cycle emissions are produced from the processes of storing and transporting the fuel during distribution, and any required conversion process between carriers. (ABS, 2021)

5.2. Pros and cons of Hydrogen as a Marine Fuel

Compared to diesel operation the assumption is that CO2 tailpipe emissions are far lower or even non-existent when using hydrogen as a fuel; if we're talking about green hydrogen the well-to-wake emissions are expected to be dramatically lower as well. On the downside, using Hydrogen directly as a fuel as opposed to using it as a raw material to manufacture other renewable fuels requires a lot of space onboard." (Wartsila, 2022)

Even as a liquid, Hydrogen storage takes up significant space compared to marine gas oil. To get the same equivalent energy content requires a tank volume that is almost eight times more than that of marine gas oil. Land-based storage for liquid and compressed hydrogen already exists so there is technology that can eventually be adapted for use in maritime applications. Hydrogen is also very light compared to diesel, so if you are limited by weight rather than space onboard then it could make sense. (Wartsila, 2022)

Furthermore, Hydrogen has one of the highest energy density values per unit of mass at around 120 megajoules per kilogram, which is three times higher than diesel. Or to put it another way, about 300 kg of hydrogen provides the same energy as about a tonne of diesel. (Wartsila, 2022)

Hydrogen could be stored onboard either as Liquid Hydrogen, which gives you the biggest storage capacity in the smallest possible space, or possibly as Compressed Hydrogen in 200 or 700 bar pressurised tanks. Liquid storage, however, brings its own set of challenges due to the extremely low temperatures. (Wartsila, 2022)

To keep Hydrogen in liquid form it needs to be stored below -253 C, which is highly energy intensive and places huge demands on the storage and supply system in terms of insulation requirements. The extreme cold can lead to oxygen from the air condensing on the pipework, resulting in a risk of explosion. There will be boil-off to deal with as well, which means you will need an energy-intensive reliquefaction solution. Leakages are another important consideration because of the highly explosive nature of hydrogen. In principle it is possible to use a similar setup as with LNG but with a greater focus on insulation and preventing leakages." (Wartsila, 2022)

5.3. Hydrogen bunkering, safety, and design

5.3.1. Hydrogen bunkering and supply

The bunkering operation supplies fuel to a ship for cargo transfer or use by the onboard machinery. Currently in the industry, liquid Hydrogen is expected to be bunkered similarly to LNG, and gaseous hydrogen may be bunkered with frequent loading/unloading between ships and terminals. (ABS, 2021)

Hydrogen refueling or bunkering infrastructure must be approved by the related authorities, including regional authorities, governments, fuel suppliers and possible road transport regulations, and must accommodate ship-specific fuel arrangements. Bunkering arrangements may also depend on simultaneous operations such as cargo loading/unloading or other dockside activity. (ABS, 2021)

The bunkering facilities for liquid Hydrogen are expected to have higher capital costs than LNG bunkering facilities. This is due to the increased cryogenic storage requirements for liquid hydrogen and the advanced components needed for pipes, seals, and tanks, such as bayonet joints for cryogenic liquid hydrogen. (ABS, 2021)

Consideration should be given to Hydrogen bunkering infrastructure regarding hydrogen permeation, embrittlement, material compatibility, lowtemperature use and hydrogen attack. For compressed gaseous hydrogen bunkering operations, it may be assumed that a dispensing concept similar to the land-based truck or a bus dispensing could be applied in marine application design facilities. During transfer from one tank to another, the operation needs to be done in a way that keeps the hydrogen at the correct temperatures and volume. This can be done through a 'cold inbound' or 'warm inbound,' which will change the re-refrigeration process of the fuel. (ABS, 2021)

Alternatively, and depending on the Hydrogen volume required for the designed fuel range, many installed hydrogen tanks can be modular or fitted externally and may require simple cylinder replacement procedures to refuel the vessel. In this case, procedures should be in place and followed to verify the proper and safe handling, connection and disconnection of hydrogen cylinders into the ship's fuel systems. On-site port availability of Hydrogen may be a critical decision factor due to the higher cost of dedicated hydrogen pipelines or distribution supply chains. While infrastructure investment to increase the scale of hydrogen availability may appear large, when considering the total shipping costs (i.e., fuel costs) of a 15- to 20-year-old vessel, infrastructure modifications could be a relatively small fraction. (ABS, 2021)

5.3.2. The implications of ship design and layout for safety

Future vessels may require integrated designs based on the operational profile, the selected fuel arrangement, power generation and propulsion systems chosen. Power generation systems such as hydrogen integrated with fuel cell and battery storage systems can change the architecture of current engine room design. For example, fuel cell installations may be large, but they may not require as much accessible maintenance space as typical marine engines do, therefore having the potential to use the volume within the engine room more efficiently. (ABS, 2021)

However, the weight of large fuel cell installations should be considered. Fuel cells and electrical hybrid systems may achieve more efficient use of space on vessels since they allow the distribution of electrical equipment throughout the vessel. As Hydrogen has low energy content per volume it will require larger tanks for equivalent energy storage and their location on board will be a critical design factor. Many small applications of hydrogen tanks are installed on decks or tops of superstructures to take advantage of natural ventilation in case of small leaks. (ABS, 2021)

Other, larger applications may consider storing Hydrogen in tanks as independent or integrated structures. The energy content of stored hydrogen varies by its density (i.e., pressure and temperature), but in all cases more hydrogen by volume is required to meet equivalent volumetric energy densities of other marine fuels. The additional space for fuel may require larger vessel sizes, decreased cargo space and/or more frequent bunkering of the vessel. In addition, for hydrogen fueled ships, storage systems may need redesign regarding the hydrogen fuel containment system, gas valve unit and equipment for managing tank temperature and pressure. Liquid Hydrogen cargo management systems may also require systems for boil off gas handling, reliquefication, gas valve unit/train, vent piping systems and exhaust masts. Appropriately rated electric equipment should be installed in hazardous zones or ventilation pathways which may be susceptible to gas ingress to limit potential ignition from sparks. Hydrogen detectors should also be located appropriately to identify potential flammable mixtures of gas. Appropriate fire, heat or smoke detectors with alarm systems are also recommended to identify fires early. (ABS, 2021)

5.4. International Regulations and Standards

Although Hydrogen has yet to be widely adopted as a fuel into the maritime industry with a few pilot projects, it has already been implemented in land-based uses. There are no international marine requirements mandated by the IMO; however, some of the information, rules and regulations from land-based resources are referenced in MSC.420(97). These include safety measures, methods of transportation and standard hydrogen production procedures. (ABS, 2021)

Various referenced codes and regulations exist for hydrogen component standards and equipment design, fire codes and other hydrogen-specific safety codes, and general safety codes or standards that include hydrogen. The International Organization for Standardization (ISO) Technical Report ISO/TR 15916 Basic Considerations for the Safety of Hydrogen Systems focuses on providing technical information that form the basis of understanding hydrogen safety issues. The report addresses the recent interest in using hydrogen as a fuel and aims to address the unique hydrogen-related safety properties and phenomena and best engineering practices to minimize risks and hazards from hydrogen. (ABS, 2021)

Further international standards that may be referenced by designers considering marine projects are listed here: • IEC 60079. The International Electrotechnical Commission Standard for Explosive Atmospheres include hazardous areas and standards for gas detection applicable to hydrogen. – 60079 – Part 10.1 Classification of areas – Explosive gas atmospheres – 60079 – Part 29.2 Gas Detectors – Selection, installation, use and maintenance of detectors for flammable gases and oxygen • IEC 61892. The International Electrotechnical Commission Standard for Mobile and Fixed Offshore Units includes ventilation provisions for battery-generated hydrogen. – 61982 – Part 7 Electrical Installations – Hazardous Areas • ISO 11114. The International Organization for Standardization Gas Cylinders Standard includes advisories about compatible materials and test methods for selecting hydrogen embrittlement resistant steels. (ABS, 2021)

5.4.1. National Standards

Fire codes for hydrogen have existed in the industry for many years. The National Fire Protection Association (NFPA) code NFPA 2 Hydrogen Technologies Code specifies equipment and system recommendations to address aspects of hydrogen storage, use and handling, including liquefied and gaseous hydrogen for power generation, road, rail and marine applications. Other national hydrogen standards are listed below for equipment, piping, ventilation and hazardous area guidelines, and may be referenced by any designers considering marine projects:

- ANSI/AIAA G-095A-2017: Guide to Safety of Hydrogen and Hydrogen Systems. This American National Standards Institute and the American Institute of Aeronautics and Astronautics code provides general safety guidance for controls, usage, personnel training, hazard management, facilities, detection, storage, transportation, and emergency procedures, originally developed by the National Aeronautics and Space Administration (NASA) for applications in spacecraft.
- ASME B31-12 Hydrogen Piping and Pipelines. The American Society of Mechanical Engineers Code applies to the design, construction, operation and maintenance

requirements for gaseous or liquid hydrogen piping and gaseous hydrogen pipelines. This standard is also referenced within marine guides for piping on board ships.

- NFPA 55 Compressed Gases and Cryogenic Fluids Code. This code formed the basis of NFPA 2 Hydrogen Technology Code.
- CGA G-5.4 Standard for Hydrogen Piping Systems at User Locations. This Compressed Gas Association standard describes the recommended piping systems for gaseous and liquid hydrogen.
- CGA G-5.5 Hydrogen Vent Systems. This standard describes guidelines for the design and safe operation of gaseous and liquid hydrogen vent systems. (ABS, 2021)

5.4.2. ABS Rules on Hydrogen

Existing ABS Rules for fuel cells include the Guide for Fuel Cell Power Systems for Marine and Offshore Applications, published in November 2019 with references to the Marine Vessel Rules (MVR) Part 5C, Chapter 13 for vessels using gases or other low-flashpoint fuels. The Fuel Cell Power Systems Guide considers the IMO's draft Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations and will be updated upon finalization of the interim guidelines. (ABS, 2021)

The Fuel Cell Guide mainly focuses on fuel cell design requirements, but also includes provisions for hydrogen as fuel, including the fuel containment system, material and general piping systems, fire safety, electrical systems, and control, monitoring and safety systems. Parts of this guide specific to hydrogen storage and supply systems may also be applicable to internal combustion engines using hydrogen. (ABS, 2021)

The guide references standards for handling hydrogen, including the ASME B31-12 for piping and the ISO 11114-4 for hydrogen embrittlement testing. Certain systems, equipment or components may be required to be certified under ABS's Type Approval program to a certain Tier level to confirm their safe construction, appropriate testing and installation. (ABS, 2021)

5.5. Storage of Hydrogen onboard ships

Significant technical advances may be needed for hydrogen to be considered a viable, large-scale, commercial fuel option, particularly for applications with large volumes of Hydrogen fuel that may require increased space on board, especially for long routes and deep-sea voyages. Hydrogen stored as cargo can be kept in its densest cryogenic liquid form to increase trade volume and storage onboard. However, larger fuel volumes and storage arrangements for gaseous and liquid hydrogen onboard may require a trade-off between some cargo space, depending on the hydrogen density, vessel operations, onboard power systems and route. Hydrogen fueled vessels traveling close to or operating near bunkering facilities, with the opportunity to bunker often, may experience minimal problems with fuel reduction or cargo space loss. (ABS, 2021)

For liquefied Hydrogen at low pressures, the energy loss during storage and boil off gas generation may be a challenge for long-term storage applications, depending on the pressure rating of the cryogenic tank and the length of time left dormant. The boil off rate is around one to five percent per day for standard land-based liquid hydrogen storage tanks. Improved insulation and slightly higher storage costs can reduce liquid hydrogen boil off down to 0.02 percent volume per day. To avoid losses, the boil off gas from liquefied gas tanks can be consumed in an engine or fuel cell. Tanks of pressurized gaseous hydrogen do not experience boil off gas issues. (ABS, 2021)

5.6. Hydrogen Fuel supply

The purpose of the fuel supply system (FSS) is to deliver fuel at the correct temperature and pressure to the consumer. The use of low-flashpoint fuels and gases further complicates the fuel supply and consumer systems and creates a greater interdependence between the key systems than conventional fuel systems. (ABS, 2021)

The FSS can be one of the more complex and expensive systems required for gas-fueled applications. It may also not be integrated with the original equipment manufacturer (OEM) fuel consumer but is designed to comply with the OEM’s specifications. Managing hydrogen injection pressure, speeds, concentration, and temperature in combustion engines is essential for proper ignition timing and efficiency. (ABS, 2021)

Many fuel cell installations are accompanied by battery energy storage systems (BESS), and associated power management controls that can shave peak loads from fuel cells, or supply required power at low loads, allowing the fuel cell to operate at optimum performance and fuel consumption rates and protect against transient power loads. (ABS, 2021)

5.7. Engine characteristics for burning Hydrogen

Hydrogen as a fuel has been demonstrated in internal combustion engines, gas turbines and fuel cells. When consumed in a fuel cell, electric energy, water and heat are generated in a fuel-efficient process. Marinized fuel cells are available with a wide range of available power, especially when connected in series to increase output for any size marine power requirement. (ABS, 2021)

For large vessel power requirements, multiple fuel cells may be required to scale up the delivered power. In addition, to manage low or high energy demand, BESSs are typically installed to allow fuel cells to operate at optimum loads. Scaled-up installations of fuel cells and associated hybrid or battery systems may not yet be cost-competitive with alternative power generation options as capital expenses (CAPEX) can be high. Operational expenses (OPEX) may benefit from lower maintenance costs of fuel cells but suffer from high fuel costs in the near term. For this reason, it is important that the prime movers, including both fuel cells and combustion engines, be as fuel efficient as possible and therefore maximize the use of fuel stored onboard and the extent of OPEX. Training and appropriate expertise of fuel cell and hybrid systems should also be provided to crews and operators who may not be familiar with this relatively new technology, vessel arrangement and operational practices. (ABS, 2021)

Hydrogen for combustion engines has typically been implemented as a supplementary/mixed fuel blend in conventional gas and dual fuel (DF) engines. Hydrogen has many properties that contribute to its use as a combustible fuel. The low ignition energy is important in combustion as the amount of energy needed to ignite hydrogen is about one order of magnitude less than that required of MGO. Hydrogen's high autoignition temperature plays a key role in defining the compression ratio of the engine, and affects the maximum power output (i.e., mean effective pressure) that can be delivered. Wartsila and MAN engines state that hydrogen combustion is possible in some engine types as a DF with natural gas or other gas fuels. Several studies of hydrogen combustion in engines show that even small percentages of hydrogen in the blended gas fuel can improve engine efficiency and lower carbon emissions. When used as a mono-fuel, hydrogen engines require modification to optimize the combustion timing and reduce engine knock. Typically, mono-fuel hydrogen engines require larger cylinder and engine size. However, large aftertreatment systems to manage NOx and particulate matter (PM) may not be required depending on the air-fuel ratio and engine emissions performance. (ABS, 2021)

In addition to mono-fuel hydrogen combustion, hydrogen can also be combusted with gas or other conventional fuels such as diesel. In DF applications, hydrogen is injected into the cylinders, compressed, and a small quantity of pilot diesel fuel is added to initiate combustion. Such a combustion system is used in Behydro© H2 /diesel DF engines with up to 85 percent hydrogen fuel content. The percent volume of hydrogen in the blend is directly related to the load profile and size of the engine, where higher loads can be fueled by higher hydrogen percentages. H2 -diesel co-combustion can combine fuel flexibility and efficiency with environmental performance. There are several possible means of hydrogen combustion within internal combustion engines with various benefits and challenges, as shown in below figure. (ABS, 2021)

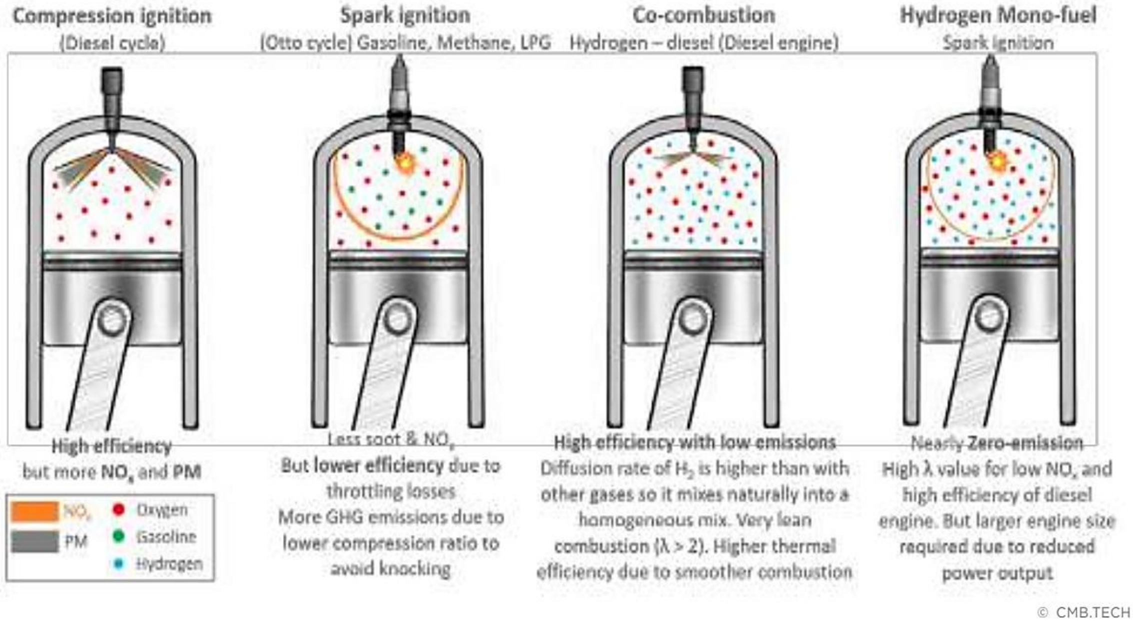

Figure 5-3: Possible Internal Combustion Systems Involving Hydrogen. (ABS, 2021)

With a wide range of flammability, Hydrogen engines can run on air to fuel ratios ranging from 34:1 to 180:1. Both mono-fuel and dual-fuel Hydrogen engines may operate on a lean-burn combustion cycle and reduce NOx emissions. However, depending on the air/fuel ratios achieved there is the possibility that NOx reduction technologies may be required, such as selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) technologies. Figure 9 shows the H2 /Diesel co-combustion process. (ABS, 2021)

CHAPTER 6

Forecast to 2050

Introduction

In the ever-evolving world of shipping, the quest for cleaner and more sustainable propulsion systems has reached a critical juncture. The traditional reliance on fossil fuels, primarily heavy oils, has become increasingly untenable due to the industry's significant contributions to global carbon emissions and the need to meet stringent environmental regulations. As a result, alternative fuels have emerged as a beacon of hope, promising a path toward reducing the maritime sector's environmental footprint and ensuring its long-term viability.

In this concluding chapter, we will delve into the multilayered realm of alternative fuels in shipping, summarizing the key insights and discoveries we have gathered throughout this comprehensive exploration. We will examine the diverse array of alternative fuels that have gained prominence, including LNG, Hydrogen, and Ammonia. These fuels have offered innovative solutions to address the sector's twin challenges: reducing emissions and complying with increasingly stringent regulations.

Moreover, we will consider the practical aspects of implementing these alternative fuels in the maritime industry, touching upon issues such as infrastructure development and safety considerations. As the transition to cleaner fuels represents a profound transformation for the sector, these practicalities become crucial in shaping the future of shipping.

In conclusion, the maritime industry's journey towards embracing alternative fuels is not just a technological shift; it represents a paradigm shift—a shift towards a more sustainable, environmentally responsible, and economically viable future for the sector. However, this transition is not without its challenges, and its ultimate success will depend on collaboration among governments, industry stakeholders, and innovative technological solutions. As we embark on this transformative journey, the promise of a cleaner, greener, and more efficient shipping industry beckons on the horizon, offering hope for a brighter and more sustainable maritime future.

6.1. Status of Fuel Technology Transition

A review of the world fleet status and current order book with respect to the implementation of alternative fuel technology indicates an accelerated uptake compared with last year. LNG is still the most prominent alternative fuel technology choice and can also be used in dual-fuel solutions with fuel oil. Furthermore, there has been an increase in the number of ships capable of using methanol as fuel in dual-fuel solutions. The gross tonnage of LNG-fueled ships on order (excluding LNG carriers) is more than twice that of such vessels in the existing fleet. The order book for ships capable of using methanol as fuel is 20 times larger than the gross tonnage of methanol-fueled ships currently in operation.

This indicates that the trend of ordering larger ships with alternative fuel propulsion is continuing, but at a greater pace. **LNG** is a popular fuel choice in the car carrier and containership segments, with 133 and 196 ships on order, respectively. Additionally, there has been a notable increase in the use of LNG for tankers (83) and bulk carriers (39). Out of the 1,376 ships currently on order with alternative fuels, 306 are LNG-fueled LNG carriers, 523 are other types of LNG-fueled ships, and 295 are using battery/hybrid propulsion.

Methanol has previously been a choice exclusively for tankers in the **methanol** trade, with 23 ships in operation and 14 new tankers on order. This year, the containership segment is dominating with 142 ships on order able to use methanol as fuel.

Presently, 72 LPG carriers using **LPG** as fuel are sailing, while 93 LPG carriers and 4 ethane carriers have been ordered with LPG-burning capability.

The following figures present the status of the alternative fuel uptake in the world fleet and the order book (as of July 2023). Measured in gross tonnage, 6.5% of ships in operation and 51% on order can operate on alternative fuels (including LNG carriers), compared with last year's numbers of 5.5% and 33%, respectively. By number of ships, this year's figures are 1.8% and 26%, with 1,376 out of 5,258 ships ordered with alternative fuel capability.

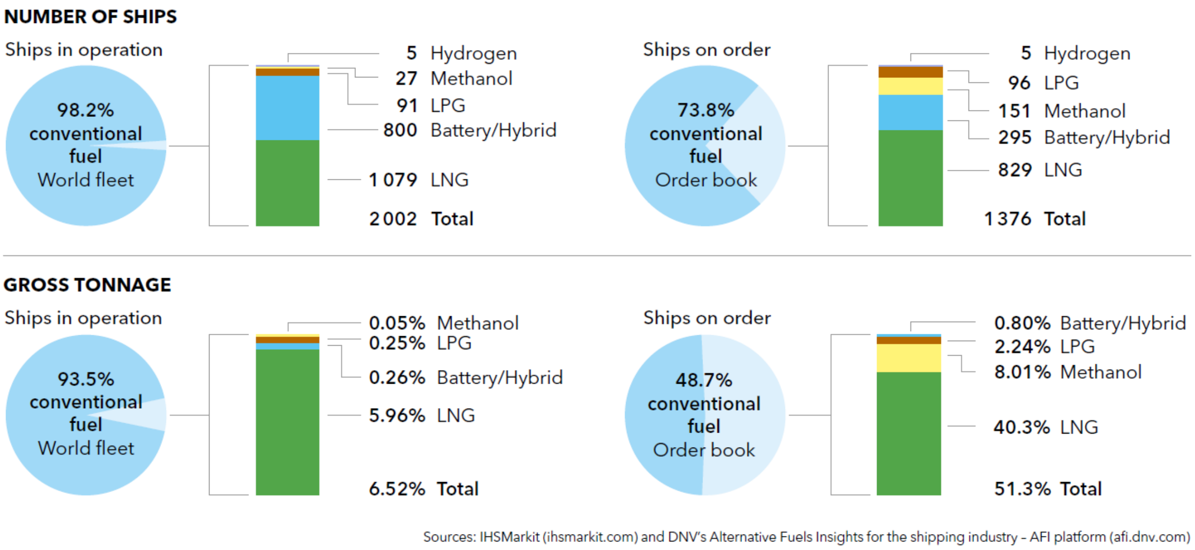

Figure 6-1: Alternative fuel uptake in the world fleet in number of ships (upper) and gross tonnage (lower), as of July 2023 (DNV)

Figure 6-2:Development of LNG, LPG and methanol fuel technology uptake by number of ships, excluding gas carriers. (DNV)

Measured by number of ships, the uptake is dominated by battery/hybrid and LNG-fueled ships. However, in gross tonnage terms, LNG fuel dominates, reflecting that battery/hybrid solutions are applied mostly on smaller vessels. Of the 1,079 ships in operation using LNG fuel, 659 are LNG carriers and 420 are ships of other types. The statistics also show a growing uptake of methanol and LPG, as well as the first hydrogen-fueled newbuilds. (IRENA, 2021)

Although there are ongoing demonstration projects for ammonia-fueled ships, there are none in the official order book. Using ammonia as a ship fuel requires the continued development of suitable energy converter technology, which is still a few years into the future. Furthermore, the lack of prescriptive rules and regulations for handling ammonia is making it difficult to plan for its implementation on board. This lack of regulatory development is also causing issues for the adoption of hydrogen as a fuel. These implementation barriers come in addition to the challenges currently applicable to most carbon-neutral fuels: **increased capital investment, limited fuel availability, lack of global bunkering infrastructure, additional training of crew, high cost of fuel,** and **additional demand for storage space on board**. The uptake of vessels capable of operating with ammonia as fuel is expected to pick up once the technology becomes available, supported by the fact that ships have been ordered as ‘ammonia ready’, implying that some preparation for potential conversion to ammonia propulsion has been done at the newbuild stage. (IRENA, 2021)

It should be noted that most of the ships which can use alternative fuels can also operate on fuel oils in dual-fuel solutions. Also, the alternative fuel may be derived from fossil energy sources, which emphasizes the need for requirements that address greenhouse gas emissions from well-to-wake. (IRENA, 2021)

6.2. Current Fuel Production and Demand

The availability of carbon-neutral fuels is one main concern for the shipping industry striving towards decarbonization. Demand for carbon-neutral fuels for all sectors will increase as local, regional, and global regulations are tightened and cargo owners require low- to zero-emission services to fulfil their own decarbonization targets. The current fuel market for shipping is about 280 Mtoe per year, mainly fossil fuel, and towards 2030 the energy industry is ramping up production of carbon-neutral fuel alternatives. However, as shipping will compete with aviation and road transportation, and with other industries, production of carbon-neutral fuel alternatives needs to accelerate if the emission-reduction goals are to be met. (IRENA, 2021)

6.2.1. Existing fuel-supply chain

To estimate today's fuel consumption, we use published IMO and International Energy Agency (IEA) data, as well as finally considering activity-based studies using automatic identification system (AIS) data. We estimate that shipping today consumes about 280 Mtoe of fuel annually. (IRENA, 2021)

For 2021, the reported fuel oil consumption for ships of 5,000 gross tonnage (GT) or more in international trade was 209 Mtoe according to (IMO, 2022). Almost all (99.9%) the fuel that was reported was either heavy fuel oil (HFO), light fuel oil (LFO), marine gas oil (MGO) or liquefied natural gas (LNG). Beyond the fuel consumption reported by the IMO (2022) for ships above 5,000 GT (see following Figure), there is an additional amount consumed by ships of less than 5,000 GT. (IRENA, 2021)

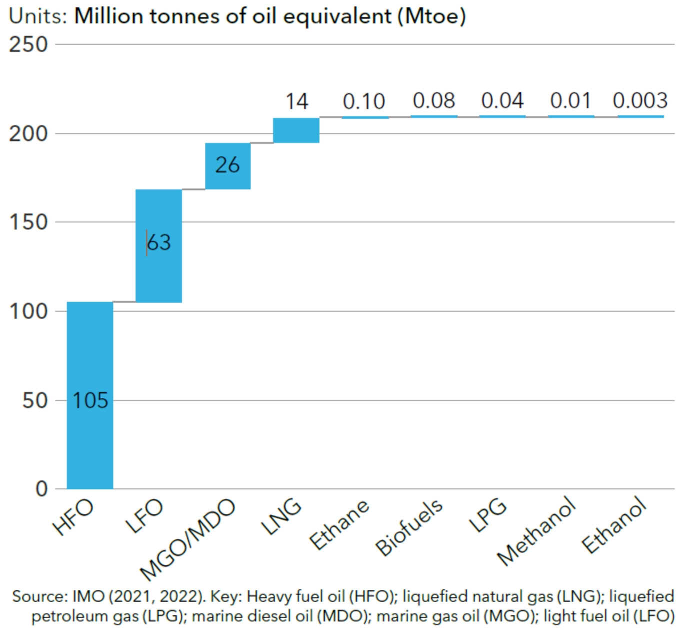

Figure 6-3: Fuel consumption for ships >5,000 GT based on reported DCS data to IMO (2021) (IMO, 2022)

The total bunker volume sold to ships in international trade was 213 Mtoe in 2019, according to sales figures from IEA. In addition to ships in international trade, there is also fuel consumption by the domestic and fishing fleet, reported by IEA as a further 57 Mtoe in 2019 (IEA, 2019). LNG consumption rise from 12.0 Mtoe in 2019 to 14.5 Mtoe in 2021 (IMO, 2022), and LNG comprises about 7% of the total fuel consumption in 2021 for ships above 5,000 GT. (IRENA, 2021)

However, more than 95% of the LNG consumption is boil-off from the cargo on gas carriers and therefore not bunkered as fuel.

Among carbon-neutral fuels, biofuel is the most widely used in shipping today and often used as a blend-in with fossil fuels. Biofuels can be blended in with a variety of different marine fuels, such as MGO, marine diesel oil (MDO), high sulfur fuel oil (HSFO), Very Low Sulphur Fuel Oil (VLSFO), and so on. The typical blending ratio of biofuel is currently in the range 20% to 30% but is also available as 100% biofuel. The bio-blended fuels represent an available decarbonization option, as it is possible to use the infrastructure in the same way as for conventional marine bunkering fuel today. Additionally, biofuels already have an established infrastructure due to their use in multiple sectors (IRENA, 2021). For example, Port of Rotterdam sold more than 500,000 tons of bio-blended fuels in 2022 and Port of Singapore reported a sale of 140,000 tons bio-blended fuel, distributed over 90 bunkering operations. Overall, the sales of bio-blended fuels increased by more than 70% between 2021 and 2022. (IRENA, 2021)

6.2.2. Demand for carbon-neutral fuels in shipping

Demand for carbon-neutral fuels in shipping will be driven by GHG regulations and policies such as carbon pricing, expectations of cargo owners and consumers, and access to investors and capital. The demand for carbon-neutral fuels is therefore strongly dependent on global, regional, and national regulations. (IRENA, 2021)

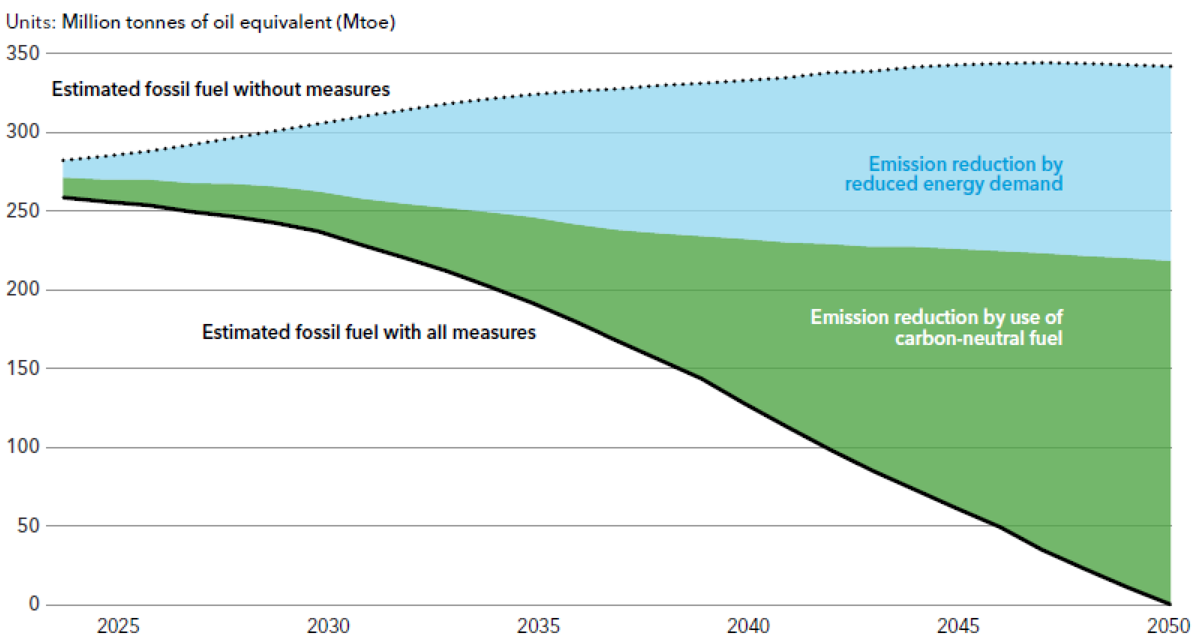

Figure 6-4: Simulated results for future demand of carbon-neutral fuels in shipping (IRENA, 2021)

To meet defined regulatory requirements, shipping companies will seek the most economically favorable GHG emission-reduction measure at any given time. It is therefore assumed that a combination of speed reduction and energy-efficiency initiatives will ensure individual vessel compliance in the short term. The Figure above depicts an estimation for the demand for carbon-neutral fuels towards mid-century in a Decarbonization by 2050 scenario, according to results from the 2022 edition of Maritime Forecast to 2050. The estimated demand for carbon-neutral fuels takes into account an expected increase in shipping activity, as well as the fleet-wide impact of speed reduction and implementation of energy-efficiency measures. This simulated scenario requires about 17 Mtoe of carbon-neutral fuels for shipping in 2030. (IRENA, 2021)

6.2.3. Supply of carbon-neutral fuels

When the shipping industry is looking ahead to 2030, two central queries arise: How much of the different carbon-neutral fuels will be produced, and how much will be available for shipping. Today the supply of carbon-neutral fuels is very limited for all industries, including shipping. (IRENA, 2021)

In addition, the industry is characterised by its high dependency on fossil fuels. As much as 99% of the energy demand from this end-use industry is met by fossil fuels, with Fuel Oil and MGO comprising as much as 95% of total demand. Consequently, international shipping is responsible for around 3% of annual global GHG emissions on a CO2-equivalent basis. Indeed, if the international shipping industry was a country, it would be the sixth- to seventh-largest CO2 emitter, comparable to Germany's current CO2 emission levels. IMO warns that if no actions are taken, carbon emissions linked to international shipping will grow substantially. (IRENA, 2021)

In the long term, complex drivers influence the final activity levels and thus the energy demand of international shipping. Economic development will continue to foster global trade as well as local shipping activity. In parallel, the electrification of end-use sectors anticipates a trade boost of materials to support the enhancement of T&D infrastructure. On the other hand, as the world embarks on total decarbonisation, activity and energy demand for tankers and some dry bulk carriers are likely to decline. Circular economy principles and consumers favouring locally produced goods may also result in a decline in energy demand. (IRENA, 2021)

Since 2011, various EE mandates have been introduced to the shipping industry. However, historical trends show that during low oil price periods, the shipping sector pays less attention its energy usage. However, during high oil prices periods, the shipping industry tends to adapt and perform more efficiently, without the need for external market regulations. This behaviour speaks to the need to tighten EE mandates and develop suitable mechanisms for monitoring and enforcing compliance with EE mandates. (IRENA, 2021)

Considering the average age of the existing vessel fleet and the technical lifetime of large and very large vessels *i.e.* 25-30 years, there is an urgent need to enable an environment focused on fostering investment in carbon-zero vessels and renewable fuels, particularly green H2. Renewable powerfuels appear to be the most promising renewable fuels, particularly e-ammonia. As the cost of renewable energy continues to fall and electrolysers and H2 storage costs fall progressively, renewable ammonia is set to become the backbone for decarbonising international shipping in the medium and long term. The ammonia engine expected to be ready in 2023 will be a key milestone in unlocking the use of renewable ammonia in the years to come. (IRENA, 2021)

Overall, in the context of international shipping, limiting global warming by 1.5°C can be achieved by four CO2 reduction measures. The i) indirect electrification by employing powerfuels and the ii) employment of advanced biofuels will contribute to reducing around 60% and 3% of CO2 emissions, respectively, while iii) improvements in vessels' EE performance and iv) the reduced sectoral demand due to systemic changes in global trade dynamics will contribute to reducing CO2 emissions by 20% and 17%, respectively. (IRENA, 2021)

Climate goals and decarbonisation ambition can be raised, but moving from nearly zero CO_2 to zero emissions requires a 100% renewable energy mix by 2050. For this purpose, adopting appropriate and timely co-ordinated international policy measures is needed. Stakeholders associated with the shipping industry must be fully mapped out and engaged, working to establish strategic partnerships with a common goal. Furthermore, taking early action is critical; applying realistic carbon levies will not only foster the deployment of renewable fuels but also prevent investment in fossil fuel infrastructure that risks becoming stranded. In parallel, it will be critical to invest in the production of powerfuels in geographical areas with high renewable energy potential and devote significant efforts to understanding the production costs of powerfuels in the short and long term.

The estimation being presented on the picture below is based on a comprehensive mapping of ongoing projects and initiatives for carbon-neutral versions of fuel oil, methane, methanol, ammonia, and hydrogen. These fuel types can be used as carbon-neutral fuels for ships but can also be used as fuel by other sectors or for other industrial purposes. For example, the hydrogen derivate ammonia can be used for fertilizer production and methanol in the chemical industry. The number of projects for production of carbon-neutral fuels is high: more than 2,200 relevant projects are mapped and populated into our database, as per following Figure. However, most of these projects have not yet started construction or even reached an investment decision.

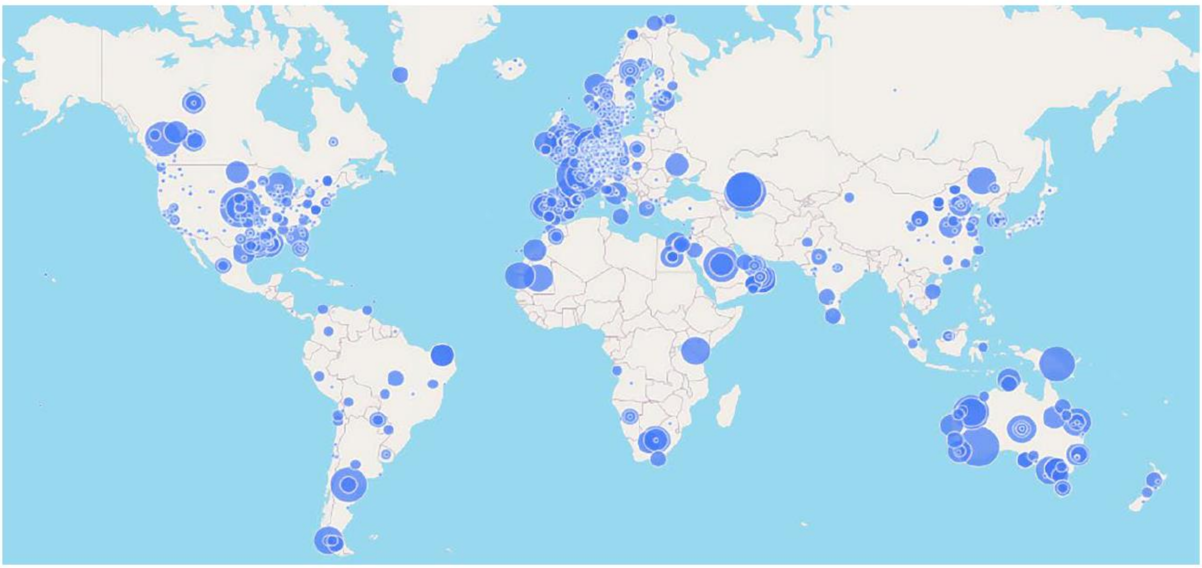

Figure 6-5: Map of planned and existing projects in the database for products that can be used as carbon-neutral fuels by ships, by capacity (size of bubble) and location (IRENA, 2021)

It is expected that the lead time for new production facilities for carbon-neutral fuels is long, depending on the type of fuel and the size of the plant. As an example, in (Wappler, et al., 2022) the lead time is estimated to be 6 to 10 years for green hydrogen projects over 1 GW. It is therefore expected that only a few projects that are not already announced will be operational before 2030. Even if the database is comprehensive, it cannot be regarded as complete, as some projects are not disclosed to the public for various reasons. (IRENA, 2021)

A central question for the shipping industry is what the future fuel market will look like. What fuels will be made available for shipping and at what price. Fuel producers need to consider which fuel type(s) to make, and for which markets. This is decided by factors such as access to energy feedstocks and other inputs, such as sustainable CO_2 and the availability of storage and distribution infrastructure. Another key aspect is which markets will demand carbon-neutral fuels, and their willingness to pay. The price elasticity – in other words, the change in demand because of a change in price – can be expected to vary between shipping, aviation, power production and other sectors as well as between each shipping segment. The fuel suppliers also need to relate to production standards and other policy incentives and requirements which can be general or sector specific, impacting the cost, GHG intensity, and quality requirements of production. (IRENA, 2021)

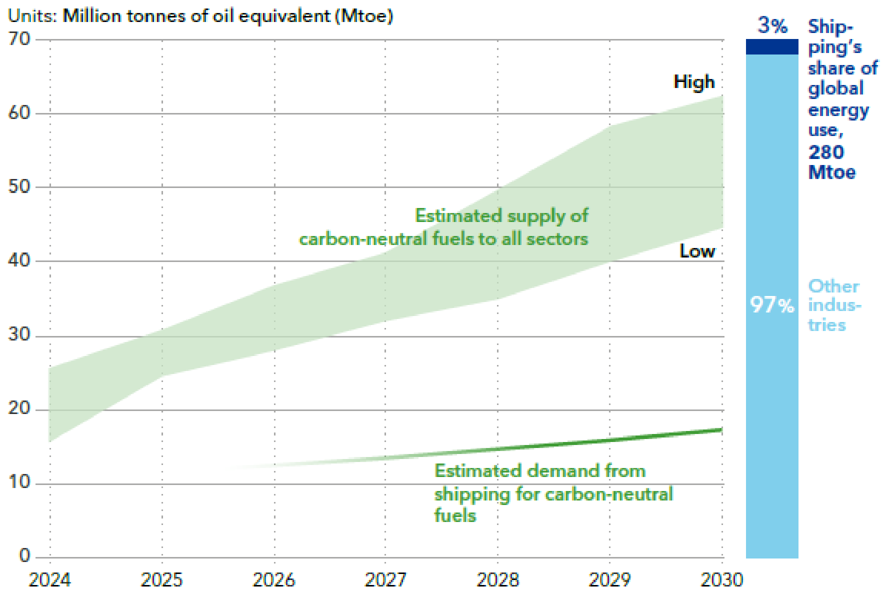

Figure 6-6: Cross-sector supply of carbon-neutral fuels vs. total shipping demand (IRENA, 2021)

Shipping companies will on their side, have individual demands for certain fuels based on price, availability, technical readiness on each vessel as well as on a fuel's GHG intensity. Their decisions are also impacted by various policy requirements (e.g. CII rating, EU ETS, FuelEU Maritime) and expectations from cargo owners, finance institutions, and others. The increasing cost for carbon-neutral fuels due to competition with other industries can also make other alternatives more competitive, such as onboard carbon capture (medium term) and nuclear propulsion (longer term). (IRENA, 2021)

Policymakers need to consider on how to use the limited renewable resources across different sectors. Ideally, energy should be used in such a way as to provide the largest global GHG emission reduction as early as possible, a relevant question both for biofuels and for low-GHG-intensity electricity production. To accelerate the use of electro fuels in shipping, FuelEU

Maritime provides an additional incentive for the use of Renewable Fuels of Non-Biological Origin (RFNBO), even though the renewable energy could be better used to initially replace fossil fuels for producing grid electricity. (IRENA, 2021)

6.3. Plausible Scenarios for marine fuel demand in 2050

Predicting marine fuel demand for 2050 is a complex task that is depended on various factors, including global economic growth, technological advancements, regulatory changes, and shifts in energy sources for the maritime industry.

In total, there are four plausible scenarios:

- **Baseline Scenario:** This scenario assumes a gradual transition to cleaner fuels, with traditional fuels still dominating but with improved emission reduction technologies.
- **Accelerated Transition Scenario:** In this scenario, stricter regulations, breakthrough technologies, and heightened environmental awareness lead to a more rapid shift to sustainable fuels.
- **Disruptive Technology Scenario:** A significant breakthrough in propulsion technology (e.g., highly efficient fuel cells) could drastically reduce the demand for traditional marine fuels.
- **Economic Contraction Scenario:** Global economic downturns or trade disruptions could result in reduced shipping activity and lower fuel demand. (IRENA, 2021)

Predicting the marine fuel demand for 2050 is a complex task with numerous variables at play. While the industry is moving toward cleaner and more sustainable fuels due to regulatory and environmental pressures, the pace and extent of this transition will depend on various factors. It is crucial for stakeholders in the maritime sector to adapt to evolving conditions and work collaboratively to achieve the industry's sustainability goals. Accurate projections will require continuous monitoring of developments in technology, regulation, and global economic trends. (IRENA, 2021)

6.3.1. Ammonia- Potential leading source of energy in the next 30 years

The use of ammonia as marine fuel and as described in the previous sections, will become an important source of energy for the world's shipping fleet within the next 30 years, analysts estimate. According to the estimates of the Norwegian classifier DNV, shipping within this specific period of time is expected to have made its transition to alternative fuels with 50% being low and zero carbon emissions, where this particular fuel will prevail representing 35% of fuel mix, while 19% will be natural gas and 18% biomass. (IRENA, 2021)

Taking into consideration Clarksons's Green Division, 191 ships on order are ready to use Ammonia which means that the ships being built will allow their owners the option to use ammonia when the fuel becomes available. This might lead, for example, to the construction of an LNG fueled container ship as well as fuel tanks built to facilitate conversion to use ammonia. Some of the first ships expected to use ammonia as fuel are ammonia gas carriers. These ships can use the cargo as fuel, minimizing their time in port, as no separate tanking process is required. In addition, their crews are familiar with the safe handling and transportation of this particular fuel. (70% of the ammonia that is widely traded globally and used in fertilizers is carbon-free, making it a promising alternative fuel.) (IRENA, 2021)

The independent research and development center Maersk Mc-Kinney Moller for Zero Carbon Shipping, which seeks to accelerate shipping’s transition to a zero-carbon future, is working on multiple fronts to address the safe use of ammonia and limit risks to crew. This is done in cooperation with Lloyd’s Register. (IRENA, 2021)

Currently, a total of 5.5% of fleet capacity today can run on alternative fuels, up from 2.3% in 2017, according to Clarksons’ Green Technology Tracker survey, which estimates this will reach 6.5% until 2025. Although orders for alternative fueled new ships have been slightly slower in 2023, 48% of the total order book capacity is now alternative fueled, compared with 11% in 2017. Methanol has been preferred this year with a 14% share of orders by tonnage compared to 22% for dual-fuel LNG, according to Clarksons figures. (IRENA, 2021)

The order book also has plenty of optionality built into it with 371 orders for ships to be able to use LNG alternatives as fuel, 191 orders to use ammonia alternatives, 130 orders to use methanol alternatives and 9 orders for “off-the-shelf” hydrogen. Clarksons estimates that Energy Saving Technology (EST) has already been fitted to over 6,250 vessels, representing 27.3% of fleet capacity. (IRENA, 2021)

6.4. General Conclusion

As we evaluate these future marine fuels through the lenses of environmental impact, energy efficiency, availability, and economic feasibility, it becomes evident that no single fuel emerges as the silver bullet for the maritime industry. Instead, the most promising path forward involves a nuanced approach that recognizes the unique advantages and limitations of each fuel type. (IRENA, 2021)

In the short term, LNG may serve as a bridge fuel, offering a substantial reduction in emissions compared to traditional marine diesel. It can provide an immediate solution for meeting emissions reduction targets while infrastructure for greener alternatives is developed. However, the industry must not become complacent with LNG and should continue to invest in long-term sustainable options. (IRENA, 2021)

In the medium to long term, hydrogen and ammonia hold great potential, especially when produced from renewable sources. These fuels align closely with the maritime industry's sustainability goals and have the advantage of zero emissions when combusted. Investment in green hydrogen and ammonia production, storage, and transport infrastructure is essential to realize their potential. (IRENA, 2021)

In charting a sustainable course for future marine fuels, collaboration among governments, industry stakeholders, and environmental organizations is imperative. The maritime industry is not only an economic powerhouse but also a custodian of the world's oceans. As we embark on this journey toward a greener horizon, the choices we make today will define the legacy we leave for future generations. It is a journey that demands innovation, commitment, and a shared vision of a cleaner, more sustainable maritime industry. By setting sail together, we can navigate the challenges and uncertainties and ultimately reach a destination where the oceans and our planet thrive alongside a flourishing maritime sector. (IRENA, 2021)

Concluding, the future of marine fuels holds great promise and significant challenges. As we strive to reduce the environmental impact of the shipping industry and address climate change, alternative fuels like hydrogen, ammonia, and biofuels are emerging as promising solutions. However, the transition to these new fuels will require substantial investment, infrastructure development, and global cooperation. To achieve a sustainable and eco-friendly maritime sector, it is imperative that governments, industry stakeholders, and environmental organizations work together to accelerate the adoption of cleaner marine fuels, ensuring a cleaner and healthier future for our oceans and the planet as a whole. The path ahead may be challenging, but the rewards in terms of reduced emissions and a more sustainable maritime industry are well worth the effort. (IRENA, 2021)

6.5. Suggestions for Future Research

The objective of the present thesis was to examine the medium- and long-term options on energy efficiency of vessels and more precisely the use of alternative fuels to reach compliance with current and upcoming requirements and regulations. (IRENA, 2021)

However, the dynamic nature of the maritime industry, coupled with the ongoing advancements in research and technology, underscores the need for periodic reexamination of the legislative framework. As environmental regulations become more stringent and innovative solutions continue to emerge, it becomes evident that the evolution of this framework is an ongoing process. By revisiting this study in the coming years, we can gauge the effectiveness of legislative adjustments in addressing environmental concerns, fostering technological progress, and ensuring the industry's sustainability. Such future examinations will provide valuable insights into whether the legal framework remains aligned with the changing needs and aspirations of the maritime sector. It will also help us assess how well the industry and its regulators adapt to the challenges and opportunities that lie ahead, ensuring that maritime operations remain not only efficient and profitable but also environmentally responsible and secure in an ever-changing global landscape. (IRENA, 2021)

Future research on nuclear power in shipping presents an intriguing avenue to address the industry's pressing sustainability challenges. Investigating advanced nuclear propulsion systems, such as small modular reactors or thorium-based reactors, tailored to the specific needs and constraints of maritime operations is crucial. Research should focus on enhancing safety, compactness, and efficiency while also addressing the challenges of nuclear waste management and security. Additionally, examining the economic feasibility, regulatory frameworks, and public acceptance of nuclear-powered vessels will be vital to determining the practicality and potential adoption of this technology within the maritime sector. As shipping seeks cleaner and more efficient energy sources to meet emission reduction targets and stringent environmental regulations, nuclear power represents a compelling area for future research and innovation. (IRENA, 2021)

APPENDIX A

Energy Efficiency Measures

A.1. Operational Measures

A.1.1. Voyage performance management

Just-in-time arrival and ship speed optimization

Just-in-time (JIT) is a method whereby a ship optimizes and maintains a particular speed to arrive at a port or piloting station in a timeframe that guarantees a berth, throughway or servicing (Hakirevic, 2020). The correct implementation of this process allows for port operation efficiency and decreases the time a vessel spends in anchorage outside of a port, which decreases fuel consumption and energy demand (Hakirevic, 2020).

Optimizing speed during a ship's journey is another important EE fuel conservation measure. This process is applicable to new and existing vessels and is relatively easy to implement. In practical terms, a ship that reduces its speed by 10% could potentially save 20% of its fuel in a single voyage. Issues arise however with slower speeds due to economic conditions. Slower speeds decrease the amount of total cargo that can be transported annually, leading to economic shortfalls. Slow steaming – in which ships sail at slower speeds during sections of their voyage where time allows – can mitigate economic loss and allow for fuel savings for ships that have established design speeds. Cargo optimization is an important factor in integrating slower ship speeds. Fully utilizing a vessel's full cargo capacity is overall a beneficial strategy because it mitigates energy and fuel consumption over the long term (ABS, 2013).

Weather routing

Weather plays an important role in ship pathing. Planning a route based on the weather allows for a safe voyage and an accurate time of arrival. Fundamentally, weather routing has been based on the fastest and safest route. However, with the increasing importance of EE, particularly after 2013, ships have focused on weather routing optimised for a safe and energy-efficient route. As indicated by ABS (2013), current technology enables ships to have on-route navigational software that allows for up-to-date weather information. Installing and maintaining this software is estimated to cost USD 200 to USD 1 000 per voyage, dependent on the type of software (ABS, 2013). Furthermore, this software can be used on all ship types. Energy and fuel savings from weather routing are highly dependent on the route length and the climate, but are more impactful during severe weather events (ABS, 2013).

Autopilot improvements

Inefficiencies in rudder control during voyages occur frequently. To mitigate energy consumption from this issue, autopilot software can be used to make calculated decisions about rudder movement and to optimise its utilisation (ABS, 2013). Introducing and updating autopilot software is estimated to save a maximum of 1% of fuel consumption in vessels. Although a relatively small fuel and energy conservation method, this software also benefits vessels' navigational aspects (Kabir, 2017).

Trim, draft, and ballast optimization

The draft, ballast and trim of a vessel are instrumental in determining its fuel and energy consumption. The trim of the ship dictates the ability of the ship to maintain a maximum speed while keeping the shaft power at a constant, thus reducing energy and fuel usage (The Motor Ship, 2015). The optimal trim is dependent on the type of ship, and this is dependent on the difference between the aft draft and the bow draft. To optimize trim, even distribution of the cargo needs to be practiced with consideration of the locations of the ballasts (ABS, 2013). Overall savings of fuel and energy consumption from optimizing trim are estimated to be up to 5% (Kabir, 2017).

A.1.2. Energy management systems

Reducing onboard power demand

To increase vessels' EE, the power demand of all onboard machinery and equipment needs to be decreased. Optimizing the performance of onboard apparatuses requires fine-tuning in line with the manufacturer guidelines for each component. Another option would be the outright replacement of poorly performing equipment with high performing and more energy-efficient models (ABS, 2013). The process of streamlining a vessel's power demand requires a thorough analysis of the ship's baseline and maximum energy use. The next step involves identifying key pitfalls and losses of energy, and then developing a process of calibrating or replacing poorly performing equipment. The principal systems that require optimization are the main and auxiliary engines and key smaller equipment, such as lighting; fans; cargo heating and cooling; onboard electronic systems; and heating, ventilating and air-conditioning (HVAC) units (ABS, 2013).

Fuel quality and consumption reporting

Fuel usage is the main contributor to greenhouse gas (GHG) emissions in the shipping industry. Fuel consumption is directly linked with energy demand on vessels. Therefore, all ships have a system of fuel consumption monitoring and reporting for bunkering logistics and fleet cost management. To maintain a correct system of EE management on a vessel, owners and fleet managers should use a fuel consumption measuring system that can target EE measures and bunker management with viable accuracy (ABS, 2013). A fuel consumption measurement system should report and monitor tank-level status, bunker and sludge discharge events, fuel-mass flow, power delivered to each component of the ship, and information regarding voyage and vessel operation. Fuel quality is a determining factor in energy and fuel consumption and is dependent on the water, fuel sulphur and fuel ash content (Kabir, 2017). It is estimated that if a vessel's fuel content has 1% water, fuel consumption in the vessel increases by 1% utilizing standard HFO. To maintain decent fuel quality, third-party testing should be considered (ABS, 2013).

A.1.3. Vessel maintenance measures

Hull roughness management

Hull roughness determines the amount of friction between the ship and the water. If there is too much frictional force applied onto the ship, energy demand and fuel consumption are increased. To mitigate this impact, various methods can be applied to maintain optimum roughness of the hull. There are two aspects that need to be considered: physical and biological roughness. Physical roughness is defined as the surface profile of the hull determined by possible damage or decay to the hull structure. Most physical roughness factors occur during docking or dry-docking, when paint and coating can become scratched. If due caution is taken, physical factors can be avoided. Biological roughness is caused by animals such as barnacles and fouling of the hull from slime or algae (ABS, 2013). One method to prevent fouling of the hull is to use an anti-fouling coating. Currently there are three main types of coating. These are controlled depletion polymer coating, self-polishing copolymer and foul-release coating. It is estimated that with a high-quality coating, propulsion fuel consumption can be decreased by a total of 4%. Hull cleaning is another method used to mitigate biological roughness in hulls. Through the thorough cleaning of a hull, starting from the propeller and then moving forward along the ship, it is estimated that light slime clean-up can reduce fuel consumption by between 7% and 9%. Heavy slime cleaning provides a higher reduction in fuel consumption, up to 18%. Animals attached to ship hulls such as barnacles are considered macro fouling, and the removal of these can account for fuel savings of between 20% and 30% (ABS, 2013).

Propeller roughness management

Although propeller roughness may not impact fuel consumption vastly, relative to hull roughness, it is estimated that it could increase fuel consumption by 6% (ABS, 2013). The common factors that affect propeller roughness are corrosion and fouling from organisms similarly affecting hull roughness. Therefore, propeller maintenance is appealing to shipowners' usage measures such as propeller polishing and propeller coating. Propeller polishing should be completed regularly to maintain the performance of the propeller and to prevent build-up of slime, algae and other organisms. During this regular servicing of the propeller, damages in the forms of dent and scratches should also be attended to. Propeller coating functions the same way as hull coating, protecting the propeller from fouling and preventing corrosion (ABS, 2013). This is vital for energy and fuel saving on vessels.

A.2. Design Measures

A.2.1. Hull and superstructure

Ship sizing

Ships that have larger capacities tend to be more energy efficient due to their ability to transport more cargo at the same speed as smaller vessels while expending less power output. Comparing a container ship with a capacity of 4 500 TEU (twenty-foot equivalent unit) and one with 8 000 TEU, it is estimated that the ship with the larger capacity has a 25% overall fuel consumption reduction in comparison to the smaller ship. The EE and fuel consumption reduction diminishes the larger the ship gets. A comparison between the 8 000 TEU ship and a 12 500 TEU ship observed a 10% reduction of fuel consumption in the larger ship (ABS, 2013). Limitations occur with larger ships because ports may not be able to berth them. Furthermore, larger ships are only more efficient relative to smaller ships if their full cargo capacity is used (Lassesson and Andersson, 2009).

Principal dimensions

Hull length/beam dimensions play a key role in determining how efficiently a ship traverses the water. To decrease fuel consumption and energy demand, the design of new ships should optimise the length/beam ratio by increasing length and decreasing the beam of the vessel while maintaining draft (ABS, 2013). Optimising length/ beam designs decreases fuel consumption by 3-5% in all ship types. Improving the hydrodynamic performance of a vessel's hulls is achievable through understanding key resistances affecting the hull and optimising the hull form (lines). Through optimising the hull, fuel savings are estimated between 5% and 8% (ABS, 2013).

Ship weight

The structural weight of a vessel has an impact on how a ship performs in terms of EE and fuel consumptions. The integration of high-tensile steel and other composite materials into ship structures allows for weight reduction. Optimising lower weights for large cargo ships allows for increased deadweight for the ship and increases its transport efficiency (ABS, 2013). The benefits of a lighter structural weight are proportional to the size of the ship, with larger ships achieving better efficiencies and fuel consumption reductions. Using high-tensile steel results in a potential fuel savings of 0.2-0.5% fuel consumption per tonne of cargo transported (ABS, 2013).

Aft-body and forebody optimisation

The fore and aft of a vessel are important aspects to consider when integrating energy-efficient design measures into ships. Design measures integrated to the forebody of the vessel include the design of the bulb, waterline entrance, the forward shoulder and the design of the bilge. A well-optimised bulbous bow allows for a reduction in wave-making resistance that works in tandem with bow wave from the hull to create a wave-cancelling effect that reduces the overall wave resistance on the ship's structure. In designing a bulbous bow, careful consideration of the placement of the forward shoulder and the bilge is vital. The importance of aft-body optimisation includes the mitigation of stern waves, improved flow towards the propeller and the avoidance of the eddy effect. Through the improvement of the stern flow, there is a potential for increased propulsion efficiency. Currently, designs in EE aft-body measures provide marginal results at high costs, and thus are not economically viable (ABS, 2013).

A.2.2. Propulsion systems

Propeller optimization

Various forms of high-efficiency propellers exist to improve a vessel's propulsion. Each propeller installation is required to be designed specifically to suit a ship's operational profile and stern hydrodynamics. Currently, the optimal propellers for ships are those that have large diameters and fewer blades that function at lower revolutions per minute (RPM) than smaller, faster propellers. However, this is dependent on the size of the engine and vessel. It is important to consider hull hydrodynamics as well when installing a new propeller (ABS, 2013).

There a variety of propellers, each with specific benefits. The controllable pitch propeller has a low performance rate compared with a fixed-pitch propeller in situations that require a fixed RPM condition due to high RPM and small pitch values. However, it is possible to program the propeller controller to match the controllable pitch propeller optimal pitch settings, which maximizes and optimizes efficiency performance better than a fixed-pitch propeller (ABS, 2013). Ducted propellers function in a cylindrical duct, which uses a process of either accelerating or decelerating the flow in front, over and behind the propeller to provide propulsion. Further examples of propellers are Kappel propellers, propellers with end-plates to reduce tip vortex, contra-rotating and overlapping propellers, and podded and azimuthing propulsion. It is estimated that fuel and energy savings from optimizing propellers range from 3-10% (ABS, 2013).

Enhancement of propulsion devices

Many devices can improve EE in vessels from the development stage. Wake-equalising and flow separation-alleviating devices improve the flow around the hull of a ship by mitigating issues arising from propeller and hull resistances. These devices include Grothues spoilers, which are small, curved triangular plates fitted at the side of the hull in front of the propeller; wake equalising ducts, which function similar to the Grothues spoiler; and stern tunnels, which deflect water towards the propellers (ABS, 2013). The installation of wake equalising and flow separation alleviating devices is estimated to save 0-5% in fuel consumption.

Pre-swirl and post-swirl devices can be incorporated into vessel design to mitigate energy and fuel consumption. Pre-swirl devices can be retrofitted onto existing ships as well as onto newly designed ships. Installing pre-swirl appendages can mitigate between 2% and 6% of fuel consumption. Post-swirl devices have performed similarly to pre-swirl devices in terms of EE. Both of these devices are used to condition the flow towards the propeller (ABS, 2013).

Air lubrication systems

Air lubrication systems can prove instrumental in mitigating resistances on a vessel, and thus improving propulsion. Two forms of air lubrication exist, air cavity systems and micro-bubble systems (ABS, 2013). In air cavity systems, a thin layer of air is applied onto the bottom of the hull, which reduces skin friction due to lower wet surface area on the ship. Micro-bubbles, although not as effective as air cavity systems, are easier and less expensive to maintain, leading to lower energy demand. Introducing air lubrication systems to a vessel can lower fuel consumption by a maximum of 10% (ABS, 2013).

A.2.3. Power systems

Main engines

With internal combustion engines (ICEs) still the predominant engine used in ships, efforts need to be made to improve EE in ICEs to reduce fuel consumption and further decrease GHG emissions.

A key EE measure to implement in ships is main engine efficiency measurement instrumentation to track fuel consumption and energy demand. A shaft power meter is the most accurate way to measure engine power output in real time. This meter is installed directly onto the propulsion shaft. Two versions of the meter exist: the strain gauge and the optical gauge. To track the current fuel consumption of each primary consumer, a fuel flow meter can be installed. The most commonly used fuel flow meters are the positive displacement and the Coriolis gauges (ABS, 2013).

Main engine performance measurement and control is another aspect vital to maintaining EE on vessels. Diesel analysers are one such tool. These monitor engine balance, ignition timing, cylinder overload prevention and cylinder wear and are useful for planning maintenance. These analysers come in two forms: portable, which is the most commonly used form, and fixed. Furthermore, introducing automated combustion control systems such as computer-controlled surveillance and intelligent combustion control, as well as delta tuning (for low load operation) systems, can optimise engine control, thereby reducing energy and fuel consumption (ABS, 2013).

Auxiliary equipment and engines

Improvements to a ship’s auxiliary systems in the design stage can boost the vessel’s EE. Shaft generators are prime examples of an energy supplier to the rest of the ship. These use constant RPM from the main engine to produce electricity for all the auxiliary equipment and base energy demand for a vessel. Furthermore, hybrid auxiliary power generation that uses fuel cells (FCs), diesel/gas generators and batteries can improve ship energy performance (Lassesson and Andersson, 2009). The number of service generators is highly dependent on the sizing of the ship (ABS, 2013).

HVAC systems have a smaller impact on energy demand than other aspects of a vessel. However, prioritising the incorporation of highly efficient HVAC systems can mitigate energy consumption that can be used in other areas to greater effect. Further auxiliary aspects can be improved on in the development stage of a ship, such the optimisation of fans, pumps and compressors throughout the ship. Waste heat recovery can be used to provide electrical gain using steam exhaust gas heat recovery (ABS, 2013).

Inclusion of wind and solar energy

Integrating renewable energy sources into the design of ships is a relatively new innovation. Wind energy is considered viable for optional energy generation for vessels because wind resources are abundant. Various measures can be integrated into a ship's design, and one of the more common and commercially available measures are towing kites (ABS, 2013). These are relatively straightforward devices that deploy a kite tethered to the vessel that provide extra propulsion power, thus leading to fuel consumption savings. Another device currently in the concept stage is the turbosail. However, there are no practical applications available for large cargo vessels (ABS, 2013). Introducing solar power to vessels is also currently in development. However, due to the low output from solar photovoltaic (PV) panels, they are better used to power auxiliary systems and supplement the energy demand in a vessel. These technologies are undergoing constant innovation, and therefore future developments may prove to be more impactful for EE ship design.

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