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ALTERNATIVE FUELS AND BUNKERING OPERATION

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" This dissertation has been approved by the Three-Member Examination Committee or the Assembly of the Department of Maritime Studies at the University of Piraeus, in accordance with the Regulations of the master’s Program in Maritime Administration.

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The approval of the thesis by the Department of Maritime Studies of the University of Piraeus does not imply acceptance of the author's views."

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Abstract

The present research, which took place in the form of a literature review, aimed to evaluate and compare the different alternative fuels already available, identifying and analysing their performance, their impact on the environment, their cost and their production cycle. In addition, the relevant legislative framework and the readiness of the market to accept each of the fuels was investigated in order to identify which could be used more easily and safely. Through the study, it was found that alternative fuels are a safe alternative, which however, requires proper adaptation and evaluation before adoption. Consequently, further research is necessary to discover the most effective strategies for transitioning to more sustainable shipping.

Introduction

Shipping is the commercial transportation of freight. Contrary to the name, the term shipping refers to the transportation of commodities from one to another location by any means of transportation, not exclusively by ships. There are four primary means of transportation that often serve as the foundation of the shipping sector: ships, aeroplanes, freight trains and haulage lorries (Clarkson, 2024). This logistical procedure is critical for international trade and business because it allows raw materials, finished goods, and resources to be transported across borders and continents (Andersson, 2016).

Shipping encompasses a broad spectrum of transportation, using several kinds of vessels including bulk carriers, container ships, tankers and cargo ships. Every form of transportation has a specific use and can carry everything from cars to machinery, oil, cereals, consumer products (Speed Commerce, 2024).

Bunkering is the act of providing ships with fuel, whereas a bunker refers specifically to gasoline and oil. This fuel is utilised for operating machinery on the vessel and for energising the engines that push the ship across the ocean (Winward, 2024).

Between ports, bunkering is often necessary since ships cannot carry enough fuel to cover long distances. Typically used in marine operations, bunkers fall into three main types: Low sulfur fuel oil, High sulfur fuel oil, Low sulfur marine gas oil (Winward, 2024).

Low sulfur fuel oil known also as LSFO is a type of fuel oil with a much lower sulphur content. This sulphur decrease is required to meet severe environmental regulations aimed at lowering air pollution. High sulphur fuel oil (HSFO) is a type of fuel oil that contains a higher concentration of sulfur and is subject to fewer limitations. Low sulphur marine gas oil (LSMGO) is a more environmentally friendly choice that contains less sulphur. It is intended specifically for engines that require cleaner fuel. Each of these bunkers has a particular role in different conditions. The selection of the proper bunker is dependant on numerous aspects, including regulatory mandates, engine compatibility, and environmental issues (Tran, 2020).

Ship-to-ship (STS) operations allow bunkering both at a port or offshore. A ship fuels on land from a pipeline installation, tank truck, or bunker barge. Once at sea, a specialty vessel called a bunker barge finishes the bunkering process. Usually, a bunker hose is used for fuel delivery into the container (Testa, 2019).

Three phases separate bunkering operations: preparation, execution, and completion. Before starting any project, one must be well-prepared since it provides the structure for seamless running. This preventive action is meant to lower the frequency of oil spills, which damage the surroundings and might compromise human health.

The ship will be refueled on the following step. Efficient and controlled fuel transfer aboard the ship is done through close coordination among the bunkering team, precise equipment management, and strict adherence to safety protocols. The final phase of bunkering ensures that the procedure is completed safely and precisely.

A serious concern that develops during ship bunkering is the possibility of fuel contamination, which occurs when unsuitable pollutants or compounds interact with the bunker oil. Contaminated gasoline can substantially compromise the engines of a ship, therefore affecting operations, raising maintenance expenses, and generating safety concerns (Kamal and Kutay, 2021).

False bunkering and inadequate supply chains produce differences in fuel quality, which costs shipowners $5 billion and makes nearly 600 ships useless in 2022 (Winward, 2024). Technical breakdown, human error, or unanticipated circumstances could all cause spills and leakages in the management of oil bunkering (Winward, 2024). These events could have long-lasting effects on the environment, influencing marine ecosystems and putting the bunkering vessel in financial and legal hot line. Strict safety protocols, surveillance systems, and industry standards compliance (Winward, 2024) would help to minimize the hazards related with oil bunkering activities.

For long years, marine commerce fuels have mostly consisted in residual fuels, which spew significant amounts of greenhouse gasses and air pollutants. Still, more and more authorities are encouraging vessel operators to use cleaner energy sources. The International Maritime Organisation has established decarbonisation targets for international shipping in the coming years in response to the declining worldwide sulphur limit for bunker fuels, therefore enabling to reach net-zero emissions by roughly 2025 (Lin, 2023).

The company also intends to apply gradually greenhouse gas rules for marine fuels. The dynamics of the bunker market can be much changed by the application of shipping rules. The International Maritime Organization's (IMO) policies clearly show this: boats—except from those fitted with scrubbers—must use fuels with a maximum sulphur level of 0.5% starting from 2020 (Lin, 2023).

According to S&P Global analysts, if governments and businesses make greater efforts to reduce carbon emissions, the demand for low-carbon bunker fuel is expected to rise from 845,000 metric tonnes in the previous year to 12.5 million metric tonnes in 2030. This need is projected to further climb to 116.5 million metric tonnes in 2050 (Lin, 2023).

Approved an updated Greenhouse Gas Strategy by the 80th session of the Marine Environment Protection Committee, known as MEPC 80, of the International Maritime Organization aims to drastically lower worldwide marine transportation's greenhouse gas emissions (DNV, 2023). The revised goals are a 20% decline in emissions by 2030, a 70% drop by 2040 (in contrast to 2008 levels), and the ultimate target is net-zero emissions by 2050 (DNV, 2023).

Definition of Alternative Fuels

Over twelve alternative fuels are currently being produced or in the process of being developed. Government and private fleets are the main customers of these fuels, however there is a great interest among individual consumers. The utilisation of alternative fuels, such as electricity, rather of conventional fuels and vehicles, aids in enhancing efficiency, reducing expenses, and mitigating emissions.

Biodiesel is a sustainable fuel made from animal fats, vegetable oils, or recycled cooking grease for use in diesel cars. Moreover, electricity may run completely electric cars as well as plug-in hybrid electric cars. Ethanol can be described as a widely used renewable fuel derived from maize and other botanical resources. Ethanol can be combined with gasoline to run vehicles. One potential free from pollution fuel alternative that shows promise is hydrogen. Fuel cells allow one to create it from renewable sources and use it as gasoline for electric cars.

Domestically abundant, natural gas offers substantial economic savings compared to petrol and diesel fuels. Propane is an easily accessible gaseous fuel that has been extensively utilised in cars worldwide for many years. Renewable diesel is a certain type of fuel which is produced from biomass and may be used in diesel engines. Also, sustainable aviation fuel is produced from renewable sources and allows for a decrease in overall carbon dioxide emissions throughout its life cycle as compared to traditional fuels. Finally, a number of newly emerging fuels are classified as alternative fuels according to the E. P. A. (U.S. Department of Energy, 2024).

Alternative fuels for marine applications

Among the most basic members of a class of chemical compounds called alcohols is methanol (CH_3OH). Its components include a methyl group (CH_3) joined to a hydroxy group (OH). Methanol used to be obtained by the destructive distillation of wood. Direct synthesis of hydrogen in presence of a catalyst and carbon monoxide gas is the contemporary way of producing methanol. Synthesis of methanol makes increasing use of syngas, a mixture of hydrogen and carbon monoxide obtained from biomass (Ott et al., 2000).

Methanol in its pure form is a crucial substance in the process of chemical synthesis (Britannica, 2024). The derivatives of this substance are extensively utilised in the synthesis of numerous chemicals, including significant synthetic dyestuffs, resins, medicines, and perfumes (Klier, 1982). Significant amounts are transformed into dimethylaniline for the production of dyestuffs and into formaldehyde for the manufacturing of synthetic resins. Additionally, it finds application in vehicle antifreezes, rocket fuels, and serves as a versatile solvent. As a high-octane fuel, methanol burns cleanly and could be a major replacement for petrol in vehicles. Mostly, wood-derived methanol is used to make industrial ethyl alcohol unfit for human use (Klier, 1982).

Transparent liquid methanol melts at 64.96 °C (148.93 °F) and solidifies at −93.9 °C (−137 °F). When coupled with air and burns with a flame devoid of light, it can form explosive combinations (Britannica, 2024). It is fully soluble in water. Methanol possesses an aroma that closely resembles ethyl alcohol, the intoxicating substance found in alcoholic beverages (Britannica, 2024). However, it is a highly lethal poison, and consuming mixes containing methanol has resulted in numerous instances of blindness or fatality (Britannica, 2024).

"Multi-fuel" engines, which can run on a broad spectrum of fuels and in varying ratios, are under development by several manufacturers at present(Louisiana Gov, 2024). The on-board computer is a basic component of these vehicles capable of running on several fuels. Special sensors can identify the particular kind or types of gasoline present (Louisiana Gov, 2024) . The particular fuel(s) being used determines how automatically the fuel injection, ignition, and emissions control systems are tuned (Louisiana Gov, 2024).

Methanol is typically blended with petrol or ethanol in varying proportions, typically ranging from 5 to 85 percent, with the lower percentages being more prevalent. These fuel blends enhance the petrol supply and decrease air pollution. "M85", a fuel consisting of 85% methanol, is available in many regions. Thanks to federal incentives, the production costs of this antiknock addition are now comparable to the costs of creating other antiknock additives (Akiyama et al., 1990).

The transition from petrol to methanol may provide challenges in the distribution chain. One surfactant that can adsorb water is methanol. Filters can be blocked and extra running problems created by accumulated silt and water sludge in pipelines, storage tanks, and vehicle fuel tanks (Louisiana Gov, 2024). These systems need to be thoroughly cleaned and readied before introducing methanol fuels. Methanol concentrations exceeding ten percent have a corrosive effect on some metals, rubber, and plastic components of internal combustion engines. Consequently, manufacturing materials must be modified to allow the use of this fuel. Manufacturing material solutions include specially formulated polymers, rubber, and substantial utilisation of stainless steel (Louisiana Gov, 2024).

Liquefied natural gas (LNG) is the result of chilling natural gas to a temperature low enough to transform it into a liquid form. For a change to more ecologically friendly, low-carbon energy systems, this specific fossil fuel has not yet fully realized its possibilities. Conventional energy sources now used for heating homes and businesses, cooking, and transportation include natural gas. But while petroleum is a fossil fuel, it is only temporary (National Grid, 2024). Still, LNG becomes the best fossil fuel choice to help mankind move to a carbon-free future as the globe works for net zero carbon emissions and adopts renewable energy sources (Sakmar, 2013). Natural gas is turned into a liquid form at temperatures as low as -161oC (-259F), which produces LNG. The process reduces the substance's volume to 1/600th of its original unliquified volume and its weight to half that of water.

LNG emits 40% less CO2 than coal and 30% less than oil1, making it the most environmentally benign fossil fuel. It generates far less smoke, dust, and particulates than coal and oil. Furthermore, it emits trace levels of sulphur dioxide, mercury, and other elements that are considered dangerous to the Earth's atmosphere.

As mentioned, LNG is a transparent, odorless, and colorless liquid. Methane accounts for roughly 85-95% of its total weight. The main component of LNG, methane, has less carbon than other fossil fuels. Natural gas composition varies depending on its source and processing, although it often contains trace amounts of ethane, propane, butane, and nitrogen.

LNG solves the "energy trilemma," which consists in attaining a harmonic balance among three important elements in our energy decisions: assuring energy affordability, guaranteeing energy security, and lowering carbon emissions to reach net zero (Sakmar, 2013).

LNG could help to make reasonably priced energy more easily available. A major problem is fuel poverty, hence guaranteeing the availability of reasonably priced energy is quite important. By providing a variety of supply choices throughout a global market, LNG reduces the financial obligations related with the cost of living (Mokhatab et al., 2013).

Furthermore, LNG can be a consistent backup when variations in renewable energy sources occur. Changing to renewable energy sources means running into fluctuations in supplies. Solar energy will be depleted, for example, in times of no sunlight and wind power will be less when there is no wind. Ensuring a regular energy supply is vital; LNG is well-suited to solve changes in renewable energy output, therefore guaranteeing a continuous supply of electricity (National Grid, 2024).

Importantly in allowing the change to a more ecologically friendly energy future is Grain LNG, the largest import LNG plant in Europe. The facility has the capacity to accommodate a wide variety of LNG compositions, making it the most versatile in the world. Additionally, it has the capability to distribute gas promptly and efficiently to any desired location (Mokhatab et al., 2013).

Classed as a fossil fuel, natural gas is rather important in helping to drive the change toward green energy. In the quest of a net zero carbon emissions aim, LNG also fulfills additional functions. It could be the source of low-carbon hydrogen, created without releasing carbon from raw materials. This makes it a candidate for inclusion in a future hydrogen-based economy (National Grid, 2024).

Chemical fuels offer a favourable method for storing energy over a long period of time. They are in the form of fluids, which makes them dependable and relatively easy to transport. They can also have great weight and volume energy densities. Moreover, the infrastructure needed to run chemical fuels is already developed all around the globe. Development of sustainable fuels for energy storage by means of synthesis from surplus power—a process known as "power-to--X"—is essential to solve the present energy and climate change crisis.

As technology for extracting hydrogen from seawater advances, chemical storage of the produced hydrogen will become increasingly important. This is because pure hydrogen has a very low energy density per unit volume, making worldwide distribution difficult in terms of safety and infrastructure costs.

In a future nitrogen-based economy, where nitrogen is easily available and the main carrier of hydrogen, ammonium has the potential to be employed as a mechanism of storing and transferring renewable hydrogen. At a rather low cost, ammonium can help to raise the density of hydrogen (Herbinet et al., 2022).

As fuel, ammonium offers a number of benefits. Its built large-scale distribution network and quite high power to fuel to power efficiency define it. Moreover, ammonia has a restricted flammability range and a high-octane rating of 110–130, so it is quite safe in terms of explosive risk.

However, it is important to note that ammonia is hazardous and releases high levels of pollutants (NOx and NH3 residuals) when burned. Additionally, it has a relatively poor reactivity as a fuel. Multiple investigations were undertaken as part of continuous endeavours to tackle the primary obstacles of limited responsiveness and pollution reduction in ammonia systems. Recent years have seen significant increase in the desire in using ammonia for fuel purposes (Herbinet et al., 2022).

Any fuel created from biomass—that is, both plant and algal material as well as animal waste—is known as biofuel. It is considered a renewable energy source since biofuel can be easily replaced unlike coal, natural gas, and petroleum. Given the present trend of rising gasoline prices and growing knowledge of the part fossil fuels contribute to global warming, biofuel is frequently advocated as a reasonably cheap and environmentally friendly replacement for petroleum and other fossil fuels (Demirbas, 2007).

The expansion of particular biofuels worries many critics about the environmental and financial expenses related to the refining process as well as the possible displacement of vast areas of cultivable land from food output (Demirbas, 2007). Some highly used biofuels, notably wood, can be straight burned as the main fuel source to produce heat. On the other hand, the heat can be used to run generators inside a power plant thereby producing electrical energy (Demirbas, 2007).

Several modern power plants burn biomass, which includes grass, wood, and other organic materials (Liu et al., 2021). Liquid biofuels are especially appealing because of the enormous existing infrastructure dedicated to their use, notably in transportation. Produced by fermenting starch or sugar, ethanol—also known as ethyl alcohol—is the liquid biofuel most often created today (Liu et al., 2021). Principal ethanol producers are Brazil and the United States. Mostly produced from maize grain, ethanol biofuel is blended with gasoline in the United States to create 'gasohol,' a fuel with 10% ethanol. In Brazil, sugarcane is used primarily to produce ethanol biofuel (Liu et al., 2021).

Usually used either as a pure 100% ethanol fuel or as a component in gasoline blends, this biofuel has ethanol level up to 85% (Selin et al., 2024). Unlike ethanol biofuel derived from food crops, cellulosic ethanol comes from low-value biomass with a high cellulose content—such as municipal trash, agricultural leftovers, and wood chips (Selin et al., 2024).

Usually produced from either different grasses grown on low-quality soil or from sugarcane bagasse, a byproduct of sugar manufacturing, cellulosic ethanol is mostly utilized as a petrol additive due to its lower conversion rate than first-generation biofuels (Selin et al., 2024).

Mostly derived from oily plants like soybeans or oil palms, biodiesel, the second most often used liquid biofuel, has a small contribution from other oily sources such waste cooking fat from restaurant deep-frying (Liu et al., 2021). Popular throughout Europe, biodiesel is utilized in diesel engines and is often mixed with petroleum diesel fuel in different levels (Liu et al., 2021).

Utilizing cyanobacteria and algae as a potential source of "third-generation" biodiesel shows potential, but it has proven to be economically challenging to develop. Certain species of algae have lipid content that can reach up to 40 percent of their weight. These lipids has the ability to be transformed into biodiesel or into synthetic petroleum (Selin et al., 2024).

Some estimates show that, per unit area, algae and cyanobacteria might produce 10 to 100 times more gasoline than second-generation fuels could (Selin et al., 2024). Further biofuels include methane gas and biogas, which can be derived from biomass breakdown devoid of oxygen. Moreover in development as biofuels are methanol, butanol, and dimethyl ether (Somerville, 2007).

When assessing the economic advantages of biofuels, it is necessary to consider the energy input required for their production. As an illustration, the cultivation of maize for ethanol production involves the utilisation of fossil fuels in many stages such as operating farming machinery, making fertilisers, transporting maize, and distilling ethanol (Liu et al., 2021).

When comparing different types of ethanol, corn-based ethanol delivers a very moderate gain in energy, but sugarcane-based ethanol provides a larger rise. However, the energy increase from cellulosic ethanol or algal biodiesel has the potential to be much bigger (Liu et al., 2021). Biofuels have environmental benefits, but their manufacturing methods can potentially have major negative environmental consequences. Plant-based biofuels, a type of renewable energy, have a minor overall impact on global warming and climate change (Somerville, 2007). This is due to the fact that the carbon dioxide emitted into the atmosphere during combustion has already been absorbed by plants during photosynthesis. A "carbon neutral" material produces no net carbon emissions (Somerville, 2007). However, industrial-scale production of agricultural biofuels might result in increased greenhouse emissions, negating the benefits of utilizing renewable fuels.

The pollutants include nitrous oxide from soil treated with nitrogen fertilizer and carbon dioxide produced during the manufacturing process from the burning of fossil fuels. In this aspect, cellulosic biomass is seen to be more beneficial (Selin et al., 2024).

Evaluating the benefits of biofuels also mostly depends on thinking on land use (Liu et al., 2021). The use of conventional feedstocks, such soybeans and maize, as the main component of first-generation biofuels started the controversial debate on the contradiction between fuel and food production. Moving arable land and feedstocks away from the human food chain will help biofuel production affect the economics of food pricing and availability (Liu et al., 2021). Moreover, the natural surroundings of the earth could be threatened by the increasing output of energy crops for biofuel (Demirbas, 2007).

For instance, the concentration on using ethanol made from corn is transforming grasslands and brushlands into corn monocultures while the reliance on biodiesel is destroying old tropical forests to create room for oil palm plantations (Demirbas, 2007). Natural habitat loss can alter the hydrological system, increase erosion, and at last lower the richness of animal habitats. Since the plant material included either burns or lets decay, land clearance might lead to the unexpected release of a large amount of carbon dioxide (Demirbas, 2007).

Usually agricultural items, low-diversity sources such as corn, soybeans, sugarcane, and oil palms characterize the main disadvantages of biofuels (Selin et al., 2024). Using somewhat different mixes of species is another approach; the North American tallgrass prairie serves as a concrete example (Selin et al., 2024). By converting unproductive agricultural land into high-diverse biofuel sources, one can enhance wildlife habitats, lower erosion, clean waterborne pollutants, store carbon dioxide from the atmosphere as carbon compounds in soil, and so increase the fertility of degraded areas. Should technical developments take place, these biofuels could be used directly for energy generation or transformed into liquid fuels (Selin et al., 2024).

Among the several technologies and fuel options under discussion, hydrogen generated from renewable energy (green hydrogen) has been underlined as one that might offer a 'almost zero' carbon solution (EMSA, 2023).

Although numerous key technologies (like engines) are still under development and shipping has low knowledge with hydrogen as a fuel, there is enough land-based expertise with its manufacture and consumption to provide a strong basis for the change to a marine fuel (EMSA, 2023).
Among the various constraints are hydrogen's low energy density, which raises storage needs onboard a ship; the cost of the technology; and the urgent need to expand global capacity to create and transport green hydrogen. At last, hydrogen-fueled boats might show to be a superior solution for short-sea (EMSA, 2023) than deep-sea (EMSA, 2023).

1.Methanol

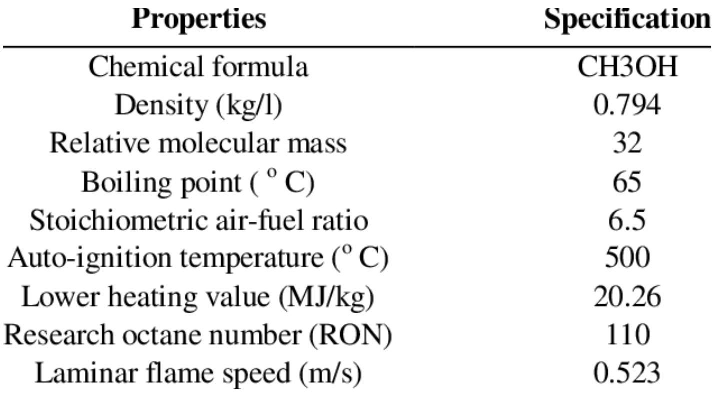
1.1. Properties of fuel

The chemical formula for methanol, often known as methyl alcohol, is CH3OH. Methanol is a polar solvent. Methanol is also known as wood alcohol. The name came from the damaging distillation of wood, which generated methanol. Nowadays, methanol is mostly manufactured industrially by hydrogenation of carbon monoxide (Toppr, 2024).

A methyl group joined to a polar hydroxyl group makes up methanol. Annual production of methanol exceeds twenty million tons. Other commercial compounds are derived from methanol (Toppr, 2024). Among other specialty chemicals, these compounds include methyl benzoate, formaldehyde, methyl acetic acid, tert-butyl ether, peroxy acids and anisole (Toppr, 2024).

Healthy persons have small quantities of methanol in their bodies. Furthermore, producing methanol are phytoplankton and anaerobic bacteria. Methanol abounds in star-forming zones of space. Astronomy also uses it to pinpoint such sites. Spectral emission lines help to detect methanol (Ott et al., 2000). Methanol is a flammable, light, volatile, colorless liquid. It smells strongly like alcohol, much like ethanol. Molecular weight, or molar mass, of methanol is 32.04 grams per mole. Methanol's density is 729 kg/m3. Methanol's boiling point is 63.7°C and melting point is -97.6°C (Ott et al., 2000).

Methanol fuel is proposed for use in road transportation. A methanol economy has the advantage of being easily adaptable to gasoline internal combustion engines with few engine modifications. Methanol has a lower energy density than gasoline. This means that twice as much methanol would be necessary (Caldwell, 1995). One potential fuel for ships is methane. This fuel helps the marine sector to satisfy its ever strict environmental regulations. Methanol cuts some particles, nitrogen oxides (NO2), and sulfur oxides (SO2). By adding a little amount of dual fuel, methanol can be used with great efficiency in marine diesel engines after few modifications (Ott, 2000).



Properties	Specification
Chemical formula	CH3OH
Density (kg/l)	0.794
Relative molecular mass	32
Boiling point (°C)	65
Stoichiometric air-fuel ratio	6.5
Auto-ignition temperature (° C)	500
Lower heating value (MJ/kg)	20.26
Research octane number (RON)	110
Laminar flame speed (m/s)	0.523

Figure 1: Methanol Properties (Source: https://images.app.goo.gl/UKjmpgJ8EZW6HSLf8)

Methanol is produced from hydrogen and carbon monoxide reacting on a catalyst (Waugh, 1992). Supported by alumina, copper and zinc oxides make the most often employed catalyst. ICI used it first in 1966. High selectivity of more than 99.8% marks the reaction at 5 to 10 MPa (50 to 100 atm) and 250oC (482oF).

Three moles of hydrogen for every mole of carbon monoxide follow from the synthesis gas generation from methane (Waugh, 1992). Two moles of hydrogen gas per mole of carbon monoxide are all that the synthesis calls for(Waugh, 1992). One has the ability to add carbon dioxide to the methanol synthesis reactor to handle extra hydrogen; it also combines to produce methanol using the equation (Waugh, 1992).

Methane monooxygenases among other enzymes help to catalyze methane into methanol. Mixed-function oxygenases, these enzymes oxygenate and generate water and NAD + simultaneously (Toppr, 2024). Commercially, methanol is easily available in many purity levels. ASTM purity categories A and A A guide grading commercial methanol. Grade A and grade AA have both methanol purity by weight at 99.85% (Toppr, 2024). Furthermore present in grade AA methanol are traces of ethanol. Apart from water or liquid, some typical pollutants are acetone and ethanol, which are quite challenging to separate by distillation (Toppr, 2024).

1.2. Environmental Performance (in a life cycle perspective)

The major emissions in fossil fuels pertain to the stoichiometric end-of-life emissions linked with the use of methanol as a fuel in internal combustion engines for automobiles, trucks, buses, and ships (Methanol Institute, 2022). By means of renewable feedstocks, these emissions are climate neutral in paths, therefore lowering the overall climate emissions and significantly improving the carbon footprint (Li et al., 2018). Variations in feedstock within the same category, technical differences in installation configurations, and supply chain differences produce significant changes in lifetime carbon footprint results. The results vary so one should avoid using default carbon footprint estimations for fossil or renewable methanol, or even by feedstock category (Li et al., 2018).

Modern facilities produce methanol with an estimated carbon footprint of about 110 g CO2 eq/MJ, surpassing the state-of- the-art value of roughly 97 g CO2 eq/MJ maybe due to developments in carbon accounting guided by current data (Liu et al., 2020). The imprint has especially sensitivity to the natural gas source. Derived from lower carbon-emitting natural gas sources, the emissions linked with the methanol supply chain can be lowered to almost 103 g CO2 equivalent per megajoule (Liu et al., 2020).

By means of exhaust CO2 recycling to the methanol reactor, methanol generation is increased and facility emissions are lowered, therefore lowering the lifetime emissions per MJ of product to 93-101 g CO2 eq/MJ. The results fall between 13 g CO2 eq/MJ larger than the value the EU Joint Research Centre (JRC) used in computations under RED II and 4 g CO2 eq/MJ better (Methanol Institute, 2022). Only China produces coal, and its carbon footprint—about 300 g CO2 eq/MJ—attributable to major emissions from both coal mining and the methanol conversion process. Minimal carbon footprint is shown by energy generation from biomethane, solid biomass, municipal solid waste (MSW, which makes up a substantial share of organic waste), and other renewable energy sources (Methanol Institute, 2022).

Many of these pathways achieve 10-40 g CO2 eq/MJ; some of them show negative emissions (-55 g CO2 eq/MJ for methanol derived from biomethane sourced from cow manure), so indicating that CO2 is either efficiently extracted from the atmosphere or that the pathway avoids emissions that would have otherwise occurred in alternative processes. There is little literature on methanol's carbon footprint, and occasionally it is out-of-date (Methanol Institute, 2022).

The Methanol Institute (MI) (Methanol Institute, 2022) commissioned the Amsterdam-based independent consultancy firm studio Gear Up (sGU) conducted a lifecycle carbon footprint assessment (LCA) study of several methanol production feedstocks and technologies in order to improve the understanding of carbon footprint evaluation in the industry and simultaneously get insights on the present condition of methanol's climate effects (Methanol Institute, 2022).

This experiment produced anonymised results by sGU computing the carbon footprint of methanol using data from 12 companies. The Methanol Institute supports manufacturers of methanol, distributors, consumers, and global technology leaders. Based on the data, most methanol is currently generated worldwide from fossil energy sources—mostly by steam reforming natural gas (Methanol Institute, 2022). While some businesses are manufacturing methanol from renewable sources, others are researching techniques to produce methanol from different renewable inputs—such as bio-methanol obtained from biomass, biomethane, or the gasification of municipal solid waste and e-methanol generated by combining carbon dioxide sources with green hydrogen derived from the electrolysis of water run-through renewable energy (Methanol Institute, 2022). The methanol molecule controls end-of-life emissions: for every gramme of fossil-based methanol 44/32 gram of CO2 is emitted (Methanol Institute, 2022).

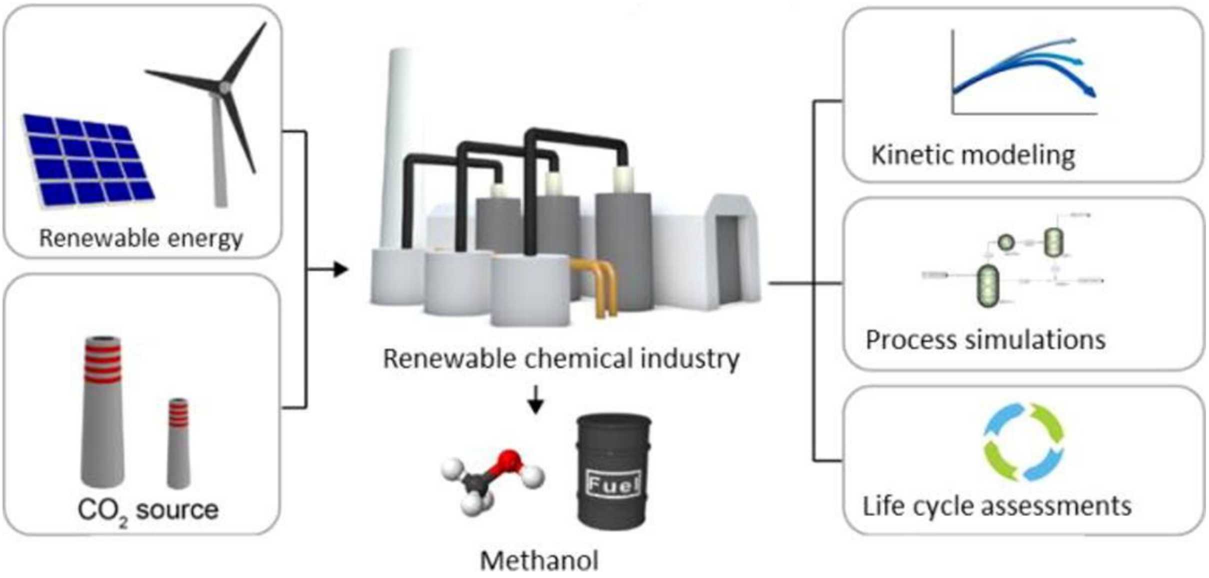


Figure 2: Methanol life cycle (Source: https://images.app.goo.gl/edtkUhg845eSXS3o6)

From a lifetime standpoint, the environmental evaluation of methanol used as ship fuel shows that methanol generated with natural gas has more GHG emissions than traditional fuels (IMO, 2021). Still, the manufacturing of methanol from biomass has great potential to lower significant emissions as long as the electricity consumed in the process is rather clean (IMO, 2021). The lifetime NOx emissions from methanol are estimated to be 45% of those from conventional fuels per unit energy, whereas the lifetime SOx emissions of methanol are approximated as 8% of those from conventional fuels per unit energy. The reductions in NOx and SOx can be ascribed to methanol since it produces reduced emissions during the combustion phase (IMO, 2021).

1.3. Production pathways (incl. cost and availability)

Using hydrogenation of syngas with heterogeneous catalysts as ZnO/Cr2O3 and Cu/ZnO/Al2O3, large-scale methanol synthesis from fossil-based resources is being achieved (Kumaravel et al., 2021). Fermentation or gasification of feedstock can also produce a limited amount of methanol to generate bio-based syngas, thereafter hydrogenation can be performed. Large-scale methanol generation from renewable feedstocks for industrial uses is still in the exploratory stage, nevertheless (Kumaravel et al., 2021). Considered as one of the most often used and reasonably priced solvents, methanol is a biomass source for the sustainable synthesis of fine chemicals advantageous for the pharmaceutical sector (Liu et al., 2020).

Among the several pharmaceutical compounds that can be synthesized from methanol are C-methylation, C-methoxylation, N-methylation, N-formylation, methoxycarbonylation, and oxidative esterification. In this regard, methanol is a crucial C1 source for pharmaceutical sector chemical operations (Liu et al., 2020). When coupled with an iridium nanocatalyst, methanol produced from feedstock can be employed as an alkylating reagent for bio-alcohols, claims Liu et al. (2020).
In certain instances, owing to structural similarity, methanol may substitute ethanol in organic reactions. In addition to its therapeutic use, methanol significantly contributes to biofuel production through transesterification processes (Kumaravel et al., 2021). From a cost standpoint, methanol as a fuel shows only promise under particular conditions. Among these include the vessel's considerable sailing time spent in ECAs and the expensive expense of MGO (IMO, 2021).

1.4. Uptake as marine fuel

Methanol as a fuel for shipping is an appealing option for all types of vessels. Green methanol will assist owners and operators transition to a more sustainable future. Methanol as a fuel is a lightweight, flexible, colorless, and combustible alcohol. It is a widely available molecule that may be synthesized from a variety of sources, including biomass, natural gas, and CO2. (Lloyd’s Register, 2024). It is being investigated as a possible alternative fuel for shipping as the sector advances toward decarbonization. In an internal combustion engine, methanol reacts with oxygen in the air to produce carbon dioxide, water, and heat/energy. Despite the carbon dioxide emissions, methanol transportation could be a viable option for reaching net-zero carbon lifecycle emissions if the methanol is produced from biomass or renewable hydrogen and CO2 (Lloyd’s Register, 2024).

1.5. Technology readiness level

The new application integrates all these components along the methanol flow and examines their interactions. The evaluation indicates that further safety barriers are required throughout the entire methanol fuel system (Lloyd’s Register, 2024). From a technical perspective, this is entirely feasible for shipowners, applicable to both new constructions and retrofitted systems (IMO, 2021). At present, 29 ships operating on methanol are in service, with 228 additional vessels on order, indicating a substantial increase in methanol-fueled ships in the forthcoming years (Lin, 2024).

1.6. Safety

Aiming at lowering risks to the vessel, its crew, and the environment, Code of Safety for Ships establishes mandatory rules for the arrangement, installation, control, and monitoring of machinery, equipment, and systems using low-flashpoint fuel, considering the characteristics of the fuels involved (IMO, 2021). The IGF Code states that the general functional need calls for the safety, dependability, and safety of the systems to be equal to those of new and similar conventional oil-fueled main and auxiliary machinery (Lin, 2024). This degree of safety is achieved in the fuel system by means of a risk assessment, hazard identification (HAZID), or failure mechanism, effects, and criticality analysis (FMECA). This occurs all through the design phase; should the risk level be judged high, further risk-reducing strategies should be included (IMO, 2021). The design of the bunkering station and system is more complicated than that of ordinary fuel oil since methanol is a fuel with special chemical and physical properties (IMO, 2021).

Methanol is hazardous and with a low flashpoint of roughly 12°C (IMO, 2021). The lowest temperature at which a liquid releases vapors in sufficient concentration to produce an ignitable mix with air is called flashpoint (Lin, 2024). Together with a low ignition energy need, the methanol feature generates additional control barriers (IMO, 2021). As such, additional monitoring and control systems like overfill alarms, automatic shutdown systems, ventilation monitoring, and gas detection are mandated by the requirements (IMO, 2021). These safety measures are aimed to prevent personnel methanol exposure due of their dangerous properties. Methanol is harmful whether swallowed, comes into touch with the skin, or is breathed as fumes (Lin, 2024). Large concentrations of methanol are converted into formic acid or formate salts, both of which damage the central nervous system and can cause blindness, coma, and death (IMO, 2021).

The elevated toxicity indicates that the ingestion of merely 10 mL of pure methanol can metabolize into formic acid, potentially resulting in irreversible blindness due to optic nerve damage. 30 mL may be lethal, whereas the median lethal dose is approximately 100 mL (IMO, 2021). The deleterious consequences commence after several hours, and appropriate antidotes frequently avert irreversible harm (IMO, 2021).

1.7. Ship design impact

Lindanger, the inaugural dual-fuel methanol-powered tanker, was constructed in 2016 to DNV standards. Currently, 18 out of the 24 vessels in the worldwide methanol tanker fleet are classified by DNV, positioning DNV uniquely to facilitate the adoption of methanol technology within the shipping sector. Proman, the world's second-largest methanol manufacturer, and the shipping firm Stena Bulk established a joint venture, Proman Stena Bulk, to leverage synergies in developing a fleet of contemporary, sustainable MR chemical tankers. The joint company's existing newbuild program includes six advanced dual-fuel MR tankers, all constructed to DNV classification, with three owned by the joint venture and three owned by Proman. Four vessels have already been delivered. A new section of the DNV publication “Alternative Fuels for Containerships” elaborates on the characteristics and specifications of methanol, with many of its findings applicable to other vessel categories as well. The capital expenditure for a methanol-fueled newbuild or retrofit is reduced due to the absence of requirements for pressurization or expensive cryogenic fuel tanks and systems. Methanol fuel tanks occupy approximately 2.5 times the volume of oil tanks, and cofferdams are necessary in certain instances for safeguarding purposes. Methanol is a poisonous and combustible fuel with a low flashpoint that necessitates specific safety measures, which are considerably less complex than those required for LNG (DNV, 2023).

1.8. Regulatory readiness

Shipowners in commissioning methanol-fueled ships have found the IMO interim norms for vessels running methyl or ethyl alcohol as fuel to help them. Customers now have access to a complete regulatory framework for using methanol as ship fuel that combines the IMO's IGF Code for vessels running low-flashpoint fuels (DNV, 2023).
A classification society is a non-governmental body creating and maintaining technical guidelines for the operation and construction of offshore structures and vessels. Classification

societies certify that a vessel's construction meets relevant requirements and conduct frequent in-service surveys to assure continued compliance.

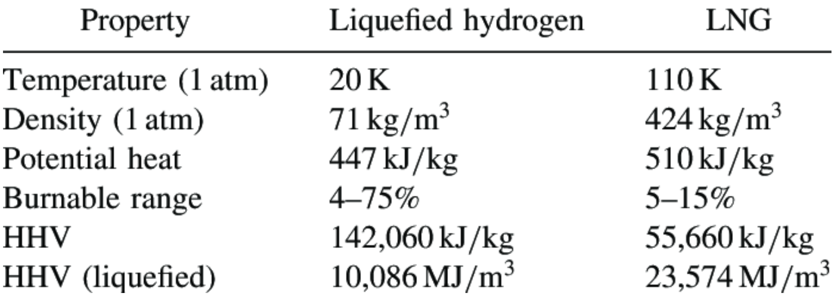
Regarding alternative fuels such as methanol, various classification organizations such as DNV-GL and LR develop their own interpretations of IMO rules; the overall content is more or less comparable, but some aspects may be more conservative or vice versa (Marine Methanol Classification Societies, 2024).

2.LNG

2.1. Properties of fuel

Natural gas is far easier to transport and store since it is liquefied to roughly 1/600th of its natural gaseous volume. LNG is mostly made of methane, but it may also contain traces of ethane, propane, and butane. This liquefaction process permits the feasible transportation of natural gas across large distances, even where pipelines are unavailable (Kumar et al., 2011).

First, natural gas is filtered to remove pollutants like water, sulfur, and other particles, resulting in a safe source of methane. After that, this cleaned gas is chilled to quite low temperatures—usually around -162°C—where methane becomes liquid. Heat exchangers and specially designed refrigeration systems are used to supply the required cooling (Pavlenko et al., 2020).



Property	Liquefied hydrogen	LNG
Temperature (1 atm)	20 K	110 K
Density (1 atm)	71 kg/m^3	424 kg/m^3
Potential heat	447 kJ/kg	510 kJ/kg
Burnable range	4–75%	5–15%
HHV	142,060 kJ/kg	55,660 kJ/kg
HHV (liquefied)	10,086 MJ/m^3	23,574 MJ/m^3

Figure 3: LNG Properties (Source: https://images.app.goo.gl/ott8NfkwBk5XN4VVA)

LNG may be carried across oceans and continents utilizing specifically built ships known as LNG carriers due to low volume. Highly insulated storage containers on these ships help to maintain the LNG liquid at shockingly low temperatures (Power Up, 2024).

After arriving at its destination, LNG is kept in massive tanks at specialized terminal facilities until it is regasified and sent to the gas network or used for other reasons. These transportation and storage capacity ensure a consistent supply of this critical energy source in areas far from large natural gas resources (Kumar et al., 2011).

2.2. Environmental Performance (in life cycle perspective)

Starting with the extraction of natural gas from below-ground sources, a natural gas liquefaction (LNG) process consists in several necessary phases. After that, the gas is moved via pipes to a liquefaction plant, where it is cleaned to get rid of pollutants including sulfur, carbon dioxide and water.

The gas is cooled to roughly -162°C (-260°F) to transform it into a liquid, lowering its bulk for easier transport. Once liquefied, the LNG is kept in cryogenic tanks and transferred in specially built tankers to receiving terminals, where it is regasified and distributed through pipes for use in residential, industrial, and power generation sectors. End users finally use the natural gas for power, heating, and manufacturing.

2.3. Production pathways

The gas entering the LNG plant is processed to remove water, hydrogen sulfide, carbon dioxide, benzene and other components that can freeze under the low temperatures needed for storage or be damaging to the liquefaction facility.

Usually, LNG has more than ninety percent methane. It also includes nitrogen, some heavier alkanes, butane, ethane, and propane in minute quantities. One can arrange the purification procedure to produce practically 100% methane (Merkulov et al., 2020). A rapid phase transition explosion (RPT) is one of the hazards of LNG; this happens when cold LNG comes into touch with water.

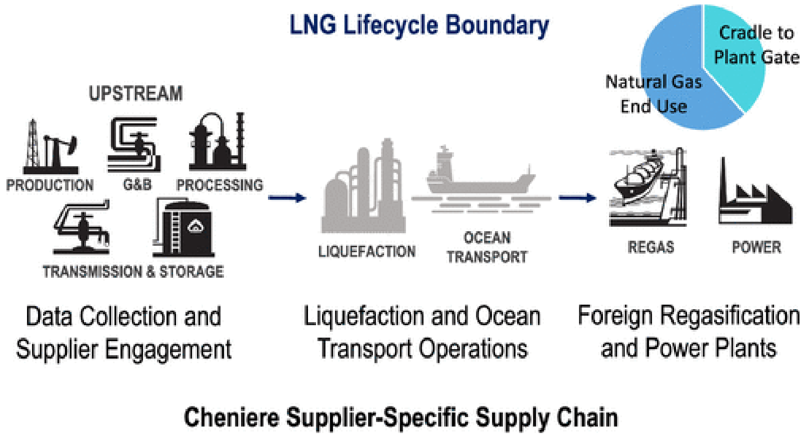


Figure 4: LNG Life Cycle (Source: https://images.app.goo.gl/2zUSF5jd4b4bnCd27)

Loaded onto ships, LNG is transported to a regasification station where it is let to expand and convert into gas. Usually linked to a storage and pipeline distribution network, regasification terminals allow independent power plants (IPPs) or local distribution companies (LDCs) natural gas to be delivered (Saraf, 2006).

2.4. Uptake as marine fuel (status and projection)

LNG has been a fuel alternative for an extended period, with initial trials dating back to the 1970s. Until a few years ago, LNG as a ship fuel was limited to LNG carriers—utilizing the boil-off gas from their cargo—and smaller boats such as ferries, offshore support vessels, and other coastal tonnage.

Recently, orders for LNG-powered large vessels have surged, initially in the cruise and container sectors, then extending to all other segments, including tankers and bulk carriers. In 2020 and 2021, orders for LNG-fueled vessels constituted a substantial portion of newbuilding gross tonnage for the first time. The increase in orders for larger vessels may catalyze a significant transformation in the sector by generating sufficient bunker demand to facilitate and enhance the development of LNG bunkering infrastructure globally.

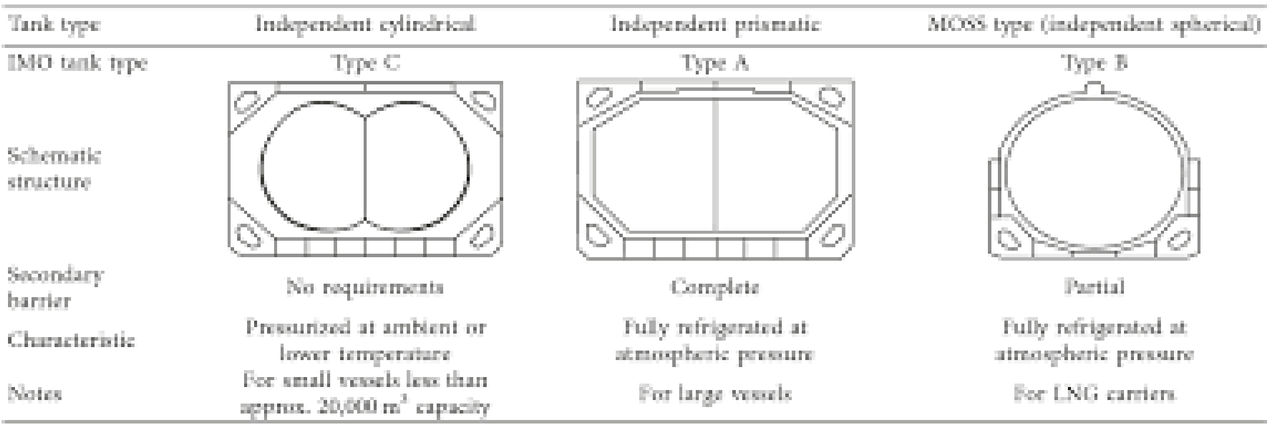
New larger vessels will bolster the bunker demand required for the development of infrastructure at key ports globally. LNG is now readily accessible along the majority of principal trade routes, with over 100 LNG bunkering options operational worldwide. Consequently, with an equivalent number in development and discourse, this will evolve concurrently with the fleet (DNV, 2023).

2.5. Technology readiness level

LNG is now regarded as a developed alternative fuel option. Numerous technological decisions must be taken based on particular vessel design and operational specifications. Making appropriate selections is crucial for achieving a competitive design (DNV, 2023).

One of the primary problems for LNG-fueled vessels is optimizing the utilization of the vessel's available area for the fuel tank and its accompanying equipment. Onboard LNG storage necessitates greater room than traditional fuel oil storage. This is mainly due to LNG's poorer energy density compared to fuel oil, necessitating a larger tank to achieve equivalent operational range. Furthermore, the low temperature of LNG necessitates greater room for tank insulation and the requisite gas handling systems.

The International Maritime Organization has delineated three fundamental, separate types of LNG tanks: Type A, Type B, and Type C. Moreover, there are membrane tanks that are completely integrated into the ship's structure.



Tank type	Independent cylindrical	Independent prismatic	MOSS type (independent spherical)
IMO tank type	Type C	Type A	Type B
Schematic structure			
Secondary barrier	No requirements	Complete	Partial
Characteristic	Pressurized at ambient or lower temperature	Fully refrigerated at atmospheric pressure	Fully refrigerated at atmospheric pressure
Notes	For small vessels less than approx. 20,000 m^3 capacity	For large vessels	For LNG carriers

Image 1: LNG TANKS (Retreved from: https://images.app.goo.gl/29Me7pZW9MjkVhy99)

The primary distinctions among the tank systems are design pressure, tank dimensions, design of the secondary barrier and tank configuration.

The IGF Code has as a crucial requirement that the system not let natural gas escape into the environment for fifteen days. Various methods for controlling tank pressure are easily available (DNV, 2023):

- Energy use by the ship (gas turbines, boilers, engines, etc.)
- Re-liquefaction
- Thermal oxidation of vapours (gas combustion unit)
- Accumulation of pressure

One of the most important decisions is the engine one choice. Two-stroke engines of both high-pressure (diesel cycle) and low- pressure (Otto cycle) are now available. While low-pressure engines have simpler designs at a rather lower investment cost, high-pressure engines offer reduced fuel consumption and nearly eliminate methane emissions. Dual-fuel and spark-ignition (gas-only) arrangements allow smaller 4-stroke engines (DNV, 2023).

2.6. Safety

The energy potential of a given volume of LNG in its gaseous form is thereby far higher than that of the same volume of natural gas (U.S. Department of Transportation, 2023). LNG's natural qualities as well as the design and operation of LNG facilities and means of transportation contribute to assure their safety (U.S. Department of Transportation, 2023).

Impoundment systems built around LNG tanks and pipelines in land-based LNG plants are meant to stop LNG from spreading should a leak happen. Installations of fire and vapor suppression systems help to lessen the effects of a release. Automatically activating firefighting and vapor suppression systems are gas detectors, fire detectors, and temperature sensors. Should a fire strike, water spray might be employed for heat impacted exposures or high expansion foam could be used to lessen radiant heat impact on exposures. Certain facilities have vapor barriers set in place to stop fumes from spreading onto nearby homes. In the case of an inner pipe release, vacuum jacketed pipe offers still another layer of protection. Devices for emergency shutdown go active when operational parameters deviate from the usual range. To guarantee the integrity of several safety systems, the operator of the LNG facility has to create and apply thorough maintenance plans (Alderman, 2005).

The LNG facility operator must create thorough policies outlining the usual running conditions for every equipment before starting operations (U.S. Department of Transportation, 2023). Changing or replacing a piece of equipment calls for all procedures to be checked and modified if needed to ensure system integrity. Every staff person has to complete courses on operations and maintenance, security, and firefighting. The operator has to cooperate with local authorities and let them know about the many types of fire control devices available inside the structure. Federal regulations also provide for tight facility security including controlled access, communications systems, enclosure monitoring, and patrols (U.S. Department of Transportation, 2023).

2.7. Ship design impact

Design of the ship has to be changed to fit the characteristics of LNG when it is used as fuel. Regarding the usage of LNG as a bunker fuel, the maritime sector has seen a surprising shift of view. The argument on the feasibility of LNG as a bunker fuel has evolved over the past few years from polite curiosity to gravely contemplating it.

Apart from LNG carriers, there are currently roughly 40 LNG-powered ships in use globally and another 40 newbuildings confirmed. Although no deep-sea LNG-fue ships are in use as of now and these figures are still somewhat small, demand for LNG powered ships - including deep-sea - is likely to rise quickly in the next couple of years. Lloyd's Register's latest bunkering infrastructure analysis projects 653 deep-sea LNG-fueled ships in use by 2025, requiring 24 million tons of LNG yearly. Under the basic case scenario with current Emission Control Areas (ECAs) and a 0.5 percent worldwide sulphur limit in bunker fuel applied from 2020, this is just The expected number of LNG-fuelled ships dropped to roughly 1,960 units in 2025 when the study assumed comparatively cheap LNG, say 25 percent lower than current market pricing.

Many ship design issues must be considered if ship owners are to turn their heads and if this turning of heads gets momentum (Balcombe et al., 2020).

Design of the ship must be changed to fit the characteristics of LNG when it is used as fuel. LNG's half density compared to diesel fuel means that the same range calls for bigger storage tanks. It is also liquid only at very low - cryogenic - temperatures (- 163°C), so it calls for storage tanks, pipe systems and handling to prevent contact with personnel and with the ship's structure. Giving the ship a second diesel fuel source helps to guarantee fuel availability. The liquid can only reveal materials unaffected by cryogenic temperatures, like stainless steel, aluminium, and Invar. LNG bunkering facilities are still not extensively accessible; hence it is advisable to give the ship a backup diesel fuel source to guarantee fuel availability. LNG can be quite volatile in gas state, particularly in an enclosed environment at the proper mix with air; so, a ventilation system is required for safety. LNG will also generally slowly evaporate when kept, so a way to deal with boil off gas is needed - venting to air is not allowed (Iannaccone et al., 2020).

2.8. Regulatory readiness

In the past few years, there has been a substantial change in the regulatory framework for the use of LNG as a marine fuel in shipping. LNG is regarded as a more environmentally friendly alternative to conventional marine fuels, and its utilization is subject to a variety of international and regional regulations (Green Voyage, 2024). The usage of LNG as a fuel in the maritime sector is much regulated by the IMO. Under the MARPOL Convention, the IMO adopted the worldwide sulphur limit on January 1, 2020, therefore lowering the allowed sulphur content in marine fuels to 0.50% (down from 3.50%). Nearly entirely free of sulphur, LNG helps shipowners follow this rule.

In Emission Control Areas (ECAs), Tier III NOx emission limits are enforced. LNG, as a fuel, can comply with these strict limits because of its lower nitrogen oxide emissions over conventional heavy fuel oils. The IGF Code provides required provisions for the machinery, tools, and systems required to manage low-flashpoint fuels, including LNG, and assures their safe running condition (Green Voyage, 2024).

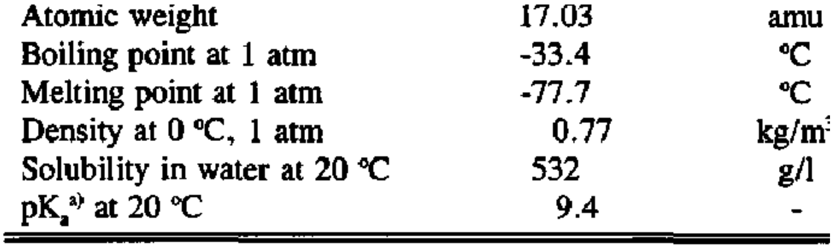
3.Ammonia

3.1. Properties of fuel

Ammonium is naturally occurring and produced by human activities. Essential for both plants and animals, nitrogen is supplied by this source. Ammonia is produced in the intestines by bacteria there (National Center for Biotechnology Information, 2024). The colorless gas ammonium has a unique smell. Because ammonia is used in window cleaning products, several household and industrial cleaners, and smelling salts—many people are familiar with this odour. Water can dissolve ammonia gas (National Center for Biotechnology Information, 2024).

Liquid ammonia or aqueous ammonia refers to this kind of ammonia. Liquid ammonia turns quickly into a gas when exposed to air. Directly applied to agricultural soil, ammonium is transformed into fertilizer for lawns, gardens, and crops. Ammonia is found in many home and business cleaners (National Center for Biotechnology Information, 2024).

Ammonia solutions are defined by the Agency for Toxic Substances and Disease Registry (ATSDR) as clear, colorless liquids with more than 35% but not more than 50% ammonia dissolved in water. It attacks metals and tissues corrosively. Though ammonia is lighter than air, the ground will first attract the vapors from a leak. Short-term high concentration exposure or long-term low concentration exposure could have harmful effects on health related to breathing. Extended duration of time of fire or heat exposure to containers could cause them to explode violently (Xu et al., 1999).



Atomic weight	17.03	amu
Boiling point at 1 atm	-33.4	°C
Melting point at 1 atm	-77.7	°C
Density at 0 °C, 1 atm	0.77	kg/m
Solubility in water at 20 °C	532	g/l
$pK_a^{a)}$ at 20 °C	9.4	-

Figure 5: Ammonia Properties

Ammonia anhydrous smells strongly and looks to be a clear, colorless gas. Frostbite may follow from direct contact with the unconfined liquid. Though gas is generally considered to be nonflammable, the addition of oil or other combustible components increases the risk of fire. It does, however, burn with strong ignition and within given vapor concentration limitations. Though they are lighter than air, vapors from a leak first hug the ground. Containers left long-term in fire or heat can cause violent rupturing and rocketing. Short-term inhalation of huge volumes or long-term low concentration vapors have harmful effects on health. Applied in manufacturing other chemicals, refrigerant, and as fertilizer (National Center for Biotechnology Information, 2024).

3.2. Environmental Performance

Conventional ways for generating ammonia from natural gas are the Haber–Bosch process, water-gas shift reaction, and steam methane reforming (SMR). Because the process runs on fossil natural gas, every metric ton of ammonia generates 2.6 metric tons of life-cycle greenhouse gas (GHG) emissions (Liu et al., 2020). Ammonia is the second most produced chemical in the world, and its production generates over 420 million tons of CO2 annually, accounting for approximately 2% of the global fossil energy consumption. Ammonia synthesis that relies on renewable energy or utilizes by-products from industrial operations is of interest in order to decrease its carbon intensity (Liu et al., 2020).

3.3. Production pathways

Since over 80% of the worldwide ammonia production is used in the manufacturing of fertilizers, mostly urea and ammonium salts, the main demand for ammonia is related with agriculture. Among the other uses are polyamides (about 5%), which are used in textiles; nitric acid (about 5%), which is used in the manufacture of explosives; and several medications and cleaning agents. Combining hydrogen (H2) and nitrogen (N2) produces ammonia mostly by means of the Haber-Bosch process. While enormous plants may have capacity of 2000–3000 t/d (European Fertilizer Manufacturers' Association, 2000), large plants usually have output capacities of 1000–1500 tons of ammonia per day (t/d).

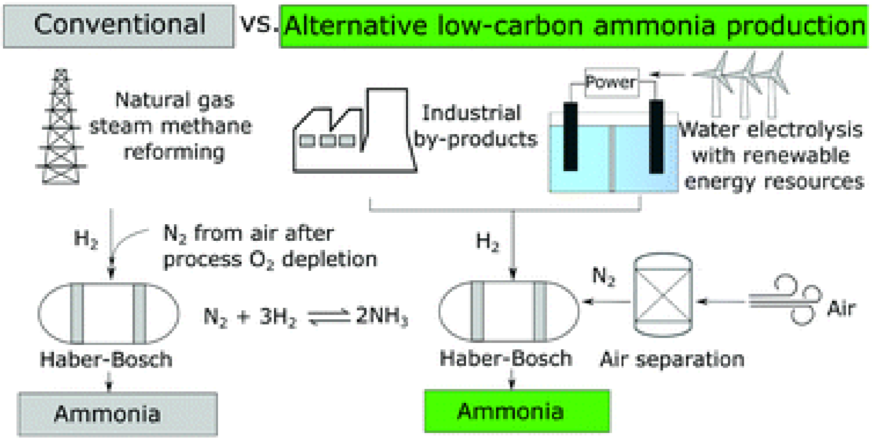


Figure 6: Ammonia Production (Source: https://images.app.goo.gl/Lk8uR9bSbd8XB5FB9)

The first stage in the manufacture of ammonia is the combining of the required reactants, N2 and H2. The process whereby the required nitrogen is taken from the air called nitrogen fixation. Many ways can produce hydrogen.

Usually running on a mix of coal, oil, and natural gas among hydrocarbon feedstocks, hydrogen is produced. Still, other paths from renewable fuels—such as biomass—are also quite sensible and have drawn a lot of interest recently. Alternatively from hydrocarbon fuels, hydrogen can also be generated electrolyzed from water and electricity.

Hydrocarbon feedstock plants' ammonia generating process consists in three primary phases. The stage of syngas production starts with the synthesis gas (syngas) generation from hydrogen, carbon monoxide, and carbon dioxide. Carbon monoxide is then transformed to raise the syngas' hydrogen concentration. The syngas purifying process subsequently eliminates acid gas, usually CO2, producing pure hydrogen. Last phase of the ammonia synthesis process creates ammonia (Jabarivelisdeh et al., 2022) when hydrogen combined with nitrogen. The hydrogen generation method used affects the green and blue ammonia value chains; green ammonia is generated by water electrolysis whereas blue ammonia is generated by a typical process utilizing natural gas but including carbon capture (Mayer et al., 2023).

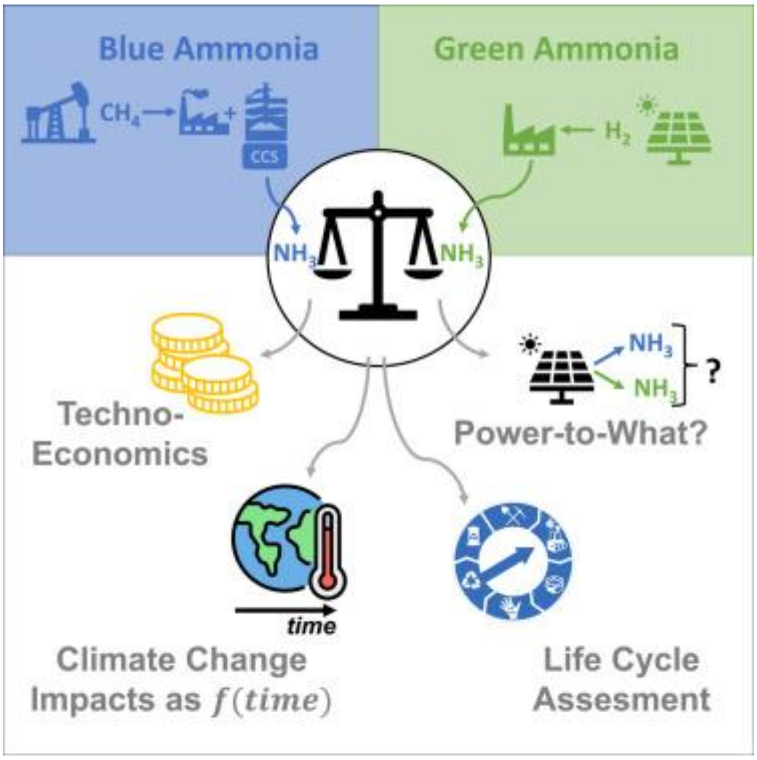


Figure 7: Green and blue ammonia production (Source: https://images.app.goo.gl/2gU3macAfsbZAuZdA)

3.4. Uptake as marine fuel

The ammonium formula is NHE. Nitrogen and hydrogen make up this chemical. It takes on a liquid state at -33C and has an energy density almost half that of bunker fuels, hence it is not necessary to keep it in high-pressure or cryogenic vessels (Jacobsen et al., 2022).

The International Maritime Organization (IMO) now controls hydrocarbon use under 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 practical sense, loading and discharging ammonia as a commodity at the port is like bunkering ammonia as a fuel (Jacobsen et al., 2022).

Still, the alternative of bunkering ammonia from cargo terminals is not a workable one. In this case, terminal access for goods could be limited, hence a lot of time is needed. To properly control ammonia, it is essential to advance the ideas of universal sailors and onshore workers able of running various kinds of engines and bunkering (Jacobsen et al., 2022).

3.5. Technology readiness level

Internal combustion engines compatible for running on ammonia (Gezerman et al., 2022) have been developed by engine makers including MAN Energy Solutions and Wärtsilä (Gezerman et al., 2022). Though they are under evaluation in controlled environments and pilot projects, these engines have not yet been extensively applied in full-scale commercial operations. There is ongoing development in the technology for safe ammonia bunkering and storage. Although ammonia has been used in sectors including fertilizers, its storage and transfer on vessels present safety, regulatory, and engineering problems currently being solved (Ghavan et al., 2021).

Not one ship in use right now runs on ammonia as fuel. Although no current vessels use ammonia propulsion, ammonium-powered engines are not commercially accessible. But two- and four-stroke ammonia-fueled engines as well as guidelines for ammonia fuel handling are under development (Bureau Veritas, 2024).

3.6. Safety

One of the main forces behind vessel design is the need to find ways to reduce the crew's exposure to the breach danger (Jacobsen et al., 2022). From idea to material selection (which protects the structures from corrosive exposure of ammonia) and finally operational measures, design and layout must be handled with great degree of safety. Currently on the market are several relevant technology and design ideas meant to control ammonia (Jacobsen et al., 2022).

Risk assessment should be given special focus on the agenda since it helps to prevent disasters. This would explain the possibility of leaks, gas detection devices, and certification all along the supply network. Furthermore, new laws and rules must be developed; existing rules could help to reinforce and grow upon each other (Jacobsen et al., 2022).

Far more poisonous than traditional fuels is ammonium. At normal temperature and pressure, this is a corrosive and combustible gas that poses a major risk to human exposure by inhalation and skin contact most likely leading to long-term consequences (Jacobsen et al., 2022). It may have similarly impact on aquatic life (Jacobsen et al., 2022). Generally speaking, personnel members onshore and aboard have to have suitable personal safety gear. Moreover, all tanks must be in perfect condition, leaks must be stopped, and gas cannot be let to escape into a small area (Jacobsen et al., 2022).

Duong et al. (2023) study testing and numerical studies using several ammonia bunkering techniques—including terminal - to - ship, ship – to - ship, and truck – to - ship transfers. Moreover, the review reveals that ammonia toxicity is more relevant for the problems of vapor cloud dispersion and ammonia bunkering than for its flammability (Duong et al., 2023). At last, the main issues and ideas for further developing ammonia as a maritime fuel as well as for ammonia bunkering are discussed. Duong et al. (2023) at last offer fresh ideas to solve the problems and research gaps linked with ammonia leakage during bunkering periods.

3.7. Ship design impact

Using ammonia as a fuel raises safety issues that can only be resolved with sufficient technological and operational measures developed together with considering human aspects. Together, the Maersk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) and the Lloyd's Register (LR) Maritime Decarbonization Hub investigated ammonia safety aboard ships.

The report claims that several mitigating strategies—including operations, crew training, and ship design—are required to keep toxicity hazards to personnel under designated tolerance limits. Ship builders have to push technological innovations if they wish to present scalable and sustainable alternative energy sources like ammonia as a marine fuel.

The atmospheric ammonia storage tank should be double-walled, double integrity, with insulation on the outer wall, and designed for an internal pressure of 14 kPa. The tank should be designed, manufactured, erected, and tested in accordance with the generally accepted API standard (Lloyd’s Register, 2023).

3.8. Regulatory readiness

The IGC Code regulates the transportation of ammonia; guidelines apply for certain of the components of the ammonia supply chain, including inland manufacturing, distribution, storage, and utilization. Still, this paradigm would need adjustments to raise ammonia's usage as a marine fuel (EMSA, 2022).

Class societies have the choice in the interim of using well-established, risk-based "alternative design" approval approaches applied for alternative fuels to help shipowners in the lack of harmonized international rules (EMSA, 2022). With the aim of lowering GHG emissions from transportation, the EU's "Fit-for-55" package of policies is planned to offer incentives and drive for shipping to use alternative low- and zero-carbon fuels, such (green) ammonia (EMSA, 2022). There are also under development other regional projects. Particularly, the International Maritime Organization (IMO) is now working on the development of fuel lifecycle analysis rules for the computation of fuel emissions as well as other technical and market-based solutions considering ammonia and their renewable production paths (Schinas & Stefanakos, 2014). Strengthening of the current regulatory framework, which may involve the creation of ISO standards for bunkering and couplings, as well as additional work on unified requirements by IACS as necessary (EMSA, 2022) will help ammonia to be adopted as a maritime fuel (EMSA, 2022).

Reiterating its dedication to assessing and enhancing the IMO's Initial Strategy for lowering GHG emissions from shipping, the Marine Environment Protection Committee (MEPC) at its 78th session MEPC 79 assessed several concepts on the use of biofuels and biofuel combinations as well as NOx compliance. MEPC 78 approved a single interpretation of MARPOL Annex VI regulation 18.3, therefore enabling the NOx compliance process for blends including up to 30% biofuels. To let IMO Member States control discharge water from EGCSs used to comply with the MARPOL Annex VI global sulphur limit in marine regions under their jurisdiction, the EU has proposed (MEPC 80/5/5) draft legislative modifications to MARPOL Annex VI (IMO, 2022).

4.Biofuels

4.1. Properties

Transportation fuels generated from biomass, such ethanol and biodiesel, are "biofuels". Usually mixed with petroleum fuels—more especially, gasoline and diesel fuel—these fuels can also be used by themselves. Furthermore cleaner-burning fuels that produce less air pollution are ethanol and biodiesel. Rising environmental issues and limited petroleum supplies have drawn a lot of interest for it. Trans esterification creates biodiesel fuel using recycled cooking oils, animal fats, or renewable vegetable oils. Biodiesel is the alternative fuel experiencing fastest global expansion. Made from potatoes peels, rice, sugarcane, sugar beets, yard clippings, fermenting cereals like corn, sorghum, and wheat as well as ethanol is a type of alcohol fuel (Eagri, 2024).

The following define some of the qualities of the effective biodiesel:

A.Kinematic viscosity

B.Density

C.Calorific value

D.Melting or pouring point

E.Cloud point

F.Flash point

G.Acid value

H.Iodine value

I.Cetane number

J.Stability - oxidative, storage, and thermal

K.Carbon residue

L.Ash %

M.Sulfur percentage

Kinematic viscosity: Viscosity informs about flow characteristics and fluid deformation under pressure. Viscosity affects fuel atomizing and injector lubrication. Low viscosity fuels could not be sufficient lubricant for the exact fit of fuel injection pumps, which would cause leaks or more wear. Additionally impacting fuel atomization is fuel viscosity (Eagri, 2024). High viscosity diesel fuels often produce bigger droplets upon injection, which causes ineffective combustion, more emissions and exhaust smoke.

Density: Density is weight expressed per unit volume. Denser oils carry more energy. For instance, diesel is denser and hence generates more energy per liter even if petrol and diesel fuels offer equivalent energy by weight. Although diesel weights 835 kg/m3, biodiesel is sometimes denser than diesel fuel; sample values range from 877 kg/m3 to 884 kg/m3. Therefore, the density of the last product is mostly influenced by the employed feedstock (Rodionova et al., 2017).

Calorific value: Heating value, also known as heat of combustion, is the quantity of heating energy created during the burning of a unit value of fuel. Moisture content is a key factor in determining heating value. However, liquid biofuels have bulk densities that are comparable to those of fossil fuels.

Melt or pour point: This is the temperature at which oil in solid form begins to melt or pour. If temperatures dip below the melting point, the entire fuel system, including all fuel lines and the fuel tank, must be heated.

Cloud point: Cloud point refers to the temperature at which an oil begins to harden. Heating is required when driving an engine at temperatures below an oil's cloud point to prevent gasoline waxing (Eagri, 2024).

Flashpoint (FP): Diesel fuel's lowest temperature at which it will ignite—that is, flash—in the presence of an ignition source is its flash point temperature. A fuel's flash point inversely varies with its volatility; so, safe and appropriate diesel fuel handling depends on minimal flash point temperatures. The flammability of a substance depends on its flash point. With a flash point of 150°C, neat biodiesel's is far higher than that of diesel fuel derived from petroleum (±70°C).

Acid value: The total acid value indicates the existence of free fatty acids generated during oil degradation and combustion. It can also be caused by incorrect manufacture, such as residual catalyst or excessive neutralization.

Iodine value: The iodine value is an index of the number of double bonds in biodiesel, and thus a metric that quantifies the degree of unsaturation. It is expressed in terms of the amount of iodine that will react with 100 grams of fat or oil under specific conditions. It represents the amount of iodine absorbed by 100 grams of a specific oil. It is often used to assess the chemical stability features of various biodiesel fuels against such oxidation.

Aniline point / Cetane number (CN): It is a relative measure of the time between the start of injection and the fuel's automatic igniting. The higher the cetane number, the shorter the delay time and the greater the combustibility. In general, diesel engines perform better on fuels with Cetane numbers greater than 50. Cetane number is typically determined directly with a test engine. Cetane tests give information on the ignition quality of diesel fuel. No. 2 diesel fuel typically has a cetane rating of 45 to 50, whereas vegetable oil ranges from 35 to 45. Biodiesel typically contains 50-60%.

Biodiesel's chemical nature of fatty acids and methyl esters causes it to age faster than petroleum diesel fuel (Rodionova et al., 2017). Typically, biodiesel has fourteen different forms of fatty acid methyl esters. The individual percentage of these esters in the gasoline influences the final qualities of biodiesel. Poor oxidation stability can induce fuel thickening, gum formation, and sedimentation, all of which can lead to filter clogging and injector fouling. Thermal degradation happens at high temperatures and destroys hyper peroxide in gasoline faster than oxidative degradation. Biodiesel and biodiesel blends are significantly more thermally stable than diesel. Biodiesel and its blends should not be kept in a storage tank or vehicle tank for longer than six months. The use of appropriate antioxidants is recommended based on the storage temperature and other factors (Sivaramakrishnan et al., 2012).

Carbon residue: This refers to the tendency of gasoline to generate carbon deposits in an engine. The carbon residue is an essential measure of biodiesel quality since it contains glycerides, free fatty acids, soaps, polymers, and the remaining catalyst. Ash percentage is a measure of the metal content of the fuel. High quantities of these compounds can lead to injector tip clogging, combustion deposits, and injection system wear. The ash content is crucial for the heating value since it lowers as ash content increases. Biofuels often have lower ash content than most coals, and their sulphur concentration is substantially lower than many fossil fuels.

Sulfur percentage: The percentage by weight of sulfur in diesel fuel is limited by law to very low percentages. Many studies argue that pure biodiesel is basically sulphur-free, making it an ultra-low sulphur fuel (Eagri, 2024).

4.2. Environmental Performance

Life-cycle assessment (LCA) studies of biofuels have lately attracted a lot of interest in order to guide the formulation of biofuel policies. The variation in results makes it difficult to derive overall generalizations from the corpus of research. This variable has real-world variances, data problems, and methodological choices among other explanations. Analyzing 67 LCA studies released between 2005 and 2010, van der Voet et al. (2010) investigate the complex roots of variations in results related with LCA technique in their 2014 study.

Coproduct allocation is a significantly important and notably challenging issue to address. Various allocation methodologies, all sanctioned by the International Organization for Standardization (ISO) standard for Life Cycle Assessment (LCA) studies, can result in improvement percentages relative to fossil fuels ranging from negative values to over 100%. The management of biogenic carbon is a significant concern. Most studies exclude both the extraction and emission of biogenic CO2; nevertheless, other life cycle assessments incorporate both factors, resulting in significantly divergent conclusions about the greenhouse gas performance of biofuel systems (van der Voet et al. 2010).

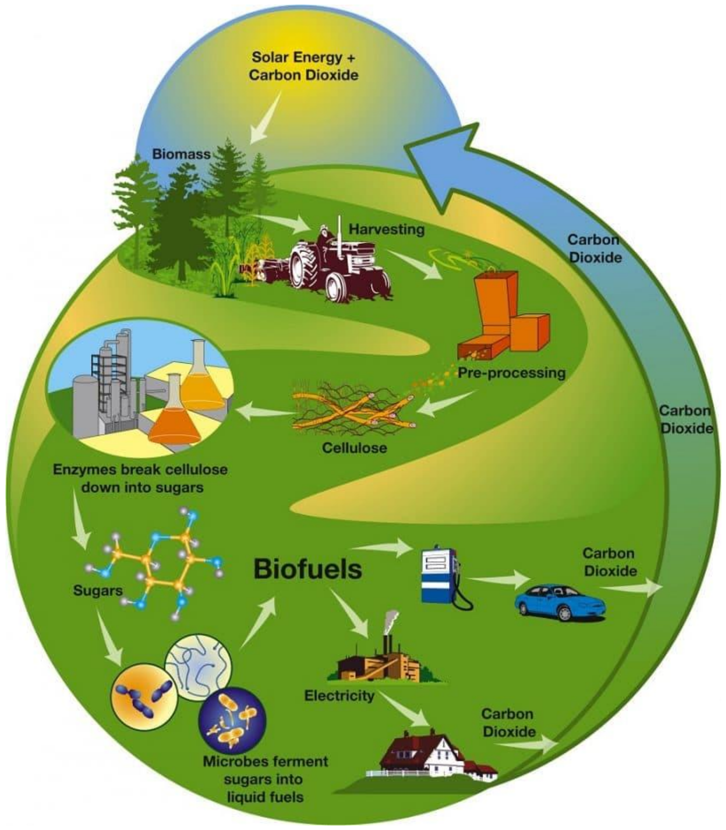


Figure 8: Biofuels Life Cycle (Source: https://images.app.goo.gl/MseJk5XaKpZddpsb6)

4.3. Production pathways

Biomass energy consists of biogas, liquid biofuels (biodiesel, ethanol, methanol, butanol), and solid biofuels (usually wood, but any substance burned to generate energy from heat). Solid biofuels may be burned directly to generate energy, whereas biogas and liquid biofuels require a conversion procedure to produce useful fuel (Rodionova et al., 2017).

There are various techniques that convert biomass into fuels that power houses, fuel automobiles, and meet other energy requirements. Biomass processing is determined by the type of biomass (e.g., manure or oilseed crops) and the intended use. The three primary ways for obtaining energy from biomass are (USDA, 2022):

1.Direct consumption: Direct consumption involves burning solid fuel to power generators.
2.Anaerobic Digestion: Anaerobic digestion is the process of decomposing bacteria. In this procedure, bacteria decompose moist waste without being exposed to oxygen, producing methane gas.

3.Conversion of liquid or gaseous fuels.

The National Renewable Energy Laboratory provides a detailed explanation of how biomass can be converted into biofuels. Both direct consumption and bacterial decomposition produce energy that can be utilized to generate heat for generators. Biofuels must be transformed from their original state before being used as liquid or gaseous fuels. The most simple method is to ferment sugary (starch) or fat-rich crops into ethanol, which may then be blended directly with gasoline to power cars. In the Northwest, oilseed crops such as canola and sunflowers are utilized to produce biofuel. Energy producers employ a two-step process to deconstruct plant cell walls into their most basic chemical form, followed by synthesis and upgrading. The first process, deconstruction, degrades the biomass into its most basic components and can occur at either low or high temperatures (Rodionova et al., 2017).

Low-temperature deconstruction involves hydrolysis, a process in which biomass is chemically or physically processed to open the structure of plant cell walls before being broken down with chemicals or specific proteins to produce fuels or compounds that can be converted into fuels. The second stage, synthesis and upgrading, involves rebuilding these components into useful fuel (liquid or gas). There are numerous methods of synthesis and upgrading, which differ depending on the products of deconstruction and the chemicals being produced (USDA, 2022).

4.4. Uptake as marine fuel

Vegetable oils are the main raw source of biomass, the renewable energy obtained from biological organisms (Class NK, 2024). Biofuels are sometimes considered carbon neutral since the carbon dioxide (CO2) they do generate during combustion is absorbed by source plants, etc. during their growth stage; they also do not emit sulfur oxides (SOx). Moreover, depending on the type of fuel used, biofuel use can be beneficial when used as a drop-in marine fuel since current marine diesel engines converted to biofuel do not usually require changes. These factors have driven an increasing number of biofuel studies in recent years, which has correspondingly raised biofuel-related problems (Class NK, 2024).

Although they are typically regarded to produce zero CO2 emissions—that is, they are carbon neutral—biofuels emit CO2 when burned. This is so because the CO2 emitted into the atmosphere is subsequently absorbed by plants and other creatures during their growing stage. Nevertheless, the IMO is now developing a method for assessing the CO2 reduction effect of biofuel in life cycle accounting in order to consider the GHG emission reducing effect (conversion factor in IMO EEDI and EEXI, as well as emission factor in IMO DCS and CII) of ships using biofuels. Approved is interim guidance (MEPC.1/Circ905) on the use of biofuels under IMO DCS and CII (Class NK, 2024).

4.5. Technology readiness level

Biofuels appear to be a simple decarbonization solution for transportation. They are suited for all vessel types, large or small, deep-sea or short-sea, gas- or liquid-fueled, without requiring considerable modifications. Biofuels or blended biofuels are both lower carbon alternatives to fossil fuels from a well-to-wake standpoint. Similarly, because they can be generated anywhere over the world and present no significant obstacles for bunkering, initial infrastructure would not be a large challenge (Bureau Veritas, 2023).

4.6. Safety

Grain, plant biomass, vegetable oils, processed municipal and industrial waste are among the renewable materials used to generate biofuels. They are flammable or combustible, hence the manufacturing process could contain hazardous chemical reactions. Companies have to guard their staff against the risks associated with these fuels and their production techniques (OSH Academy, 2024).

Potential dangers in biofuel production and handling include the following (OSH Academy, 2024):

1. Fire and explosion hazards of Biofuels
2. Chemical reactivity risks during manufacturing.
3. Toxicity Risks in Biofuel Manufacturing

These hazards are in addition to common workplace hazards such as walking/working surfaces, electrical hazards, and other comparable risks. There have been biofuel-related mishaps that resulted in fatalities and injuries from burns, explosions, and toxic exposures.

4.7. Ship design impact

Though they are thought to be somewhat easy to use, improper handling of biofuels could cause harm to equipment on board a ship. The lack of long-term testing means that knowledge regarding biodiesels and bioliquids is lacking as well as their fit with present onboard systems.

Biofuels must thus be assessed individually to guarantee that the fuel specification and quality are suitable for the intended uses of the vessel.

Shipping is regarded as a difficult to abate sector, and many in the business believe that it should be prioritized for biofuel supply above other sectors such as road transport, because to the difficulties involved in, for example, electrifying the maritime fleet. Over the next decades, biofuels should be rather important for shipping. Shipping cannot rely just on biofuels, nevertheless, to reach its decarbonizing targets given limited production capacity and industry competitiveness. The marine sector will thus keep looking for fresh approaches to achieving net zero emissions (DNV, 2023).

4.8. Regulatory readiness

The use of biofuels may be subject to fuel oil quality regulations under Reg. 18.3 of MARPOL Annex VI, in addition to requirements applicable to traditional petroleum-based fuel oils. Regarding the applicability of Reg. 18.3, MARPOL Annex VI, fuel oil obtained from petroleum refining is subject to Reg. 18.3.1. Meanwhile, Regulation 18.3.2 of MARPOL Annex VI applies to fuel oil obtained from processes other than petroleum refining. For biofuels, the implementation of MARPOL Annex VI Regulations 18.3.1 or 18.3.2 is dependent on parameters such as biofuel mix ratio and engine modification/adjustment. In terms of biofuels, MEPC 78 accepted a Unified Interpretation (UI) that explains the application of MARPOL Annex VI Regulations 18.3.1 and 18.3.2. MEPC79 also approves UI modifications that include synthetic fuels in the applicable scope (ClassNK, 2024).

A fuel oil containing no more than 30% by volume biofuel or synthetic fuel must meet the criteria of MARPOL Annex VI Regulation 18.3.1. (That is, such fuel oil is not subject to Reg. 18.3.2.2, which states that "fuel oil...shall not cause an engine to exceed the applicable NOx emission limit...".) In addition, a fuel oil containing more than 30% by volume of biofuel or synthetic fuel must comply with MARPOL Annex VI Regulation 18.3.2. For the application of Reg. 18.3.2.2, "fuel oil...shall not cause an engine to exceed the applicable NOx emission limit..." should be construed as (ClassNK, 2024):

(i) Where a marine diesel engine can run on biofuel, synthetic fuel, or blends containing these fuels with no changes to its NOx critical components or settings/operating values other than those specified in that engine's approved Technical File, such a fuel oil should be permitted to be used without undergoing the assessment required by Reg. 18.3.2.2.

(ii) Where a marine diesel engine can run on biofuel or synthetic fuel, or blends containing these fuels, with changes to its NOx critical components or settings/operating values that differ from those specified in the engine's approved Technical File, such a fuel oil must undergo the assessment required by Reg. 18.3.2.2. For the assessment, an onboard simplified measurement method based on NTC 2008 6.3 is offered. In addition, an allowance of 10% of the applicable limit may be granted for potential deviations when conducting measurements on board.

5.Hydrogen

5.1. Properties of fuel

Hydrogen (H) is the simplest gaseous substance in the chemical element family, being colorless, odorless, tasteless, and flammable (Lubitz & Tumas, 2007). The hydrogen atom's nucleus consists of one proton with a positive electrical charge and one electron with a negative electrical charge. Under normal conditions, hydrogen gas is a loose collection of hydrogen molecules, each of which is made up of two atoms, forming a diatomic molecule called H2. Although hydrogen is the most abundant element in the universe (three times more abundant than helium, the next most abundant element), it makes up only around 0.14 percent of Earth's crust by weight (Lubitz & Tumas, 2007). It does, however, occur in huge quantities as part of the water in oceans, ice caps, rivers, lakes, and the atmosphere. Hydrogen is contained in every animal and vegetable tissue, as well as petroleum, as a component of a variety of carbon compounds. Even though it is frequently stated that carbon compounds are more well-known than any other element, hydrogen compounds may be more numerous because hydrogen is found in almost all carbon compounds and forms a wide range of compounds with all other elements (except some noble gases) (Lubitz & Tumas, 2007).

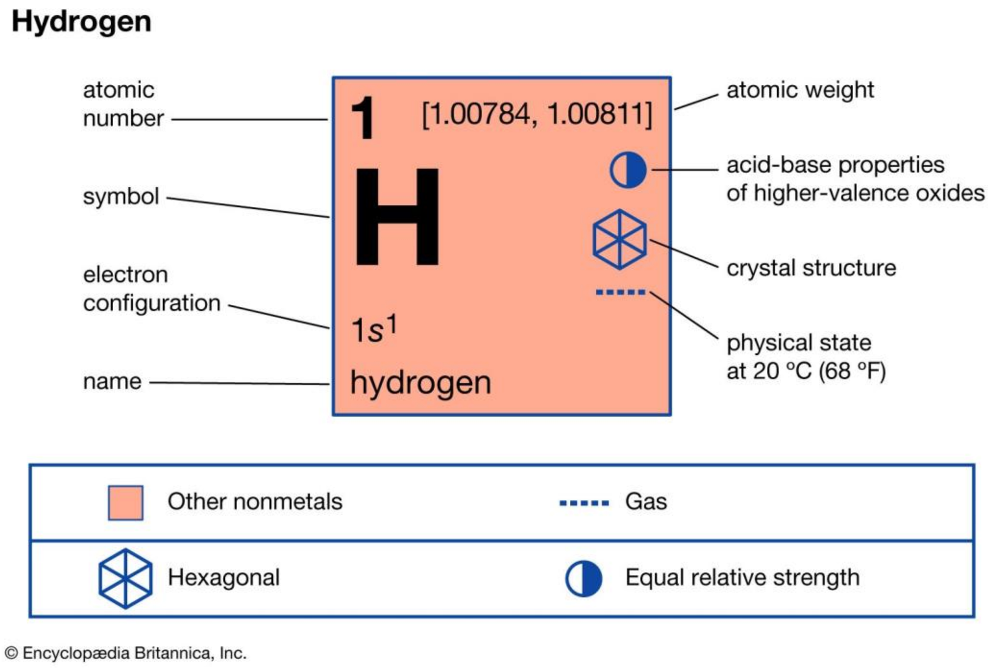


Figure 9: Hydrogen Properties (Source: https://images.app.goo.gl/NJ7GERcgwyrU7Sbj7)

The primary industrial application of elementary hydrogen is the production of ammonia (a hydrogen-nitrogen molecule, NH3) as well as the hydrogenation of carbon monoxide and organic compounds (Ramachandran et al., 1998). Hydrogen has three recognized isotopes. Hydrogen isotopes have mass numbers of 1, 2, and 3, with the mass 1 isotope, also known as protium, being the most abundant (Gourcy et al., 2005). The mass 2 isotope, known as deuterium or heavy hydrogen (symbol D or 2H), has a nucleus of one proton and one neutron and makes up 0.0156 percent of the regular hydrogen mixture (Gourcy et al., 2005). Tritium (symbol T, or 3H), with one proton and two neutrons in each nucleus, is the mass 3 isotope and accounts for approximately 10−15 to 10−16 percent of hydrogen. The practice of assigning separate names to hydrogen isotopes is justified by their significant differences in characteristics (Jolly, 2024).

Little attraction between molecules causes the rather low melting and boiling points. The fact that hydrogen gas expands from high to low pressure at ambient temperature increases its temperature while most other gases drop shows the presence of these weak intermolecular interactions (Jolly, 2024). Thermodynamic ideas hold that repulsive forces exceed attraction forces between hydrogen molecules at normal temperature; else, the expansion would cool the hydrogen. Attractive forces take front stage at −68.6° C, which causes hydrogen to cool when expanded below this temperature. The cooling effect is sufficient at temperatures below liquid nitrogen (−196° C) to attain the liquefaction temperature of hydrogen gas (Jolly, 2024).

Hydrogen is transparent to visible, infrared, and ultraviolet light with wavelengths under 1800 Å. Because its molecular weight is smaller than that of any other gas, its molecules move quicker at a given temperature and disperse more quickly. As a result, hydrogen distributes kinetic energy quicker than any other gas, and it has the highest heat conductivity (Jolly, 2024).

5.2. Environmental Performance

The analysis of the life cycle of hydrogen generation offers significant fresh angles on the many environmental consequences related with distinct strategies. Particularly steam methane reforming (SMR), technologies derived from fossil fuels greatly increase carbon emissions, which stresses the importance of moving to better and more sustainable energy sources. Less greenhouse gas emissions mean that the ecologically friendly substitute offered by the development of solar or wind-powered electrolysis is desirable. As the global energy industry strives to replace depleted fossil fuels, hydrogen is a vital carbon-neutral, high-energy-density replacement (Osman et al., 2024).

It is vital to appreciate the delicate balance between achieving zero-carbon operations and reducing the environmental impact of the extensive infrastructure required for renewable energy production. The life cycle analysis shows potential burden-shifting within environmental effect categories, underlining the significance of complete evaluations to support long-term decision-making in the changing context of hydrogen production (Valente et al., 2017).

Furthermore, biohydrogen production from waste represents a promising and environmentally friendly energy alternative. By exploiting biowaste and biomass, it provides a long-term supply of hydrogen while addressing waste management concerns. Despite the environmental consequences of production, ongoing research and technological improvements improve efficiency and mitigate these negative effects. The economic viability of creating biohydrogen from trash is improving, making it a more appealing alternative for a sustainable energy transition (Osman et al., 2024).

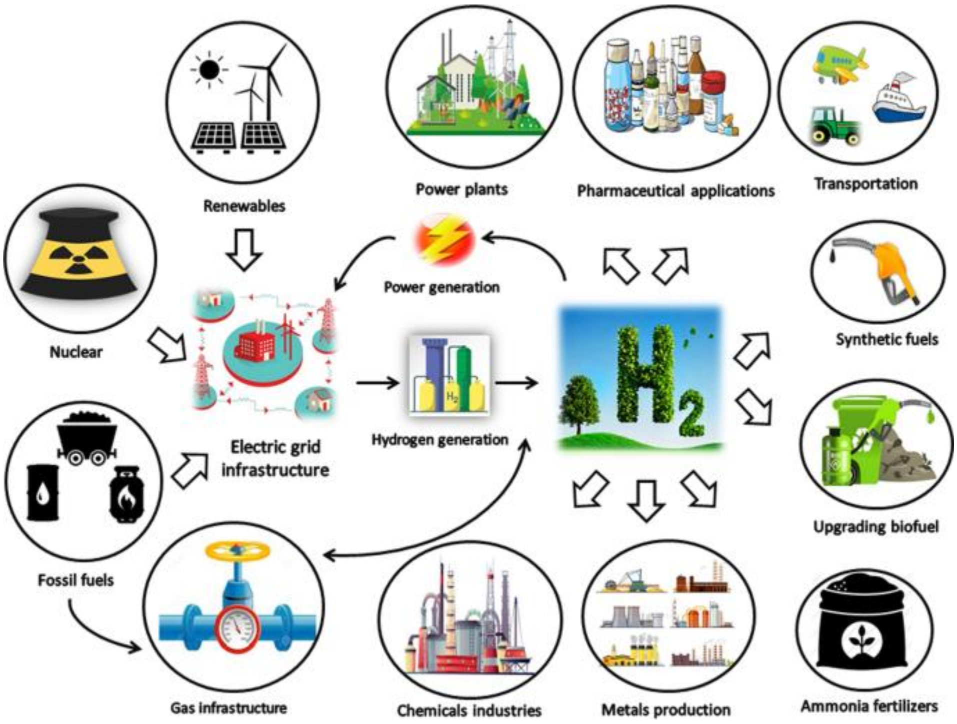


Figure 10: Hydrogen Life Cycle (Source: https://images.app.goo.gl/G3eC4t64bs1NhbYD7)

Fuel cells or single-fuel internal combustion engines can run hydrogen as a zero-carbon maritime fuel. In a dual-fuel combustion engine, hydrogen use can greatly lower carbon emissions. Low tank-to-wake (TTW) emissions of hydrogen are well-known; these help to explain the emissions produced by any energy source. Nevertheless, the whole life cycle of hydrogen generation has to be assessed in order to estimate the total greenhouse gas emissions related with hydrogen. Generation of hydrogen from fossil fuels could not produce less carbon and greenhouse gas emissions (ABS, 2021).

Well-to-tank (WTT) emissions are all pollutants produced during the fuel production, storage, and transportation operations to the end consumer. This includes emissions from the processing of coal or natural gas to produce hydrogen, as well as fossil fuels used to provide grid energy for hydrogen generation via electrolysis.

Prioritizing carbon-neutral production, storage, and transportation solutions helps one remove hydrogen emissions before fuel delivery. Low well-to--tank emissions can be obtained by producing hydrogen using renewable, "green" technologies that lower upstream carbon and greenhouse gas emissions. Zero-carbon WTW fuel results from removing WTT and TTW emissions from the fuel life cycle. In the hydrogen market, sustainability verification systems or guarantees of origin (GO) certificates—like the EU CertifHy project—can be applied to monitor and measure emissions related with hydrogen generation. Though they are not now mandated by the IMO, such plans can be adopted at the regional or national levels (ABS, 2021).

5.3. Production pathways

There are essentially three main ways to produce hydrogen: blue, green, and purple. Blue hydrogen reduces carbon emissions by using coal gasification or natural gas in concert with carbon capture and storage (CCS). On the other hand, green hydrogen is created by electrolysis of renewable energy sources like solar or wind electricity, therefore stressing a sustainable and environmentally beneficial approach (Dash et al., 2023; Ishaq et al., 2022). Originally a relatively new concept, purple hydrogen combines carbon capture and storage (CCS) to reduce any leftover emissions with blue and green approaches by using renewable energy for manufacture. Particularly for green hydrogen, the cost connected with hydrogen production is a significant obstacle. Steam reformation produces around three times more expensive than natural gas per energy unit. Nearly twice the cost of natural gas-based methods, electrolysis—using electricity—incurs a cost of about 5 cents per kilowatt-hour.

Recent reports, such as the one from Renewable World Energy, indicate that the United States may offer wind energy at an unprecedented low price of 2.5 cents per kilowatt-hour. This might render hydrogen generation power four times less expensive than that derived from natural gas. Notwithstanding financial obstacles, hydrogen can be amalgamated with natural gas for more efficient transmission via existing pipes. Furthermore, this amalgamation may mitigate CO2 emissions from existing natural gas reforming facilities (Ishaq et al., 2022).

Biohydrogen, a carbon-free and high-energy-dense fuel, presents potential for clean energy generation; yet, its complexity presents obstacles for optimization (Alagumalai et al., 2023). It is produced biologically via methods such as fermentation, biophotolysis and microbial electrolysis cells, employing biowastes to minimize expenses and environmental contamination. This sustainable strategy also tackles trash management and land contamination concerns. Biohydrogen, with its potential to be sourced from inexhaustible resources such as garbage, attracts significant attention as a prospective energy carrier (ABS, 2021).

Production of biohydrogen mostly uses microbial electrolysis. Thanks to their sustainability and economy, photobiological, dark fermentation, and photofermentative technologies—which use biological organisms for hydrogen generation—have become rather popular. Effective conversion of complicated organic feedstock into fermentable glucose is the key determinant of affordable biohydrogen generation. Different biomass types necessitate different pretreatment methods; for lignocellulosic materials, for example, their complex composition of cellulose, hemicellulose, and lignin calls for considerable pretreatment (Osman et al., 2024). Three well-known reformation techniques—steam reforming, which uses water as an oxidant and hydrogen source; partial oxidation, which uses atmospheric oxygen and a catalyst; and autothermal reforming, which combines the first two (ABS, 2021)—hydrogen is generated from natural gas.

In all cases, syngas (carbon monoxide and hydrogen) is produced and then converted into hydrogen and carbon dioxide via the water-gas shift reaction. To reduce the carbon intensity of fossil-fuel hydrogen production, renewable and sustainably sourced biomass can be used to make syngas by gasification (ABS, 2021). Nuclear facilities can also be used to manufacture hydrogen by steam reformation of methane or high-temperature thermochemical processes, eliminating hydrogen generation methods based on fossil fuel burning. Alternatively, electricity can be used to electrolyse water. Electrolysers work like inverted fuel cells, converting water and energy into hydrogen and oxygen gasses. This process can manufacture green hydrogen from renewable energy sources such as wind, solar, and nuclear power. In this case, hydrogen can be viewed as an electro-fuel with a zero-carbon footprint from its production (Knight et al., 2023).

Alternative hydrogen production methods include high-temperature water splitting, photobiological water splitting, and photoelectrochemical water splitting; however, these technologies are not currently used for large-scale hydrogen synthesis. When comparing alternatives to electrolytic hydrogen generation, it is critical to understand that the extreme purification required to obtain grade 4.5 purity (i.e., 99.995% pure) for proton exchange membrane (PEM) fuel cells may raise production costs. Mono-fuel and dual-fuel combustion engines, on the other hand, do not require considerable purification and can handle diluents (such as methane, carbon dioxide, or carbon monoxide) that would otherwise severely damage a PEM fuel cell (Knight et al., 2023).

Nevertheless, despite possible trade-offs like more emissions, lower running efficiency, and higher temperatures, this purity criterion might not be a problem in other fuel cells, such solid-oxide fuel cells (SOFC) (Knight et al., 2023). The only life cycle emissions from hydrogen generated and consumed in an emission-free way are from storage and transit throughout distribution as well as any required carrier conversion operations. Comparing hydrogen to other marine fuels, at 120.2 MJ/kg it has the highest energy content per mass of any chemical fuel. Mass energy wise, it beats MGO by 2.8 and alcohols by 5–6. Hydrogen fuel can thus increase the running efficiency of an engine and lower particular fuel usage at the same time (Knight et al., 2023).

Nonetheless, due to its lower volumetric energy density, liquid hydrogen may require four times the space of MGO or around double the space of LNG for a comparable energy capacity. When comparing fuel energy and required quantities, it is also important to consider the consumer's energy efficiency as well as electrical energy losses in fuel cells (Tashie-Lewis et al., 2021).

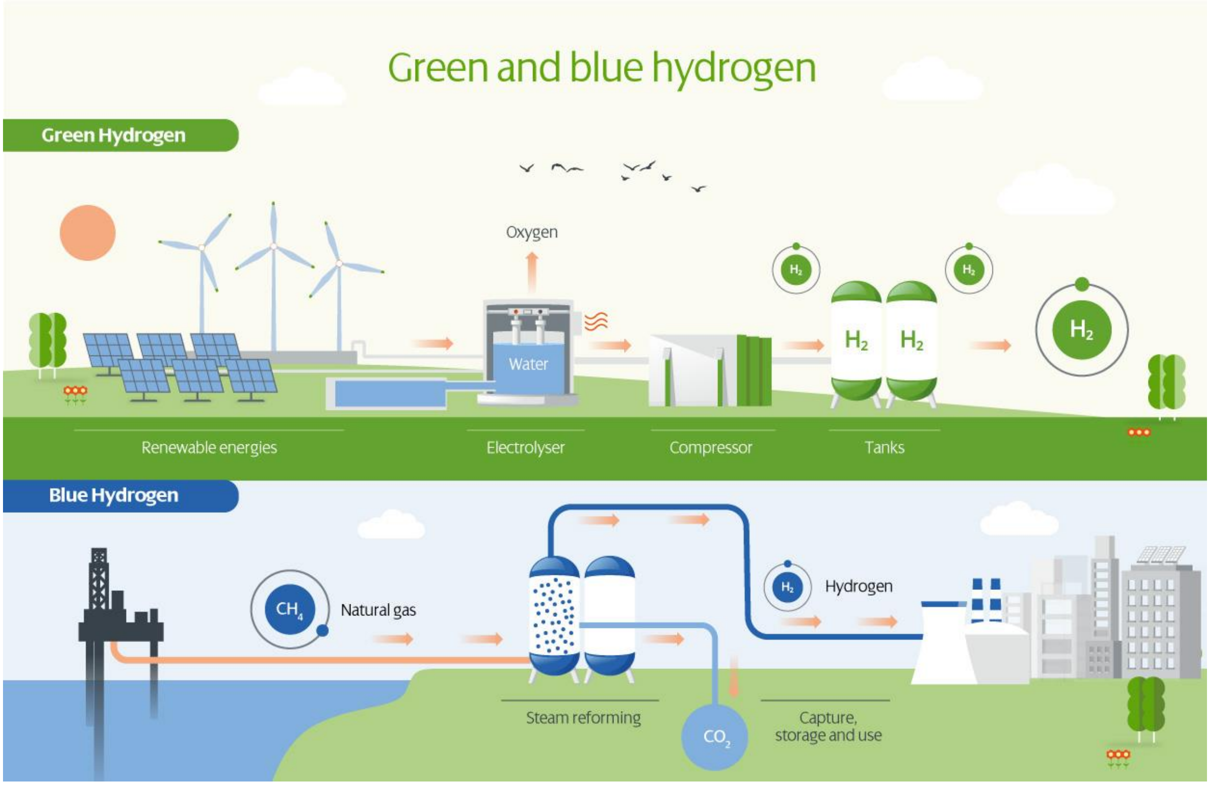


Figure 11: Green and blue hydrogen production (Source: https://images.app.goo.gl/CigGNSuLgi3GAR1B9)

5.4. Uptake as marine fuel

Extra fuel quantities may be needed for all marine fuels to offset tank to output shaft power efficiency losses. Temperatures must be below -253°C (- 424.4°F if hydrogen is to liquefy). Accounting for the required layers of materials, vacuum insulation for cryogenic storage, and other structural designs helps one to considerably increase the required space for liquid hydrogen storage in view of the very low temperature. Other materials, notably metal hydrides, can also hold hydrogen. This storage system links hydrogen with metal alloys in a porous and loose structure using little pressure and heat. Then pressure and heat release help to remove hydrogen. While metal hydride and alternative hydrogen storage methods using solid materials may not be a weight-efficient solution for onboard hydrogen storage in ships, technologically viable and safe methods may not be either. Hydrogen could be provided inside molecules like ammonia or methanol (ABS, 2021) given the issues with low-temperature or high-pressure storage (ABS, 2021).

These fuels could need less energy than either compressing gaseous hydrogen or cooling liquefied hydrogen. Once internal reformers have produced hydrogen, some fuel cells can use ammonia, methanol, or another hydrogen carrier fuel. However, these methods could need more energy for fuel reforming and hydrogenation, hence their electrical generating efficiency could be less than that of direct containment and use of pure hydrogen in fuel cells (Raucci et al., 2015).

Many finished and current fuel cell studies aim to assess and raise their energy efficiency. Each of the several fuel cells available has running and cost problems; examples include alkaline and solid oxide fuel cells (SOFC). Usually shown by the proton exchange membrane fuel cell (Raucci et al. 2015), these cells employ hydrogen and oxygen to produce heat, water, and electricity.

Combining hydrogen with a compatible fuel is known as hydrogen fuel blends. Hydrogen and LNG is the most often used combination since it can lower the greenhouse gas impact and exhaust gas emissions (ABS, 2021). Diesel fuel can be co-combusted with hydrogen; depending on the ratios used, exhaust gas aftertreatment technology may be required to lower nitrogen oxide (NOx) emissions. Peak engine performance (ABS, 2021) may require further small tweaks to engine timing and management systems.

5.5. Technology readiness level

Two to three times more hydrogen fuel applications store hydrogen gas in pressure tanks ranging from 350 to 700 bar (about 5,000 to 10,000 psi), than industrial hydrogen storage, which is typically limited to 200 bar (about 3,000 psi). Depending on the method or material used for tank insulating and strength, insulated pressure tanks can be used to increase the density of gaseous hydrogen between ambient and cryogenic temperatures (- 253° C) as well as atmospheric and high pressures. Cryocompressed hydrogen (ABS, 2021) is hydrogen retained in insulated pressure containers. Liquefied hydrogen tanks may develop pressure. If temperatures rise at low pressures; the liquid hydrogen then starts to evaporate and boil off. Consequently, pressure relief valve designs should be included into gaseous and liquid hydrogen tanks to stop pressure accumulation if needed. Cryogenic tanks may need substantially more insulation layers — two or three times the thickness of thermal insulation in a Type C LNG tank — because of the very low temperatures that they reach.

Liquefied hydrogen could likewise be kept in a Type C tank with vacuum - insulation. Any system should be completely free of air, oxygen, and other oxidizers before adding liquid hydrogen. Before entering the environment, the system must also run low in hydrogen (Van Hoecke et al., 2021). This process helps to stop the formation of harmful gas combinations. With its cryogenic temperature, liquid hydrogen is quite hazardous. When ordinary air gases, including nitrogen and oxygen, come into touch with cryogenic liquid hydrogen, they will either solidify or liquefy, perhaps causing fuel contamination or unwelcome accumulation. Liquid hydrogen systems (Guan et al., 2023) should be purged using inert and nonreactive noble gas helium. Evacuations in gaseous hydrogen systems with temperatures above -193°C (or -316°F) can be produced from a noble gas or nitrogen. Hydrogen's small molecular size allows it to distribute across materials, breaking through containment system walls and over time infiltrating some fluids or other solid materials to reach concentration equilibrium (Van Hoecke et al., 2021). It is important to store hydrogen in materials meant to restrict hydrogen loss and permeability. Hydrogen embrittlement may affect some metallic materials and equipment subjected to hydrogen gas. These might comprise tank interior surfaces, weldments, pipes, valves, gasoline nozzles, and pressure relief valves or pipes (Van Hoecke et al., 2021).

When a metal absorbs hydrogen and gathers it at grain boundaries, a metal experiences hydrogen embrittlement — that is, weak areas. Brittle failure mechanics, minuscule fractures, material defects, and leaks can all follow from hydrogen absorption (Guan et al., 2023). Hydrogen embrittlement in metals is influenced by the content of material stress, stress or strain rate, hydrogen pressure, temperature, purity, types of impurities, material composition, tensile strength, grain size, material microstructure, and material heat treatment history. Should it remain dormant, hydrogen will progressively enter the material and flee (Guan et al., 2023). Care should be made to guarantee that hydrogen atoms escape during heat treatment and to use welding techniques carefully to prevent the development of hard microstructures during metal forming. High-temperature hydrogen attack (ABS, 2021) presents still another material concern.

Under hydrogen attacks at temperatures above 200° C (392° F), low-alloyed structural steel has been documented to break down in which carbon reacts with hydrogen to generate methane and cause material embrittlement. Until they reach high temperatures—as those found in combustion engines, fuel reformers, and fuel cells—hydrogen attacks on tanks and pipes are rare. Low temperature embrittlement and material thermal contraction and deformation resulting from thermal cycling are other elements to take under account for safe hydrogen storage at cryogenic temperatures. Both cycle pressures and temperatures as well as material degradation brought on by hydrogen storage may limit storage vessel life. The number of use cycles and the material attributes define the lifetime of a storage vessel. Manufacturers of cryogenic tanks and hydrogen pressure vessels can offer details on the service lifetime of their creations (ABS, 2021). All system components—including tanks, pipes, fittings, pressure release valves, and vent masts—for cryogenic hydrogen should be protected from usual air condensation or ice buildup, therefore preventing system clogging or obstructing ventilation channels. Most of air condensate is oxygen; so, following condensate evaporation could produce an oxygen-rich and maybe flammable gas concentration (ABS, 2021).

5.6. Safety

Although hydrogen leaks in open spaces are expected to dissipate quickly, any leak in an open or enclosed space can provide a significant fire risk because of the quick development of a flammable gas mix. Among all the elements except helium, hydrogen is a gas or cryogenic liquid with one of the lowest melting and boiling temperatures. The fuel must be kept at temperatures below -253° C in order to generate liquid hydrogen, which can call for large energy consumption. Other common gases or chemicals can liquefy or solidify at this temperature when they come into touch with liquefied or cryogenic hydrogen; thus, they should be separated. Human touch with uninsulated tanks, pipes, valves, or cryogenic materials can cause serious skin injury or cold burns. While hydrogen is non-toxic, at high doses it can act as an asphyxiant by substituting accessible oxygen. Still, proper care and laws help to lower the risks associated with hydrogen explosions. Electrostatic charges produced by hydrogen gas or liquid flow or agitation can cause sparks and ignite flammable hydrogen concentrations. Ensuring all hydrogen handling equipment is protected from electric charge accumulation and potential sparks can help to prevent hydrogen fires. Invisible, burning essentially outside the visible light spectrum, hydrogen flames can be challenging to find. Reaching a maximum speed of 3.15 m/s, hydrogen also burns quicker than other combustible materials.

A mixture subjected to ignition sources could burn via detonation (supersonic combustion, which is not possible in open air) or deflagration (subsonic combustion). Appropriate pressure relief systems, rupture disks, or relief panels (ABS, 2021) should all be part of hydrogen gas systems' defenses against deflagrations that pass via pipes and containment systems. More difficult to control than deflagrations, denonations produce notable pressure increases (up to 20 times atmospheric pressure).

Eliminating the likelihood of toxic hydrogen concentrations by good gas management, pipe purging, and ventilation procedures would help to drastically lower the risk of deflagration and detonations (Depken et al., 2022).

The main safety measures to take while carrying and utilizing hydrogen are proper ventilation, hydrogen gas detection, and sufficiently rated electrical equipment in hazardous areas and enclosed spaces where hydrogen may leak and build to levels that could cause flammable circumstances. Hydrogen concentration, storage pressures (i.e., jet speed from a leak), the amount of stored hydrogen, insulation, release location, and meteorological conditions (ABS, 2021) define the formation and possibilities of flammable hydrogen and air mixes. Chemicals typically added to natural gases to identify leaks should be avoided when utilizing gaseous hydrogen as fuel since the sulfur in those compounds can react with and breakdown hydrogen.

When using gaseous hydrogen, dedicated hydrogen sensors could be helpful; but, in areas with significant transient airflow, where escaping gas could be unintentionally steered away from sensors, they may not be practicable. Therefore, it is better to embed leak detection mechanisms in the hardware itself, including verifying that these values show the absence of leaks by monitoring pressures during periods of no gas flow and so negating the device itself.

Dry chemical or carbon dioxide extinguishers allow one to put out a hydrogen fire (Depken et al., 2022). Appropriate water spray cooling and insulating systems should be in place to keep the hydrogen from heating up as well as pressure release systems to prevent over-pressurization should a hydrogen fire spread to other materials around or near confined hydrogen in pipelines or tanks. Preventive strategies can help to lower the probability of gaseous hydrogen beyond the explosive temperature limit inside confinement or of a liquid hydrogen boiling liquid expanding vapor explosion (ABS, 2021).

5.7. Ship design impact

Integrated designs based on operational profile, fuel arrangement, power generation, and propulsion system choice may be required of future ships. The architecture of current engine room designs (ABS, 2021) may be changed by power generating technologies including hydrogen paired with fuel cell and battery storing systems. Fuel cell installations, for instance, can be large but they might not need as much easily available maintenance space as standard marine engines, therefore enabling better use of the volume of the engine room. Still, one should take great thought on the weight of large fuel cell installations.

By spreading electrical equipment all around a vessel, fuel cells and electrical hybrid systems could help to maximize available space on board. Larger tanks will be needed for similar energy storage since hydrogen has a low energy content per volume; their position on board will be a major design issue. To maximize natural ventilation in the case of minor leaks, many small hydrogen tanks are positioned on decks or the tops of superstructures (Alkhaledi et al., 2022).

Other, more extensive uses could investigate tank storage of hydrogen, either alone or as part of a combined system. While density (pressure and temperature) affects the energy content of stored hydrogen, more hydrogen by volume is always needed to meet the same volumetric energy densities of other marine fuels. Larger vessel sizes, less cargo room, and/or more frequent bunkering of the vessel could be required by the higher fuel amount. Moreover, hydrogen-powered ship storage systems including the tank temperature and pressure management system, gas valve unit, and hydrogen fuel containment system could need certain changes. Liquid hydrogen cargo management systems could call for boil-off gas handling, reliquefication, gas valve units or trains, vent pipe systems, and exhaust masts. Properly rated electric equipment should be placed in hazardous areas or ventilation channels prone to gas intrusion in order to lower the danger of spark ignition. Placed strategically, hydrogen detectors should be able to identify possibly hazardous gas combinations. Early detection calls for suitable fire, heat, or smoke detectors with alarms (ABS, 2021).

5.8. Regulatory readiness

The first IMO strategy on reducing greenhouse emissions from ships, approved by Resolution MEPC.304 in April 2018, reaffirms the IMO's commitment to the Paris agreement. It aims to attain zero greenhouse emissions from international shipping by the end of the century, and it may urge member countries to pass legislation and policies to initiate decarbonization and GHG reduction programs. One year later, the Interim Guidelines for ship safety are being created, according to IMO (ABS, 2021).

These rules apply only to fuel cell installations and do not address hydrogen storage or usage. Only the specific prescriptive conditions for LNG in Part A-1 of the IMO Code apply to ships subject to the International Convention for the SOLAS.

Other low-flashpoint fuels may be used as marine fuels aboard ships as long as they complement the IGF Code's goals and functional criteria and provide an equivalent level of safety (Jacobdon, 2021). This equivalency must be proved using the SOLAS novel concepts approval process stated in SOLAS regulation II-1/55, as well as the IGF Code, which employs an alternative design risk assessment approach. Future development and implementation of IMO standards for hydrogen as a marine fuel, as well as fuel cell recommendations, may help to increase marine hydrogen fuel adoption and the associated infrastructure for hydrogen generation and distribution.

The Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk is the only IMO tool that applies to ships carrying liquefied hydrogen cargo. Such ships are required to adhere to the International Code of Construction and Equipment for Ships Carrying Liquefied Gases in Bulk. The Interim Recommendations were prepared and launched for a liquid hydrogen supply pilot project; hence their applicability may be limited to that project. The IMO understands that before revising the IGC Code to add rules for the carriage of liquefied hydrogen, data from this ongoing pilot project and other Member State experiences are required. With only a few pilot projects, hydrogen has yet to gain widespread acceptance as a fuel in the maritime industry; yet, it has already been used on land (Jacobsen, 2021).

The IMO does not impose any international maritime requirements; nonetheless, MSC.420(97) refers to numerous information, standards, and guidelines from land-based resources. These include safety protocols, modes of conveyance, and standard hydrogen-generation techniques. In addition to general safety codes or standards that include hydrogen, there are various referenced laws and regulations for hydrogen component standards and equipment design, fire codes, and other hydrogen-specific safety codes. The Technical Report ISO/TR 15916 Basic Considerations for the Safety of Hydrogen Systems contains technical information that can help understand hydrogen safety risks. The report discusses the growing interest in hydrogen as a fuel, as well as efforts to address specific hydrogen-related safety issues and phenomena, as well as optimal engineering solutions for reducing hydrogen risks and hazards.

Designers planning marine projects can examine the worldwide criteria listed below (ABS, 2021):

1.IEC 60079. Hazardous zones and gas detection rules for hydrogen are based on the International Electrotechnical Commission Standard for Explosive Atmospheres 60049 - Part 10.1 Area Classification: explosive gas atmospheres Part 29.2 Gas Detectors: Selecting, installing, using, and maintaining detectors for flammable gases and oxygen.

2.IEC 61889. The International Electrotechnical Commission Standard for Mobile and Fixed Offshore Units specifies the venting of hydrogen produced by batteries.

3.ISO 11114. The Gas Cylinders Standard specifies appropriate materials and testing techniques for selecting steels that are resistant to hydrogen embrittlement.

4.The National Fire Protection Association (NFPA) code NFPA 2 Hydrogen Technologies Code covers liquid and gaseous hydrogen for use in power generation, transportation, and marine activities, as well as equipment and system standards for hydrogen storage, use, and handling.

5.Safety Guide for Hydrogen and Hydrogen Systems, ANSI/AIAA G-095A-2017. The NASA developed this ANSI and AIAA code, which provides broad safety guidelines for controls, use, personnel training, hazard management, facilities, detection, storage, transportation, and emergency procedures for use in spacecraft.

6.The A. S. M. E. C. governs the design, building, operation, and maintenance of gaseous and liquid hydrogen pipes and pipelines. This standard is also referenced in Maritime Rules for Ship Plumbing.

7.CGA G-5.4 standard applies to hydrogen piping systems at user sites. This C.G.A. standard specifies the appropriate pipework techniques for gaseous and liquid hydrogen.

8.CGA G-5.5 standard specifies the requirements for the safe operation and design of liquid and gaseous hydrogen venting systems. The Guide for Fuel Cell Power Systems for Marine and Offshore Applications, released in November 2019, addresses the Marine Vessel Standards (MVR)

9.Current ABS standards for fuel cells are updated whenever intermediate standards are established based on the IMO's proposed intermediate Guidelines for the Safety of Ships with Fuel Cell Power Installations.

Though it focuses primarily on fuel cell design criteria, the Fuel Cell Guide also covers hydrogen as a fuel, including the fuel containment system, material and general pipeline systems, fire safety, electrical systems, control, monitoring, and safety systems. Parts of this guide that discuss hydrogen storage and delivery systems may also apply to hydrogen-powered internal combustion engines. The document cites ISO 11114-4 for hydrogen embrittlement tests and ASME B31-12 for pipe specifications for hydrogen handling. Some systems, tools, or components may need Tier level certification through ABS's Type Approval program to assure safe construction, testing, and installation (ABS, 2021).

Conclusion - Advantages & challenges

In the above paper, a detailed presentation of the characteristics and properties, life cycle and environmental impact, production, utilisation in shipping and safety of specific alternative fuels was carried out. Furthermore, the technological readiness, the institutional framework and the appropriate transitions at ship design level required for their safe and seamless utilisation were examined.

As the investigation of the alternative fuels: methanol, hydrogen, biofuels, ammonia and LNG has shown, each alternative fuel has its own potential to contribute to the reduction of carbon dioxide emissions, but also has its own challenges, related to cost, safety, lack of regulatory framework and lack of appropriate ship configuration and technology to allow their safe management.

A comparison of alternative fuels shows that, depending on the type of ship, distance, technological developments and local regulations, the fuel that best meets the needs and is an advantageous, environmentally and economically viable option can be chosen. Of course, the safety of the crew and the ship, as well as the marine environment, must be a priority in all cases, which means that the widespread adoption of a fuel requires an appropriate institutional framework, with an emphasis on risk management and the adoption of all necessary measures.

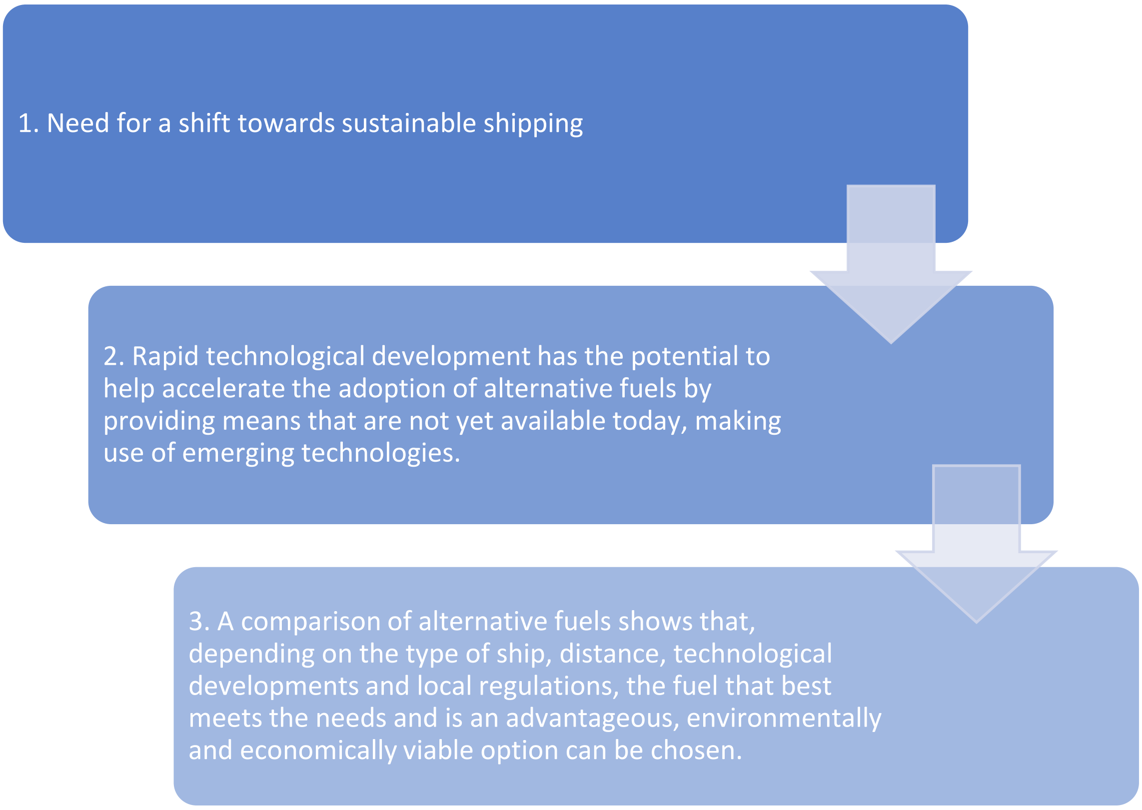
Furthermore, for the selection of the appropriate fuel, it is important to focus on the availability and the life cycle of each fuel. Although a fuel may perform better in environmental terms, if its production or transport entails significant economic and environmental costs, then its widespread adoption becomes impossible.

Table 1: Comparison

CRITERIA	METHANOL	LNG	AMMONIA	BIOFUELS	HYDROGEN
PROPERTIES	LIQUID, EASY TO STORE	GAS, NEEDS CRYOGENIC TANKS	TOXIC STORED UNDER PRESSURE	LIQUID	GAS, NEEDS CRYOGENIC TANKS
ENVIRONMENTAL	LOW CO2	LOW CO2	ZERO CO2	LOW SULFUR	ZERO CARBON

PERFORMANCE					EMMISSIONS
PRODUCTION PATHWAYS	FOSSIL RENEWABLE	MOSTLY FOSSIL	SYNTHESIS FROM RENEWABLE SOURCES	PLANT WASTE MATERIALS	ELECTROLYSIS OR NATURAL GAS
UPTAKE	GROWING INTEREST	WIDELY ADOPTED	LIMITED ADOPTION	LIMITED ADOPTION	LIMITED ADOPTION STRONG POTENTIAL
TECHNOLOGY READINESS	HIGH	HIGH	LOW	MEDIUM	LOW
SAFETY	TOXIC MANAGEABLE	FLAMMABLE	TOXIC CORROSIVE FLAMMABLE	SAFER OVERALL	HIGLY FLAMMABLE CRYOGENIC HANDLING RISK
SHIP DESIGN	REQUIRES MODERATE RETROFITING	SIGNIFICANT REQUIREMENTS	SIGNIFICANT REQUIREMENTS	MINIMAL IMPACT	HIGH IMPACT
REGULATORY READINESS	GROWING ACCEPTANCE	WELL REGULATED	NEED REGULATIONS FOR TOXICITY	WELL REGULATED	GROWING ACCEPTANCE

Given the need for a shift towards sustainable shipping, it is necessary to carry out several detailed studies examining all the above-mentioned factors, so that regulatory frameworks for the use of alternative fuels and design improvements can be safely established on the basis of scientific data and measurements. Rapid technological development has the potential to help accelerate the adoption of alternative fuels by providing means that are not yet available today, making use of emerging technologies.



1. Need for a shift towards sustainable shipping

2. Rapid technological development has the potential to help accelerate the adoption of alternative fuels by providing means that are not yet available today, making use of emerging technologies.

3. A comparison of alternative fuels shows that, depending on the type of ship, distance, technological developments and local regulations, the fuel that best meets the needs and is an advantageous, environmentally and economically viable option can be chosen.

Figure 12: Important conclusions

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