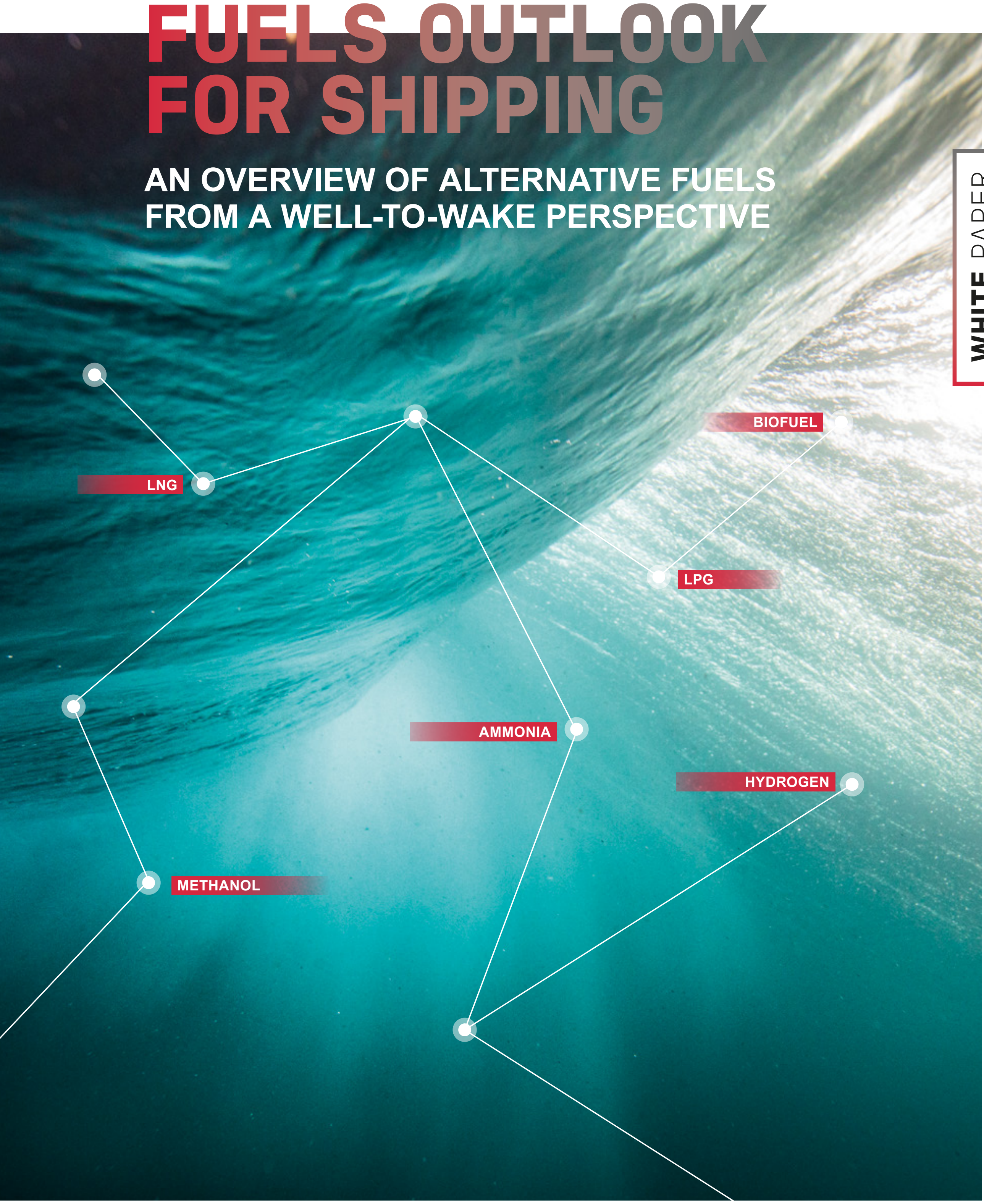
SEPTEMBER, 2022

ALTERNATIVE FUELS OUTLOOK FOR SHIPPING

AN OVERVIEW OF ALTERNATIVE FUELS FROM A WELL-TO-WAKE PERSPECTIVE

WHITE PAPER



BUREAU
VERITAS

EXECUTIVE SUMMARY

Following the 2015 adoption of the Paris Agreement, the International Maritime Organization (IMO) set targets to reduce greenhouse gas (GHG) emissions from the shipping industry. The IMO is aiming for a minimum 50% reduction in total annual GHG emissions by 2050, as compared to 2008 levels. Many shipping industry bodies and IMO members, however, are advocating for a net zero target for 2050. This would require much more ambitious interim objectives for 2030 and 2040 to stay on track to meet the Paris Agreement.

To achieve decarbonization goals, innovative propulsion systems need to be introduced onboard ships that will rely on alternative fuels. In parallel, shipowners will need to manage challenges of safety, cost, availability and regulatory requirements.

Ships require a constant energy supply for propulsion and other onboard systems. Fuel requirements and consumption are essential parameters to factor in at the design phase. Adopting alternative fuels will raise important considerations as to the operating profile and architecture of the ship and the need to train crews in their safe storage and use, for instance.

Assessing a fuel's real climate impact necessitates an accounting of its GHG emissions released from extraction or production and distribution to final use onboard the ship, known as well-to-wake (WtW) emissions.

STANDARD MARINE FUEL EMISSIONS

Most ships are powered by liquid petroleum fuel oils known as "marine fuels," which are products of the crude oil refining process. These carbon-based fuels – which include marine gasoil, heavy fuel oil, intermediate fuel oil and marine diesel oil – emit high GHG levels.

The United Nations Framework Convention on Climate Change (UNFCCC) has identified the three GHGs that contribute most to climate change:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)

Hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride are less prevalent, but still harmful. The IMO has also defined six further substances requiring emissions control: nitrogen oxide (NOx), sulfur oxide (SOx), particulate matter, carbon monoxide, non-methane volatile organic compounds and black carbon. NOx and SOx emissions are restricted in Emission Control Areas (ECAs) designated by the IMO, Black carbon is also under growing scrutiny following the latest IMO MEPC findings, notably due to its impact in the Arctic.

A WELL-TO-WAKE APPROACH TO EMISSIONS

Currently, at international level, the sector's first regulations are based on a tank-to-wake (TtW) approach (e.g., EU MRV, IMO DCS or CII which do not include upstream considerations). A WtW approach is important as a fuel's sustainability ranking may be influenced by several factors and parameters. For example, a fuel produced with renewable energy but transported to its final use point may have higher WtW emissions than a fuel produced and consumed locally.

To achieve decarbonization in WtW terms, the shipping sector will need to broadly cooperate with stakeholders, from upstream energy and chemical suppliers to authorities and financiers.

HOW TO ASSESS ALTERNATIVE FUELS

When considering the viability of alternative fuel options, marine stakeholders must account for multiple factors:

- Ship type and operating profile, which determine how much fuel a vessel needs and can carry
- Fuel characteristics (e.g., flashpoint, energy density, optimal pressure and temperature conditions for storage, low calorific value), which determine the volume of fuel needed onboard, fuel containment system size and type and fuel supply system
- Safety considerations (e.g., toxicity, flammability)
- Global availability of the fuel and bunkering facilities
- CAPEX and OPEX
- Regulations
- Energy converters commercially available
- Environmental footprint

REGIONAL REGULATIONS

Amid concern that international regulations are taking longer to be defined and adopted, some regional and local authorities are establishing their own regulations and incentives to reduce carbon and other GHG emissions. These include, but are not limited to, China and the EU. The latter has notably proposed a WtW approach when drawing-up its FuelEU Maritime regulations proposal, still to be voted on. Based on a cost estimation, the current EU ETS and FuelEU Maritime proposals could result in significant levels of taxation and penalties for ships.

These first efforts to implement market-based measures and WtW emissions are paving the way toward strengthened ambitions at an international level to align with the Paris Agreement.

LOW-CARBON AND CARBON-NEUTRAL FUELS

Shipowners can already use low-carbon and carbon-neutral fuels to minimize their vessels' carbon footprints, but every option has its pros and cons.

- Liquefied natural gas (LNG) offers an immediate CO_2 emissions reduction and has a well-developed supply chain and global bunkering facilities, requiring cryogenic conditions for its storage (-162°C). It is nonetheless a carbon-based fuel subject to the problem of methane slip.
- Liquefied petroleum gas (LPG) is a mature fuel for propulsion which also offers a significant reduction in CO_2 emissions. It requires lower CAPEX than LNG as fuel, but is a highly flammable gas which creates risks in the event of leaks. It should be noted that marinized LPG fueled four-stroke engines are not yet commercially available.
- Methanol is a hazardous chemical that requires safety measures due to its flammability and toxicity, but is manageable. It is bio-degradable, water soluble and can be stored as a liquid at ambient temperatures. When produced from fossil sources, it may not offer a significant reduction in CO_2 emissions compared to conventional fuel oils. However, it could be competitively produced as a biofuel and from renewables and low carbon hydrogen as an e-fuel. Finally, methanol also comes with challenges like its low energy content, low flashpoint and its toxicity with prolonged exposure.
- E-fuels are a promising solution, but one that will require a high level of renewable energy availability. Green hydrogen (e-hydrogen) is produced from water using mostly electrolysis and electricity from renewable sources. It can then be used in the production of e-methane, e-methanol, e-ammonia and e-distillates. E-fuels production plants may have high CAPEX and OPEX requirements to remain economically viable, which will impact the cost of e-fuels.
- First-generation or conventional biofuels are now a widely developed fuel source for land transport. They are also compatible with modern marine engines and can be used safely onboard ships. Yet questions remain about the full supply chain sustainability of biofuels. There is also concern about the wide-scale availability of advanced biofuels (second- and third-generation) for the shipping industry, which may be in competition with other sectors.

TOMORROW'S ZERO-EMISSION FUELS

The shipping industry is looking at ammonia and hydrogen as potential pathways to marine decarbonization, as both fuels can produce zero carbon emissions.

- Ammonia is a widely traded commodity already transported by the same tankers that transport LPG and other liquid chemicals with similar characteristics. Ammonia-powered two-stroke engines are under development in order to use ammonia as a fuel. However, ammonia is a toxic and corrosive molecule, requiring specific safety considerations when used as a fuel. Beside toxicity, the pungent smell of ammonia will be a source of olfactory discomfort, even if released in infinitesimal amounts. Additionally, its combustion should be controlled to minimize emissions of nitrous oxide (N_2O), a gas with 273 times the global warming potential of CO_2. Its energy density is also low – about three times less than conventional fuel oils, significantly reducing space onboard for the transport of cargo.
- Hydrogen is also a zero-carbon fuel when produced from renewable electricity, and is already being tested onboard inland navigation vessels and short-sea ships. Nonetheless, hydrogen is both an explosive and highly flammable molecule. It requires safety precautions to prevent hazards and mitigate residual risks. It also has low volumetric density, requiring ships to store significant quantities onboard or to drastically adapt their operating profiles. It must be stored using

cryogenic technology at very low temperatures (-253°C) or under very high pressure conditions (>250 bar). Other technologies of hydrogen storage do exist such as storage in metal (metal hydrides developed for submarine), storage of hydrogen atom in a chemical compound (such as Liquid Organic Hydrogen Carrier, LOHC).

SUPPLY AND SCALABILITY

Large scale renewable electricity access will be key to producing fuels like:

- e-ammonia
- green hydrogen
- e-methane
- e-methanol
- e-diesels

The maritime industry's needs will be in competition with other sectors for wind and solar power. According to IRENA (2022) Renewable Capacity Statistics, a total of 8.8 EJ was generated by wind and solar power in 2020.

Renewable electricity capacity will need to increase significantly to replace the 10-12 EJ required to propel the shipping industry. Taking into account an average e-fuels production efficiency of 50%, it is estimated that shipping industry would today require 20-24 EJ of renewable electricity.

Alongside e-fuels, biofuels also promise to play a crucial role in decarbonizing the shipping industry. First-generation biofuel production is not expected to increase significantly (+5%) up to 2030, according to OECD-FAO projections. Second-generation biofuels using agricultural and forestry residues have the potential to fuel the entire shipping industry. This is dependent on large-scale investments and using feedstock solely for this purpose.

The shipping industry will eventually have new market opportunities to seize. It will transport the green hydrogen produced on remote "off-grid" production sites in liquid forms (liquefied hydrogen, e-ammonia and other e-fuels) to consumption market locations, while liquid tankers are likely to transport ever growing quantities of biofuels.

MARKET CONSIDERATIONS

A rough estimation of alternative fuel's future production costs is possible if certain assumptions are made. However, caution should be exercised in drawing conclusions as to which fuel will prove the best solution based on cost assumptions at this stage. The best solution may vary according a variety of other factors including location, vessel type and operations.

Future fuel prices will impact a vessel's OPEX costs. LNG price fluctuation in recent years underlines that predicting future prices for energies is complex, if not impossible. In the wake of the conflict in Ukraine and the Covid-19 pandemic, fossil fuel energy markets have also proven to be highly volatile and reactive. However, some observers see the current fossil energy price spike as a positive new reference line, confirming the mid-to-long-term economic viability of a wider low- and zero-carbon fuels market.

With the provision of certain market-based measures (MBMs) and incentives, the gap between the long-term prices of bio and e-fuels and current fossil-based fuels could be further narrowed.

CONCLUSION

As 2050 approaches, Bureau Veritas believes the maritime world will gain in prominence in a safe zero-carbon future.

Assessing alternative fuel options must be done from a WtW basis to achieve true decarbonization in the shipping industry. Only through a complete life-cycle analysis can the environmental impact of fuels be properly evaluated.

Bureau Veritas recognizes that all shipping industry players will start their decarbonization from different points and progress at different speeds. A WtW approach will also call for greater collaboration and transparency with upstream supply and production chains. Bureau Veritas will support our clients along their sustainability journey, however ambitious their short-, mid- and long-term goals may be.

CONTENT


ZERO
EMISSIONS

1. INTRODUCTION: UNDERSTANDING THE EMISSIONS CHALLENGE

The shipping industry is undertaking the considerable challenge of significantly decarbonizing its operations within the next decade. This is in line with the ongoing global energy transition, which will enable stakeholders to preserve the world for future generations.

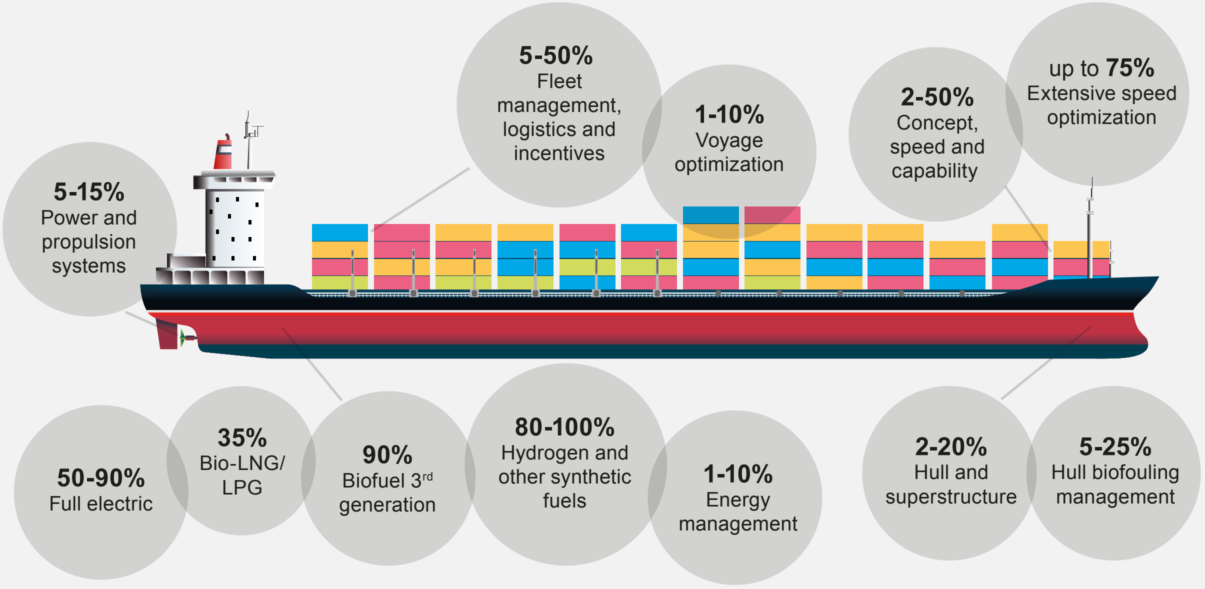
The Paris Agreement is a guiding light for the global response to climate change. Developed by the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement entered into force in 2016, following an adoption during COP 21 in Paris on December 12, 2015. Its goal is to limit the increase in the global average temperature to well below 2°C above pre-industrial levels, and preferably to 1.5°C.

THE SCALE OF THE EMISSIONS CHALLENGE IN SHIPPING

This goal impacts the shipping industry, which transports approximately 80% of the world's goods, according to the 2021 United Nations Conference on Trade and Development. According to the International Energy Agency (IEA), in 2019, the whole transportation sector was responsible for 24% of global carbon dioxide (CO_2) emissions. The agency also concluded that in the same year, shipping was responsible for 11% of the transportation sector's CO_2 emissions. This supports data from the IMO's 4th GHG study showing that shipping's share of total global anthropogenic emissions had increased from 2.76% in 2012 to 2.89% in 2018. In other words, although shipping is the most efficient means of transportation in terms of CO_2 equivalent emissions per metric ton-mile, there is work to be done.

DESIGN, OPERATIONAL AND ECONOMIC SOLUTIONS

Achieving the goals of the Initial IMO GHG Strategy will require a mix of technical, operational and innovative solutions applicable to ships. Some of them, along with the indication of their approximate GHG reduction potential, are highlighted below.



Source: IMO, Freepik

The main source of ships' emissions is exhaust gas from internal combustion engines. These emissions are known as "tank-to-wake" emissions. However, when considered from a lifecycle perspective, emissions generated during fuel production and across the supply chain must be included (i.e., "well-to-tank" emissions). Among the exhaust gases emitted by ships, CO_2 directly affects the climate and is of particular importance due to its high concentration and long lifetime in the atmosphere. However, exhaust gases do not only consist of CO_2. Other gases like carbon monoxide (CO), sulfur oxides (SOx), nitrogen oxides (NOx), methane (CH_4), and particulate matter (e.g., black carbon) also impact the global climate, local environments, nature and human health.

The International Maritime Organization (IMO) has set goals to reduce emissions from shipping, including a headline goal of a minimum 50% reduction in total annual greenhouse gas (GHG) emissions from international shipping by 2050, as compared to 2008 levels. These targets may be further increased due to the acceleration of global warming and changes in public and political opinion. The IMO has now placed the revision of its GHG strategy high on its agenda; upcoming discussions will center on whether the IMO should upgrade its 2050 ambition to relative carbon neutrality.

To reach – and perhaps even exceed – these goals, the shipping industry must find alternative fuels to power vessels' propulsion and auxiliary systems. This presents a challenge: bringing about a fundamental shift in fueling practices while maintaining reasonable comparative costs to other modes of cargo transportation.

The IMO developed and published many of the graphics presented in this white paper. They confirm the absolute necessity of finding alternative fuels for shipping activities and cutting carbon emissions to limit global warming. Energy savings must be leveraged, but this is not sufficient to meet the Paris Agreement decarbonization targets. Ideally, ships would move directly to using zero-emission solutions like hydrogen and ammonia to achieve more than an 80% reduction of carbon emissions. However, a worldwide shift toward these types of fuel is still far off.

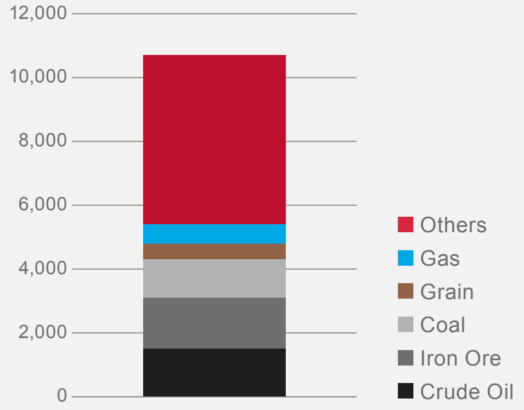
Today, the transportation sector is almost completely dependent on fossil fuels. For stakeholders looking to limit their carbon footprint, this begs the question: what are the alternative fuel options? And more broadly, how can the shipping industry move toward carbon-neutral and/or carbon-free fuels?

A WORLDWIDE SHIFT TOWARD ZERO-CARBON ENERGY SOURCES IS STILL FAR OFF.

THE CONSEQUENCES OF THE WIDER USE OF ALTERNATIVE FUELS IN THE GLOBAL ECONOMY FOR THE SHIPPING INDUSTRY

The necessity to cut GHG emissions by changing fuels applies equally to many other transportation sectors and to their contributing sectors. Decarbonizing the global economy may have a significant impact on the types and volumes of cargo transported by sea. Today nearly 30% of sea freight volumes is dedicated to transporting of fossil fuels (see Figure 1).

FIGURE 1: ~30% OF CARGO VOLUMES ARE USED FOR TRANSPORTING FOSSIL FUELS
(million Tons)



Source: Bureau Veritas

Changing fuels will have a major impact on the maritime business worldwide. All projections show that alternative fuels will have a much higher cost than the fuel oil used in the past decades. This will create a considerable change in an industry which plays an indispensable role in the global economy. It could also constitute a paradigm shift in a fiercely competitive global industry that has historically strived to keep costs low.

However, at Bureau Veritas, we believe that the maritime world will gain in prominence in a safe zero-carbon future. Carbon pricing will highlight the efficiency of cargo shipping over aviation or other less efficient means of transport. As such, the maritime industry could form the backbone of low- and zero-carbon transportation.

Shipping will play an ever more important role in connecting low-carbon and renewable energy production sites with markets. The emergence of new trade routes will have significant implications for energy providers and ports worldwide. They will now need to be designed and constructed in accordance with the new energy production sites.

Decarbonizing the economy requires new sources of energy and new type of fuels. This will have a major impact and create new demands on the shipping industry. In the future, lower quantities of fuels may be transported. However, as renewable and low-carbon fuels are on average three times less dense than conventional fuels, an increase in global ship capacity is likely to be needed for fuel transportation. Furthermore, the development of carbon capture technology will create an emerging market for the transportation of liquefied CO_2.

BUREAU VERITAS' ROLE IN EMISSIONS REDUCTION

A part of our broader societal commitment, Bureau Veritas has a central role to play in helping the shipping industry understand and reduce emissions. Our mission is to shape a world of trust. We do this by reducing clients' risks, improving their performance, and helping them innovate to meet challenges of quality, health and safety, environmental protection and social responsibility.

As a Business to Business to Society company, Bureau Veritas contributes to transforming the world we live in. We do this externally by supporting clients' corporate social responsibility (CSR) commitments through the Bureau Veritas Green Line of Services, and internally, through our own CSR strategy.

Our internal scope of action comprises three pillars, each connected to one or several of the 17 Sustainable Development Goals (SDGs) adopted by the United Nations (UN) in 2015. These are, respectively, creating a better workplace (SDG 3, 5, 8), environment (SDG 13 and 14), and business practices (SDG 16). Externally, our CSR performance is subject to an independent rating, the results of which are published regularly on our corporate website.

Since 1828, Bureau Veritas has offered classification and value-added services to the maritime industry, enacting our belief that ship, crew and environmental safety are of the utmost importance. We help ship owners and operators ensure safety, achieve regulatory compliance, remain competitive, and optimize environmental performance to meet increasingly strict industry-wide regulations.

AT BUREAU VERITAS, WE BELIEVE THAT IN A SAFE ZERO-CARBON FUTURE, THE MARITIME WORLD WILL GAIN IN PROMINENCE.

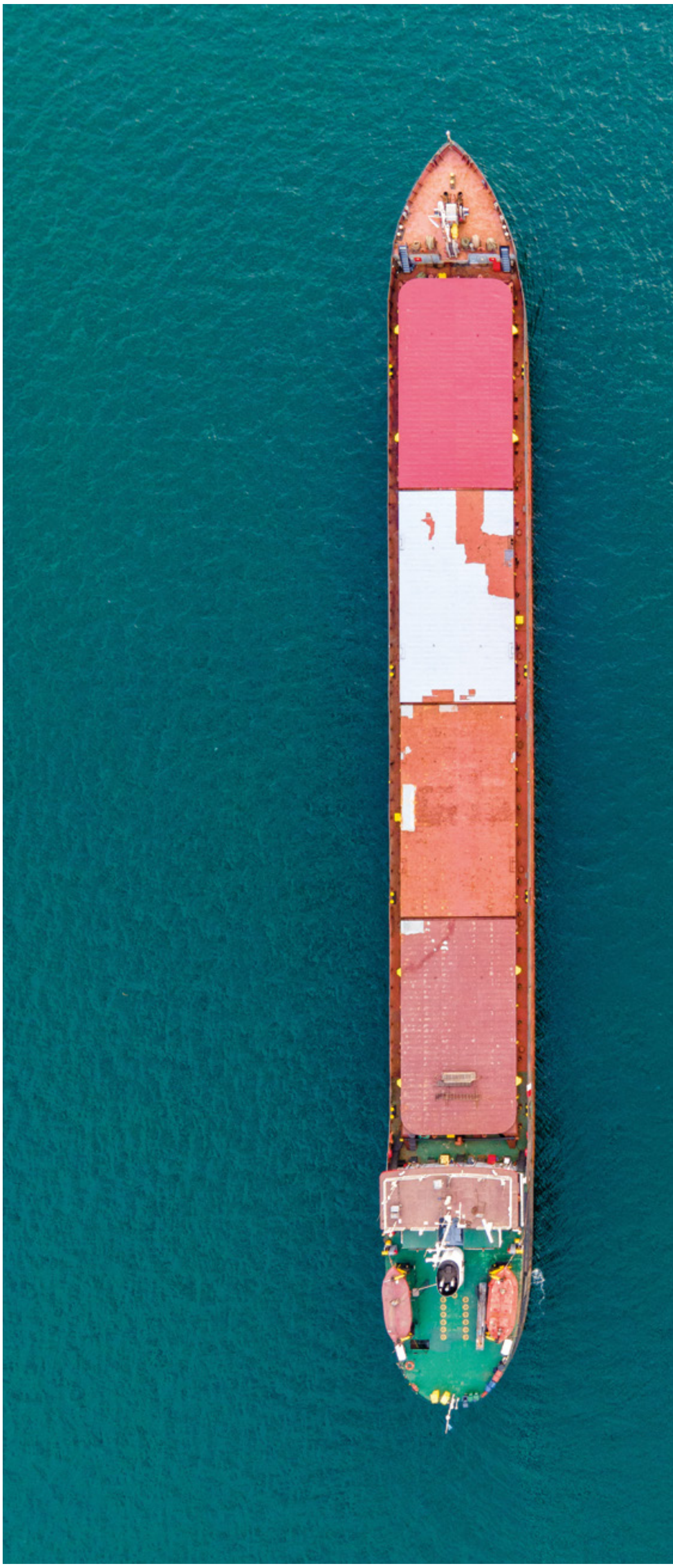
2. SCOPE OF THIS WHITE PAPER

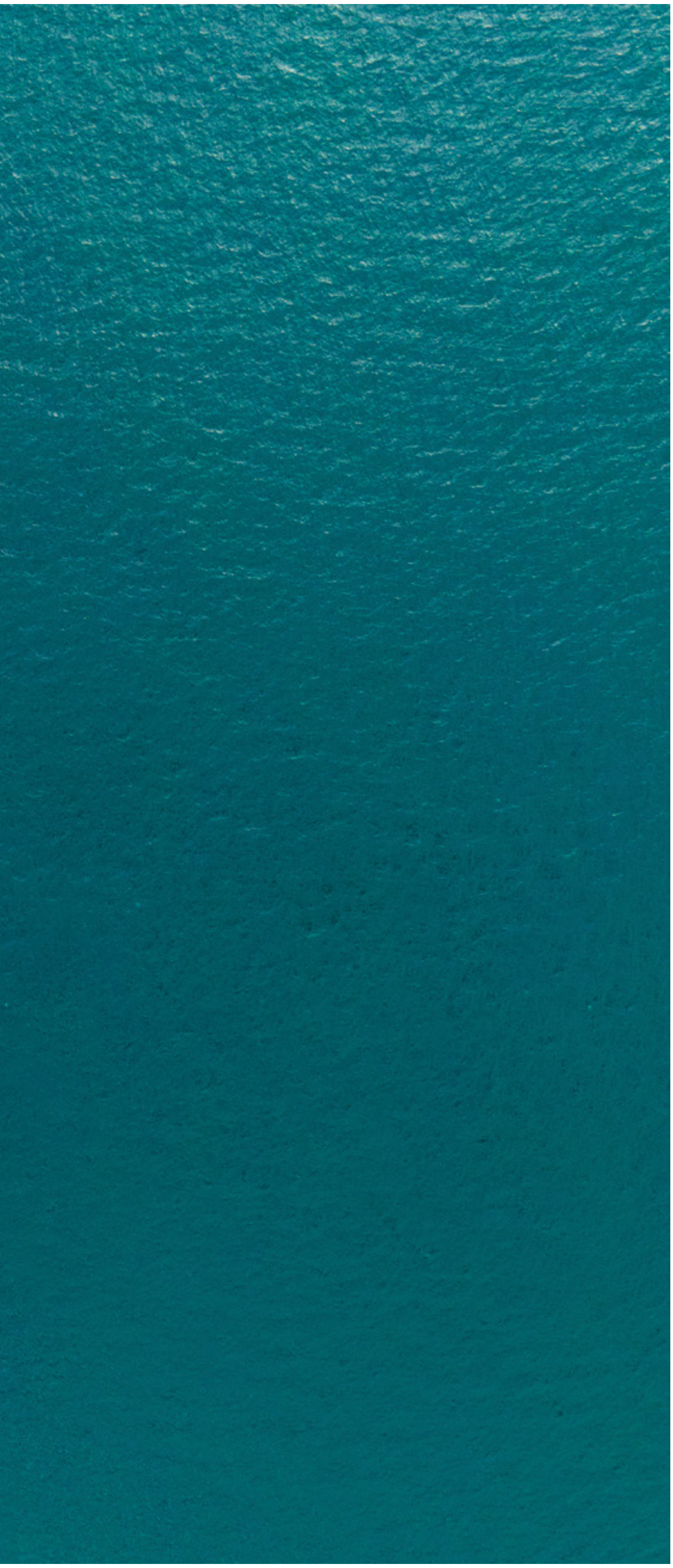
This white paper presents alternative fuels for the shipping industry in terms of technological maturity, availability, safety, emissions and regulations. Our analysis covers the changing needs provoked by the energy transition and sustainability ambitions.

We start by outlining the current state of marine fuels and the challenges ahead to decarbonize the shipping industry. We then present an overview of different alternative fuels, their advantages and challenges. Issues such as bunkering and well-to-wake emissions are approached and situated in the real-world context of global and regional regulations.

Our objective is to give the reader an overview as a starting point for more detailed discussions with Bureau Veritas and industry experts. Choosing an alternative fuel for maritime operations is not only based on a financial evaluation in a closed shipping eco-system, but could include the use of technology under development and new operational risks, as well as considering the availability of the fuel, local government incentives and perhaps even geo-politics.

This white paper is a natural successor to our previous publication, *Reducing ship emissions*, which described the IMO tools and requirements needed to reduce ship emissions. As with all our publications, this white paper aims to inform all stakeholders of the current context and market perspectives. We intend with this document to provide a global overview of the progress in alternative fuels and their role in the decarbonization of the shipping industry as of today.





3. THE CHALLENGE

At minimum, successful new technologies must provide the same service as previous solutions, but at a lower cost or greater efficiency. This constraint may be viewed as less important given the urgency of reducing emissions. However, the upper limit level that shipping stakeholders and transportation buyers are ready to accept has yet to be defined.

Changing marine fuels will imply major changes to the entire fuel supply and logistics chain from extraction and production, to storage and distribution. Analyzing the fuel life cycle will require unprecedented collaboration between all stakeholders in the energy production and marine industries.

The number of years required to develop new technology and infrastructure and a ship's typical expected service life (around 25 years) mean that existing vessel designs continue to operate for a certain period. Therefore, the IMO's GHG reduction targets must require shipping to embrace transitional solutions, until permanent solutions can be implemented.

Shipping is the most efficient means of transportation for limiting CO_2 emissions per metric ton-kilometer. It is more than 25 times more efficient than air freight, and two to three times more efficient than train freight. However, investment in new technologies and innovations for new and existing ships will depend on the financial capacities of shipping stakeholders and market constraints.

One way to overcome this problem is through collaboration, the sharing of knowledge and resources across the industry. Timing is a key factor. The industry must balance short- and long-term objectives, obtaining immediate CO_2 emissions reduction from the existing fleet, while moving toward more substantial emissions objectives in the mid- to long-term.

> **SHIPPING IS THE MOST EFFICIENT MEANS OF TRANSPORTATION FOR LIMITING CO_2 EMISSIONS PER METRIC TON-KILOMETER. IT IS MORE THAN 25 TIMES MORE EFFICIENT THAN AIR FREIGHT.**

4. CONTEXT

4.1. SHIP ENERGY NEEDS

The energy production from the ship's power plant supplies its primary and secondary essential services: fuel preparation and distribution, propulsion, cooling systems, communication equipment, etc. The energy has to be available constantly to keep the vessel running.

Marine machinery systems able to supply the required electrical and mechanical power onboard are based on three main technologies:

- Steam turbines
- Diesel engines
- Gas turbines

The world-wide merchant fleet represents around 60,000 vessels with an expected lifespan of more than 25 years. New ships under construction today will be in service up to 2050, meaning that the choice of propulsion system is a crucial question. This choice will impact all costs, from design and construction to operation, maintenance and recycling as well as resale price.

It is common practice for ships to be self-supplied with energy for operations when at berth. The onboard auxiliary engines produce the required electricity, typically from diesel oil, to limit emissions at port. Many port authorities are now preparing and imposing "cold ironing," or providing electricity via a shore to ship connection. Vessels in port need a non-negligible amount of power and the port facilities have to be suitably equipped to assure the requested energy peak loads.

4.2. CURRENT STANDARD MARINE FUELS

Fuel is any material that is burned to produce power. Today, most marine power plants use liquid petroleum fuel oils, known as marine fuels(1). These are split into residual (e.g., Heavy Fuel Oil, HFO) and distillate (e.g., Marine Gasoil, MGO) fuels, but all originate from refined crude oil. The ship engines, or internal combustion engines, combust the fuel with oxygen from the air to produce mechanical energy.

Blends of the two main types of fuel are referred to as Intermediate Fuel Oils (IFO). An example of this is Marine Diesel Oil (MDO), which is MGO mixed with a small quantity of HFO.

Fuel oil is a fossil-based energy and non-renewable. HFO remains the dominant fuel in international shipping, with 79% of total fuel consumption by energy content in 2018(2).

LNG is a fossil-based energy and is the principal fuel for natural gas carriers. LNG is now being introduced on other vessel types, including large containerships and cruise ships, due to its lower emissions and clean burning properties. There may be some gain on maintenance costs, though storage and handling arrangements are more costly compared to oil-fueled ships.

THE GLOBAL MERCHANT FLEET REPRESENTS AROUND 60,000 VESSELS WITH AN EXPECTED LIFESPAN OF OVER 25 YEARS.

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(1) ISO 8217 Fuel Class F, IMO.
(2) Fourth Greenhouse Gas Study, IMO, 2020.

In recent years, **methanol** (CH_3OH) has been developed as an alternative fuel for marine operations. Today this liquid fuel under normal conditions of pressure and temperature is mainly produced from natural gas, resulting in limited reductions in CO_2 emissions. This will change with a shift to bio and e-methanol production, so that methanol can become a true alternative to the conventional carbon-based fossil fuels.

Recently, a surge was noted in biofuel usage onboard ship, aided by regulatory alignment aiming to reduce the requirements for blends containing up to 30% biofuels.

Nuclear is another option, currently used for icebreakers and warships, that might disrupt the shipping energy transition in the future. However, nuclear-powered vessels would be subject to political considerations and technical discussions regarding how to limit and treat nuclear waste. Nuclear energy is not widely used for ships today, but there are ongoing studies to evaluate its use in shipping.

Both fossil fuels and nuclear power are considered non-renewable energy resources.

4.3. GHGs AND AIR POLLUTANTS

GHGs are gaseous constituents of the atmosphere, both natural and anthropogenic. They absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. According to the UNFCCC, the major atmospheric gases responsible for causing global warming and climate change are:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) are less prevalent, but nonetheless potent, GHGs.

According to the IMO (see Section 1), other substances that contribute to the shipping industry's environmental footprint include:

- Nitrogen oxides (NOx)
- Non-methane volatile organic compounds (NMVOCs)
- Carbon monoxide (CO)
- Particulate matter (PM)
- Sulfur oxides (SOx)
- Black carbon (BC)

The main airborne pollutants from ships can be found in the exhaust gases from the main and auxiliary engines and boilers. They are the direct result of combustion of hydrocarbon fuels.

Since 2011, the IMO has regulated NOx emission limits through MARPOL Annex VI, applied to marine diesel engines with a power output of more than 130 kW. The emission limits are expressed in Tier I, II and III:

- Tier I was retroactively applicable to engines installed on ships constructed on or after Jan 1, 2000
- Tier II is applicable to engines installed on ships constructed on or after 1 January 2011
- Tier III is only applicable in Emission Control Areas (ECA) defined in Annex VI of MARPOL

In January 2020 the IMO put into force a global 0.5% sulphur content limit for marine fuels. This has resulted in a 77% drop of overall SOx emissions from international shipping. It has also impacted particulate matter (PM) emissions, as this is directly dependent on the content of sulfur in fuel.

The World Health Organization (WHO), based on current scientific evidence, considers the following outdoor air pollutants as posing important health risks:

- PM (grouping sulfate, nitrate, ammonia, sodium chloride, black carbon, mineral dust and water) with a significant diameter of inorganic substances in air (≤PM10, ≤PM2.5)
- Ozone (at ground level, photochemical smog by sunlight, NOx and volatile organic compounds, VOCs)
- Nitrogen dioxide (NO_2)
- Sulfur dioxide (SO_2)

To cut GHG emissions, the IMO introduced the first set of international mandatory measures to improve ship's energy efficiency in July 2011, setting international shipping on the path to decarbonization
(see Figure 2 pp. 16-17*)*.

4.4. SUSTAINABILITY AND DECARBONIZATION

Sustainable shipping has become a key industry target, with stakeholders aiming to meet the needs of the present without compromising future potential. The shipping industry is focused on protecting the environment from marine and air pollution and preserving marine ecosystems. Other important topics are of great concern to the industry, including:

- Control of ballast water discharged overboard
- Underwater radiated noise
- Better management of ship end of life and conditions under which steel is collected for recycling purpose
- Improving diversity, gender balance, working conditions and well-being of seafarers and workers in shipyards

4.5. SHIP BUNKERING CAPACITY

Vessel designs include an estimated required fuel capacity based on its daily consumption at a given service speed. Measuring fuel consumption is one of the important tests carried out during sea trials prior to delivery from the yard. As different fuel types do not offer the same energy density, switching to alternative fuels will naturally impact vessel design with regards to fuel storage volume. Powered ships will need to be able to travel certain distances without stopping for bunkering.

4.6. CREW AND ALTERNATIVE FUELS

Designing and operating the fleets of tomorrow will require the maritime sector to attract and retain people with specific skills and more diverse talents. Alternative fuels each present their own challenges in terms of density, flammability, toxicity and specific maintenance procedures, so experienced, well-trained crews will be essential to operate the ships of the future.

The training of crews falls under the requirements of Flag Administrations. As a Recognized Organization (RO) acting on behalf of Flag Administrations, classification societies verify the training and certification of the crew when performing MLC audits. Engine manufacturers will need to train crews to run the various engine types that may be installed onboard vessels using alternative fuels.

The baseline requirement for crew training is the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). This convention was introduced in 1978, and has been regularly updated since. With the arrival of alternative fuels, a revision to the STCW is likely, reflecting a new shipping environment with changed risks for operations, maintenance, firefighting, etc. The shipping industry has already navigated a similar transition with the advent of LNG fuel, which will be an important learning point for new alternative fuels.

Our subsidiary Bureau Veritas Solutions Marine & Offshore offers courses through an e-Academy platform, addressing not only crew, but all marine stakeholders.

FIGURE 2: ADDRESSING CLIMATE CHANGE – A DECADE OF ACTION TO CUT GHG EMISSIONS FROM SHIPPING

REGULATIONS

Adoption of **mandatory energy efficiency regulations** for ships under MARPOL Annex VI – Energy Efficiency Design Index (EEDI) for new ships, Ship Energy Efficiency Management Plan (SEEMP) for all ships (15 July 2011)

EEDI and SEEMP enter into force

Approval of the **Third IMO GHG Study 2014** (October 2014)

EEDI phase 1 in effect – 10% reduction in carbon intensity of new ships

Adoption of a mandatory IMO Data Collection System (DCS) for ships to collect and report fuel oil consumption data from ships over 5,000GT

Adoption of the IMO Initial Strategy on reduction of GHG emissions from ships, with a vision to reduce GHG emissions from international shipping and, as a matter of urgency, aiming to phase them out as soon as possible in this century and setting levels of ambition and set of short-, mid and long-term candidate measures (April 2018)

2011 **2012** **2013** **2014** **2015** **2016** **2017** **2018**

PROJECTS / IMPLEMENTATION SUPPORT

IMO-KOICA (Korea International Co-operation Agency) GHG project on building capacities in East Asian countries to address GHG emissions from ships

"Mitigation of climate change" Global Programme included in IMO's Integrated Technical Cooperation Programme (ITCP), later renamed as **"Energy Efficiency" Global Programme**

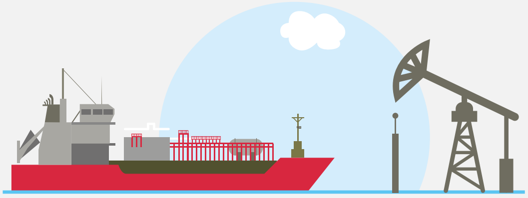
Adoption of resolution on promotion of technical cooperation and transfer of technology relating to the improvement of energy efficiency of ships (MEPC.229(65))

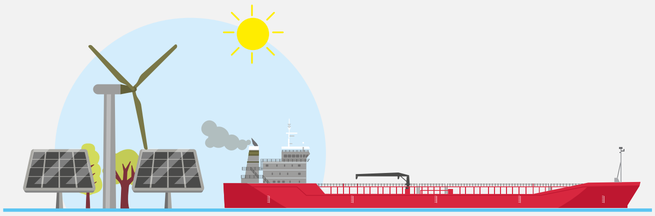
Global Maritime Energy Efficiency Partnerships Project (GloMEEP) launched with 10 lead pilot countries – a Global Environment Facility (GEF)-United Nations Development Programme (UNDP)-IMO project

Global network of five regional Maritime Technology Cooperation Centres (MTCCs) launched under IMO-executed GMN project, funded by the European Union

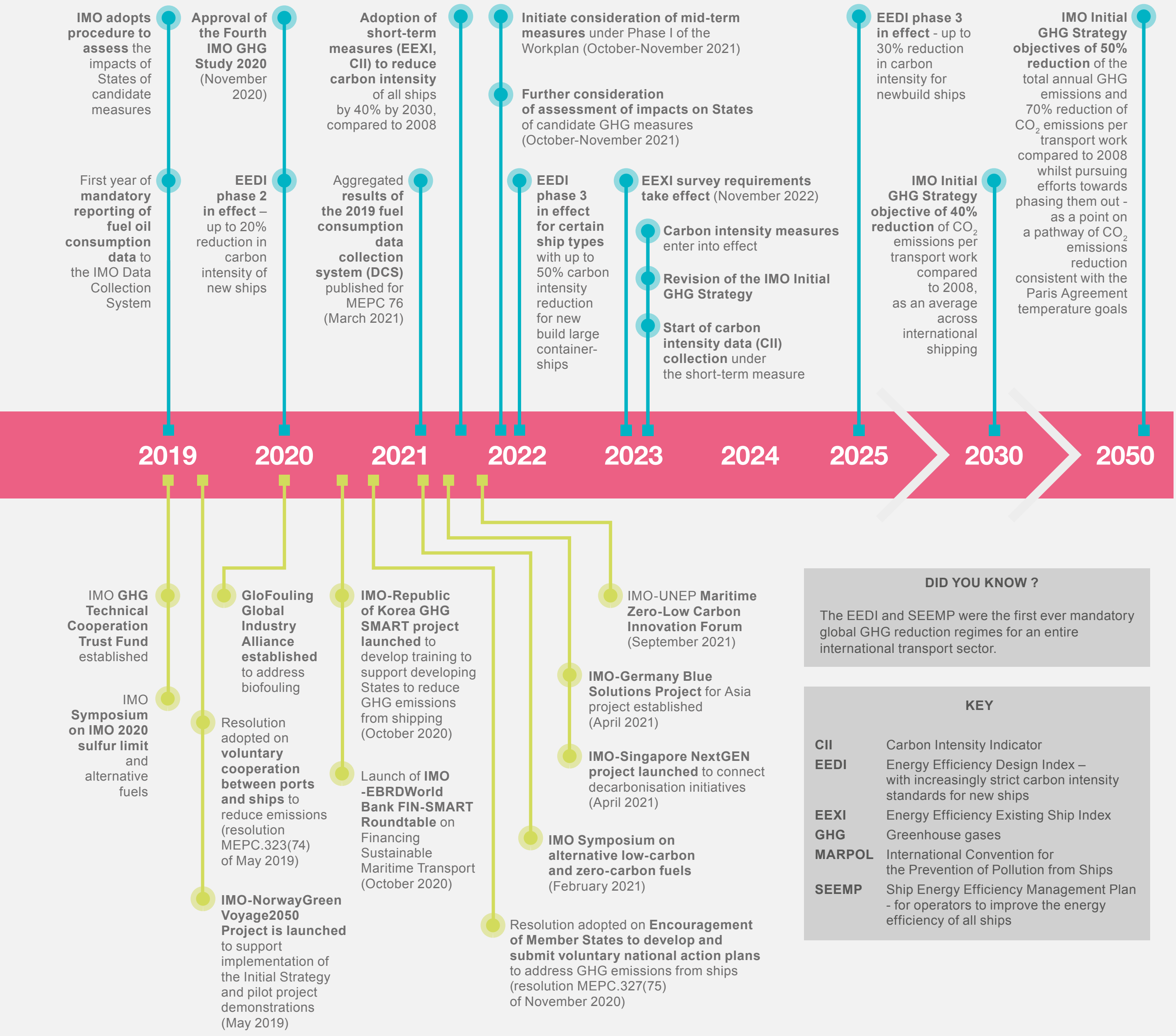
Low Carbon Global Industry Alliance launched under GloMEEP project to support an energy efficient and low carbon maritime transport system

GloFouling Partnerships project launched with 12 lead countries to tackle biofouling on ships to address bioinvasions and support energy efficiency gains through cleaner hulls. A Global Environment Facility (GEF) - United Nations Development Programme (UNDP) - IMO project





Source: IMO.



IMO adopts procedure to assess the impacts of States of candidate measures

First year of **mandatory reporting of fuel oil consumption data** to the IMO Data Collection System

Approval of the Fourth IMO GHG Study 2020 (November 2020)

EEDI phase 2 in effect – up to 20% reduction in carbon intensity of new ships

Adoption of short-term measures (EEXI, CII) to reduce carbon intensity of all ships by 40% by 2030, compared to 2008

Aggregated **results of the 2019 fuel consumption data collection system (DCS)** published for MEPC 76 (March 2021)

Initiate consideration of mid-term measures under Phase I of the Workplan (October-November 2021)

Further consideration of assessment of impacts on States of candidate GHG measures (October-November 2021)

EEDI phase 3 in effect for certain ship types with up to 50% carbon intensity reduction for new build large container-ships

EEXI survey requirements take effect (November 2022)

Carbon intensity measures enter into effect

Revision of the IMO Initial GHG Strategy

Start of carbon intensity data (CII) collection under the short-term measure

EEDI phase 3 in effect - up to 30% reduction in carbon intensity for newbuild ships

IMO Initial GHG Strategy objective of 40% reduction of CO_2 emissions per transport work compared to 2008, as an average across international shipping

IMO Initial GHG Strategy objectives of 50% reduction of the total annual GHG emissions and 70% reduction of CO_2 emissions per transport work compared to 2008 whilst pursuing efforts towards phasing them out - as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals

IMO **GHG Technical Cooperation Trust Fund** established

IMO **Symposium on IMO 2020 sulfur limit** and alternative fuels

GloFouling Global Industry Alliance established to address biofouling

Resolution adopted on **voluntary cooperation between ports and ships** to reduce emissions (resolution MEPC.323(74) of May 2019)

IMO-NorwayGreen Voyage2050 Project is launched to support implementation of the Initial Strategy and pilot project demonstrations (May 2019)

IMO-Republic of Korea GHG SMART project launched to develop training to support developing States to reduce GHG emissions from shipping (October 2020)

Launch of **IMO-EBRDWorld Bank FIN-SMART Roundtable** on Financing Sustainable Maritime Transport (October 2020)

Resolution adopted on **Encouragement of Member States to develop and submit voluntary national action plans** to address GHG emissions from ships (resolution MEPC.327(75) of November 2020)

IMO Symposium on alternative low-carbon and zero-carbon fuels (February 2021)

IMO-Germany Blue Solutions Project for Asia project established (April 2021)

IMO-Singapore NextGEN project launched to connect decarbonisation initiatives (April 2021)

IMO-UNEP **Maritime Zero-Low Carbon Innovation Forum** (September 2021)

DID YOU KNOW ?

The EEDI and SEEMP were the first ever mandatory global GHG reduction regimes for an entire international transport sector.

KEY

CII	Carbon Intensity Indicator
EEDI	Energy Efficiency Design Index – with increasingly strict carbon intensity standards for new ships
EEXI	Energy Efficiency Existing Ship Index
GHG	Greenhouse gases
MARPOL	International Convention for the Prevention of Pollution from Ships
SEEMP	Ship Energy Efficiency Management Plan - for operators to improve the energy efficiency of all ships

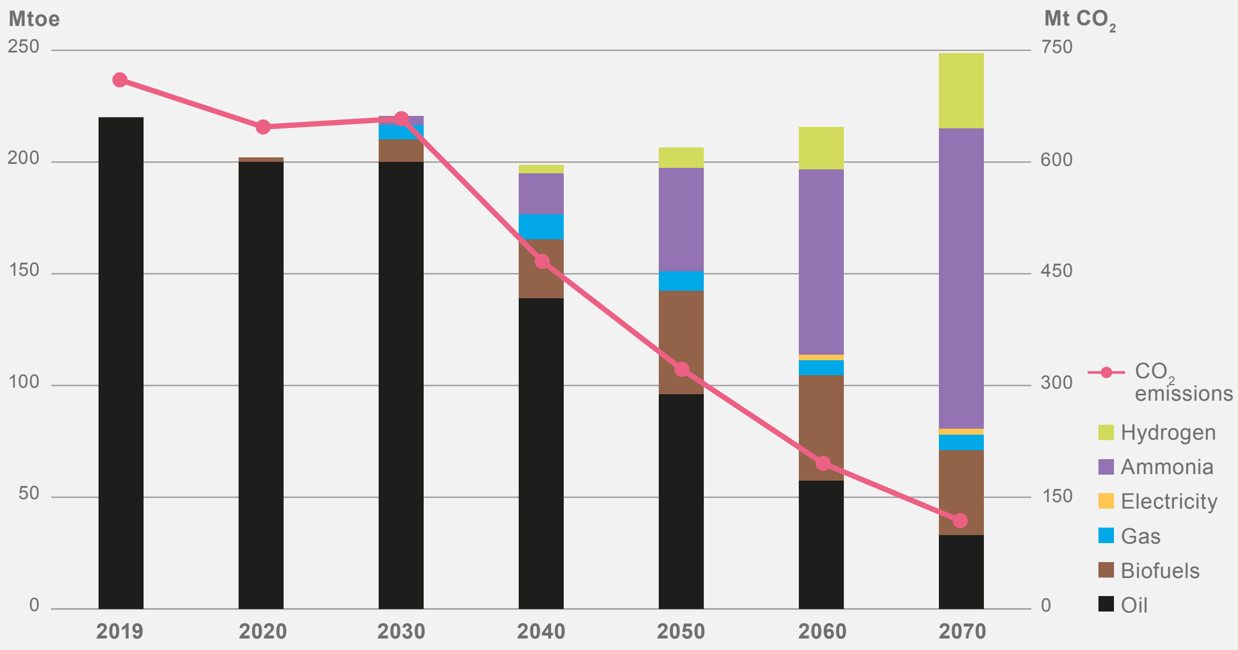
5. FUEL OVERVIEW

5.1. EXPECTATIONS

Initiatives are regularly launched to estimate the energy outlook of the shipping industry. These include research papers published by established organizations not dedicated to the maritime sector, like the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA).

According to the to the IEA report, “Energy Technology Perspectives 2020” (see Figure 3), global energy consumption and CO_2 emissions from shipping are expected to radically change between now and 2070. Hydrogen, ammonia and biofuels should be the main fuels used to reduce the carbon intensity of international shipping, decreasing emissions by more than 80% between 2029 and 2070.

FIGURE 3: GLOBAL ENERGY CONSUMPTION AND CO_2 EMISSIONS OF INTERNATIONAL SHIPPING IN THE SUSTAINABLE DEVELOPMENT SCENARIO 2019-2070



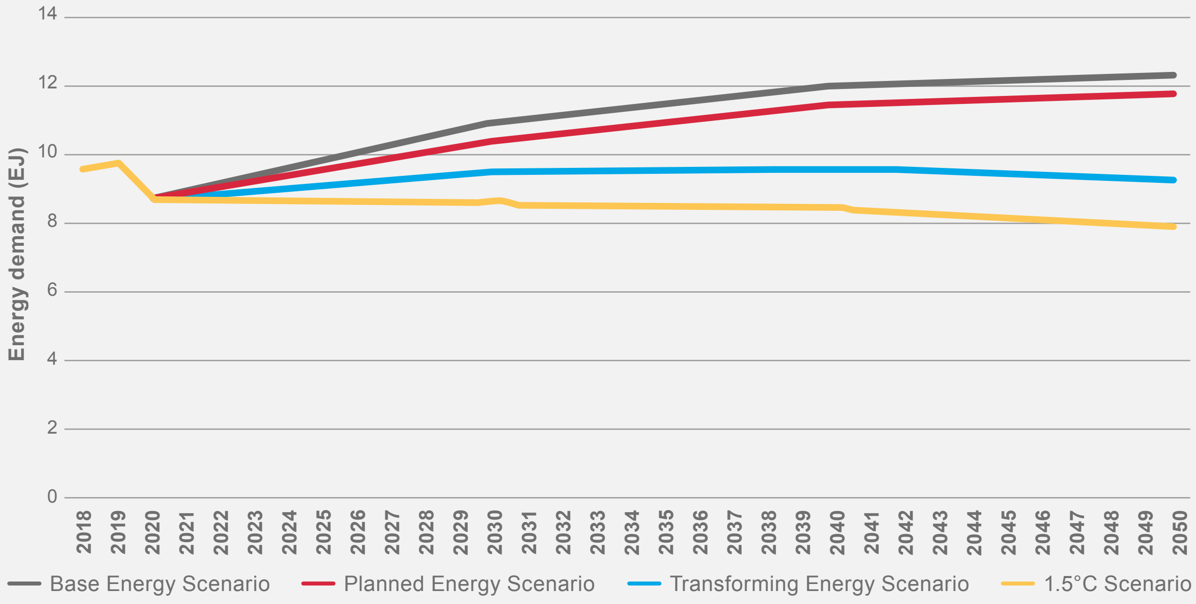
1 Mtoe = 1 million tons of oil equivalent = 41,868,000 GJ

Source: IEA 2020

IRENA reports that ammonia will be the dominant alternative fuel. Nevertheless, a mix of alternative fuels together with a reduction in overall shipping energy demand will be required to meet the 1.5°C target for 2050 (see Figures 4 and 5).

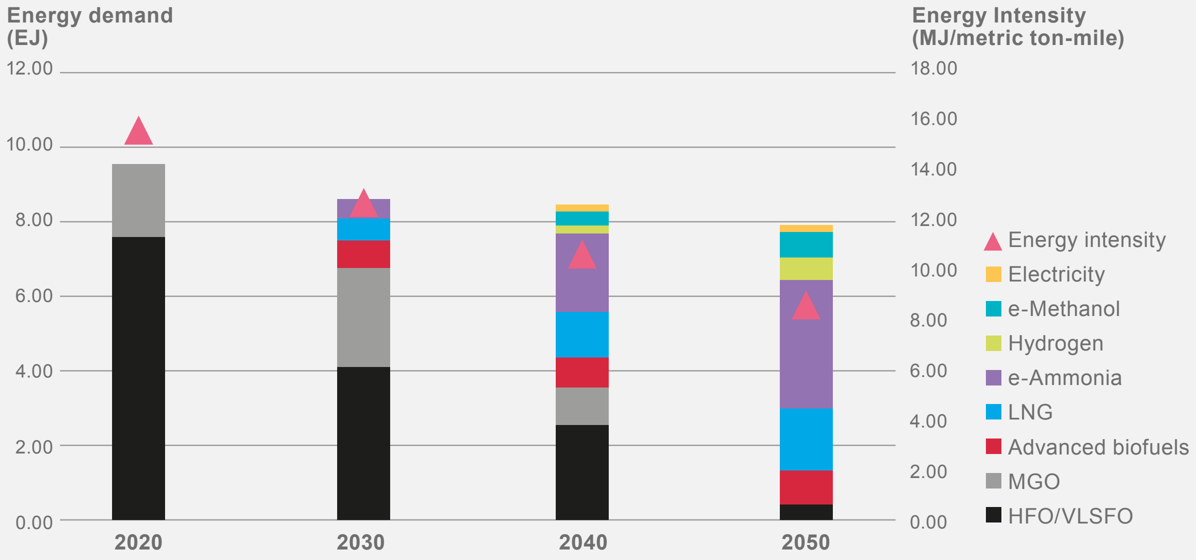
In addition to these organizations, maritime outlooks are regularly published by corporations and consortia. The recent publication from International Chamber of Shipping, "Fuelling the Fourth Propulsion Revolution: An Opportunity for All", provides an overview of some of these projections (see Figure 6).

FIGURE 4: FINAL ENERGY DEMAND PROJECTIONS, 2018-2050



Source: IRENA

FIGURE 5: 1.5°C SCENARIO ENERGY PATHWAY, 2018-2050

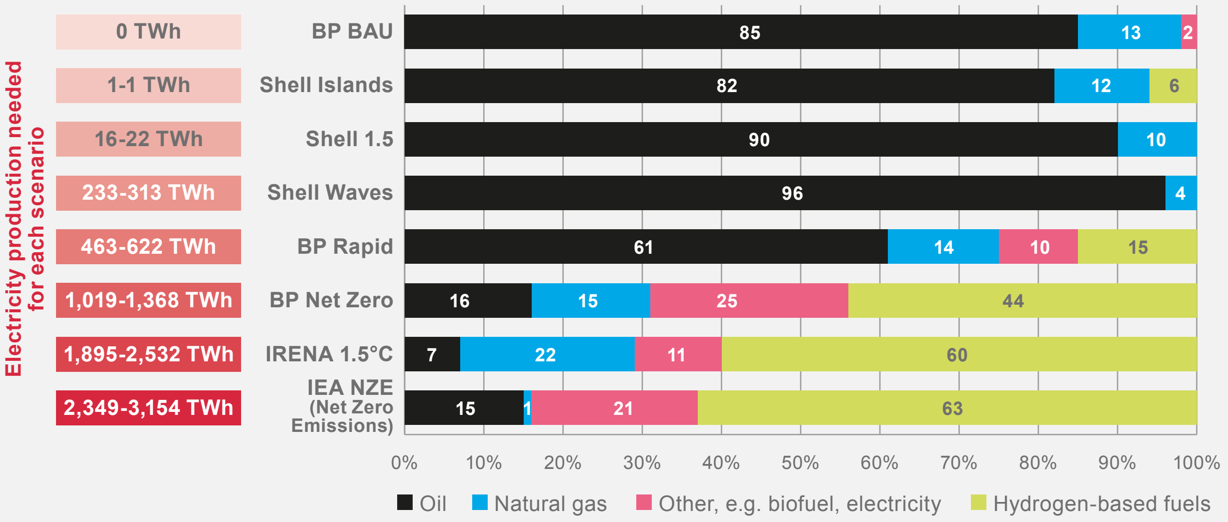


Source: IRENA

As we can see from the annual outlooks (see Figure 6), the alternative fuels landscape will be led by key drivers that could lead to vastly different outcomes. It is therefore particularly important to note that we will see a mix of alternative fuels in the near future.

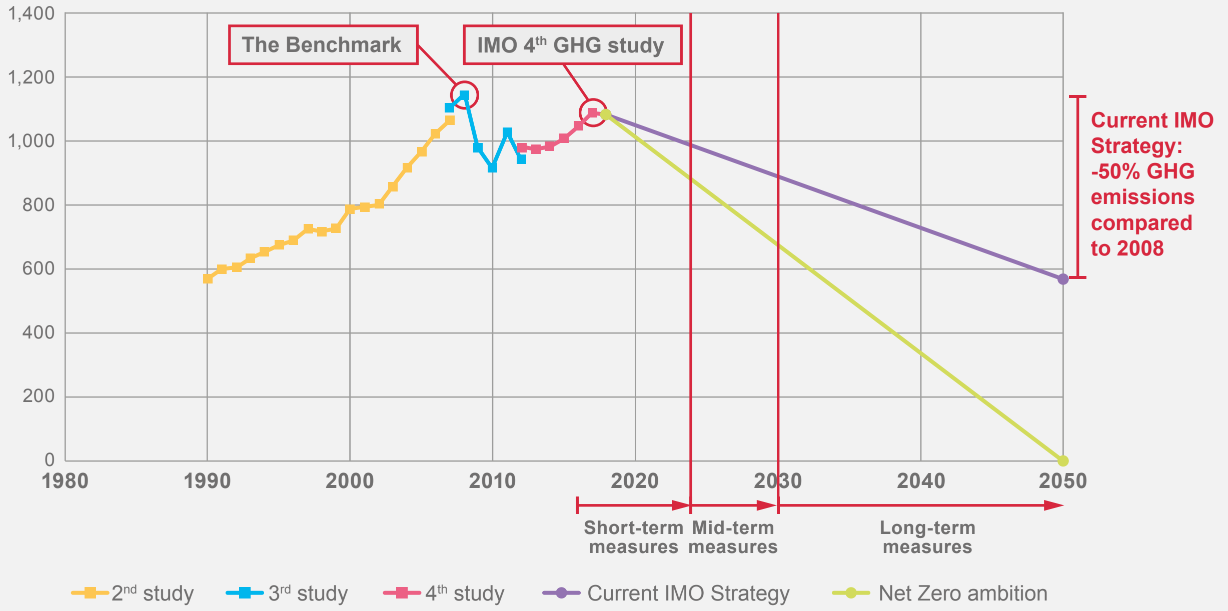
Moreover, beyond the share of each of the fuels, we must not lose sight of our goals (see Figure 7). Efforts must be made to reach targets and even exceed them by leveraging all decarbonization options, from energy savings to alternative fuels.

FIGURE 6: SAMPLE OF SCENARIOS OF FUEL MIX FOR SHIPPING IN 2050



Source: International Chamber of Shipping

FIGURE 7: GLOBAL SHIPPING GHG EMISSIONS (MtCO_{2e})



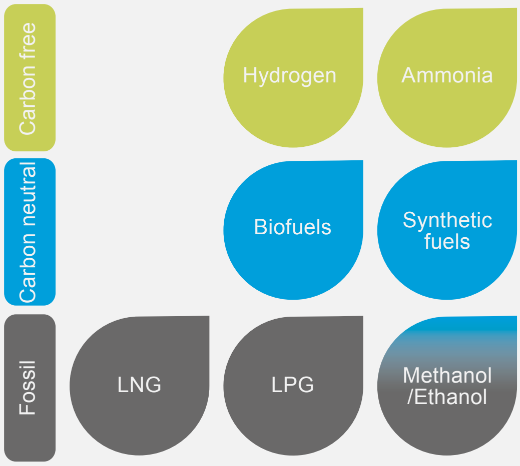
Source: Bureau Veritas

5.2. THE DASHBOARD OF ALTERNATIVE FUELS

a. Alternative fuels

Ideally, the shipping sector would move directly from fossil fuels to hydrogen-based, carbon-free options. Before hydrogen is available at scale, stakeholders can use transition fuels to reduce their carbon footprint and achieve carbon neutrality. This gives the shipping industry the opportunity to deliver substantial mid-term decarbonization results (see Figure 8).

FIGURE 8: ALTERNATIVE FUELS DASHBOARD



Source: Bureau Veritas

b. Vessel types and sizes

In the mid-term, it is likely that shipping will adopt several fuels. Due to limited availability and different fuel characteristics, certain types and sizes of vessels will have different optimal solutions. There could also be some regional variation in fuel choice.

Green corridors established between at least two ports, with appropriate investment, incentives and regulations could promote the use of one fuel over another. This enabler was first presented during COP26, and has been met with tremendous interest since then. Green corridors are likely to play a key role in the coming months as a catalyst to solve the chicken and egg dilemma and to fast-track full-scale testing of alternative fuels.

In future, small- and medium-sized ships could take advantage of several promising solutions: biofuels, battery- or hybrid battery-power, hydrogen and green methanol. On paper, green ammonia seems to be the ideal long-term solution for large ships operating in open seas from a purely environmental perspective. However, alternative fuels like synthetic methane (e-methane) and e-methanol, including advanced biofuels, are also serious contenders.

To evaluate these fuels, we must examine the following parameters:

Key considerations	Criteria & Considerations
Maturity & availability of technology	**Prototype developed, tested and available for use at scale or worldwide. Hazards controlled and operations optimized**
Specific energy (weight) & density (volume)	**Energy density expressed in either volumetric (MJ/l) or gravimetric density (MJ/kg)**
Safety considerations (flammability, toxicity)	**Bunkering, storage, onboard fuel distribution, equipment maintenance, crew and passengers**
Regulatory framework	**IMO, Class and National Authorities – Industry standards or additional industry requirements**
Global availability of fuel (terminal network)	**Ease of bunkering worldwide**
Bunkering facility availability	**Number of bunkering facilities, delays in service**
Sustainability (ESG/CSR aspects)	**Footprint on Common Reporting Standard (audit and report)**
Economics: CAPEX	**Capital expenditure or investment costs**
Economics: OPEX	**Operating expenditure or running costs**
Flexibility for future adaptation	**Enables transition to more optimal fuel solutions**

5.3. FOSSIL, CARBON-NEUTRAL AND CARBON-FREE FUELS

Fuels are basically made from carbon and/or hydrogen. Carbon neutrality can be achieved by use of biomass / waste/ organic residues to extract the carbon, or by offsetting the CO_2 emissions which means to remove the quantity of gasses from elsewhere to balance the emissions. Carbon Capture Systems may be used to combine those approaches.

Fossil fuels: are based on remains from a former geologic age and are not renewable on a human timescale, like coal, petroleum and natural gas. To limit global warming, policies now aim to preserve existing coal, gas and oil reservoirs and hunt for alternative energy sources. The burning of fossil carbon sources releases large quantities of carbon – captive for millions of years – and alters the natural balance in the atmosphere.

Carbon-neutral fuels: is a term often misused for promotion or marketing purposes. In reality, some CO_2 or other GHG emissions may be generated along a fuel's production and supply chain. The extent of these emissions must be evaluated to confirm the overall climate impact and benefits.

Biofuels are often qualified as a carbon-neutral energy carrier. This is on the provision that the CO_2 released in combustion comes from relatively recent feedstock harvesting and extraction, captured and stored in the form of biomass. Carbon-neutral fuels are generally fuels whose combustion contributes limited or no GHG emissions to the atmosphere. Evaluating biofuels as renewable energy sources requires accounting for their overall environmental impact, production, distribution and supply chains and storage in a life-cycle analysis (LCA) methodology.

Similarly, traceability of the CO_2 used needs to be established to evaluate the carbon footprint of an e-fuel. If the source is neutral in terms of CO_2 emissions, such fuels would be considered carbon-neutral, provided that the hydrogen molecules in their composition are produced from low-carbon pathways.

Carbon-free fuels: normally refers to fuels that do not have carbon in their chemical composition, such as ammonia and hydrogen. No CO_2 is released during combustion or use of these energy carriers, unless it originates from pilot fuels that may be required for internal combustion engines.

However, even carbon-free fuels may have a carbon-intensive supply chain, and may release other GHGs. When used in an engine, ammonia combustion may emit nitrous oxide (N_2O), a highly potent GHG. Furthermore, if hydrogen is released into the air, it may react with methane and ozone causing indirect greenhouse effects.

Overall, carbon-neutral and carbon-free are relatively difficult concepts. Without a full LCA, fuel's real benefits in terms of reducing greenhouse effects cannot be determined.

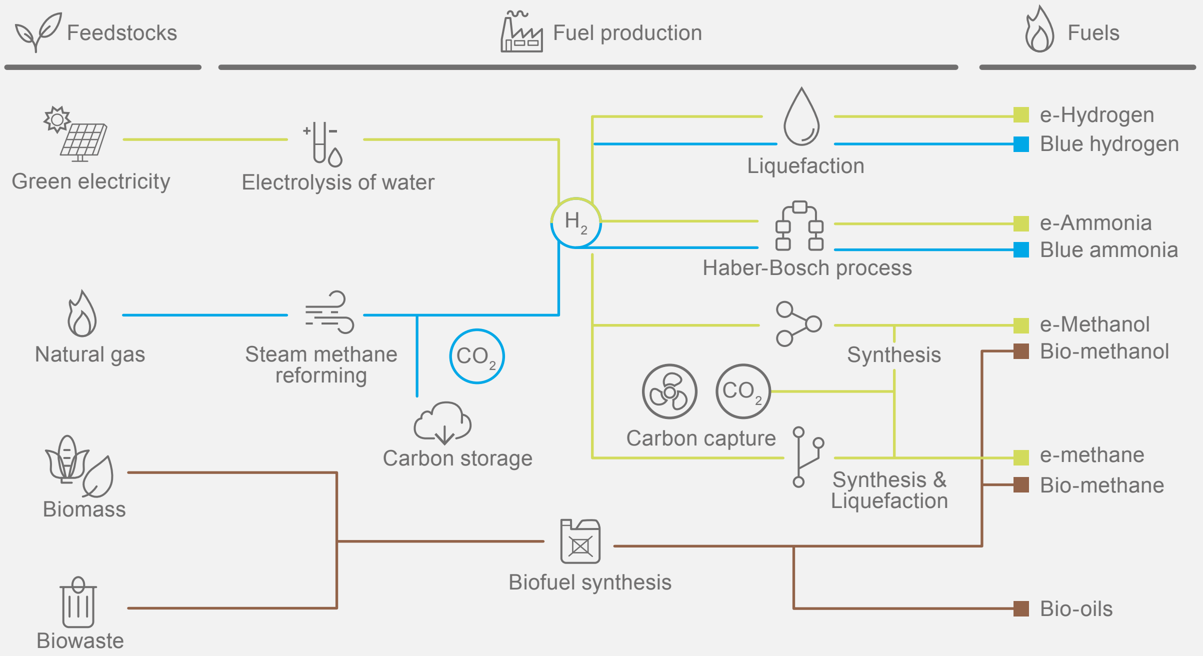
5.4. PRODUCTION PATHWAYS

Understanding the way these fuels are produced is paramount, as it will directly impact their GHG emissions on a well-to-wake basis. Production pathways show that some so-called alternative fuels can result in more GHG emissions than their hydrocarbon fuel counterparts if they come from a non-renewable source.

There are numerous processes that can be used to generate substitutes to conventional fossil fuels, but all require development and uptake. Figure 9 illustrates a simplified overview of alternative fuel candidates. However, even when great care is taken to sustainably produce low-carbon fuels from renewable sources, it is likely that GHG emissions will occur at some point in the supply chain.

There are three main categories of fuels, depending on their production pathway and/or feedstocks: fossil fuels or their derivatives, biofuels and e-fuels.

FIGURE 9: OVERVIEW OF ALTERNATIVE FUELS AND THEIR PRODUCTION PATHWAYS



Source: MMMCZCS

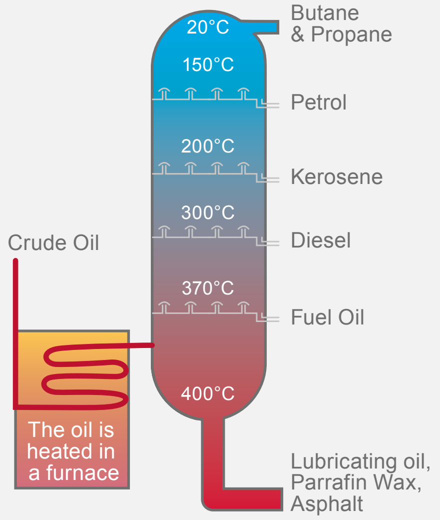
a. Fossil fuels

Fossil fuels are the most widely used fuels in the shipping industry as of today. They can be split into three main types:

- Residual fuel: heavy fuel oil
- Distillate fuels: marine diesel oil, LPG
- LNG

These fuels are extracted from geological formations and have been used in combustion engines for decades.

FIGURE 10: CRUDE OIL PRODUCTS



Source: Wikipedia

b. Biofuels

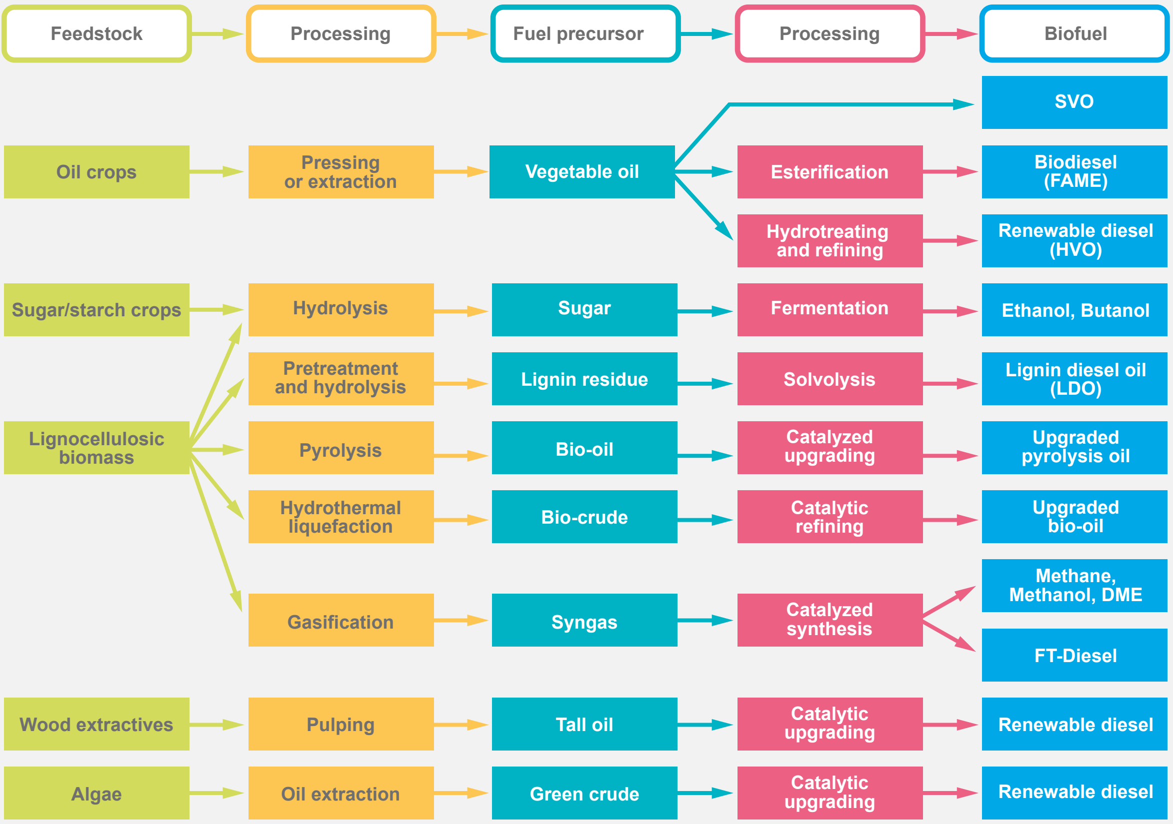
Biofuels use biomass as a primary source to generate gaseous or liquid fuels. The production of biofuels is complicated by numerous possible processes and feedstocks (see Figure 11). In principle, using biofuels is justified as this should result in a limited or zero increase in atmospheric CO_2 levels, taking life cycle into account. However, the sustainability of biofuels depends on the nature of feedstocks used. Monitoring indirect land use change (ILUC) is essential to ensure biofuel production does not lead to indirect detrimental effect on the environment from a more global approach perspective.

Biofuels can also be categorized by generation:

- **First generation:** the most commonly used biofuels worldwide, produced from agricultural crops, vegetable oil or food waste such as palm oil and soybeans. They are also frequently called conventional biofuels. FAME and HVO are the main first-generation biofuels in the shipping industry.
- **Second generation:** often referred to as advanced biofuels and made of lignocellulosic biomass, residual feedstocks from forestry or crops. They are more sustainable, as their ILUC is low and there is no competition with food sectors. Moreover, these advanced biofuels require specialized chemical processes that lead to more stable fuels compared to the first generation.
- **Third generation:** this future generation of biofuels is not yet mature and will need further development and industrialization before uptake. They are produced from algae and microbes.

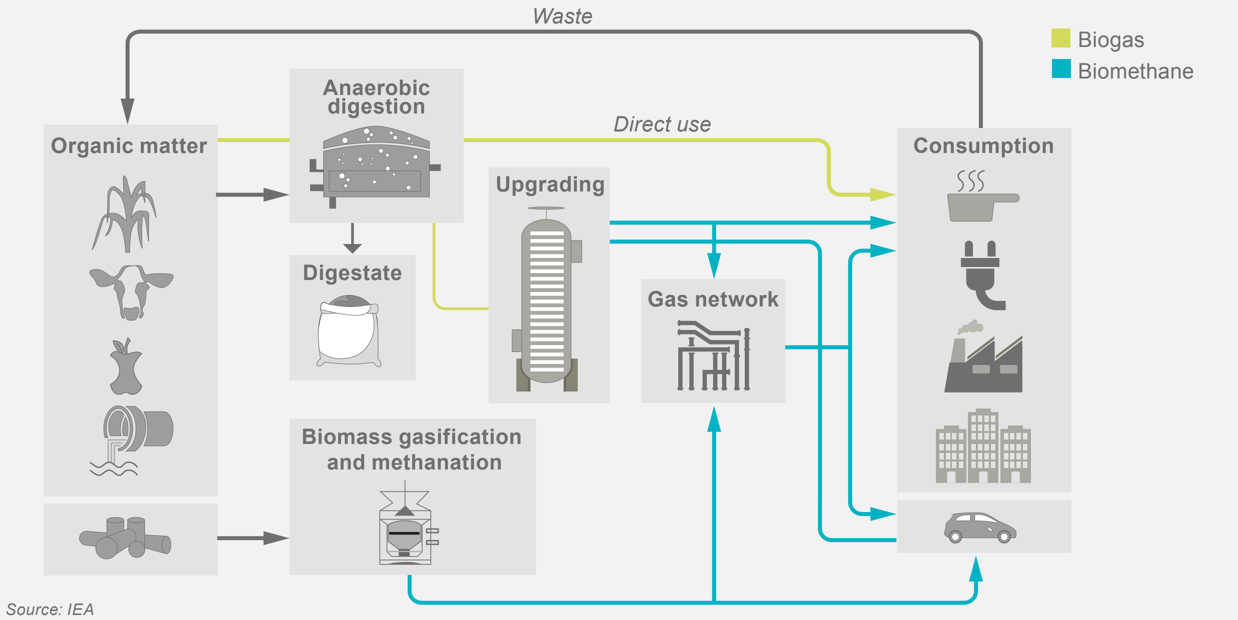
For example, biogas, also called liquid biogas (LBG), is usually produced through the anaerobic digestion of organic waste (crop residues, animal manure), municipal solid waste (MSW) or municipal wastewater. Biogas is mostly made of (bio)methane with a concentration ranging from 45-75%, the remainder being mostly CO_2. Biomethane is obtained by upgrading biogas; CO_2 is a coproduct of this reaction and can be used to produced e-methane when mixed with green H_2 (see Figure 12).

FIGURE 11: OVERVIEW OF DIFFERENT FEEDSTOCK CONVERSION ROUTES TO MARINE BIOFUELS



Source: IEA Bioenergy

FIGURE 12: BIOGAS AND BIOMETHANE PRODUCTION PATHWAYS



Source: IEA

c. Hydrogen

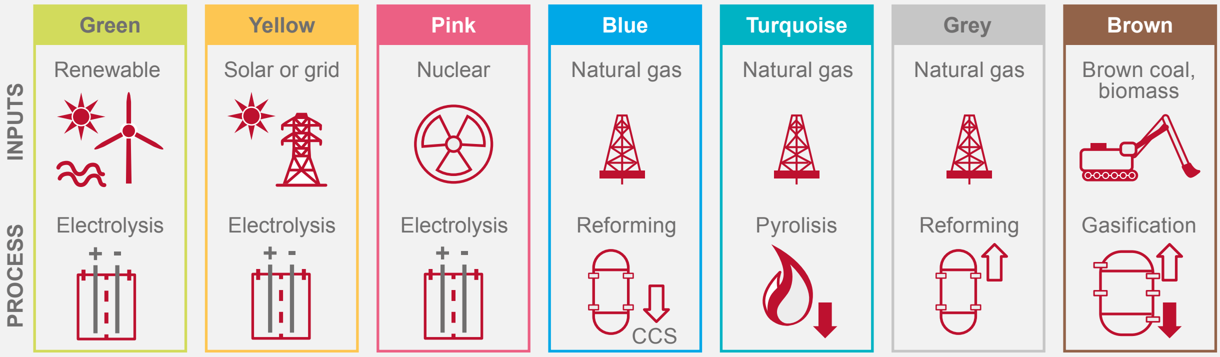
Fuels other than conventional oil-based ones can be produced from fossil fuels. Hydrogen, for example, is currently produced from fossil fuels – methane and coal – and itself used as a source to generate other chemicals like ammonia or methanol. Depending on its provenance, hydrogen is divided into seven categories (see Figure 13):

- **Black and brown:** hydrogen produced respectively from black coal or lignite through a gasification process. This results in a syngas made mostly of CO, H_2 and CO_2.
- **Grey:** hydrogen produced from natural gas in a process called SMR (Steam Methane Reforming). The resulting syngas is mostly made of CO, H_2 and CO_2.
- **Blue:** when carbon emitted during grey hydrogen production process is captured with Carbon Capture and Storage (CCS) utilities. The resulting product is H_2.
- **Pink hydrogen:** hydrogen generated through electrolysis using electricity from a nuclear power plant. This generates limited CO_2 emissions and nuclear waste which requires specific measures to mitigate its lengthy radiative effects.
- **Red hydrogen:** hydrogen generated through the high-temperature catalytic splitting of water using thermal nuclear power as an energy source.
- **Turquoise:** hydrogen produced from natural gas through a process of pyrolysis. The main advantage is that this process is CO_2-free. The only byproduct, in addition to H_2, is solid carbon.
- **Green hydrogen:** hydrogen created by electrolyzing water using renewable electricity (more details on this production pathway are given section 5.4c). Green hydrogen is now firmly in the spotlight with an essential role to play in the global economic decarbonization.

The resulting syngas or H_2 is then used to generate by-products like ammonia, methanol or methane.

Today, the majority of hydrogen, methanol and ammonia is produced from fossil fuel sources. For ships, the use of hydrogen will result in zero-emissions from a tank-to-wake perspective. However, accounting for the entire lifecycle for hydrogen produced from hydrocarbon sources would result in very high well-to-wake GHG emissions.

FIGURE 13: HYDROGEN PRODUCTION PATHWAYS FROM FOSSIL FUELS



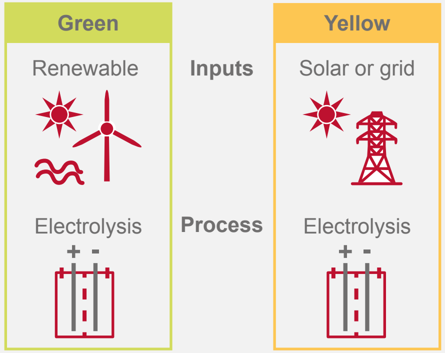
Source: Broadleaf

d. E-fuels

Electrofuels, e-fuels or Power-to-X (PtX) fuels are probably the most promising fuels for the shipping industry and for other transportation sectors like aviation. These fuels rely on green hydrogen production and therefore require huge amount of renewable energy. Other production pathways to provide hydrogen for e-fuels might be considered if their GHG emissions are low, as is the case for pink of red hydrogen.

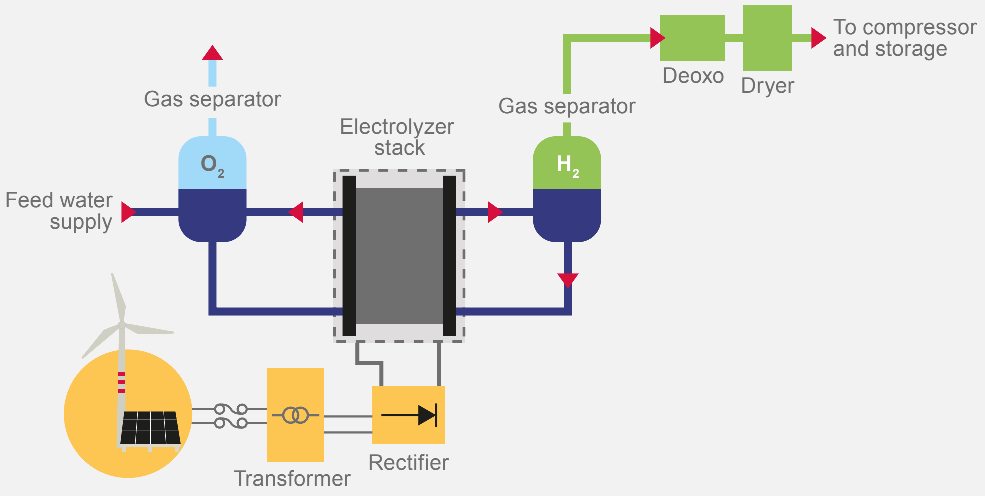
Green H_2, which can be categorized as an e-fuel, is produced from water (H_2O) through electrolysis. This is a highly energy-intensive process that uses vast amounts of renewable power to split H_2O into hydrogen and oxygen. E-methanol, e-ammonia and e-distillates can then be produced using green hydrogen as a primary source (see Figures 14, 15 and 17).

FIGURE 14: RENEWABLE HYDROGEN PRODUCTION PATHWAYS



Source: Broadleaf

FIGURE 15: GREEN HYDROGEN PRODUCTION

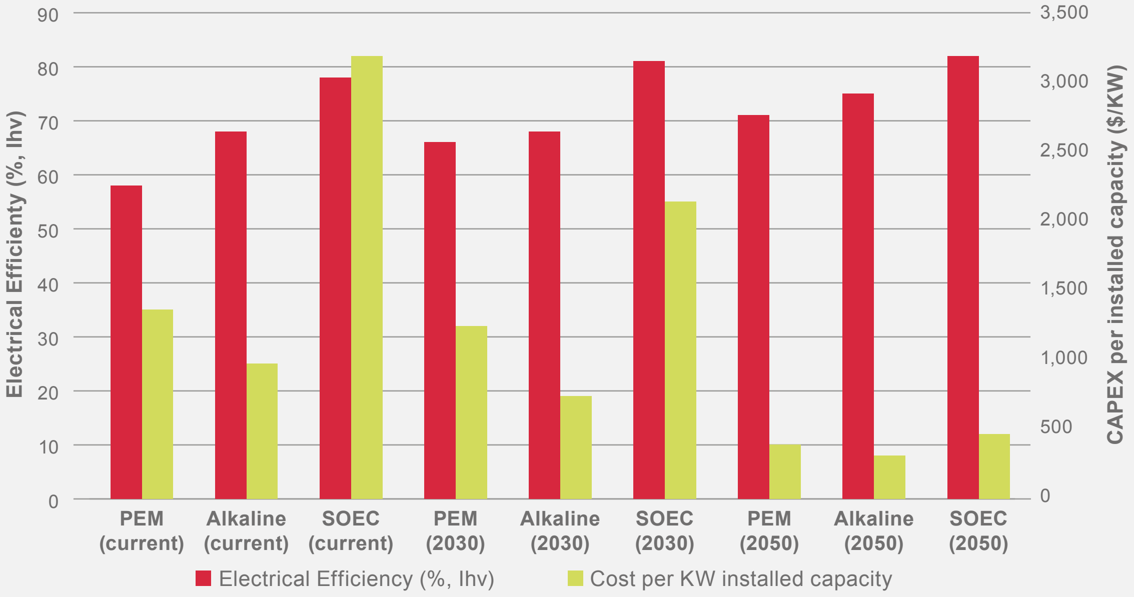


Source: IRENA

Electrolysis uses three main types of technology (see Figure 16):

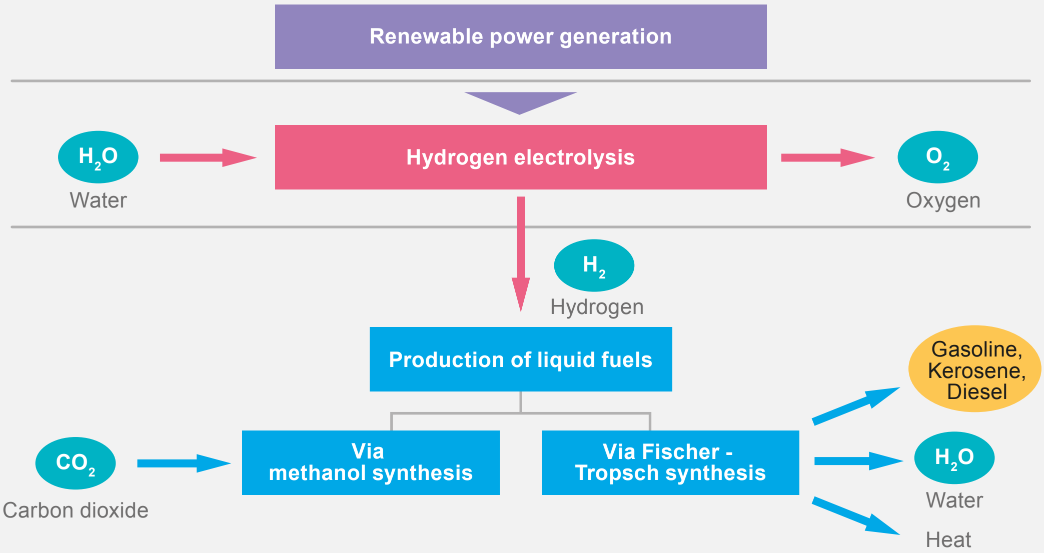
- Alkaline electrolyzer cells (AEC), which are the largest and most mature technology, used for over 50 years.
- Proton-exchanged membrane (PEM), which are around half the size of equivalent AEC systems.
- Solid oxide electrolyzer cells (SOEC), which are less mature but very promising due to their potential higher efficiency rate.

FIGURE 16: COMPARISON OF ELECTROLYZER TECHNOLOGIES' EFFICIENCY & CAPEX



Source: CORE POWER

FIGURE 17: E-FUEL PRODUCTION ROUTES



Source: Frontier Economics

To meet growing demand, electrolyzers will have to be more energy-efficient and durable, while requiring considerably less CAPEX. The reduced cost of renewable electricity and a high number of available operating hours per year will be essential.

The widespread use of e-fuels is, however, compromised by the overall low efficiency of its production process. This creates a need for new dedicated renewable electricity generation plants. Assuming an average 45% tank-to-wake efficiency, this means an overall well-to-wake efficiency for e-fuels within the range of 20-25% (see Figure 18).

Production pathway of e-diesels

E-diesel is produced from green H_2 and CO_2 using Fischer-Tropsch (FT) synthesis (see Figure 19). FT synthesis can be used for e-diesel but also a wider array of fuels. It produces an e-crude from which FT fuels can be generated (see Figure 20).

The production pathways of e-methane, e-methanol and e-ammonia (green ammonia) are described in sections 7.1, 7.3 and 7.5.

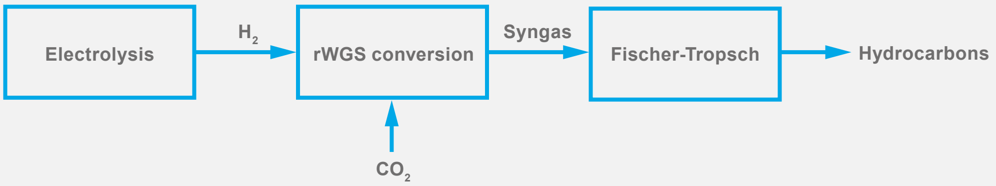
FIGURE 18: E-FUELS OVERALL WELL-TO-TANK EFFICIENCY

<table>
<tr><th rowspan="2"></th><th>Electricity</th><th colspan="2">e-Hydrogen</th><th colspan="2">e-methane</th><th>e-Ammonia</th><th>e-Methanol</th><th>e-Liquid fuels</th></tr>
<tr><th>Battery Electric Vehicle</th><th>Fuel Cell</th><th>ICE</th><th>Fuel Cell</th><th>ICE</th><th>ICE</th><th>ICE</th><th>ICE</th></tr>
<tr><th colspan="9">WTT</th></tr>
<tr><td>Renewable power</td><td>100%</td><td colspan="2">100%</td><td colspan="2">100%</td><td>100%</td><td>100%</td><td>100%</td></tr>
<tr><td>Transmission efficiency</td><td>95%</td><td colspan="2">95%</td><td colspan="2">95%</td><td>95%</td><td>95%</td><td>95%</td></tr>
<tr><td>Electrolysis efficiency</td><td>-</td><td colspan="2">70%</td><td colspan="2">70%</td><td>70%</td><td>70%</td><td>70%</td></tr>
<tr><td>e-Hydrogen</td><td>-</td><td colspan="2">67%</td><td colspan="2">67%</td><td>67%</td><td>67%</td><td>67%</td></tr>
<tr><td>Methanization efficiency</td><td>-</td><td colspan="2">-</td><td colspan="2">80%</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Ammonia syn, Haber-Bosch process efficiency</td><td>-</td><td colspan="2">-</td><td colspan="2">-</td><td>86%</td><td>-</td><td>-</td></tr>
<tr><td>Methanol synthesis efficiency</td><td>-</td><td colspan="2">-</td><td colspan="2">-</td><td>-</td><td>80%</td><td>-</td></tr>
<tr><td>Fischer-Tropsch efficiency</td><td>-</td><td colspan="2">-</td><td colspan="2">-</td><td>-</td><td>-</td><td>70%</td></tr>
<tr><td>Transport efficiency*</td><td>-</td><td colspan="2">80%</td><td colspan="2">80%</td><td>95%</td><td>95%</td><td>95%</td></tr>
<tr><td>e-methane</td><td>-</td><td colspan="2">-</td><td colspan="2">43%</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>e-Ammonia</td><td>-</td><td colspan="2">-</td><td colspan="2">-</td><td>54%</td><td>-</td><td>-</td></tr>
<tr><td>e-Methanol</td><td>-</td><td colspan="2">-</td><td colspan="2">-</td><td>-</td><td>51%</td><td>-</td></tr>
<tr><td>e-Liquid fuels</td><td>-</td><td colspan="2">-</td><td colspan="2">-</td><td>-</td><td>-</td><td>44%</td></tr>
</table>

* Transport including compression in the case of hydrogen and methane.

Source: CONCAWE

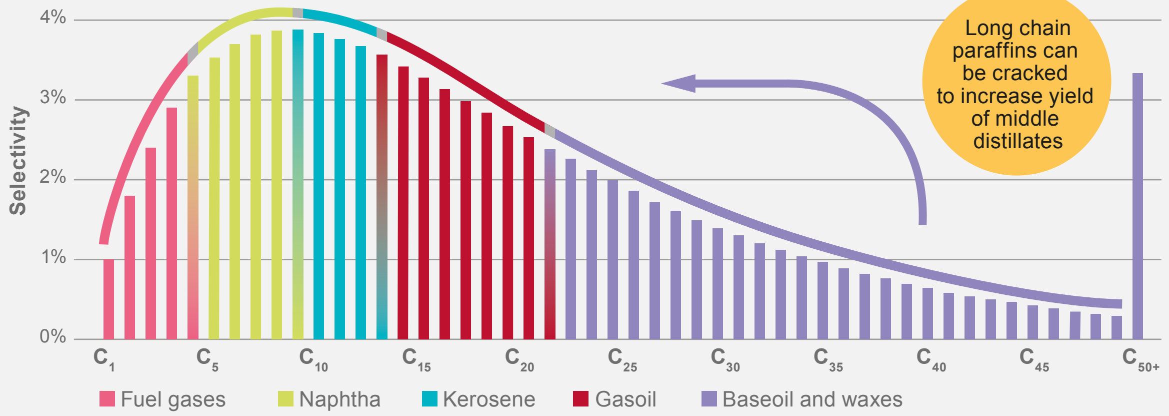
FIGURE 19: FISCHER-TROPSCH SYNTHESIS



Source: Shell Energies

FIGURE 20: FISCHER-TROPSCH E-FUEL PRODUCTS

Own calcultation, concept by Sterner/Stadler 2017



Long chain paraffins can be cracked to increase yield of middle distillates

Source: Shell Energies

Although lacking in efficiency, carbon-based e-fuels are still likely to play a key role in the future, as they promise significant CO_2 reduction and are much easier to store and transport than electricity. As well as being well adapted for use with existing infrastructure, they can significantly reduce NOx and SOx air pollution.

The cost of renewable energy and CO_2 as a primary resource will have to decrease to ensure a rapid uptake of e-fuels. High CAPEX and OPEX costs will drive e-fuel production facilities to operate at very high rates to be economically viable, impacting costs. Financial mechanisms will be required to close the gap between conventional fossil fuels and their counterparts produced from renewable or low-carbon sources, such as the Emissions Trading System (ETS) and Contracts for Difference (CfD).

5.5. EMISSIONS OF GHG AND AIR POLLUTION

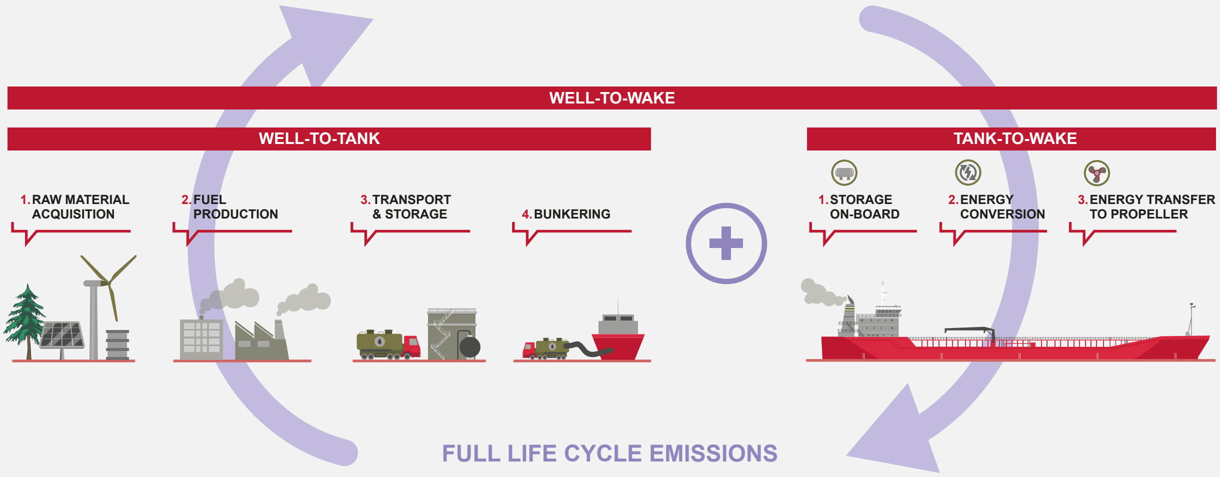
To assess a fuel's real impact on climate change, the GHG emissions released from fuel production, distribution and use onboard the ship must be taken into account. These are known as well-to-wake (WtW) emissions (see Figure 21).

- Well-to-tank (WtT) emissions: emissions from fuel production to a fuel tank onboard a ship.
- Tank-to-wake (TtW) emissions: from a fuel tank to propulsion of a ship (also called tank-to-propeller emissions).
- Well-to-wake (WtW) emissions: emissions from fuel production to propulsion of a ship.

WtW emissions integrate all upstream GHG emissions of the fuel used onboard the ship. These include GHGs emitted during raw material or feedstock acquisition, fuel production and extraction, transformation or refining, transportation, storage and bunkering. Considering WtW emissions is essential for maritime decarbonization and uptake of alternative fuels; policymakers are increasingly working to define guarantee of origin for alternative fuels.

As of today, a WtW approach to emissions has not been adopted by the shipping industry at international level. Regulatory requirements (EU MRV, IMO DCS or CII) only consider emissions in TtW terms, without upstream considerations. This matter has been subject to discussion globally and regionally since 2021 (see Section 6).

FIGURE 21: WTW EMISSIONS EXPLANATION



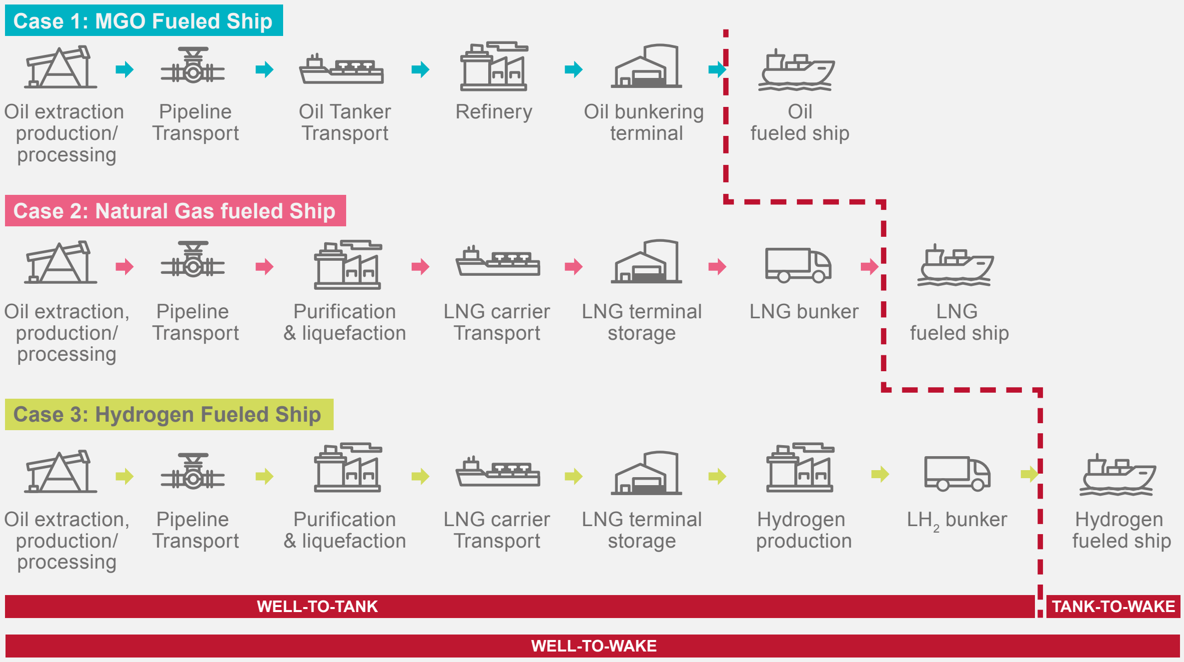
Source: Bureau Veritas

a. Complexity of the WtW approach

Figure 22 details the WtW emissions of different types of fuel, demonstrating the underlying complexity in such an approach.

TO DATE, THE SHIPPING INDUSTRY HAS NOT ADOPTED A WELL-TO-WAKE APPROACH AT INTERNATIONAL LEVEL.

FIGURE 22: WTW EMISSIONS EXAMPLES



Source: Pusan University

It is almost impossible to be exhaustive in both WtT and TtW emissions estimations. While TtW estimation appears straightforward, it is subject to variation according to each ship's design. TtW outcomes can, for instance, be impacted by the use of fuel cells, combustion engines, turbines or the installation of emission abatement technologies. As the number of combinations is almost infinite, this report intends only to clarify orders of magnitude of emissions.

Figure 23 presents an overview of WtW emissions for marine fuels, showing that:

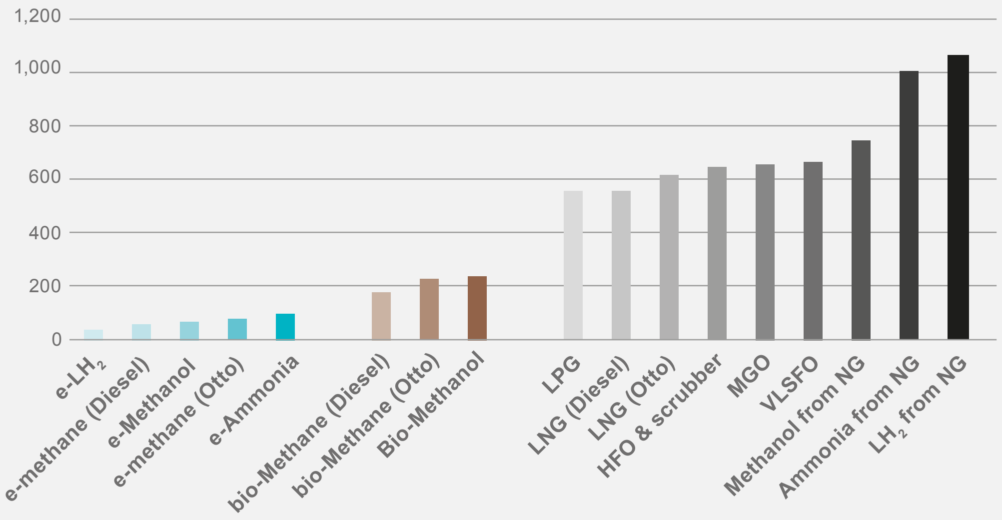
- On average, e-fuels have the lowest emissions levels compared to biofuels and fossil fuels.
- All fossil-based fuels emit more GHGs throughout their entire value chain than biofuels and e-fuels. This may have a strong impact on market-based measures like carbon taxes or ETS.
- The fuel production pathway must be included in future shipping regulations. Hydrogen and ammonia have almost no TtW emissions, but are among the highest emitters from a WtW perspective with current production pathways. Methanol, ammonia and hydrogen are all currently produced from fossil fuels, with higher WtW GHG emissions than the conventional fuels they intend to replace.
- The production of these alternative fuels must be urgently decarbonized.

Within the same production pathway, a fuel's ranking may change depending upon several parameters. For example, e-methane produced from solar panels and transported over long distances in a cryogenic state will have greater WtW emissions than locally consumed e-methanol produced from a wind farm.

In the case of low-maturity technologies such as e-fuels, the WtW calculation is more theoretical and more subject to discrepancies. Additionally, in the case of ammonia, for which no engines are currently commercially available, the impact of Nitrous Oxide (N_2O) emissions on overall GHG emissions remains uncertain. According to the IPCC, N_2O has a global warming potential (GWP 100) 273 times higher than CO_2. Even hydrogen leakage may lead to indirect radiative forcing, as highlighted in a recent UK government study which estimated a GWP of 11±5 over 100 years. This highlights the absolute need to limit leakage, even for non-direct GHG like hydrogen. Preliminary data for both ammonia and hydrogen needs to be further investigated. This will be closely followed to ensure that upcoming alternative fuels bring real added value to meet sustainability criteria.

It is clear that the shipping sector will need to cooperate with energy and chemical sectors to achieve true decarbonization. Decarbonizing the maritime sector will require a tremendous capacity of low-cost renewable energy, especially as these alternative fuels candidates are all currently essential in other areas. Green fuel production will have to answer current demand as well as new fuel needs. For instance, methanol is the building block of numerous domestic materials; ammonia (and therefore hydrogen) is used in fertilizers vital to securing food supply.

FIGURE 23: TYPICAL WELL-TO-WAKE EMISSIONS OF MARINE FUELS (gCO_{2e}/kWh - GWP100)



Source: Bureau Veritas

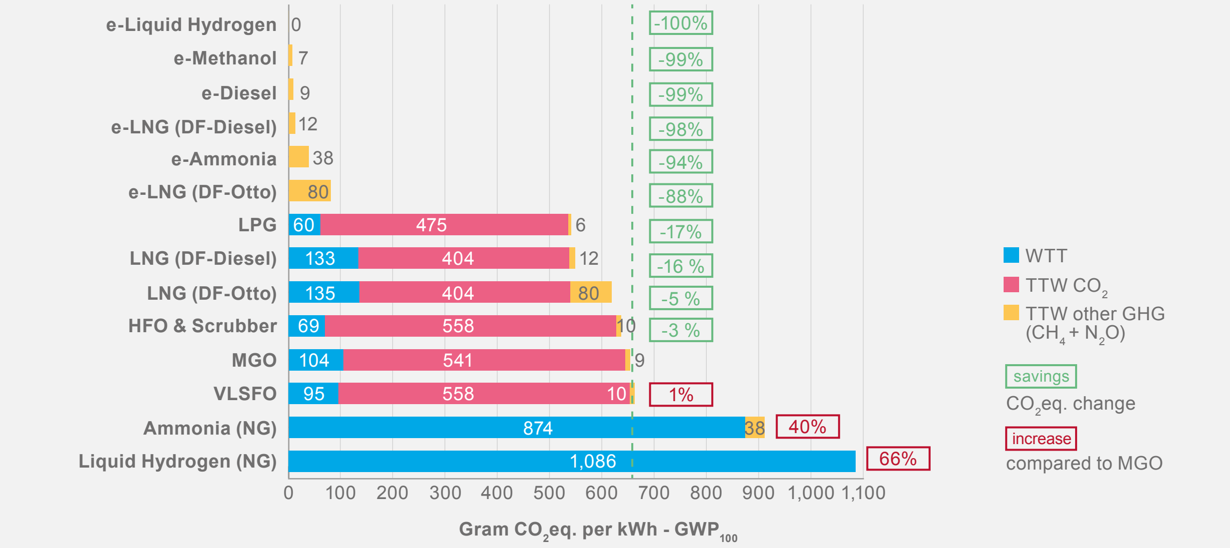
In Figure 24, which has notably included CO_2, CH_4 and N_2O emissions, we can see that some fossil-derived alternative fuels could offer GHG reductions on a WtW basis.

Using this data and other emissions studies, the GHG reductions from a WtW perspective have been estimated. As previously stated, these ranges are to be considered as orders of magnitude. WtW emissions depend on numerous parameters that can reduce or increase overall GHG emissions.

- LNG: 5% - 23% GHG emissions reduction compared to HFO
- LPG: up to 17% GHG emissions reduction compared to HFO

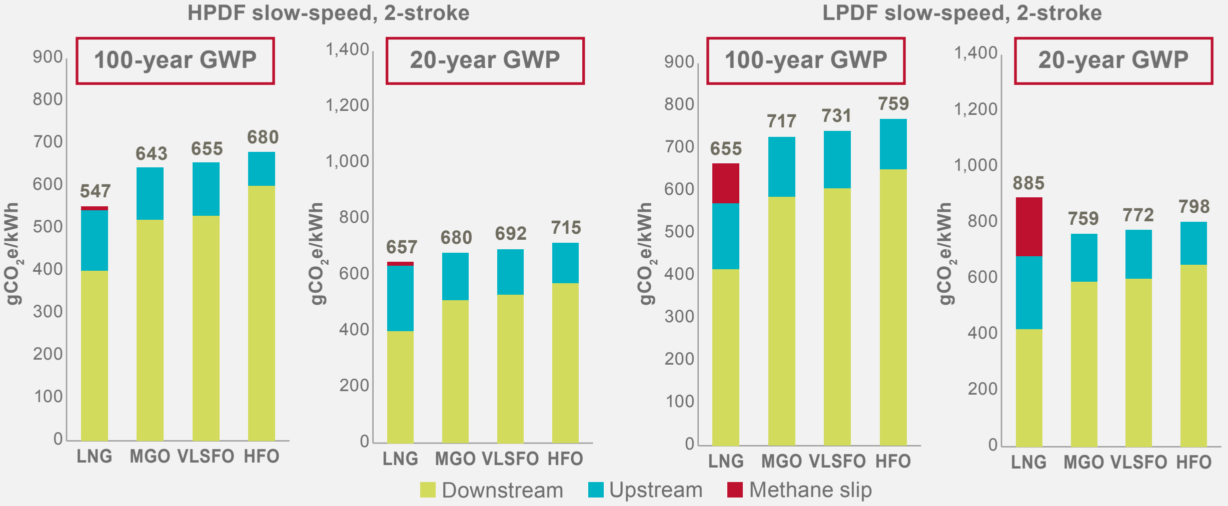
When addressing GHG emissions, we should consider that the impact of CH_4 and N_2O is much more potent than that of CO_2. Furthermore, the impact of a 100-year GWP, even if acceptable in the shipping industry, is subject to intense debate. The International Council on Clean Transportation (ICCT) has highlighted the differences that would result from a 20-year rather than 100-year GWP (see Figure 25). For example, the GWP of methane is considerably reduced with a 100-year GWP, due to its short lifespan in the atmosphere.

FIGURE 24: WTW EMISSIONS (gCO_{2eq}/kWh)



Source: SINTEF & NTNU

FIGURE 25: LIFE-CYCLE GHG EMISSIONS BY ENGINES AND FUEL TYPE (left: 100-year GWP; right: 20-year GWP)



HPDF: High Pressure Dual Fuel engine (Diesel cycle) – LPDF: Low Pressure Dual Fuel (Otto cycle) – *Source: ICCT*

Methane slip is a crucial consideration when using LNG as fuel, as it increases a ship's GHG emissions, especially in low-pressure engines. Debates are ongoing, as to the emission factor to be used for considering methane slip (see Figure 26).

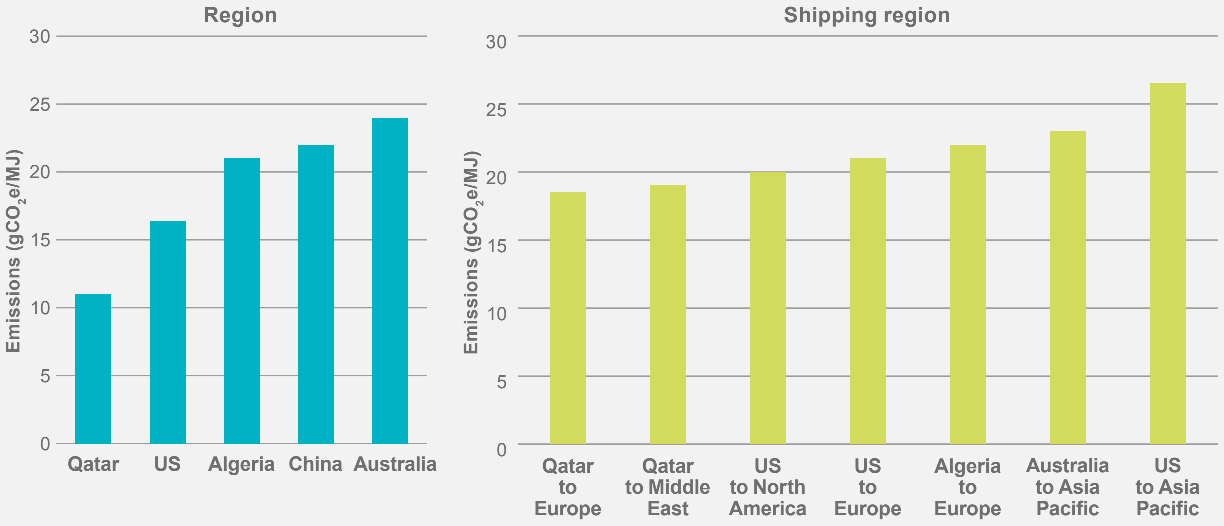
Methane leaks are another important consideration when using LNG as fuel. Unlike methane slip, these are upstream methane emissions that occur during extraction, processing, transportation and onboard handling before combustion. These leaks depend highly on production pathway and location (see Figure 27). For example, shale gas is likely to have more leaks than conventional natural gas.

FUGITIVE METHANE EMISSIONS AND METHANE SLIP NEED TO BE MINIMIZED TO ENSURE SIGNIFICANT GHG REDUCTIONS.

FIGURE 26: METHANE SLIP VALUES BY ENGINE TYPE (gCH_4/kWh)

	Two-stroke Dual Fuel Diesel Engine	Two-stroke Dual Fuel Otto Engine	Four-stroke Dual Fuel Otto Engine
SGMF (2019)	0.1	2.1	3.9
SEA-LNG (2021)	0.23	2.14	3.98
ICCT (2020)	0.2	2.5	5.5

FIGURE 27: WELL-TO-TANK EMISSIONS, DEPENDING ON LOCATION OF BUNKERING AND SOURCE OF LNG
(100-year GWP)



Source: ICCT

Fugitive methane emissions and methane slip need to be minimized to ensure significant GHG reductions. Engine manufacturers are currently working on improving engine operation and control (e.g., optimum ignition timing adjustment), optimizing engine design (e.g., combustion chamber design) or exhaust after-treatment. Studies are underway to measure and monitor real on-site methane emissions. This is an essential step to map and understand the provenance of methane leaks to further drastically reduce them.

The combustion process of ammonia is likely to lead to the emissions of N_2O. N_2O has an even greater 100-year GWP than methane (CH_4) (273 for N_2O compared to approximately 28 for CH_4).

This is why the calculation of well-to-tank emissions is so crucial. For example, a 100% green hydrogen may rely at some point on conventional fossil fuel-based transportation, either road or maritime. This means that its well-to-tank emissions will not be zero-carbon.

Equally, a fuel emission factor of a green energy will depend on the type of renewable energy used to produce it. For example, hydropower has a lower GHG emissions factor than solar power. Green hydrogen produced with hydropower electricity will therefore be greener than green hydrogen produced using solar power electricity.

Frameworks and guidelines are currently being prepared at international level by the IMO to help the industry to assess the environmental footprint of these alternative fuels.

b. Air pollution

In addition to GHG emissions, understanding air pollution from NOx, SOx and PM is essential when assessing alternative fuel contenders. Improving air pollution is a crucial health concern, increasingly raised in dense areas like big trading ports.

LNG, LPG and methanol all significantly reduce air pollution(3) (see Figure 28).

- **SOx:**
  Theoretically could be reduced by 99%, though a small amount will be emitted from the pilot fuel used in combustion (between 1.5% to 5% of pilot fuel used in dual fuel engines).
- **NOx:**
  Two-stroke low-pressure engines are Tier III-compliant, but high-pressure engines will need abatement technologies like SCR or EGR to achieve compliance.

As these air pollutants are emitted from combustion processes, fuel cells and batteries can be used to reduce a vessel's footprint.

FIGURE 28: AIR POLLUTION LEVELS FOR LNG, LPG AND METHANOL

Air pollutant	Emissions reduction compared to conventional HFO engine [%]		
	LNG	LPG	Methanol
NOx	Up to 40% for 2S Diesel cycle Up to 90% for 2S Otto cycle	Up to 20% for 2S Diesel cycle	30%-60% (Tier II compliant)
SOx	Over 90%	Over 90%	Over 90%
PM	Over 85%	Over 85%	Over 85%

Source: Bureau Veritas

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(3) No mention of biofuels, hydrogen or ammonia when used in ICE, due to current lack of consistent data. Several tests are ongoing to measure biofuel's impact on NOx emissions.

5.6. FUELS CHARACTERISTICS

a. Energy density

Fuel oil offers an excellent energy density, which goes some way to explaining its decades of dominance in the transportation sector. Depending on the choice of alternative fuel, maintaining the level of available energy in combustion will require additional fuel tank volume (see Figure 29). Certain types of alternative fuels will require higher frequency bunkering than before, or a reduced cargo capacity.

b. Flammability and auto-ignition temperature

Certain characteristics are critical to evaluating a fuel's safety:

- Flashpoint
- Flammability limits
- Auto-ignition temperature

Flashpoint: the lowest temperature at which a liquid can form an ignitable mixture in the air near the surface. In theory, the lower the flashpoint, the lower the possible ignition temperature of the fuel, and the higher the risk in the absence of additional safety measures.

Flammability limits: the range of vapor concentrations of a certain chemical, expressed in air volume percent, over which a flammable mixture of gas or vapor in air can be ignited at 25°C and atmospheric pressure. In theory, the wider the range, the higher the risk.

Auto-ignition temperature: the minimum temperature required to ignite a gas or vapor in air without a spark or flame present.

Alternative fuels have very different behavior regarding flammability, entailing their own challenges and risks (see Figure 30). Methane has relatively limited flammability ranging from 5-15%, while hydrogen ranges from 4-75%. As hydrogen also has a low minimum ignition energy (MIE) of 0.017mJ, it poses higher risks in terms of safety. Ammonia, on the other hand, has a low flammability and is difficult to ignite.

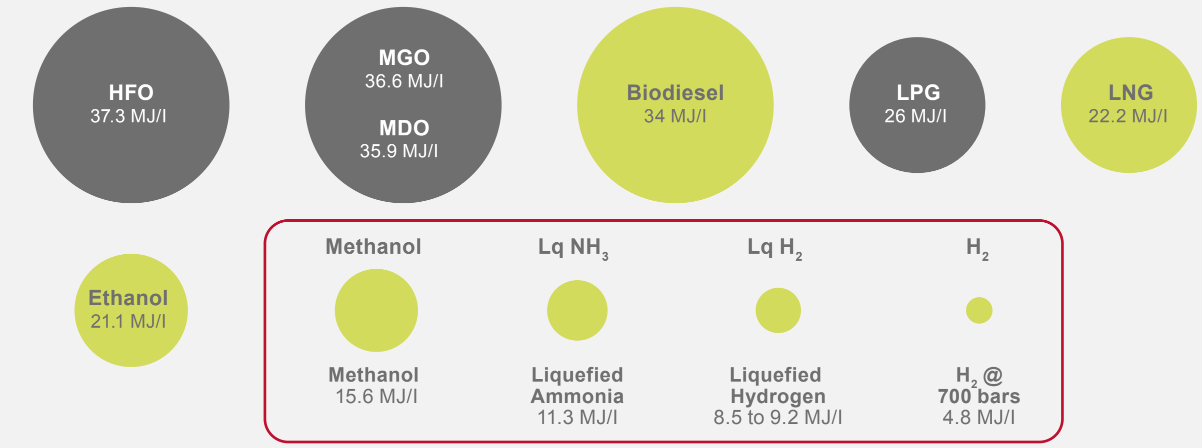
c. Overview of characteristics

Beyond energy density and flammability limits, alternative fuels have several significant differences.

The optimal storage temperature must be considered when designing a ship as it has a major impact on the equipment to be installed and CAPEX costs. Alternative fuels differ hugely in their physical properties; the flashpoint of ammonia is very high (132°C) but much lower for methanol (12°C).

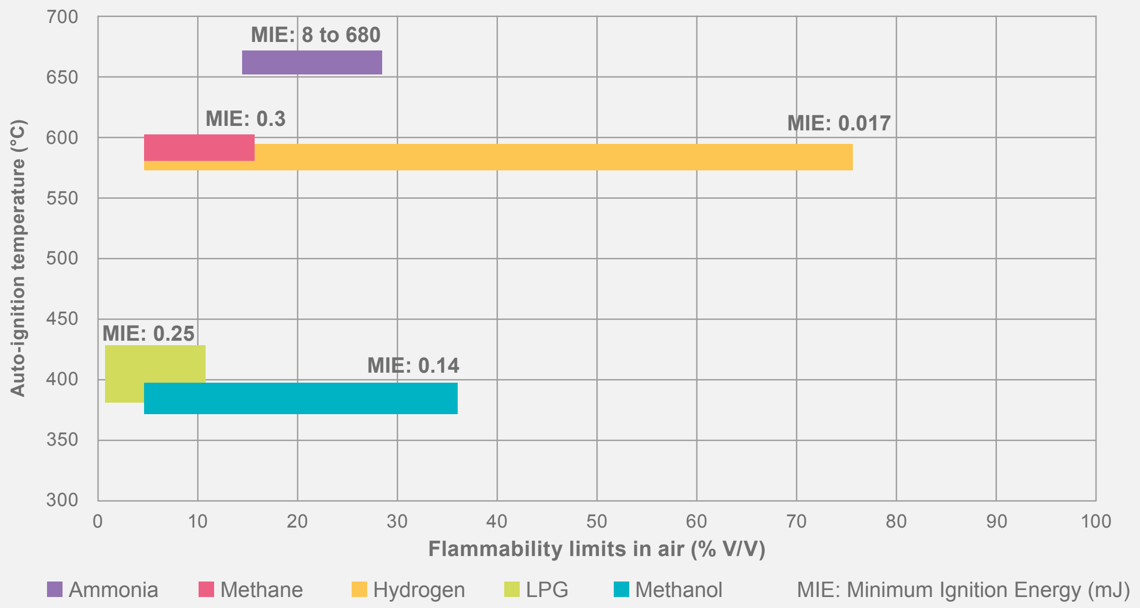
> **ALTERNATIVE FUELS HAVE VERY DIFFERENT BEHAVIOR REGARDING FLAMMABILITY, ENTAILING THEIR OWN CHALLENGES AND RISKS.**

FIGURE 29: VOLUMETRIC ENERGY CONTENT OF ALTERNATIVE FUELS



Source: Bureau Veritas

FIGURE 30: FLAMMABILITY LIMITS IN AIR AND AUTO-IGNITION TEMPERATURES OF ALTERNATIVE FUELS



Source: Bureau Veritas

TYPICAL PROPERTIES OF MAIN ALTERNATIVE FUELS

	LNG	LPG	Methanol	Bio-Diesel	Ammonia	Hydrogen
Physical properties for storage	Liquid at -162°C	Liquid at 18 bar or at -42°C or semi-20°C at 7 bar	Liquid (up to 65°C)	Liquid	Liquid at -33°C	Compressed gas at > 250 bar or liquid at -253°C
Fuel tank size for same energy content as MDO	1.8 times	1.5 times	2.5 times	1 time	3 times	5-7 times
Fuel Containment System (Cryo/ conventional)	CRYO	COLD	CONV	CONV	COLD	CRYO
Flammability limits in air (%V/V)	5%-15% (Methane)	1% to 11%	6%-36.5%	/	15%-28%	4-75%
Minimum Ignition Energy (mJ)	0.3 (Methane)	0.25	0.14	/	8 to 680	0.017
Flashpoint (°C)	-188	-104	12	>61	132	
Density of liquid phase (kg/m^3)	450	493	790	900	696	71
LCV (MJ/kg)	50	46.4	19.9	42.7	18.6	120
Energy density (MJ/L)	21.2	26.5	15.7	35.7	12.7	8.5

Source: Bureau Veritas

5.7. BUNKERING FACILITIES

a. LNG

LNG is widely available in 141 ports worldwide (see Figure 31) but bunkering facilities remain limited mostly to North America, Europe and East Asia. However, these facilities may become more widespread in coming years. According to a SEA-LNG report, there will be up to 170 bunkering ports by the end of 2022, and LNG bunkering could represent as much as 10% of global bunkering by the end of the decade.

LNG bunkering in Europe has achieved several milestones. CMA CGM is at the forefront of these breakthroughs, bunkering their ultra-large containerships in Rotterdam in November 2020 and more recently in Marseille Fos in January 2022.

SGMF (the Society for Gas as a Marine Fuel) has issued a third revision of its “LNG as a marine fuel – Safety and Operational Guidelines – Bunkering.” It adopts a more holistic approach and provides consistent industry guidelines to promote the future development of adapted infrastructure.

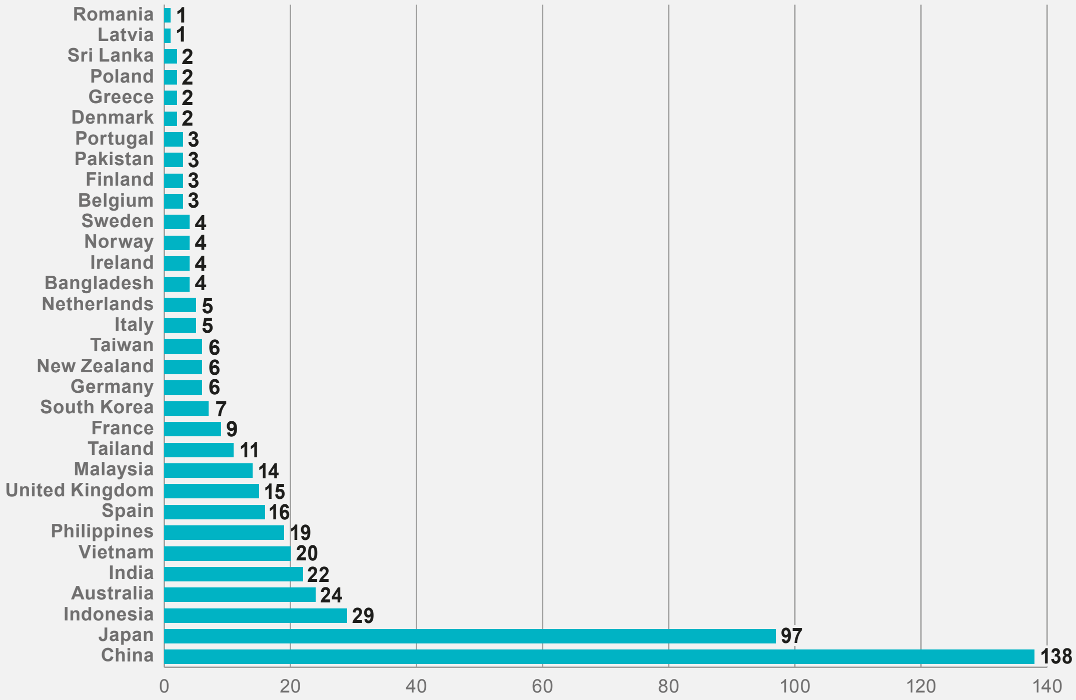
b. LPG

LPG can effectively leverage its existing facilities: more than 1,000 facilities worldwide are equipped with pressurized LPG storage tanks. In these locations, it is possible to develop bunkering infrastructures by creating distribution systems in addition to the existing storage facilities. More than 700 small LPG carriers could also be used for ship-to-ship bunkering operations.

Compared to LNG, LPG is much easier to liquefy and is therefore a more attractive bunkering fuel.

The world’s first ship-to-ship LPG transfer bunkering took place in 2021.

FIGURE 31: WORLDWIDE LPG TERMINALS



Source: ARGUS

c. Methanol

Methanol is one of the world's most widely traded chemicals, so existing facilities and established safe handling guidelines could be leveraged. Existing infrastructure (storage, distribution and bunkering) for HFO and MGO could be adapted to methanol with minor modifications.

Methanol can be bunkered by trucks to one or more vessels. As its use becomes more widespread, more adapted bunker vessels will be developed. It is estimated that a bunker barge can be converted at a relatively moderate cost.

In 2021, the first ship-to-ship methanol bunkering operation was performed in Rotterdam involving Methanex and NYK.

d. Biofuels

Use of biofuel by the shipping industry is currently limited in both supply and demand. However, difficulties for biofuels bunkering are not anticipated, as it will make use of existing infrastructure and be used as a drop-in fuel.

CERTAIN TYPES AND SIZES OF VESSEL WILL HAVE DIFFERENT OPTIMAL ALTERNATIVE FUEL SOLUTIONS.

e. Ammonia

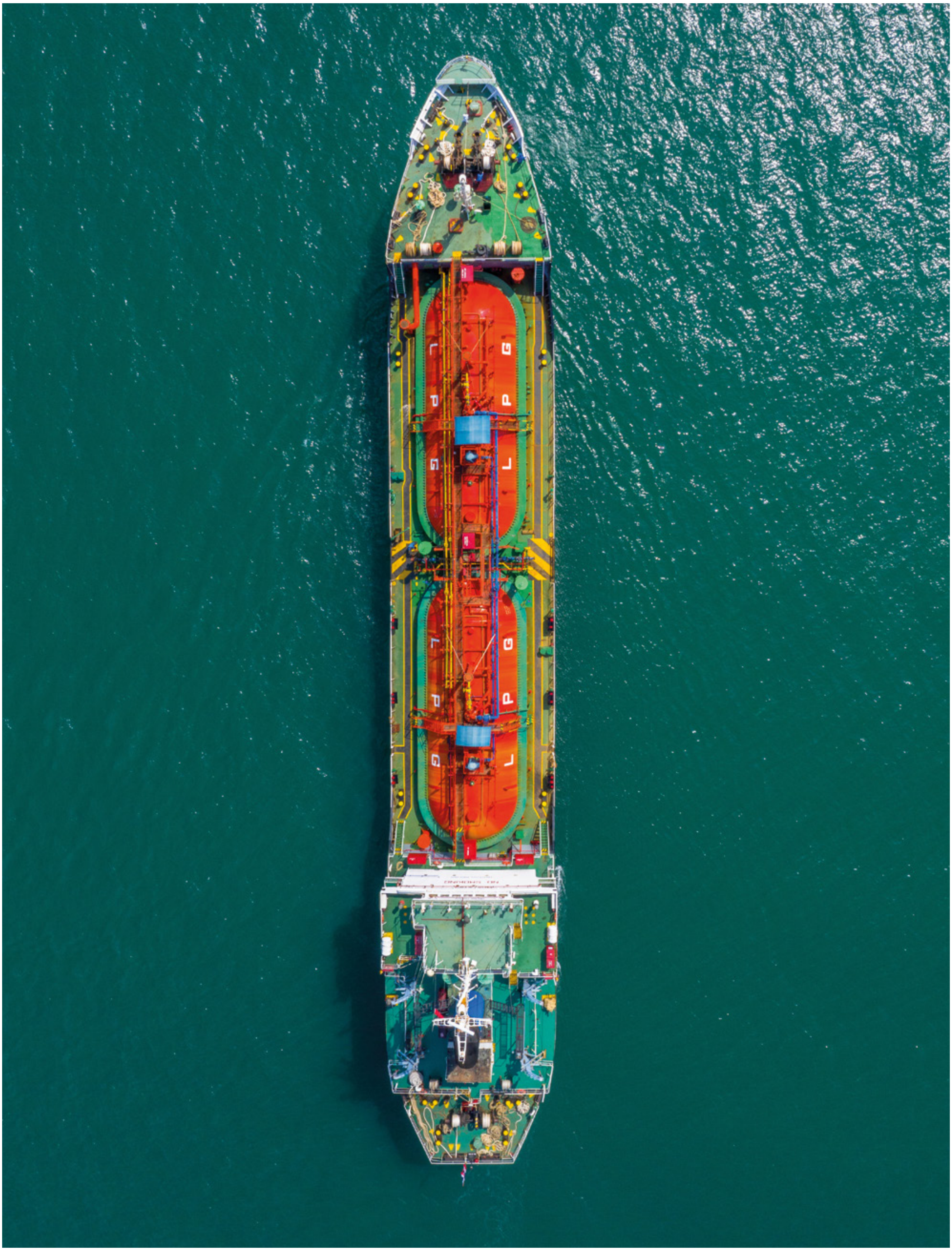
Currently no ammonia-fueled engines are commercially available, and no ships are equipped for ammonia propulsion. The ammonia supply chain and guidelines need to be created based on years of experience of handling ammonia-as-cargo on LPG carriers.

Ammonia may be stored under pressure or refrigerated onboard a bunkering ship in conditions that could differ in temperature and pressure from the ship to be bunkered. The bunkering vessel and ship to be bunkered may also have different combinations of pressurized, semi-refrigerated or fully refrigerated tanks to store ammonia. Specific equipment – heat exchangers, vapor return systems, compressors, etc. – and detailed bunkering procedures are needed to ensure safety during operation.

The Global Center for Maritime Decarbonization of Singapore has recently launched a working group to prepare guidelines for ammonia bunkering and map the eligible ammonia bunkering locations in the region.

f. Hydrogen

Currently, there is no infrastructure in place for hydrogen bunkering. The only bunkering operations made to date have used custom-made truck bunkering. Some companies are already targeting this market. A lot remains to be done and strong cooperation between all stakeholders will be key.



6. RULES AND REGULATIONS

6.1. IMO REGULATIONS

The IMO MARPOL convention includes measures to tackle and prevent environmental pollution from all sources, and air pollution in particular (see Figure 32). Additionally, in 2018, the IMO MEPC 72 adopted its GHG strategy to support the UN SDG13 on climate action, nearly three years after the UNFCCC COP21 Paris Agreement.

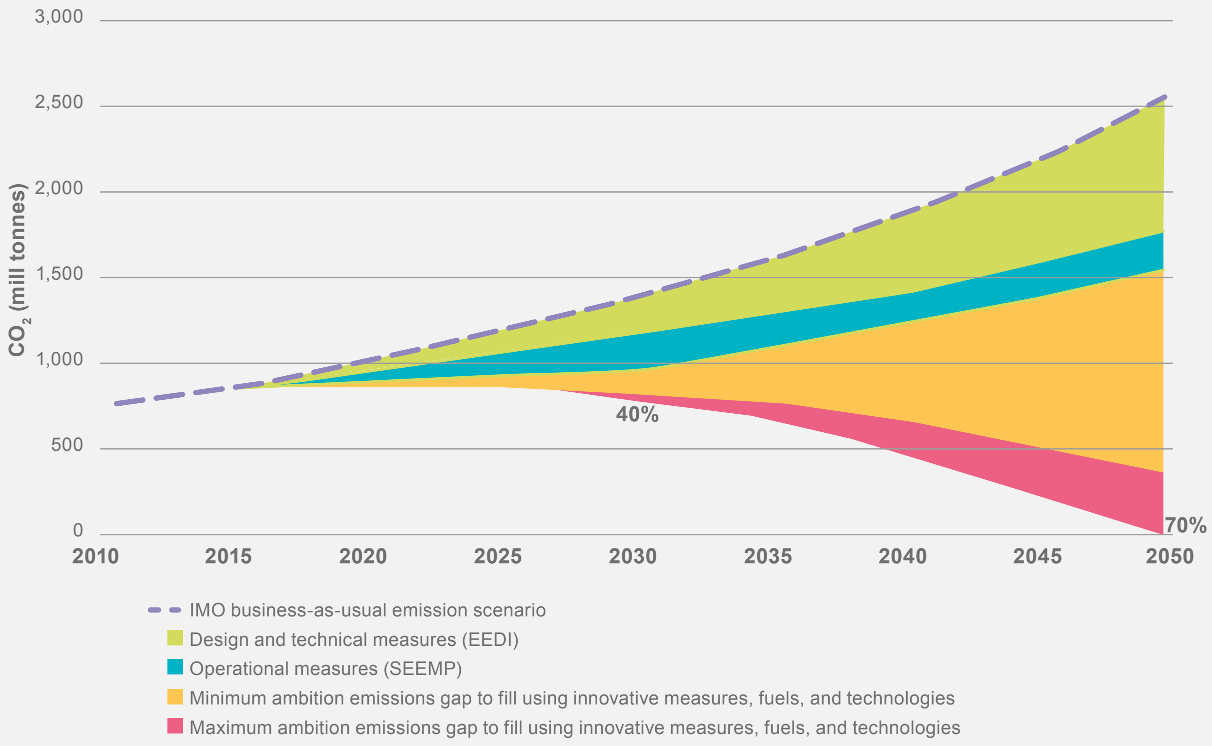
In this section, we will not describe the formulas and meaning of each measure in detail, but explain their underlying principle and briefly assess their impact on the speed of uptake of alternative fuels.
For a comprehensive overview, please refer to our white paper *Reducing ship emissions*.

The main topics addressed by the IMO's strategy at this stage are:

- **GHG emissions:**
  Total GHG emissions from international shipping should peak as soon as possible. They should be reduced by at least 50% in 2050 compared to 2008, while efforts toward phasing them out entirely are pursued simultaneously.
- **CO_2 emissions:**
  An objective has been set to reduce carbon intensity (to reduce CO_2 emissions per transport work) by at least 40% by 2030, with efforts to be made to reach 70% by 2050, compared to 2008.
- **Carbon intensity of the ship:**
  Further phases of the existing EEDI – applicable to new ships – shall be reviewed to strengthen energy-efficiency design requirements.

With these three objectives in mind, measures are then split into three categories: short-, mid- and long-term.

FIGURE 32: IMO GOALS FOR CO_2 EMISSIONS REDUCTION



Source: IMO

a. Short-term measures

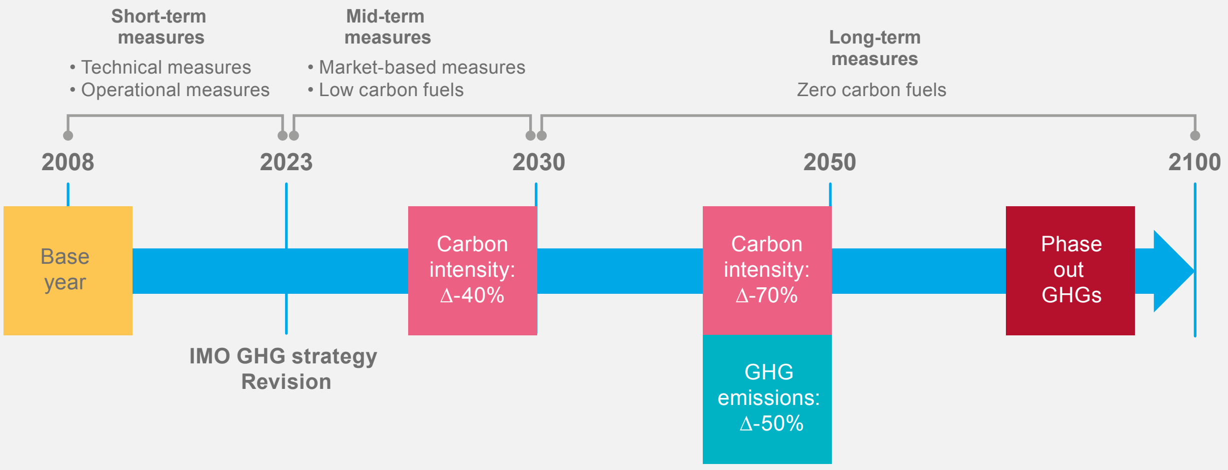
The IMO's short-term measures include those that could be finalized before 2023 (see Figures 33 and 34). All proposed measures are subject to an impact assessment study before approval.

As of today, the below short-term measures are already adopted or underway. For more information on EEDI, EEXI, CII and SEEMP, please refer to our white paper *Reducing ship emissions*.

EEDI

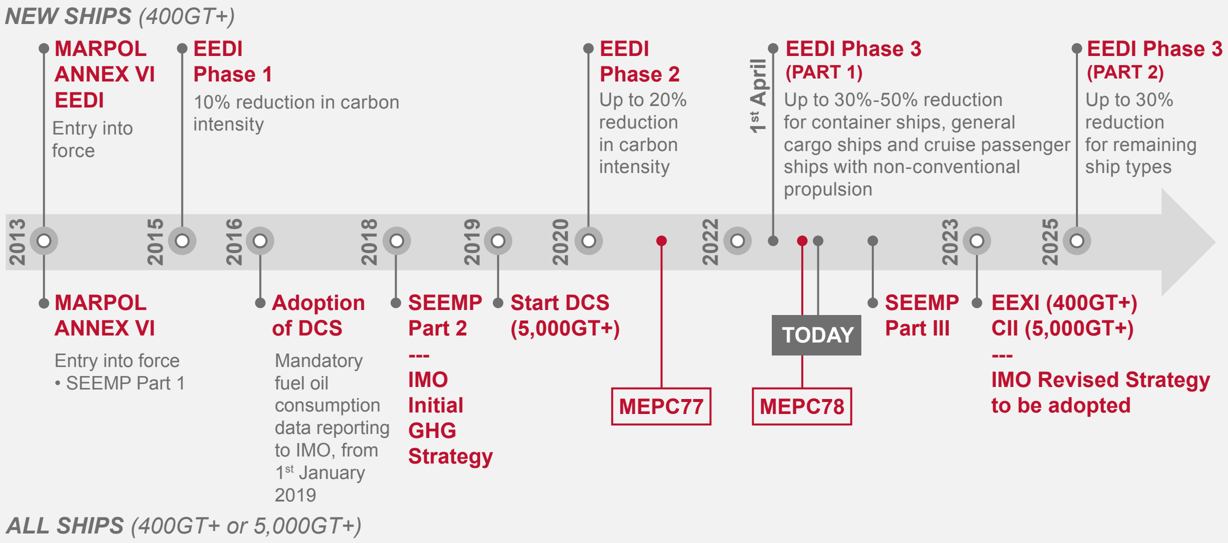
A design index in force since 2013, which is applicable to all new ships above 400GT. Based on ship characteristics, it is a theoretical performance indicator that aims to increase the energy efficiency of ships when designed and built. The EEDI is a non-prescriptive goal-based measure that allows flexibility in technology choices as long as the required index for the given ship is met. For example, EEDI can be optimized through hull form optimization, energy saving devices (ESD) like air lubrication and wind-assisted propulsion, or parameters like ship reference speed and cargo capacity.

FIGURE 33: INITIAL IMO GHG STRATEGY



Source: IMO

FIGURE 34: IMO MEASURES TO TACKLE GHG EMISSIONS AS OF TODAY



Source: Bureau Veritas

EEXI

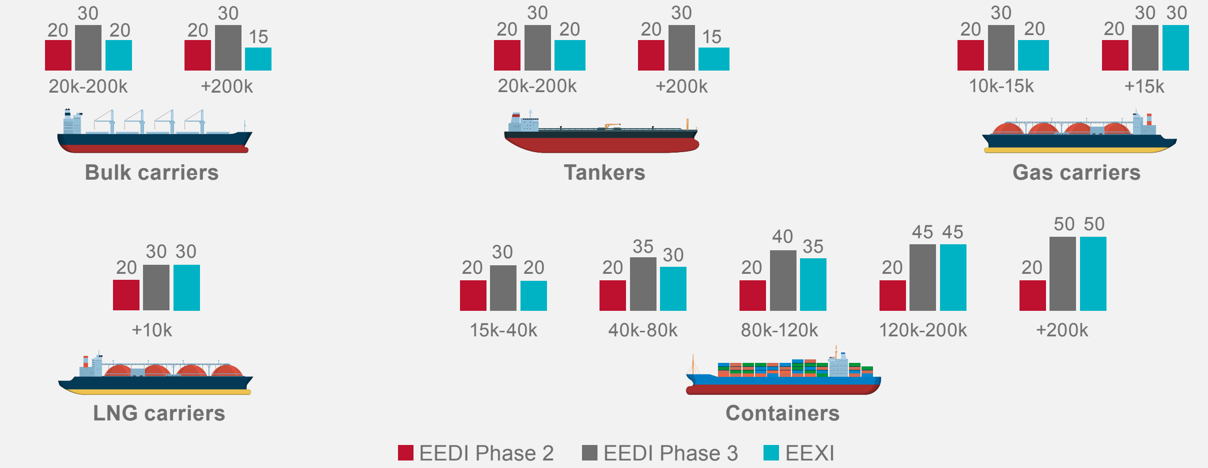
During MEPC75, the IMO confirmed that a similar theoretical carbon index will be applied to all existing ships above 400GT from 2023: the EEXI. Like EEDI for new ships, it is a goal-based mechanism to reduce the theoretical CO_2 footprint of existing ships.

All EEDI Phase III-compliant ships(4) will meet the EEXI target, but this is not the case for all ships that are only compliant with EEDI phase II(5)
(see Figure 35).

The vessel's attained EEXI value is compared to a required EEXI, which is calculated from a baseline and applicable reduction factors.

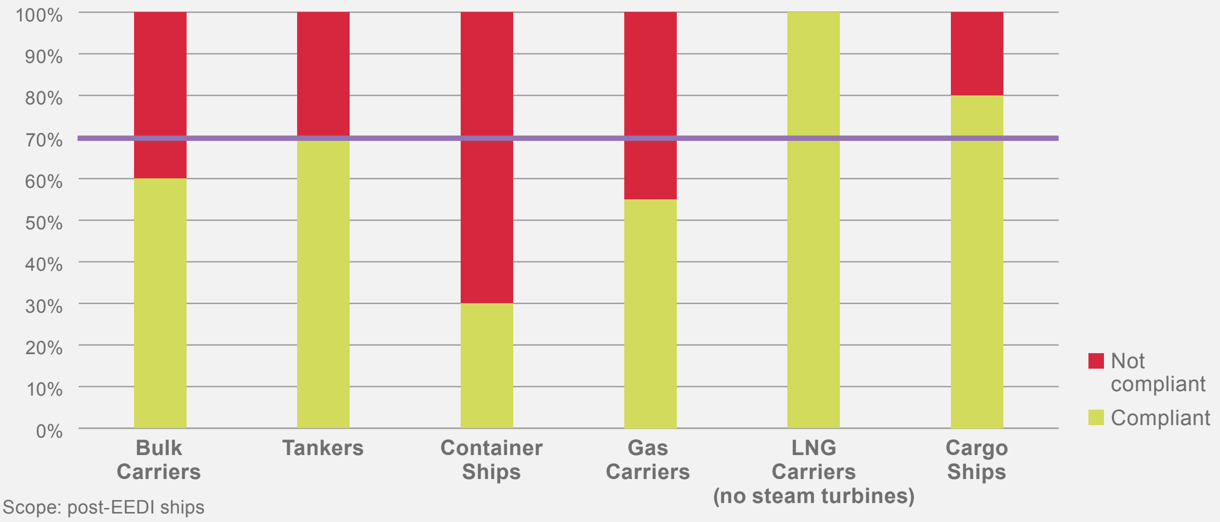
According to BV fleet data, around 70% of the post-EEDI fleet in service (all ships constructed after 2013) will comply with EEXI regulation without any modifications (see Figure 36). However, the projection for container ships is pessimistic and should not be extrapolated to the entire post-EEDI containers fleet(6).

FIGURE 35: EEXI AND EEDI



Source: Bureau Veritas

FIGURE 36: EEXI EXPECTED COMPLIANCE FOR POST-EEDI SHIPS



Scope: post-EEDI ships

Source: Bureau Veritas EEDI data

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(4) Ships built after 2025 or after 2022 for some specific types.
(5) Ships built from 2020 to 2025/2022 depending on ship type.
(6) Many containerships considered in the analysis are feeders sailing in Europe with relatively high power compared to DWT, leading to a high EEXI.

EEXI compliance can be reached through a number of means, including the use of alternative fuels. It should be noted that the established criteria for EEXI calculations are given for the use of Diesel/Gas Oil, LFO, HFO, LPG, LNG, methanol and ethanol (see Figure 37). Based on preliminary impact studies EEDI/EEXI are not initially expected to encourage a faster uptake of alternative fuels at scale, as other measures may be easier to implement for existing vessels such as use of engine power limitation (EPL) or shaft power limitation (ShaPoLi).

CII

Unlike the EEDI and EEXI, which are primarily based on the technical characteristics of an asset as designed and built, the Carbon intensity indicator (CII) addresses the way the assets are operated. It will enter into force in 2023. It is based on the fuel Data Collection System, introduced by the IMO during MEPC70, which requires all ships above 5,000GT to collect and report their fuel oil consumption for each calendar year. Data to be reported to flag administrations includes:

- The technical characteristics of the ship
- EEDI
- Fuel oil consumption by fuel type in metric tons
- Distance traveled
- Hours underway

The attained CII value is then calculated from IMO DCS reported data. Tank-to-wake CO_2 emissions are obtained by applying emission factors to fuel oil data from DCS reporting.

Annual reduction factors have been defined by the IMO until 2026 (see Figure 38). Factors for 2027 onwards will be defined further to revision of the IMO GHG strategy and analysis of upcoming data.

Using the CII attained that year, the operational carbon intensity rating of a given ship in a given year is determined following MEPC.354 (78) guidelines. Ships are given an operational carbon intensity rating of A, B, C, D or E, indicating a major superior, minor superior, moderate, minor inferior or inferior performance level respectively.

A ship rated D for three consecutive years, or rated E, must develop a corrective action plan to achieve the required annual operational CII.

Operational optimization will be needed to reduce fuel consumption and CII values. Operators may need to lower speeds where possible to reduce fuel consumption. CII is based on a tank-to-wake perspective, so using blended carbon-based biofuels or electrofuels would not help to improve a vessel's rating at this stage. This is pending ongoing IMO work considering the life-cycle analysis of fuels. The use of onboard CCS systems to reduce the release of emissions is not currently being accounted for.

An impact assessment of CII is expected from the IMO in 2026, and modifications are likely to occur by then. CII could impact the average ship lifespan; sending some assets to the scrap yards earlier than initially planned. Ship owners will have to take dedicated mitigation measures, analyzing individual fleets and their constraints as these may vary.

FIGURE 37: FUEL EMISSION FACTORS

Fuel type	Emission Factor (gCO_2 / gFuel)
Diesel/Gas Oil	3,206
LFO	3,151
HFO	3,114
LPG	3,000 (Propane) 3,030 (Butane)
LNG	2,750
Methanol	1,375
Ethanol	1,913

Source: IMO

FIGURE 38: REDUCTION FACTOR Z FOR THE CII RELATIVE TO 2019 REFERENCE LINE

Year	Reduction factor relative to 2019 reference line
2023	5%
2024	7%
2025	9%
2026	11%
2027	-
…	-
2030	-

Source: IMO MEPC.338 (76)

SEEMP

The Ship Energy Efficiency Management Plan (SEEMP) is mandatory for ships above 400GT after its entry into force in 2013.

SEEMP is ship-specific and depends on parameters like ship type, cargoes carried, routes and fuels. It seeks to improve a ship's energy efficiency by implementing energy savings solutions.

A new Part III will now be added to take into account the latest work at the IMO. In particular, it will include dedicated chapters for the Ship Operational Carbon Intensity Plan according to MEPC.346 (78).

b. Mid-term measures

These measures include instruments that could be finalized between 2023 and 2030. Candidate measures under scrutiny at the IMO are:

- Incentivizing GHG emissions reduction with new emission reduction mechanism(s), e.g., market-based measures (MBM)
- Implementing a program for the effective uptake of alternative low- and zero-carbon fuels, including updating national action plans
- Enhancing technical cooperation
- Developing a feedback mechanism to speed up overall GHG emission reduction
- Developing operational energy efficiency measures for both new and existing ships

The most promising and most debated mid-term measure candidate is probably the MBM program, which can be split in three main categories:

- Bunker or carbon levies
- A cap-and-trade Emission Trade System (ETS) based on a polluter pays principle
- Other solutions that do not fall into the two above categories

c. Long-term measures

Those measures include instruments that could be finalized after 2023 and will be further addressed later in the decade. Nevertheless, the general axes that have already been drafted by the IMO are:

- Pursuing the development and provision of zero-carbon or fossil-free fuels to enable the shipping sector to assess and consider decarbonization in the second half of the century
- Encouraging and facilitating the general adoption of other possible new/innovative emission reduction mechanisms.

d. Other IMO requirements linked to air pollution

A core part of MARPOL Annex VI addresses both air pollution and GHG emissions. It sets requirements regarding SOx and NOx including the definition of Emission Control Areas (ECA) where different constraints apply for NOx and SOx. ECA zones can as well be split into NECA (NOx Emission Control Area) and SECA (SOx Emission Control Area) zones.
There are currently four ECA zones around the world:

- The Baltic Sea, became SECA zone in 1997 (enforced: 2005), NECA zone in 2021
- The North Sea, became SECA zone in 2005 (enforced: 2006), NECA zone in 2021
- North America, including most of US & Canadian coast (enforced: 2012): an ECA zone (NECA + SECA)
- US Caribbean including Puerto Rico and US Virgin Islands (enforced: 2014): an ECA zone (NECA + SECA)

Discussions are ongoing internationally to create new ECA zones. The Mediterranean Sea will become a SECA zone from 2025 and its integration as a NECA zone will be discussed during the next two years.

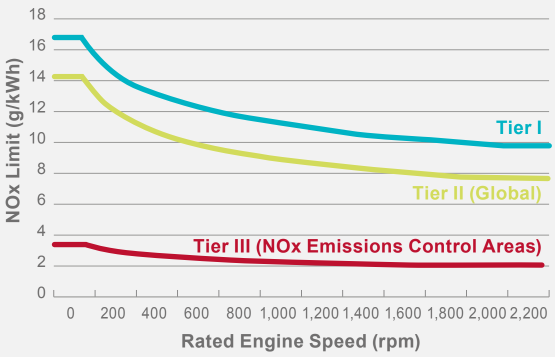
SOx

From 2020, sulfur content below 0.5% outside SECA zones and below 0.1% inside SECA zones is required. SOx requirements apply to all ships on international voyages or on domestic voyages (solely within the waters of a Party to the MARPOL Annex.) Ship operators can either use ultra-low sulfur fuels, distillates or abatement technologies (e.g., scrubber systems) to achieve compliance. Some alternative fuels like LNG, e-fuels or biofuels have a low-sulfur content. It should be noted that some states have restricted open-loop scrubber system discharge in their waters.

NOx

NOx control requirements apply to engines over 130 kW output power irrespective of the tonnage of the ship onto which such engines are installed. The Tier II limit applies for marine engines anywhere in the world, whereas Tier III limit applies only within ECA zones (see Figure 39).

FIGURE 39: NOX REQUIREMENTS



Source: IMO

BC (Black Carbon)

The MEPC77 adopted non-mandatory guidance on BC emissions in the Arctic, where they cause a reduction in ice albedo, accelerating melting, and impacting the climate. Ship operators are urged to voluntarily use distillates or other cleaner fuels, in combination with propulsion methods that have a lower environmental impact when operating in the Arctic zone.

A study submitted to the IMO in 2019 shows that the combustion of fuels of higher aromatic content emits higher concentrations of BC that may increase BC emissions by up to 85%. It also shows that BC emissions are influenced by engine loads; the lower the load, the higher the emissions. As operations in ice are at very low speed and thus very low engine loads, the IMO may reinforce its requirements for HFO and VLSFO in this region.

Complementary work is expected at IMO level to deal with the impact on the Arctic of BC emissions from international shipping. Further to resolution MEPC.342(77), Pollution Prevention and Response (PPR 9) has established a correspondence group. The group will develop draft guidelines on recommendatory goal-based control measures to reduce the impact on the Arctic of BC emissions from international shipping, recognizing possible different approaches for new and in-service ships.

6.2. EU REGULATIONS

As the global shipping sector is governed by the IMO, a central agency, the pace of regulatory constraints is under scrutiny. In this context, the European Union (EU) has implemented extra requirements for the shipping sector to achieve more ambitious GHG emissions reductions.

In July 2021, the European Commission released its Fit for 55 regulatory package to deliver the EU's 2030 ambitious climate target of at least 55% net GHG reduction by 2030 compared to 1990 levels. This goal is part of the European Green Deal's even more ambitious target of becoming the first carbon neutral continent by 2050. The Fit for 55 package proposal is to date still under discussion at EU level. Further modifications will most likely occur during the coming weeks and months before its entry into force.

Measures addressing the shipping industry part of the EU Fit for 55 package are:

- **EU Emissions Trading System** (ETS), the first MBM for the shipping industry
- **FuelEU Maritime**
- **Energy Taxation Directive** (ETD)
- **Alternative Fuels Infrastructure Regulation** (AFIR)

a. EU ETS

The first cap and trade system based on the polluter pays principle when it entered into force on January 1, 2005. It is now in its fourth phase.

A cap is set by the regulator on the total amount of GHGs that can be emitted by the installations covered. The global cap is reduced every year. Within the cap, companies buy or receive carbon allowances called European Union Allowances (EUA) to cover all their annual emissions. Every year, they must surrender enough allowances to cover the emissions of the previous year.

THE FIT FOR 55 PACKAGE PROPOSAL IS TO DATE STILL UNDER LEGISLATIVE PROCESS AT EU LEVEL.

EU GREEN DEAL – REACHING OUR 2030 CLIMATE TARGETS

Source: European Commission

The Fit for 55 package has confirmed the EU's intention to integrate shipping emissions within EU ETS framework by adding additional EUA to the trading market. EU ETS for shipping will rely on fuel oil data consumption from the EU MRV (Monitoring, Reporting, Verification).

Following the European Commission's proposal in July 2021, both the EU Council and Parliament have issued their positions in June 2022. At the time of writing, no consensus has yet been reached, and discussions are continuing, with a target of reaching consensus in September 2022. Until this is reached, it remains hard to exhaustively predict the boundaries of EU ETS for shipping. Debates are ongoing regarding the ship size threshold (400 GT or 5000 GT), phase-in period or extra-EU voyages.

This MBM's impact is hard to assess as it strongly depends on EUA prices, which can evolve and remain volatile over time (see Figure 40).

FIGURE 40: EUA TREND OVER THE PAST TEN YEARS

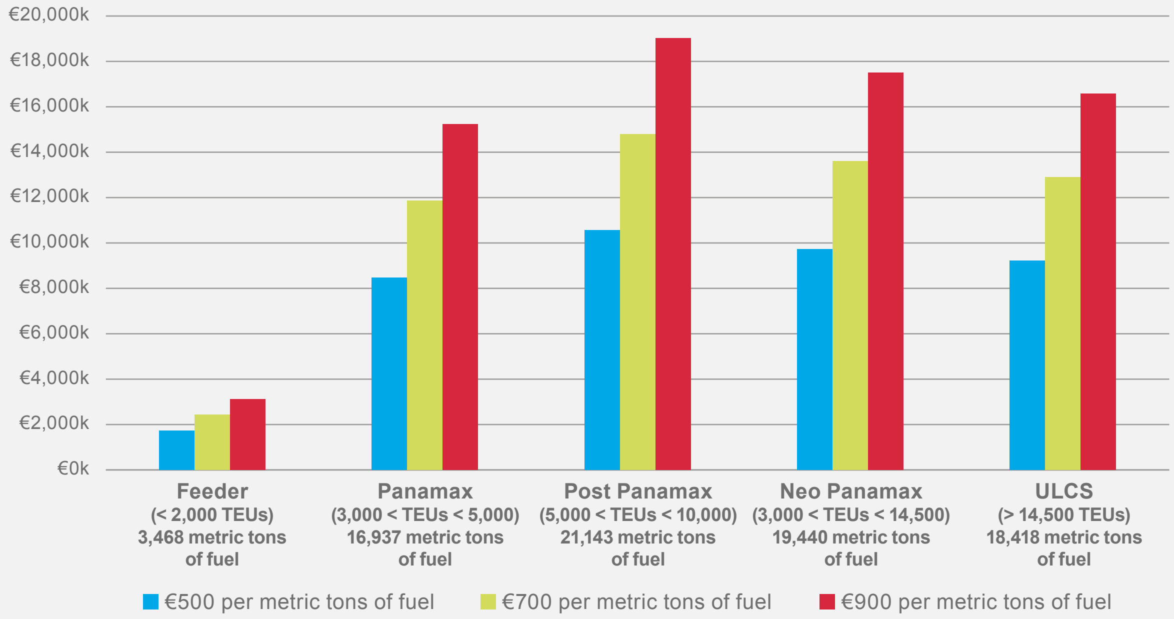
Source: Trading Economics

To illustrate, the scale of impact that this regulation may have on container vessels has been calculated in Figures 41 and 42, with assumptions made as to the cost of an EUA per metric ton of CO_2(7). The figures are based on real data. The rules governing whether CO_2 emissions are taken into account depend on whether the port of origin or destination is within EU territory(8). Therefore very large deep-sea going container vessels performing transcontinental voyages are relatively less impacted than smaller vessels performing mostly intra-EU voyages.

The graph shows that an allowance of almost €100 per metric ton of CO_2 could already represent a significant proportion of operator's energy bills. This, of course, depends on the price of energy taken as a point of comparison; as said before, we should be cautious when considering energy prices.

N.B.: Figure 42 is only intended as an illustration, and may be subject to variation as the EU ETS package is still under discussion at time of writing. Some modifications may occur accordingly until its final adoption and entry into force.

FIGURE 41: TYPICAL ANNUAL COST OF FUEL FOR EU MRV VOYAGES



Source: Bureau Veritas

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(7) Each metric ton of conventional fuel oil burned releases slightly over three metric tons of CO_2 into the atmosphere.

(8) We have assumed 100% of intra-EU voyages (with berth in EU ports) and 50% of extra-EU voyages emissions. This point is under discussion between the European Parliament, Council and Commission. The EU Parliament has recently proposed that from January 1, 2027, 100% of emissions from all voyages within, to and from the EU/EEA will be included.

The EU ETS framework is based on the EU MRV data. The environmental benefits of carbon-based alternative fuels such as bio-fuels or e-fuels, which can justify lower GHG emissions on a WtT basis only, still need to be clarified.

It is unknown at this point if regulators will consider technologies such as onboard CCS to reduce the required amount of EUA.

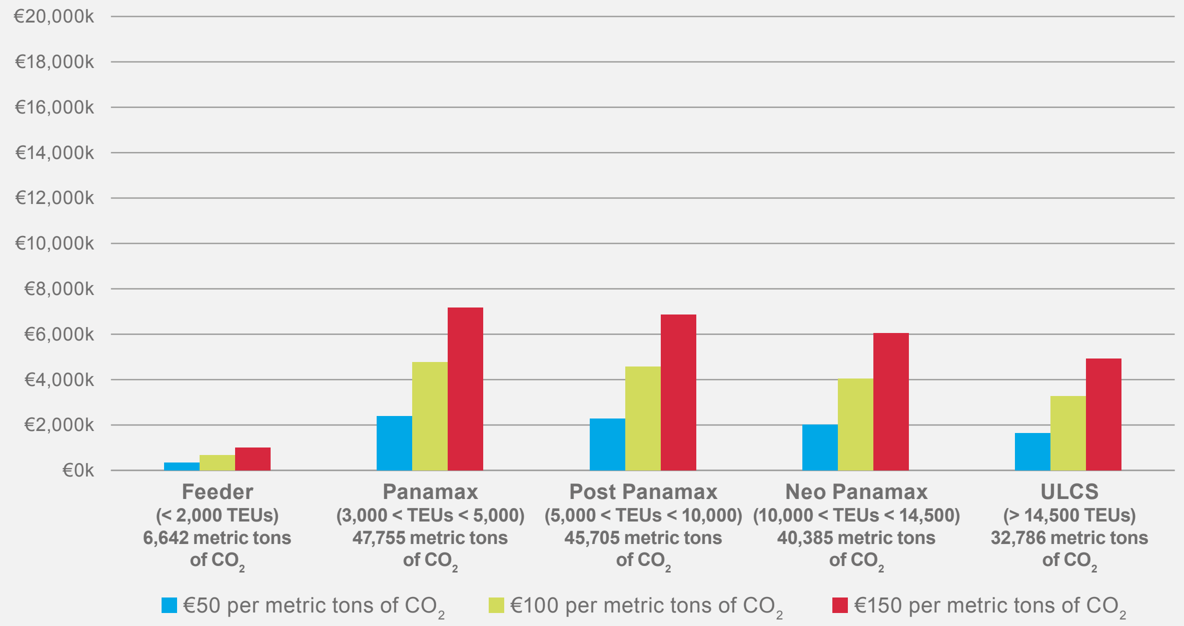
b. FuelEU Maritime

Although not yet confirmed by EU institutions and as such subject to change, this package breaks boundaries by considering GHG emissions on a WtW basis. There are two main aspects within this proposed measure, which directly concern the shipping industry:

- Setting a maximum limit on the GHG intensity of energy used onboard, lowered every five years starting in 2025
- Setting obligations of on-shore power supply (OSP) for cruise passenger ships and container ships starting in 2030

A GHG intensity index is defined for each vessel and compared to a reference value for the index. The target GHG index will then be defined based on a decreasing curve on a five-year period. For each ship, a compliance balance is calculated. If the compliance balance is negative (above the target), it is a compliance deficit.

FIGURE 42: ESTIMATION OF EU ETS COSTS BASED ON DIFFERENT HYPOTHESIS MADE ON THE PRICE OF THE EUA
(50% of extra-EU voyages [to and from EU port] emissions have been taken into account for those evaluations)



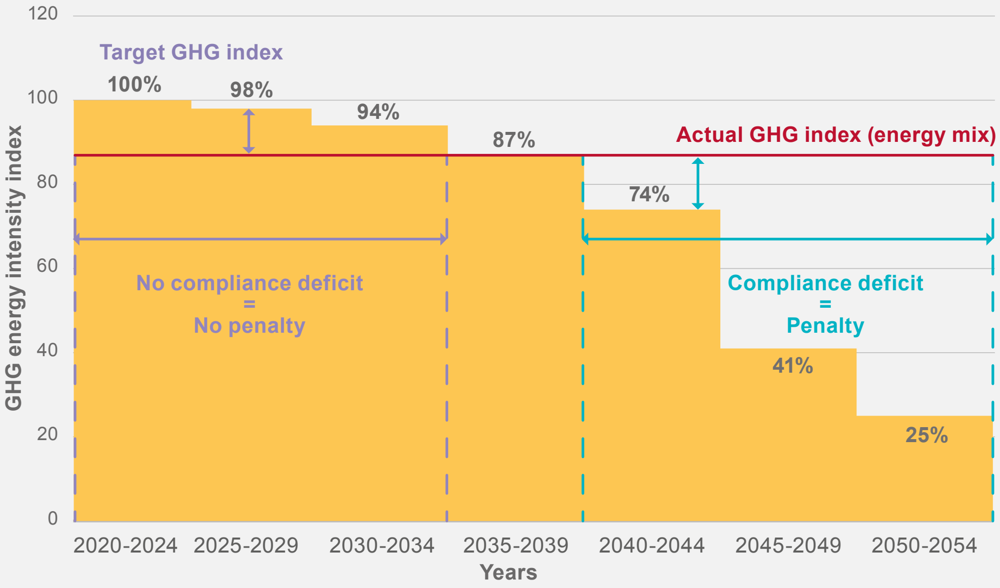
Source: Bureau Veritas

A flexibility mechanism is included, allowing companies to pool a surplus of compliance and transfer it to the following reporting period, or to other ships in the fleet. In case of overall compliance deficit, the company pays a penalty proportional to the compliance balance.

FuelEU Maritime will take into account onboard sources of renewable energy (e.g., wind assisted propulsion) through a reward applied to the GHG intensity calculation of the corresponding ship. It has been designed by EU policy-makers to favor the use of alternative fuels that lower GHG emissions on a WtW basis. However, as it takes a goal-based approach, no particular fuel is incentivized over another.

FUELEU MARITIME BREAKS BOUNDARIES BY CONSIDERING GREENHOUSE GAS EMISSIONS ON A WELL-TO-WAKE BASIS.

FIGURE 43: TARGET GHG ENERGY INTENSITY INDEX BASE 100

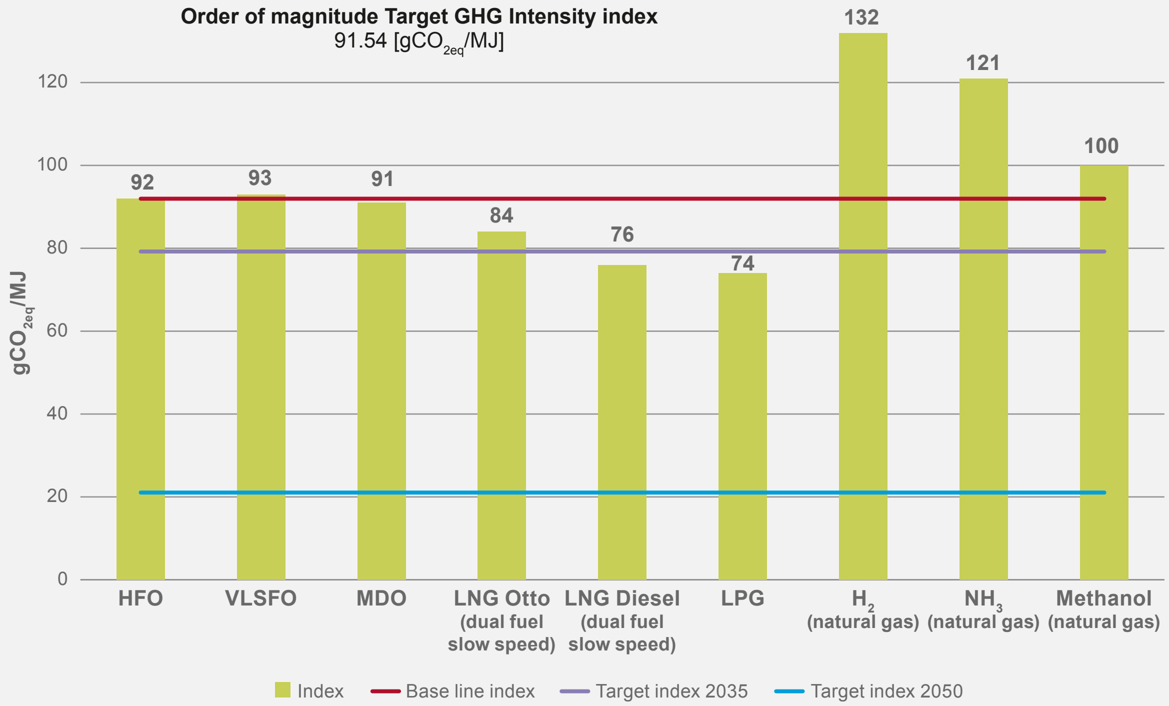


Source: Bureau Veritas

Figure 44 shows the typical GHG energy intensity index of some single fossil fuels compared to a target index value of 91.54 gCO_2eq/MJ. Biofuels or synthetic fuels are not shown in this figure, but are expected to result in values well below the target index. This would enable compliance without penalty, whether they are used in blend or not.

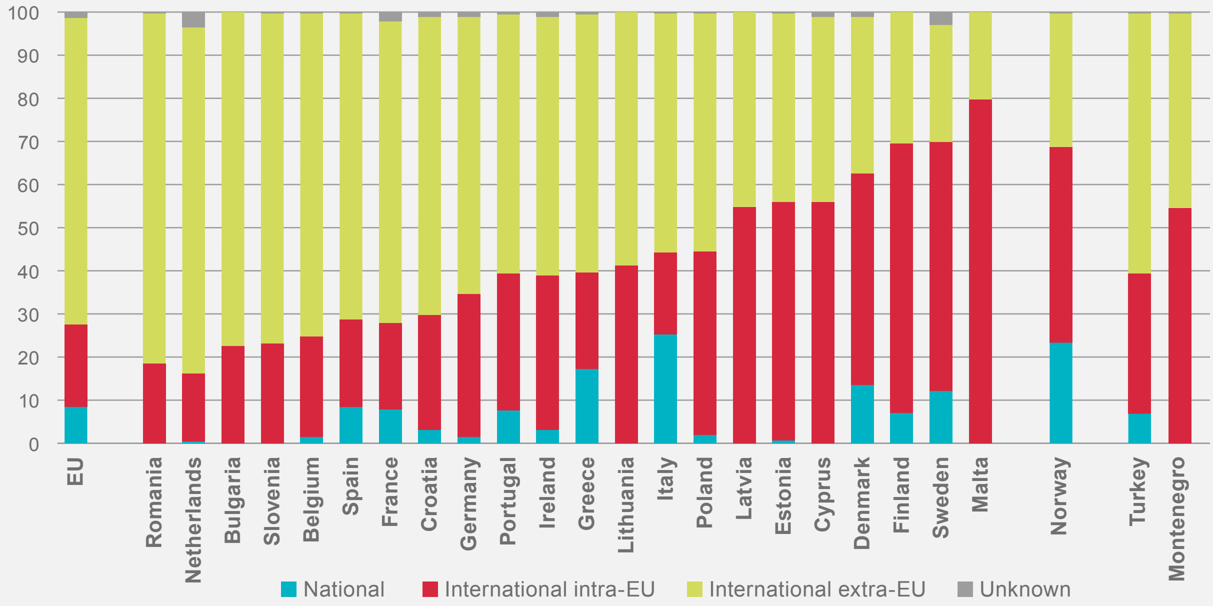
FuelEU maritime will most likely include calculation at fleet level. This means that the energy intensity balance could be pooled over several vessels. It could also be possible to bank compliance surplus for a specific reporting period to compensate future compliance deficit.

FIGURE 44: ORDER OF MAGNITUDE TARGET GHG ENERGY INTENSITY INDEX



Source: Bureau Veritas

FIGURE 45: SEABORNE TRANSPORT OF FREIGHT BETWEEN MAIN PORTS IN THE REPORTING COUNTRY AND THEIR PARTNER PORTS GROUPED BY MAIN GEOGRAPHICAL AREAS, 2020 (%, based on tonnes)



Note: Countries are ranked based on the share on 'international extra-EU' transport. The percentages of international 'intra-EU' and 'extra-EU' transport for non-EU countries express the share of total transport with EU and non-EU countries respectively. Main ports are ports handling more than one million tonnes of goods annually. Data for Iceland are not available.

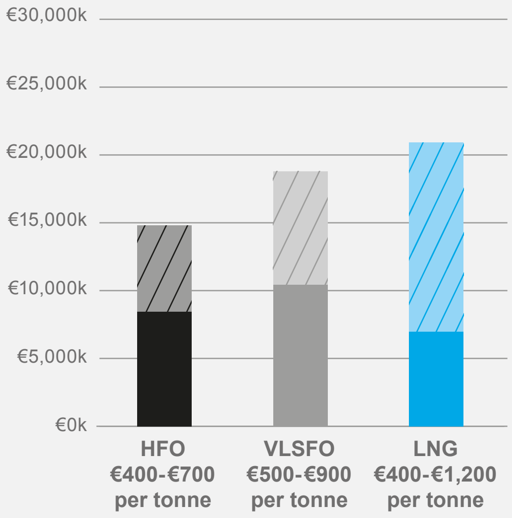
Source: Eurostat

To illustrate, Figures 46 and 47 show the potential order of magnitudes that FuelEU Maritime may have – depending on the choice of fuel – for a post-panamax container vessel. The figures shown are based on real data. It should be noted that the penalty estimate does not account for the effects of pooling and compensation.

Figure 47 demonstrates that this regulation may have a relatively moderate impact until 2035. At this point the scale of the penalty starts to increase significantly and could reach theoretically very high levels from 2040 onwards, increasing until the 2050 horizon.

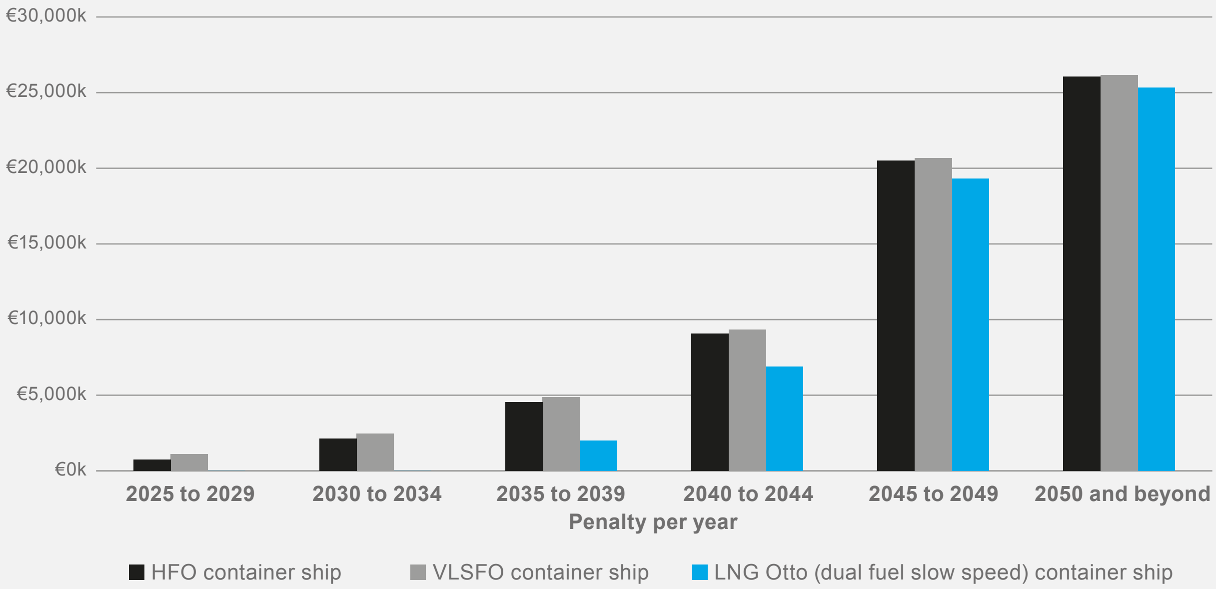
N.B.: Figure 47 is only intended as an illustration, and may be subject to variation as the FuelEU Maritime package is still under discussion at time of writing. Some modifications may occur accordingly until its final adoption and entry into force.

FIGURE 46: ESTIMATION OF FUEL COSTS FOR THE VOYAGES IN THE SCOPE OF FUELEU MARITIME FOR A POST-PANAMAX CONTAINERSHIP (estimated consumption of 21,443 metric tons HFOeq in a year)



Source: Bureau Veritas

FIGURE 47: ESTIMATION OF FUELEU MARITIME PENALTY FOR THE IN-SCOPE EMISSIONS OF A POST-PANAMAX CONTAINERSHIP (estimated emissions for the penalties calculated from consumption of 14,655 metric tons HFOeq in a year)



Penalty applying to 50%.

Source: Bureau Veritas

c. Energy Taxation Directive

As fuel supplied for use in shipping is exempted from taxation under the current directive, the Fit for 55 package proposes to introduce a minimum tax rate (see Figure 48) on the relevant fuels for:

- Intra-EU waterborne regular service navigation (ro-ro passenger ships and high-speed passenger crafts)
- Fishing vessels
- Freight transportation

As for EU ETS and FuelEU Maritime, at this stage, the directive and its associated requirements have not been adopted. The following information comes from the EC package submitted in July 2021, and may be modified in the coming months.

This would enter into force in 2023, with at least 10-year exemptions for:

- Biofuels, advanced sustainable biofuels
- Biogas, advanced sustainable biogas
- Low carbon fuels
- Renewable fuels of non-biological origin
- Electricity

For the orders of magnitude related to this directive as it is proposed today, see Figure 48.

d. Alternative Fuels Infrastructure Regulation

The AFIR proposal requires each Member State to adopt a National Policy Framework to develop the infrastructure for bunkering alternative fuels in both inland and maritime ports. EU countries would also be required to have adequate LNG bunker supply by 2025 and OSP facilities by 2030, while increasing their share of e-methane and bio-methane.

FIGURE 48: LEVEL OF TAXATION PROPOSED IN ANNEX I OF CURRENT PROPOSED ETD UPDATE

Fuel	Tax rate	Energy content	Tax per ton
Heavy Fuel Oil	€0.90 / GJ from 2023	40.5 GJ / metric ton	€36.45 / metric ton
Marine Diesel Oil	€0.90 / GJ from 2023	42.7 GJ / metric ton	€38.43 / metric ton
Natural Gas	€0.60 / GJ from 2023, then €0.90 / GJ from 2033	49.1 GJ / metric ton	€29.46 / metric ton, then €44.19 / metric ton

Source: Bureau Veritas and European Commission

6.3. CHINESE REGULATIONS

GHG emissions and air pollution are falling under growing scrutiny globally. Outside of Europe, other regions are deciding on their requirements.

On January 1, 2019, China launched its Data Collection System to tackle GHG emissions from all ships above 400GT with >750kW power, traveling to, from or between Chinese ports. The verification authority is the Chinese MSA.

Since January 1, 2022, cruise ships must use OSP when berthing for over three hours where OSP capacity is available.

To tackle air pollution, China has implemented its own domestic ECA zones. The discharge of wash water from open-loop scrubbers is prohibited in:

- Inland river ECAs
- Port waters within coastal ECAs
- The Bohai Rim area

In July 2021, China launched its own national ETS. Currently, this only covers the power generation sector, with seven others to be added shortly. Shipping is not yet planned to be included, but this may be necessary for China to reach its carbon-neutral objective by 2060.

CHINA – EU ETS COMPARISON

	China National ETS	EU ETS
Year of operation	**2021**	**2025**
Covered sectors	**Power sector only in the 1st phase, including industrial captive power plants**	**Power sector, energy-intensive industry sectors and commercial aviation within European Economic Area**
Allocations	**Free allocation**	**Allocation + auction**
Trading participants	**Key emitting entities**	**Key emitting entities, institutions and individuals**
Types of trading	**Spot trading only**	**Spot, futures and other derivatives**
Site of Trading	**The National Carbon Market Exchange Center is located in Shanghai and is responsible for the operation and maintenance of the carbon trading market.** **The registration center is located in Wuhan, Hubei Province and is responsible for registring quota allocation, quota clearing and quota transfer.** **Market participants are required to manage both trading and registration accounts.**	**Current common auction platform: European Energy Exchange (EEX)**

Source: NATIXIS GSH

6.4. INCENTIVES FROM LOCAL ADMINISTRATIONS

Some local administrations are incentivizing energy efficiency and fuel consumption improvements, or taxing the most polluting vessels. The examples below are a non-exhaustive list. Main canal crossings and Port Authorities are, for example, looking at developing sustainability criteria that will later impact the fees to be paid.

a. Panama Canal

On November 30, 2021, the Panama Canal Administrator announced the Panama Canal Green Vessel Classification system, which will include a GHG Emissions Fee. Ships will be classified by levels depending on their energy efficiency. The classification and fee will apply to all vessels over 125 feet in length, based on three factors:

- Energy Efficient Design Index (EEDI)
- Efficient operational measures such as the use of bow thrusters
- Use of zero carbon biofuels or carbon neutral fuels

The detailed impacts of this implementation remain to be seen.

b. Suez Canal

In November 2021, the Suez Canal Authority announced its intention to raise waterway tolls by 6% from February 2022, while incentivizing ships that comply with environmental standards. Details are not yet known and will be clarified in the coming months.

c. Port of Vancouver

Vancouver Port Authority offers a discount on its daily due rates per ship GT for the most environmentally friendly ships. Based on a shipping company's eligible criteria (see Figure 49), it can qualify for:

- Gold award – 47% reduced harbor dues fee
- Silver award – 35% reduced harbor dues fee
- Bronze award – 23% reduced harbor dues fee

FIGURE 49: VANCOUVER PORT ENVIRONMENTAL CRITERIA FOR APPLICATION OF HARBOR DUE RATES

Gold award criteria	Silver award criteria	Bronze award criteria
Shore Power Connection	Rightship EVDI B rating	Propeller Boss Caps Fin
Attained EEDI better than 25% compared to required EEDI	Attained EEDI better than 20% compared to required EEDI	Attained EEDI better than 15% compared to required EEDI
NOx Tier III engine	Nakashima GPX propeller	Wärtsilä EnergoProFin
BV Underwater Radiated Noise (URN) class notation	Green Marine Europe label (level 5 URN & level 2 others)	BV CLEANSHIP or CLEANSHIP-SUPER class notation

Source : Port of Vancouver.

6.5. BUREAU VERITAS CLASSIFICATION RULES

As a classification society, Bureau Veritas develops Rules containing structural, mechanical and electrical requirements for ships' design, construction and operation. Classification Rules are developed through extensive research and development to correspond with the shipping industry's needs.

The development of LNG as fuel was accompanied by a set of dedicated Rule Notes and Guidance Notes. Recently, Bureau Veritas has started to develop Rules for the new fuels under consideration like methanol, ammonia and hydrogen, while working with the shipping industry in collaborative research projects. Initial Rules for methanol and ammonia have been published, and Rules for hydrogen will follow in early 2023 (see Figure 50).

FIGURE 50: BV RULES FOR ALTERNATIVE FUELS CANDIDATES

	LNG / CNG	LPG	Methanol	Ammonia	Hydrogen	Other fuels	Fuel Cells
Bureau Veritas Rules for Classification	BV NR 529	BV NI 647	BV NR 670	BV NR 671	Working	Case-by-case BV NR 529	BV NR 547
Additional service feature for ships using alternative fuel	LNGfuel CNGfuel	LPGfuel	methanolfuel	ammoniafuel	Working	LFPfuel	fuelcell
Complementary notations	Singlefuel: engines or gas turbines using the fuel considered and fuel oil. Dualfuel: engines or gas turbines using both the fuel considered and fuel oil. -aux, when the ship uses the fuel considered only for the generating set -prop, when the ship uses the fuel considered only for the propulsion system						
Classification notation for ships prepared in view of conversion	LNGFUEL-PREPARED		METHANOL FUEL-PREPARED	AMMONIA FUEL-PREPARED	Working		

Source: Bureau Veritas

7. DESCRIPTION OF FUELS

7.1. LNG AS FUEL

a. Advantages

The use of LNG as fuel is well known to the shipping industry, and the associated propulsion technology is considered mature and proven. Regulations are well defined in the IMO IGF Code, and Class Rules are fully developed. Typically, LNG carrier propulsion systems use the natural evaporation from the tanks, or boil-off, in combination with fuel. This principle, caused by increasing gas temperature during transportation, avoids increasing pressure and venting gas into the atmosphere.

The latest LNG carrier designs have a dual-fuel propulsion system, capable of running on almost pure natural gas and HFO. In older designs, boil-off gas is used to produce steam in the boilers, which then drives the turbines and propeller of the ship. LNG offers a higher minimum ignition energy, but still requires a pilot fuel to start the combustion process.

LNG is considered a transitional fuel, as it offers cleaner combustion and reduces the vessel's CO_2 emissions compared to HFO(9). The ever-increasing supply chain and infrastructure can assure bunkering facilities worldwide. If they have been suitably designed and constructed to comply with the additional class notation "AMMONIAFUEL-PREPARED", LNG-fueled vessels could be converted to use ammonia at a later date.

b. Challenges

LNG is a non-renewable energy resource and still a carbon-based fuel. Methane slip is to be minimized and preferably completely avoided, to avoid severe additional climate impact. Other methane leaks may occur during fuel transfers along the methane value chain, including during ship transfer; these are known as fugitive methane leaks. The amount of gas released from fugitives is greater than methane slip from certain types of dual-fuel engines. Bureau Veritas' Industry division offers fugitive methane slip measuring services.

Methane slip is a natural consequence of an incomplete fuel burning process. There are discrepancies between levels of methane slip with ICE technology. After-treatment could reduce the methane slip from exhaust gas, but there are still unsolved technical issues related to methane's conversion ratio at low exhaust temperature and catalyst degradation. Further development is required to make this technology durable and efficient.

There is currently no standard to define the level of methane slip allowed in shipping, but we are seeing progress in proposals such as the EU Fit for 55 package. Bureau Veritas now offers an additional class notation "Methane Emission Measurement." This requires measuring and recording methane emissions from engines on a test bench and aims to gather data on the subject as a first step.

The impact of needed gas storage onboard and its arrangement require special attention, as they influence vessel design.

The storage and handling of LNG is based on cryogenic conditions (storage and transportation at -163°C), which impose a relatively high CAPEX for the fuel containment system. Consequently, for newbuilds, LNG as fuel is seen onboard more expensive construction projects. These may include container vessels, car carriers, gas carriers, chemical tankers, very large crude carriers (VLCC), ro-ro vessels and bulk carriers above Capesize.

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(9) Taking into account assumed methane slip.

c. Production pathways of bio and synthetic methane

Bio-methane is a gas produced from organic wastes such as manure, crop residues, household waste, water waste, industrial waste and landfills. It can be used in the same way as natural gas and can be liquefied (see Figure 17). For more details on the challenges related to the feedstocks, refer to section 7.4.

e-methane, often referred to as power-to-gas, is produced from green hydrogen – produced from electrolyzers using a renewable source of energy – and CO_2 thanks to the methanation process. Large amounts of water are generated during this process, which leads to consequent loss of half of the green hydrogen used as a primary source.

Sources of CO_2 that minimize the additional release of GHG emissions on a life-cycle analysis basis enable the required significant reduction in emissions. These include biogenic sources, from biomass or DAC, or carbon molecules used repeatedly in closed loop systems to provide substantial overall CO_2 abatement.

LNG as fuel as a retrofitting option

LNG is an option for retrofitting considered by ship owners and operators. It can be cost-effective, as it helps extend existing vessels' lives while improving their performance on the IMO requirements Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII).

Key considerations for LNG	Key points	
Maturity & availability of technology for ship power	🟩	Engines developed, tested and available for use at scale
Specific energy (weight) & density (volume)	🟩	1.8x the volume of MDO equivalent
Safety considerations (flammability, toxicity)	🟩	Not toxic. Low flashpoint (IGF code application, double wall pipelines)
Regulatory framework	🟩	Available and mature, both International Maritime Regulations and Classification Rules
Global availability of fuel (terminal network)	🟩	Widely traded commodity, available in many terminals worldwide
Bunkering facility availability	🟩	170 bunkering ports by the end of 2022
Sustainability (Environmental, Social and Governance (ESG)/CSR)	🟩	Reduction of CO_2 emissions and air pollution. Particular topic of fugitive emissions considerations but ability to transition to bio and e-methane
Economics: CAPEX	🟧	Additional costs due to cryogenic storage and supply system
Economics: OPEX	🟨	High volatility on bunker prices over last months
Flexibility for future adaptation	🟩	Enables transition to bio and e-methane

Considered low challenge — Considered medium challenge — Considered high challenge

7.2. LPG AS FUEL

a. Advantages

LPG is a mature fuel and already used in shipping. Stored as a liquid at 18 bar or refrigerated at -42°C (semi-state of -20 to -10 at 5-8 bar), it offers a reduction in CO_2 emissions. LPG technology is well developed and already well known thanks to commercially available marinized two-stroke main engines.

It offers a lower CAPEX cost than LNG. It is also non-toxic and not harmful to water. It could be a transitional fuel towards ammonia.

b. Challenges

LPG fueled marinized four-stroke auxiliary engines are not yet commercially available. Propane is heavier than air, meaning that released vapors collect in low spaces. LPG is an extremely flammable gas with flammability limits between 1-11% in air, a risk for leaks and spills.

7.3. METHANOL AS FUEL

a. Advantages

Methanol is liquid at ambient temperature and does not need to be stored in cryogenic or high-pressure containment systems. It is a widely traded commodity under the International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code). Methanol is bio-degradable and water soluble, and can be produced using renewable energy, making it a promising future carbon-neutral fuel. Methanol offers a reduction in emissions compared to conventional fuels, depending on the production pathway. In terms of engine installations, both two-stroke main engines and four-stroke auxiliary engines that are methanol-powered are commercially available and are being scaled up.

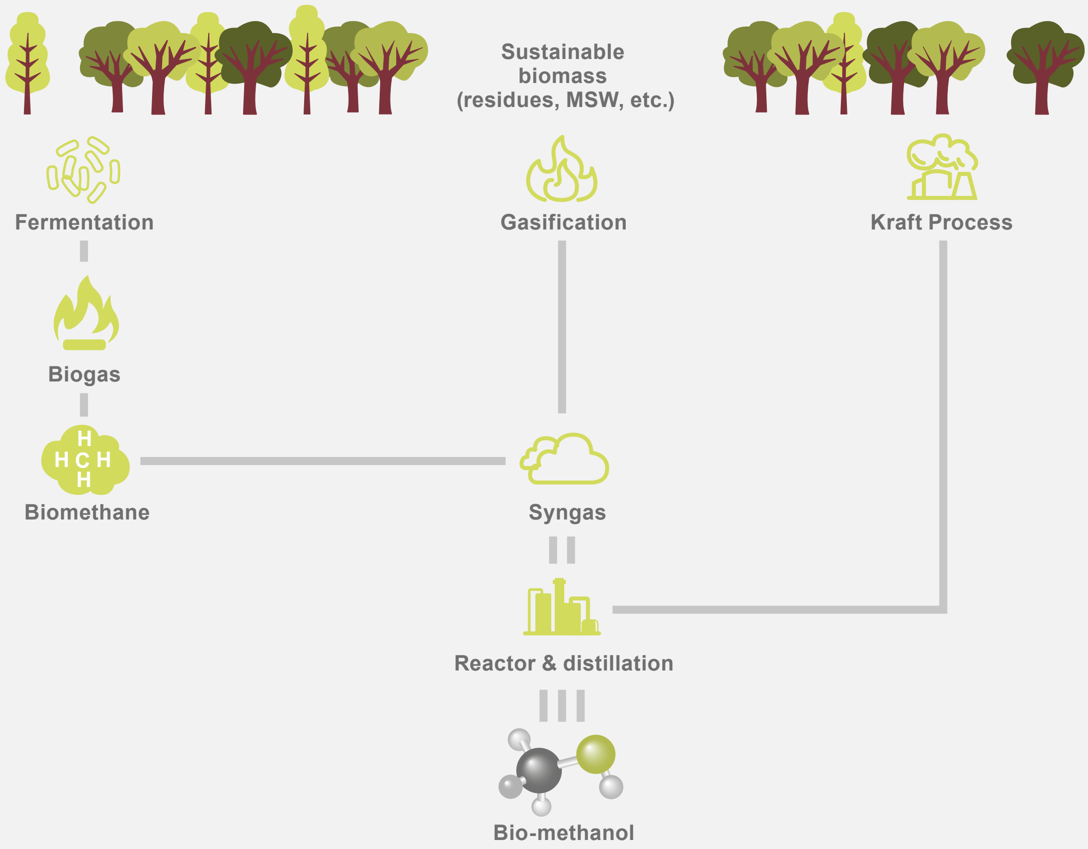
b. Production pathways of bio and synthetic methanol

Bio-methanol can be produced from the gasification of biomass to produce syngas, which is turned into bio-methanol via a process of methanol synthesis. Bio-methanol can also be produced from biogas or via a Kraft process (see Figure 51).

Key considerations for LPG	Key points	
Maturity & availability of technology for ship power	🟩	Two-stroke engines commercially available. No marinized 4-stroke engines commercialy available to date
Specific energy (weight) & density (volume)	🟩	1.5x the volume of MDO equivalent
Safety considerations (flammability, toxicity)	🟨	Low LFL (Lower Flammability Limit)
Regulatory framework	🟨	IMO working item - Tentative Classification Rules available
Global availability of fuel (terminal network)	🟩	LPG widely available in many terminals worldwide
Bunkering facility availability	🟨	Bunkering infrastructure to be developed
Sustainability (Environmental, Social and Governance (ESG)/CSR)	🟨	Reduction of CO_2 emissions and air pollution, but still fossil hydrocabon fuels with no bio or e-fuel option foreseen
Economics: CAPEX	🟩	Lower than LNG
Economics: OPEX	🟩	Mostly used as fuel on-board LPG carrier
Flexibility for future adaptation	🟩	Might support transition to ammonia as fuel

Considered low challenge — Considered medium challenge — Considered high challenge

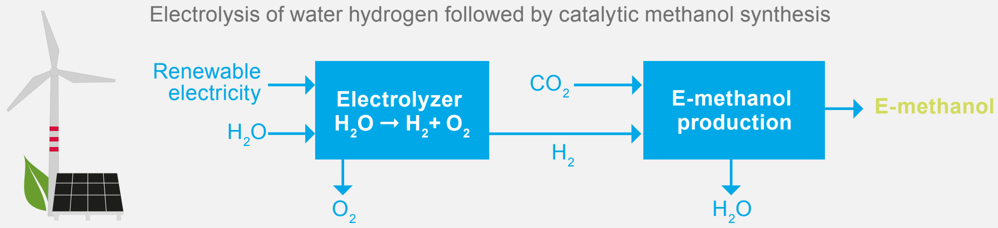
FIGURE 51: BIO-METHANOL PRODUCTION PROCESSES



Source: Methanol Institute

e-Methanol (green methanol) is produced using green H_2 and CO_2. As in e-methane production, the provenance of the CO_2 is a crucial consideration. It should preferably be produced from biogenic sources: biomass, DAC, or closed carbon loops. In the latter, the carbon molecule is reused without being released in the atmosphere (see Figure 52).

FIGURE 52: E-METHANOL PRODUCTION PROCESS



Source: Methanol Institute

c. Challenges

Methanol has low energy content. To achieve the same energy content as MGO, ships would require methanol tanks to be 2.5 times larger. The fuel burns with a flame that is nearly invisible, so special fire detectors must be installed onboard ships. Compared to other fuels, methanol has a wide flammability range and a lower minimum ignition energy. The fuel is toxic, with limits for human inhalation, exposure and skin contact.

METHANOL AS A FUEL

SAFETY
- Toxicity as a liquid and as vapour
- Flammability (flashpoint <60°C)
- Explosivity

TECHNICAL
- Liquid fuel at ambient T°C and Patm
- Tank size vs. fuel oil (≈ x2.4 for same energy)
- Engine development (2-stroke power scale-u, 4-stroke solution ready mid-2022)

COMBUSTION

$2\,CH_3OH + 3\,O_2 \rightarrow 4\,H_2O + 2\,CO_2$ + Heat

ENVIRONMENTAL
- From proven neutral origin bio-methanol with good environment credentials (advanced biofuels)

IMO REGULATORY FRAMEWORK
- MSC.1/Circ.1621 – Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel

Source: Bureau Veritas

Key considerations for methanol		Key points
Maturity & availability of technology for fuel production	🟧	Production available but supply at scale may be challenging for bio & e-methanol
Maturity & availability of technology for ship power	🟩	ICE engines exisiting. Fuel cells technology under development
Specific energy (weight) & density (volume)	🟨	2.5x the volume of MDO equivalent
Safety considerations (flammability, toxicity)	🟨	Low flashpoint fuel + toxicity depending on exposure time
Regulatory framework	🟨	IGF Code and IMO Interim Guidelines
Global availability of fuel (terminal network)	🟩	Widely traded commodity, existing terminal network. Existing infrastructures for HFO and MGO can be adapted to methanol
Bunkering facility availability	🟨	Bunkering infrastructure to be developed
Sustainability (Environmental, Social and Governance (ESG)/CSR)	🟨	Depending on production pathway
Economics: CAPEX	🟩	Storage and power conversion (liquid at ambient temperature)
Economics: OPEX	🟧	Fuel cost compared to fossil fuels
Flexibility for future adaptation	🟩	Enables transition to bio and e-methanol

Considered low challenge — Considered medium challenge — Considered high challenge

7.4. BIOFUELS

a. Advantages

Many shipping companies are interested in using biodiesel as a transitional solution for existing ships and an alternative to other solutions (e.g., alternative fuels, carbon capture). The main objective is to reduce their CO_2 footprint by using fuel made out of biomass rather than fossil fuels. Biodiesel is produced from plant and/or animal materials, or used cooking oils. Biodiesel is sometimes blended with fossil fuels (VLSFO, HFO).

Biofuels are technically an easy solution to implant across the shipping industry, given that decarbonization efforts are borne upstream on the production and supply chain side. All vessel types – large or small, deep-sea or short-sea trading, gas-fueled or traditionally liquid fueled – could burn biofuels without requiring major technical, safety or design adjustments. They are already compatible with modern ship engines. Their quality must be addressed through regular analysis to ensure it reaches the desired specifications throughout the engine's lifetime.

In the landscape of alternative fuels, biofuels, are an immediately actionable turnkey solution offering a range of advantages as a more sustainable fuel source.

Biofuels are a flexible solution that can be produced in different locations and using different sources. Biomass to make biofuels is theoretically available everywhere, limiting the amount of transportation required for distribution. They can also be mixed with fossil fuels, to reduce emissions without needing full dependency on biofuels.

In an ideal scenario, with production increasing at sufficient scale, ships would be able to refuel sustainably at any port. However, the resources for producing second- and third-generation biofuels, have to be developed to supply the volumes needed (see Section 8.1).

Blended or unblended biodiesels in particular are an achievable mid-term solution in the global CO_2 reduction chain. They are both simple and safe to use, and characteristically close to standard fuel oil, with a flashpoint above 60°C. It would require minimal investment to keep in line with evolving regulations and ensure crew safety.

BIOFUELS, AND ESPECIALLY BIODIESELS, ARE AN IMMEDIATELY ACTIONABLE TURNKEY SOLUTION OFFERING A RANGE OF ADVANTAGES AS A MORE SUSTAINABLE FUEL SOURCE.

b. Production pathways

Biodiesel is commonly known as fatty-acid methyl ester (FAME) from various oils or animal fat. FAME is mostly intended to be used as a blend.

Renewable diesel is commonly known as hydrotreated vegetable oil (HVO). It requires the same feedstock as biodiesel, but the process is different (hydrotreating and refining instead of esterification in case of FAME). This fuel can be used as drop-in fuel or blended with conventional fuels.

Fischer-Tropsch (FT) biofuels are biofuels produced from gasification. They are also known as biomass-to-liquid (BtL). Production processes use thermal energy to gasify the raw material into synthesis gas (syngas) rich in hydrogen and carbon monoxide. The syngas is then converted via Fischer-Tropsch catalysts to liquid hydrocarbons like synthetic diesel and biokerosene (as described for e-diesel in section 5.3.c). The FT fuel production process is less mature but can use many feedstocks and produce a wide range of hydrocarbons.

Syngas is produced during gasification and can also be converted to dimethyl ether (DME) by methanol dehydration as an alternative to the Fischer-Tropsch processing.

c. Storage conditions

Storage conditions for biofuels depend on the type of biofuel and the blending yield. For example:

- HVO is very stable and can be stored for long periods as it is not susceptible to oxidation or microbiological growth.
- FAME, should not be stored for longer than six months as it is susceptible to oxidation, which can leave deposits that will eventually block filters and has a short degrading time. FAME biofuel therefore needs more controls and monitoring.

Some fuels may require appropriate coating and antioxidant additives. Storage conditions are highly project- and fuel-specific, necessitating stringent fuel quality assessments before use or storage on-board. Fuel suppliers should be able to provide clear guidelines to the end-customer and the biofuel's quality should be checked regularly.

VERIFUEL SERVICES FOR BIOFUELS

Bureau Veritas' Verifuel division has extensive experience of supporting the maritime industry in testing various biofuel blends (including EN 14214 / ASTM D6751). It also provides tailored operational advice to vessels on the numerous recipes and formulations of drop-in fuels.

Verifuel offers specialized testing to determine well-to-tank carbon intensity and specific emission factors. Its consultancy and training services help develop competence around technical and operational challenges, including long-term storage, cold flow properties and microbial growth.

d. Challenges

While they are a strong option for improving sustainable shipping and advancing the energy transition, biofuels come under scrutiny due to:

- **Sustainability:** the biomass used to make biofuels must itself be produced sustainably, as the first step in the biofuel supply chain. However, there is currently no globally accepted standard or certification available to verify the green production of biofuels from end to end(10).
- **Availability:** some marine stakeholders predict that at most, biofuels could supply fuel for 30% of the global fleet. The shipping sector may lose out competitively to terrestrial transportation and aviation. Securing a long-term reliable supply of biofuels could be quite challenging for ship operators.
- **Ethics:** certain resources that can be used as biomass, such as fields, forests and crops, may be needed to meet other, more basic human needs. Ethically allocating resources is non-negotiable when planning biofuel supply chains and production.
- **Technical:** concerns of biofuel storage and consumption need to be addressed, such as oxidation stability, cold flow properties, and the risk of microbial growth. For certain engine types, a different lubricating oil may be needed. The technological challenges of maintenance may be more significant for fuels that contain a higher proportion of blended biofuels (>30%)(10).
- **Price:** when biofuels are blended with fossil fuels, energy content is reduced, requiring greater quantities of fuel. Together with the price tag on biofuels, the overall cost for shipping has yet to be fully understood.
- **Land use:** increasing demand for biofuels can have indirect detrimental effects on the environment by generating an expansion of croplands around the world.

  First-generation biofuels especially, produced from purpose-grown food crops, may create undesirable competition with food markets. Extra biofuel demand could also spur additional land to be converted for feedstock cultivation. Indirect land use change (ILUC) emissions evaluate the effects of cropland displacement necessary to maintain the supply and demand of agricultural markets.

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(10) Recent studies seem to show that most biofuels generate similar level of NOx emissions as conventional oil fuels. MEPC 78 approved a unified interpretation of Regulation 18.3 of MARPOL Annex VI in June 2022 which now means that fuels with a biofuel content up to 30% do not need further NOx testing.

Second-generation biofuels that are lignocellulosic-based – utilizing feedstock from forest biomass or agricultural residue – demonstrate 70-90% GHG reductions when compared with MGO. However, biofuels made from soy and palm oils have GHG emissions of the same order of magnitude as MGO when taking into consideration ILUC emissions (see Figure 53).

Currently, there is a need to analyze – over a period of several years – fuels that blend a higher proportion (over 30%) of biofuels.

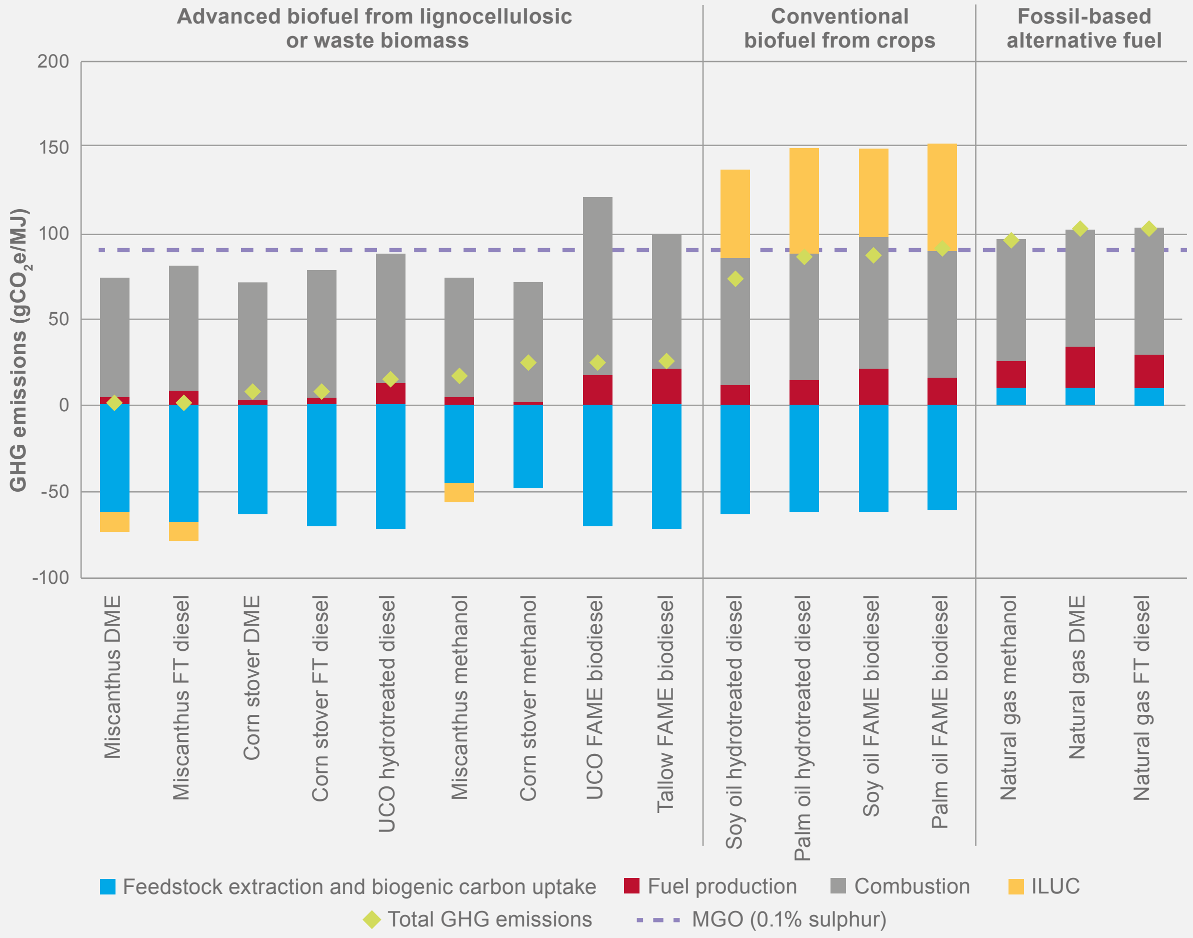
Bureau Veritas Certification has been very present in sustainable biofuel production programs since 2010, including national programs developed in Poland, Italy, and Spain. Among voluntary, EU-approved certification programs, the following are generally recognized:

- ISCC: International Sustainability and Carbon Certification (independent organization)
- 2BSvs: Biomass Biofuels voluntary program (French economic operators involved in grain production and biofuel supply chain, 2BS voluntary program)
- Red Cert: Certification programs for sustainable biomass, biofuels and bio liquids

Key considerations for biofuels	Key points	
Maturity & availability of technology for fuel production	🟧	Production available but supply at scale may be challenging for second and third generation biofuels
Maturity & availability of technology for ship power	🟩	Conventional engines. May need some amended operating procedures.
Specific energy (weight) & density (volume)	🟩	Similar to conventional fuel oil
Safety considerations (flammability, toxicity)	🟩	Similar to conventional fuel oil
Regulatory framework	🟩	Similar to conventional fuel oil
Global availability of fuel (terminal network)	🟩	Existing terminal network with precautions
Bunkering facility availability	🟩	Existing infrastructure with precautions
Sustainability (Environmental, Social and Governance (ESG)/CSR)	🟨	Depending on production pathway/generation of biofuel
Economics: CAPEX	🟩	Conventional
Economics: OPEX	🟧	Fuel cost compared to fossil fuels & competition with other sectors
Flexibility for future adaptation	🟩	Enables transition to Fischer-Tropsch (FT) synthetic fuels

Considered low challenge
Considered medium challenge
Considered high challenge

FIGURE 53: LIFE-CYCLE GHG EMISSIONS (100-year GWP) **OF THE ALTERNATIVE LIQUID MARINE FEEDSTOCKS BY STAGE**



Source: ICCT, https://theicct.org/publications/marine-biofuels-sept2020

7.5. AMMONIA AS FUEL

a. Advantages

Ammonia is a promising option for shipping, as it would mean sailing without emitting CO_2. One of its main advantages is that one of its two precursors, Nitrogen, is widely available in the atmosphere, thus can be potentially produced from any location with a free and high concentration of the precursor molecule.

Ammonia is a widely traded commodity today, as a crop fertilizer and a refrigerant and catalyst in selective catalytic reduction (SCR) systems. It is also globally traded by sea with robust safety handling and loading and offloading procedures.

Ammonia may be the most promising carbon-free fuel with no CO_2 emissions, which represents a non-negligible advantage when produced from renewable energies. Among ammonia's other promising qualities are:

AN OVERVIEW OF AMMONIA AS FUEL

SAFETY
- Highly toxic to humans
- Lighter than air when dry, ammonia vapor heavier than air in wet/humid conditions
- Corrosive

TECHNICAL
- Tank seize vs. fuel oil (≈ x3 for same energy)
- Ammonia engines not available yet (announced for 2024-2025)

COMBUSTION

$$4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O + \text{Heat (No } CO_2\text{)}$$

ENVIRONMENTAL
- Well-to-wake GHC advantage (blue or green)
- Toxic to aquatic life
- Possible combustion byproducts NOx, as well as N_2O, which is a powerful greenhouse gas

IMO REGULATORY FRAMEWORK
- For gas carriers: toxic cargo not allowed to be used as fuel as per IGC Ch 16
- For other ships: no detailed requirements, full alternative design as per SOLAS & IGF Code

Source: Bureau Veritas

Key considerations for ammonia		Key points
Maturity & availability of technology for fuel production	🟧	Production available but supply at scale may be challenging for e-ammonia
Maturity & availability of technology for ship power	🟧	Internal Combustion engines under development. Solid Oxide Fuel Cells (SOFC) technology at an early stage
Specific energy (weight) & density (volume)	🟧	3x the volume of MDO equivalent
Safety considerations (flammability, toxicity)	🟥	Toxicity at low concentrations
Regulatory framework	🟧	Mature as a cargo. IMO Working item as a fuel, tentative Classification Rules available
Global availability of fuel (terminal network)	🟩	Widely traded commodity, existing terminal network. Existing infrastructure for storage
Bunkering facility availability	🟥	To be developed
Sustainability (Environmental, Social and Governance (ESG)/CSR)	🟨	Depending on production pathway and the final development of energy converters
Economics: CAPEX	🟧	Storage at cold temperatures and additional equipment for safety reasons
Economics: OPEX	🟥	Fuel cost compared to fossil fuels for green ammonia
Flexibility for future adaptation	🟩	Green ammonia is a zero carbon fuel

🟩 Considered low challenge
🟨 Considered medium challenge
🟥 Considered high challenge

- It is in a gaseous state at ambient temperature (similar to LPG), a characteristic well known to the maritime community. LNG and LPG fuel containment systems could therefore be compatible with ammonia.
- Two-stroke internal combustion main engines are expected to be prototyped in 2024.
- Fuel Cells (SOFC technology) are in early development to be directly fed with ammonia (and thus not generating any N_2O emissions), producing no vibration, no combustion, less noise and higher efficiency compared to ICE. It would be compatible with several types of fuels (LNG, Methanol, etc.).

b. Production pathways

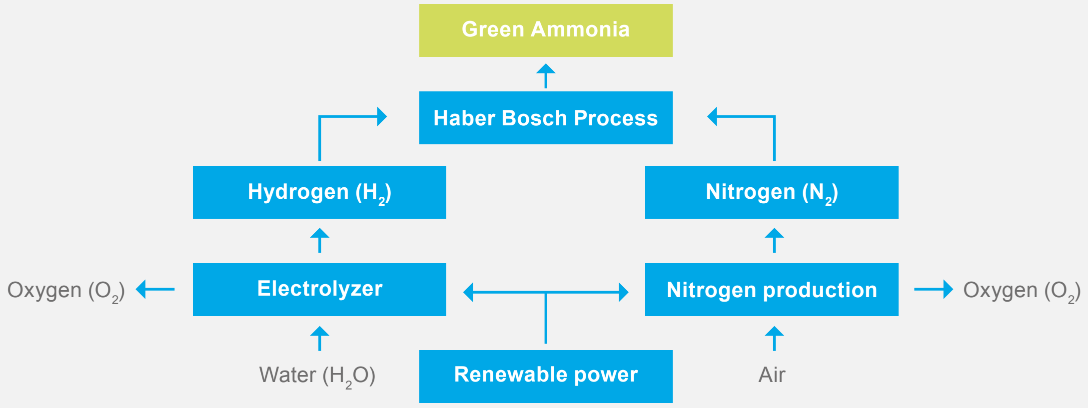
- **Green Ammonia (e-NH_3)** is produced via the Haber-Bosch process using green H_2 and nitrogen. Nitrogen is composing 78% of the air we breathe. Other processes, such as electrochemical N_2 reduction reactions, are being developed but are much less mature and will take time to be industrialized (see Figure 54).

c. Challenges

Ammonia comes with a number of challenges:

- On a WtW basis, fossil-based ammonia ranks worse than fuel oils. To decarbonize shipping, ammonia will need to be manufactured from low-carbon supply chains.
- It is corrosive and toxic, even at very low concentrations, making it essential to protect crews and passengers from exposure during all operations, including maintenance and bunkering.
- Ammonia can also be toxic to aquatic life in case of spillage.
- Liquid ammonia has a lower energy density than other hydrocarbon fuels, about half that of LNG, and about a third of standard fuel oil. This means that vessels need to carry a substantial amount of ammonia fuel onboard to sail over long distances, unless the operational profile of the ship allows for frequent bunkering stops.
- The combustion of ammonia needs to be controlled to minimize the emissions of N_2O and NOx. N_2O has a GWP 273 times higher than CO_2; high levels of this compound in exhaust fumes could jeopardize benefits in terms of climate change.
- It has a strong odor at very low concentrations, causing discomfort and alarm for crew and passengers.
- Ammonia has relatively low flammability, presenting a technical challenge for engine designers. Initial tests show it could be used with a limited amount of pilot fuels in two-stroke engines, but in four-stroke medium speed engines it may require over 10% hydrocarbon-based pilot fuels. The use of biodiesels or e-fuels as a pilot fuel could be a complementary measure to drastically reduce GHG emissions.

FIGURE 54: GREEN AMMONIA PRODUCTION PATHWAY



Source : IRENA

Toxicity

Ammonia is a toxic and corrosive gas with a strong characteristic odor. The odor threshold for ammonia is between 5-50 parts per million (ppm). However, even in low concentrations in the air it can be extremely irritating to the eyes, throat and respiratory system. As it can be seen from table below (see Figure 55), ammonia toxicity depends on both concentration and duration of exposure.

Ammonia is toxic to aquatic life in case of spillage. Un-ionized ammonia is lethal to some fish species at very low concentrations of 0.02mg/l. Its toxicity may be mitigated by chemical reactions that result in both ammonia and ammonium; the latter being non-toxic for aquatic life. The result of these reactions is influenced by water pH, but in principle ammonia should be considered as toxic for aquatic life. Furthermore, although much lighter than air, leaked ammonia rapidly reacts with moisture the air and could stay close to the ground, limiting dispersion.

DE-RISKING AMMONIA AS A MARINE FUEL

Currently, the marine industry is developing various safety and hazard identification studies to define the proper design and risk evaluation criteria for a safe ammonia-fueled ship design. Bureau Veritas and global multi-energy major TotalEnergies have collaborated on a study to de-risk the use of ammonia as a marine fuel, focusing on leak mitigation and treatment.

The joint preliminary study has evaluated the health and safety risks for crew and passengers from ammonia leaks. It has also pinpointed key safety criteria, broadening the shipping industry's understanding of ammonia as a marine fuel. So far, the study has examined different leak scenarios for single-wall and double-wall containment, as well as during bunkering operations. It has provided key insights on ventilation and vapor processing system efficiency, safety zone size requirements and the health risks of exposure to leaks.

To help de-risk ammonia as fuel, Bureau Veritas is building on a tried-and-tested approach that was used in the last decade to drive the development of LNG as fuel. Based on this, Bureau Veritas noted that unless modifications are made to design, safety distances should be much greater for ammonia than LNG. This confirmed the approach outlined in NR 671, which includes more stringent leak management on-board and vapor gas processing to avoid even small leaks reaching manned areas.

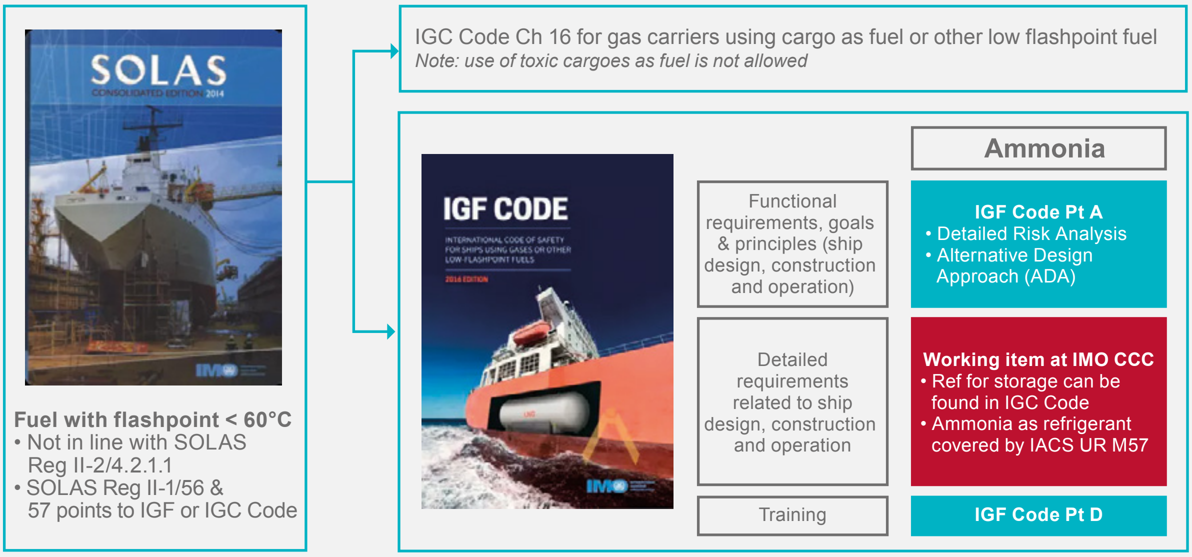
FIGURE 55: AMMONIA TOXICITY EXPOSURE LEVEL

Concentration / Time	Effects
10,000 ppm	Promptly lethal
5,000 – 10,000 ppm	Rapidly fatal
2,500 – 4,500 ppm / 30 minutes	Fatal
>1,500 ppm	Pulmonary oedema, coughing, laryngospasm
700 – 1,500 ppm	Immediate eye and throat irritation
500 ppm / 30 minutes	Upper respiratory tract irritation, watering eyes
134 ppm for 5 minutes	Watering eyes, eye irritation, nasal irritation, throat irritation, chest irritation
140 ppm for 2 hours	Severe irritation, need to leave the exposure area
100 ppm for 2 hours	Eye and throat irritation
50 – 80 ppm for 2 hours	Perceptible eye and throat
20 – 50 ppm	Mild discomfort, depending on whether an individual is accustomed to smelling ammonia

Source: Hafnia

Ammonia as fuel – Regulatory overview

A REGULATORY OVERVIEW OF AMMONIA AS FUEL



Fuel with flashpoint < 60°C
- Not in line with SOLAS Reg II-2/4.2.1.1
- SOLAS Reg II-1/56 & 57 points to IGF or IGC Code

IGC Code Ch 16 for gas carriers using cargo as fuel or other low flashpoint fuel
Note: use of toxic cargoes as fuel is not allowed

	Ammonia
Functional requirements, goals & principles (ship design, construction and operation)	**IGF Code Pt A** • Detailed Risk Analysis • Alternative Design Approach (ADA)
Detailed requirements related to ship design, construction and operation	**Working item at IMO CCC** • Ref for storage can be found in IGC Code • Ammonia as refrigerant covered by IACS UR M57
Training	**IGF Code Pt D**

Source: Bureau Veritas

Bureau Veritas Tentative Rule NR 671

Classification Rules and statutory requirements have not yet been fully developed for vessels using ammonia as fuel. Ships designed in accordance with the IGC Code that carry ammonia onboard cannot use it as a fuel due to its toxicity. Today, a ship's flag administration must be consulted to define the conditions under which the use of ammonia as fuel is acceptable.

In 2021, Bureau Veritas published requirements for an AMMONIA-PREPARED notation, which recognizes ships that have been designed to allow for later conversion to being ammonia-fueled.

Ships designed in accordance with the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGF Code) that use ammonia as a fuel should follow the alternative design approach defined in the IGF Code.

Alternative design equivalence should be demonstrated and approved by the relevant flag administration. Bureau Veritas' Rule Note NR 671 may be used for this, as it provides specific requirements for the properties of ammonia, including its toxicity. Ships must also comply with Bureau Veritas' Rule Note NR 529 for gas-fueled ships.

When a ship intends to use ammonia as fuel, the relevant port administrations must be consulted in defining the conditions under which the ship may operate in areas under their jurisdiction. This is particularly pertinent with regards to bunkering operations and a specific risk analysis may be required.

This Rule Note is based on the following principles:

- Prevent leakages to limit the consequences of NH_3 toxicity:
  - Tank and pipe design
  - Double wall piping
- Detect and manage possible NH_3 leakage:
  - Leakage detection and management through water mist system
  - Manage possible NH_3 spillage
- Control ammonia discharge into the sea
- Prevent corrosion:
  - Material selection
- Containment system: based on the IMO's IGC Code and IGF Code:
  - Boil-off management systems (for non-fully pressurized Type C tanks)

7.6. HYDROGEN AS FUEL

a. Advantages

Hydrogen is another promising option, as a potentially zero-carbon fuel (when sourced from renewable electricity via electrolysis). Inland navigation vessels and short-sea ships are particularly well-suited to integrating fuel cells using hydrogen onboard. They require limited installed power, falling within the range currently available in fuel cells. The technology to integrate fuel cells on larger vessels, such as cruise ships and containerships, is being developed and adapted to their needs rapidly.

For the moment, fuel cells are mainly envisioned for powering the auxiliary systems of larger vessels, offering a zero-emissions solution for ships idling at port or using auxiliary power. The next major technological push will entail scaling up to fully power ships' primary propulsion systems.

b. Challenges

For hydrogen to become an alternative fuel of choice, the industry needs to overcome issues relating to safety and storage design:

- Hydrogen comes with major safety risks, as it is both explosive and highly flammable.
- Flames burning hydrogen at approximately 2,000°C are invisible.
- Hydrogen also presents logistical challenges: it has a relatively low volumetric density, thus requiring significant onboard storage capacity when compared to conventional fuel oil volumes.
- As a liquid, hydrogen must be stored using cryogenic technology at temperatures of -253°C.
- Efforts to upgrade existing technology and develop new capabilities are now at prototype stage.

Key considerations for hydrogen	Key points	
Maturity & availability of technology for fuel production	🟧	Production available but supply at scale may be challenging for green hydrogen
Maturity & availability of technology for ship power	🟧	Internal Combustion engines under development from low to higher power. Fuel cells technology maturing for lower power, and higher power under development
Specific energy (weight) & density (volume)	🟥	4.5x the volume of MDO equivalent
Safety considerations (flammability, toxicity)	🟥	High flammability and explosivity
Regulatory framework	🟥	IMO working item, Classification Rules working item
Global availability of fuel (terminal network)	🟥	To be developed
Bunkering facility availability	🟥	To be developed
Sustainability (Environmental, Social and Governance (ESG)/CSR)	🟨	Depending on production pathway
Economics: CAPEX	🟥	High storage and power conversion costs to date vs. conventional systems
Economics: OPEX	🟥	Fuel cost compared to fossil fuels of green hydrogen
Flexibility for future adaptation	🟩	Green hydrogen is a zero-carbon fuel

Considered low challenge — Considered medium challenge — Considered high challenge

8. ALTERNATIVE SOURCE SUPPLY

8.1. AVAILABILITY AND SCALABILITY

a. Current and projected production levels of biofuels

Despite the many advantages provided by biofuels, and particularly biodiesels, the feedstock resources to manufacture them are limited, whether from crops, forestry or the exploitation of waste. The majority of biodiesels and biofuels available today are first-generation, that is, produced from purpose-grown food crops. Regulations will play a major role in limiting first-generation biofuels. In the EU, demand for imported oil-based biodiesel may decline significantly due to RED II requirements to reduce biofuels that induce ILUC.

Using an LCA methodology and the ILUC emissions indicator, it may be found that these conventional biofuels are of limited use on a global scale when comparing their emissions reduction with their overall climate benefit (see Section 5.5).

Currently, the global biofuels production capacity is heavily influenced by national policies supporting the agricultural sector and blending mandates for terrestrial transportation, which vary according to fossil fuel prices. In some regions, however, it is predicted that public subsidies for investments in waste and residue facilities will boost production of second-generation biofuels.

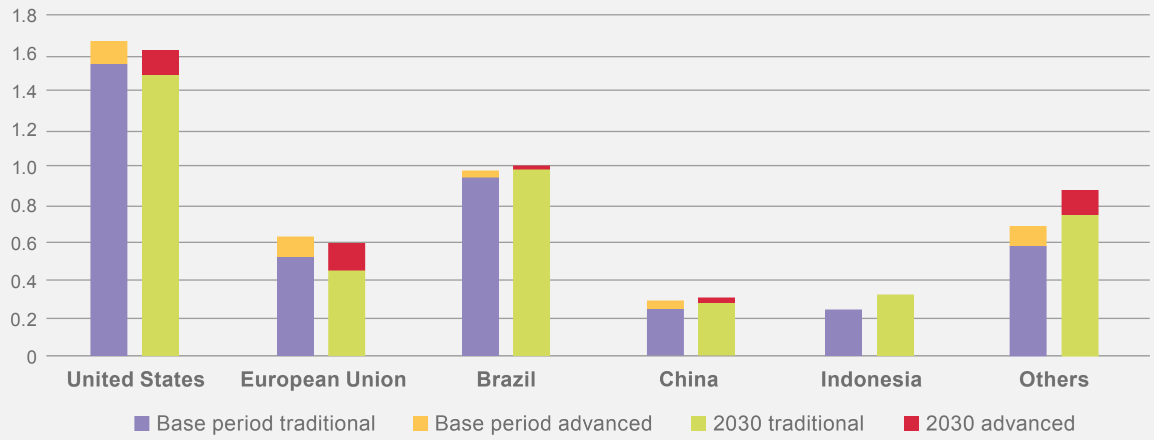
Projections

As per the OECD-FAO's latest Agricultural Outlook 2021-2030 (see Figure 56), the overall estimated production of biofuels in 2020 was equivalent to 4.5 Exajoules (EJ). Meanwhile, the total demand for the shipping industry is usually estimated between 10 EJ and 12 EJ.
The total current production of biofuels used in many different sectors represents roughly 40% of the total energy needed for the maritime industry.

Based on the OECD-FAO's projections up to 2030, biofuel production will not increase significantly, at only +5% from 2020-30. While some regions and emerging countries are predicted to increase their production, the capacity of the current main biofuel-producing regions (US and EU) is expected to decrease slightly.

These regions may have fewer incentives in the future, as biofuels and food production compete for land space. In China, a core pillar of deep-sea shipping, there is currently only limited biofuel supply capacity. With such a dense population, Chinese officials have opted not to reduce the land dedicated to food production and therefore food availability. This is further complicated globally by the possible disruptions to agricultural yields that may be caused by global warming and extreme climate events.

FIGURE 56: WORLD BIOFUEL PRODUCTION FROM TRADITIONAL AND ADVANCED FEEDSTOCK (EJ)



Note: Traditional feedstocks are here defined as food and feed crop based biofuels.

Source: OECD/FAO

In parallel, public opinion may turn away from conventional biofuels, as awareness of the potential undesired environmental effects of certain biodiesels increases. Overall, a lot of uncertainties remain, and OECD-FAO acknowledges that production levels are difficult to predict.

The development of electrical vehicles for terrestrial transportation may free up significant volumes of biofuels and biodiesel for the shipping and aviation industries. Currently, biofuels for aviation are made mainly from HVO. This potentially creates direct competition for oleochemical fuels (derived from plant oils or animal fats) between the maritime and aviation sectors. The aviation industry has a total energy demand of 12-14 EJ, on a comparable scale to the shipping industry's needs of 10-12 EJ.

If the road transportation sector's demand for oleochemical biofuels decreases over the next decades, it is likely that purchasing competition will favor the aviation sector. The maritime sector may consider dedicated biofuel supply chains to secure volumes at scale, aided by marine combustion engines' ability to accept less intensively refined fuels. In this scenario, second-generation lignocellulosic biofuels produced from residues of existing agriculture and forestry activity look promising.

LIGNOCELLULOSIC BIOFUELS FEEDSTOCK INCLUDE

- Forest biomass (hardwoods, softwoods, pulp, waste lignin and sawmill residues)
- Agricultural residues considered "crop byproducts" (corn stover, wheat straw, rice straw, sugarcane bagasse, palm oil residues)

Other potential feedstocks for second-generation biofuels include municipal solid waste, used cooking oils (UCO), and waste animal fat.

An analysis assessing the potential of biofuel feedstocks concludes that only lignocellulosic-based fuels could have the capacity to fully replace fossil fuels in the maritime sector. The study considers only those with no negative effects on food production or land use. In optimistic assumptions wherein 50% of agriculture and forestry residues are used to produce biofuels, it has been estimated that this source of biomass could provide between 14-24 EJ(11).

To make such a scenario a reality, major investments will be required to develop more advanced technologies for cellulosic feedstock at the necessary scale. Uncertainties remain as to the level of private sector investment that could be made in the coming years. Developing the needed infrastructure to produce advanced biofuels could be seen as a chance to create jobs locally and build a sustainable bioeconomy.

b. Current and projected production levels of renewable electricity

As seen in Section 5.4, access to renewable electricity at scale is vital in the production of a wide spectrum of alternative fuels: e-ammonia (green), green hydrogen, e-methane, e-methanol, e-diesels, etc. This is true in general of many proposed solutions to achieve the objectives of the Paris Agreement. The various efforts to decarbonize the global economy are all faced with the acute challenge of securing a renewable energy supply.

For the maritime industry, the competition they will face with other sectors for renewable wind and solar power may be decisive.

Studies show that wind energy's total potential – with installations in the on- and offshore coastal areas of main consumption zones – may not fulfill developed countries' renewable electricity demand. As a consequence, areas with abundant wind resources are seeing potential massive investment programs, even they are located far from large areas of consumption. This is the case in MENA countries (Middle East and North Africa), Namibia, Argentina, Chile and Australia, to name but a few.

Transporting the energy produced from these remote wind farms will probably be done either in the form of liquid ammonia, liquid hydrogen or another hydrogen carrier. This will create new market opportunities for the shipping industry. Besides unveiling new trade routes, such developments will benefit the shipping industry's decarbonization by improving the availability of zero-carbon fuels at port terminals.

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(11) IEA Bioenergy report, Biofuels for the marine shipping sector.

According to IRENA (2022) Renewable Capacity Statistics, the total electricity generated by wind and solar installations was equivalent to 8.8 EJ by the end of 2020 (see Figure 57). Assuming a WtT efficiency rate of roughly 50% for e-fuels (see Section 5.5), the global installed renewable electricity production capacity should be able to generate a total of 20-24EJ in order to fully replace the 10-12 EJ used by the shipping industry each year.

These numbers expose the enormous investments and industrial challenges ahead of us, should e-fuels produced from wind and solar energy fully replace fossil fuels in the maritime sector.

To reach net zero by 2050, some scenarios consider the transitional option of producing blue hydrogen in significant volumes from natural gas combined with CCS systems. Such an approach would favor the emergence of a hydrogen economy and subsequently stimulate the maritime world's uptake of zero-carbon fuels.

Whichever scenario materializes, the main driving factor of a zero-carbon future will be the private sector's response to public measures and the scale of the investments it makes.

8.2. MARKET CONSIDERATION AND COST EVALUATION

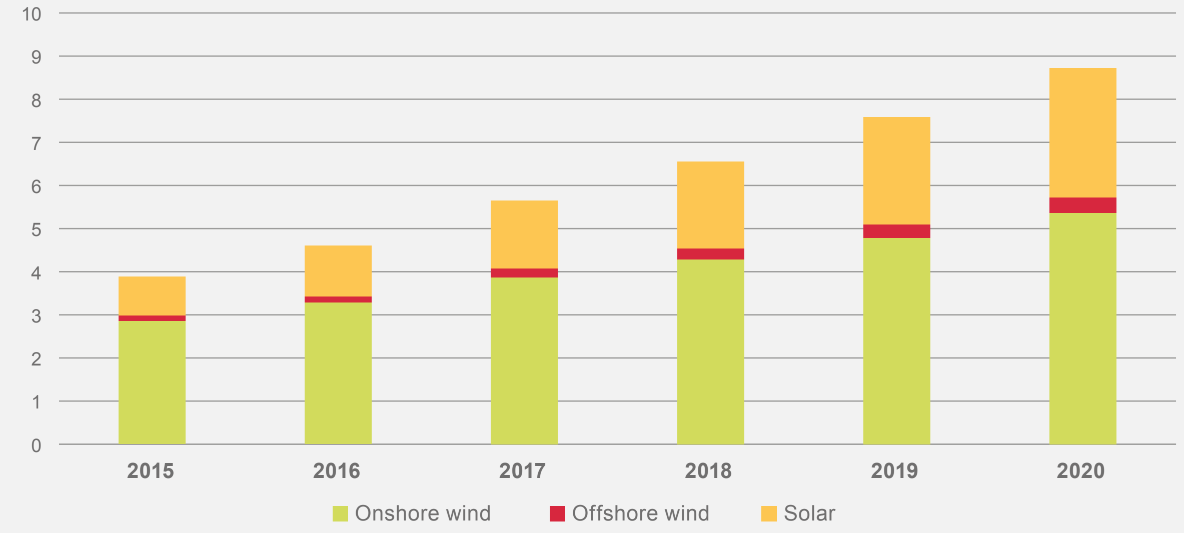
a. Energy market considerations and estimates of alternative fuel production costs

Price is a key parameter that operators have to consider when investigating a new fuel to evaluate a vessel's future OPEX. Between the Covid-19 pandemic and recent geopolitical events, energy markets have proven to be both quite volatile and very prompt to react.

The recent fluctuations and increase in LNG prices serves as a reminder that predicting future prices for energies is complex, if not impossible. Fossil fuel energy markets are driven by supply and demand and impacted by any geopolitical events that affect the main production countries. The energy market must be considered from a systemic approach that accounts for all its complexity.

Alternative fuels such as biofuels or e-fuels may be considered less vulnerable to variations on the same scale. We can anticipate less geographically concentrated production, notably for renewable electricity generation from wind energy. However, predicted major investments in countries with abundant renewables energies – solar or wind – may highlight considerations of geopolitical stability of over several decades.

FIGURE 57: WIND AND SOLAR RENEWABLE CAPACITY STATISTICS 2021 (EJ)



Source: IRENA (2021)

Figure 58 must be considered cautiously, and serve only to indicate possible production costs that may form the basis of a trend in market price. While these estimates enable a better understanding of potential future market price mechanisms, energy markets are subject to fluctuate due to many external factors.

Figure 58 shows a gap between current energy prices from the past year for the most commonly used fossil fuels and production costs of alternative fuels in the short-term, notably for e-fuels(12). In a long-term perspective, costs of e-fuels are still higher than the current price of the fossil oils used in most of the shipping industry. This is fully in line with the shipping industry's status as a "hard to abate" sector.

The turmoil of fossil fuels energy markets over the previous year is reflected in the lower and upper limits in the difference of prices. The Covid-19 pandemic has had an impact while a steep price increase was triggered by the conflict in Ukraine.

Focusing on e-fuels, the variation of long- and short-term production cost estimates are due to hypotheses on the average current and future production cost of renewable electricity. This could range from 60-70 USD/MWh currently to 20-30 USD/MWh in future. Assumptions have also been made on CAPEX costs and the operational efficiency of the production facility.

Including biofuels and bio-methanol in this graph illustrates their potential to support the global decarbonization effort of the maritime sector. The values given for second-generation fuels are based mainly on estimations from models due to the relatively low number of existing production facilities using this type of feedstock. Uncertainty remains high given the limited real data and reliance on assumptions. Nevertheless, second-generation biofuels with low environmental impact and very low GHG emissions profiles across their life cycle appear as serious contender, provided they are available at scale. In the mid-term they could represent a non-negligible part of the fuels used by the industry, occupying a broader place than initially expected by some observers.

Finally, some observers see the current fossil energy prices as a positive new reference line, confirming the mid-to-long-term economic viability of a wider low- and zero-carbon fuels market.

With the provision of correct MBMs, it could be possible to further narrow the gap between the long-term prices of bio and e-fuels and current fossil-based fuels, in the aftermath of the geopolitical situation.

Figure 58 gives an overview of the situation and provides some elements of comparison. Some key production parameters for large-scale off-grid hydrogen production sites will not be known accurately until the first projects are realized. The listed orders of magnitude of these estimates nonetheless allow us to rank alternative fuel options and build a picture of the required effort to decarbonize the shipping industry.

A note on evaluating costs

Regions with excellent wind and solar radiation conditions are primed to transform into renewable and low-carbon fuel supply hubs. Their hydrogen production costs are anticipated to be 15-20% lower than average.

The price of biofuels may be largely influenced by competition with other transportation sectors such as aviation. Similarly, e-fuels may suffer from the competition of decarbonization efforts made in other sectors requiring electricity produced from renewable energy.

While future production costs of alternative fuels can be roughly evaluated based on different assumptions, caution should be exercised in drawing conclusions. The best solution may vary according to the type of vessel and a variety of other factors (see Section 8.2).

Initial studies on the cost of transporting liquid e-fuels by ship (including e-methanol, e-ammonia and e-LNG, but excluding e-hydrogen) show that it would represent 5-10% of production costs. This variation will largely depend on the distance travelled, as landing prices at a destination port from many exporting locations is in a relatively narrow range.

The decarbonization of the shipping sector is deeply intertwined with the efforts being made to decarbonize the global economy at scale. The maritime industry could play a central role in the distribution of zero-carbon fuels in future by helping establish a level-playing field on future carbon-free energy markets.

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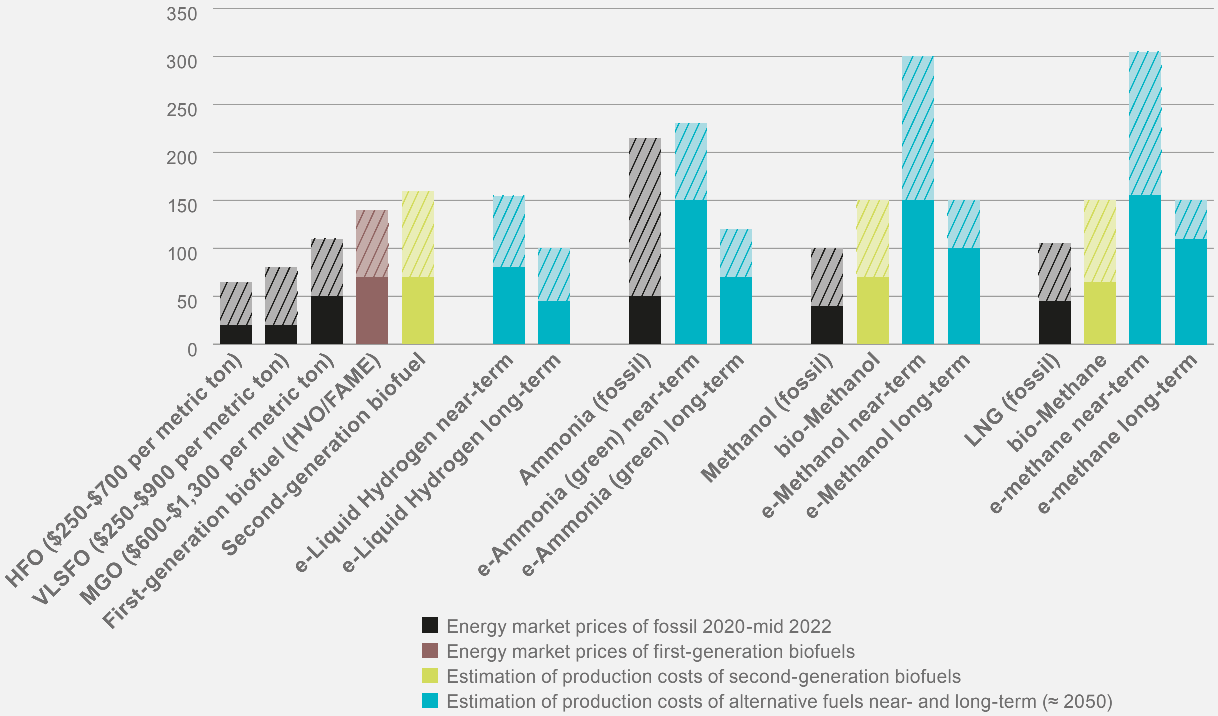
(12) No inflation or price increase was applied to the fossil-based fuels (HFO, VLSFO, MGO, LNG, ammonia, methanol) in Figure 58.

FIGURE 58: PRODUCTION COST ESTIMATION OF ALTERNATIVE FUELS VS. FOSSIL FUELS MARKET PRICES
(US $/MWh)



Source: Bureau Veritas

8.3. BEYOND ALTERNATIVE FUELS: OTHER TECHNOLOGIES TO DECARBONIZE SHIPPING

After decades of relatively stable fossil fuel production, the recent surges in energy markets support the case being made for propulsion systems that do not rely on a single source of energy. Dual fuel systems appear to provide the required flexibility, although they inevitably imply higher CAPEX costs.

There is currently no proven source of carbon neutral or zero-carbon fuels capable of fully accounting for the entire shipping industry's energy needs in the mid-term (see Section 8). While we can imagine that tankers carrying green ammonia will also likely be ammonia-fueled, it remains uncertain that other merchant vessels will be able to access it at similar prices.

Over the next two decades of the quest for zero-carbon fuels, infrastructure will have to be built to gradually replace conventional fossil fuels. Adding to the complexity, other technologies may play a pivotal role beyond alternative fuels. These might include onboard CCS systems on large ships, or the use of wind assisted propulsion to significantly reduce the primary fuel needed to move a vessel.

a. Onboard CCS

For ship owners CCS systems present the advantage of improving their control. Although requiring relatively significant CAPEX costs, they offer the ability to arbitrate between use of carbon-neutral fuels and removing carbon from exhausts. Operators may decide between different options, taking into consideration the costs of storing or using the liquefied carbon collected on-board..

b. Wind-assisted propulsion

Freed from energy market considerations, wind-assisted propulsion systems have the key advantage of a relatively predictable pay-back, once its benefits have been accurately established. Wind has an undisputed low-carbon footprint as an alternative source of energy for ship propulsion. However, these systems may not be well adapted for all ship types, and their application will depend heavily on average wind levels on operational routes.

c. Batteries and fuel cells

For small-to-medium sized ships on short-haul voyages with multiple port calls – such as passenger ferries – using batteries to store energy may be a viable option. As progress is made and economies of scale are triggered by the uptake of the technology by terrestrial transportation, the cost of batteries will become more favorable. Hydrogen fuel cells could also be serious contenders for ships that require limited autonomy and operate in coastal areas.

Though it's understandable that the shipping industry would prefer a universal solution to replace conventional fuel oils, the inconvenient truth is that this scenario is unlikely to materialize. In reality, no alternative fuel sources will exist at the scale required in a decade or more. Therefore, we can assume that in the foreseeable future, multiple fuels and technologies will be used until a clear leader emerges.

While we cannot discount any solutions, some may be more adapted to specific types of vessels and operations than others.

Ship owners must factor several scenarios into their choice of technologies, covering hypotheses for GHG emission taxation, fuel pricing and different types of fuels to be used in the ship's lifetime. Optimizing vessels for a single fuel was once the norm, but vessels designs may now need to be adapted to allow flexibility according to energy market fluctuations. As technology continues to advance, there is no such thing as definitive assessment. New technologies and design engineering optimization may yet lead us to unexpected places.

SUPPORT PROVIDED BY BUREAU VERITAS SOLUTIONS MARINE & OFFSHORE TO SHIP OWNERS

BV Solutions M&O is a subsidiary of BV Group providing technical advisory and engineering consultancy services that respond to all marine and offshore energy challenges.

Today, optimal ship design is becoming more complex, with many parameters to account for. To avoid stranded assets, ship owners need to anticipate future regulations with impact studies on their fleets as soon as possible. They should put in place a complete GHG strategy and re-evaluate them on a regular basis. Comprehensive pre-design technical and economic studies must be performed before tenders are sought from shipyards. Such assessments should consider different potential energy prices and levels of taxation on GHG emissions.

BV Solutions M&O's expert teams are able to provide the necessary technical assistance to support owners' decisions and address all the facets of the challenge. Their services cover new builds, vessels under construction or a wider GHG strategy for an existing fleet.

THERE IS CURRENTLY NO PROVEN SOURCE OF CARBON NEUTRAL OR ZERO-CARBON FUELS CAPABLE OF FULLY ACCOUNTING FOR THE ENTIRE SHIPPING INDUSTRY'S ENERGY NEEDS WITHIN THE COMING DECADE.

9. CONCLUSION

The choice of alternative fuel is complex as there will be many different types of solutions for the next decades until a more permanent and completely carbon-free solution is fully available world-wide. The delay between phasing out existing vessels with intermediate solutions to reduce carbon footprints is a financial challenge. With a general service life of at least 20 years, many of the vessels operated today will still be around in the next decade.

To achieve true decarbonization, the shipping industry must consider alternative fuel options on a well-to-wake basis. Only through a complete life-cycle analysis can the environmental impact of fuels be properly evaluated. Even then, the optimal choice of fuel may vary for different types of vessel operating in different areas or performing different tasks. Ship owners will need to carefully evaluate their CAPEX and OPEX costs in making their choices for their fleet.

Energy markets will likely remain susceptible to influence by geopolitical events, and pricing will no doubt influence the choice of future fuels. Finally, fuel availability and infrastructure will influence which fuels rise to prominence. In the short- to mid-term, it is likely there will be no clear frontrunning fuel, but rather a combination of low- and zero-carbon options.

The ultimate role of a classification society is to build trust between marine stakeholders. Through R&D partnerships, Joint Industry Projects, Joint Development Projects, Classification Rules, Approvals in Principle and risk assessment processes, classification societies help de-risk ambitious projects for alternative fuels and new technologies, including wind propulsion.

The maritime world has chosen to decarbonize its operations, despite the difficulty of this challenge. The only way to succeed is to collaborate, sharing knowledge and resources across the industry. Timing is a key factor, as stakeholders balance short- and long-term objectives. They are aiming to achieve immediate reductions in CO_2 emissions from the existing fleet while moving toward more ambitious, mid- to long-term emissions targets.

At Bureau Veritas, we recognize that everyone will start their sustainability journey from a different position and move at different speeds. We are there to support our clients in decarbonizing, however ambitious their short-, mid- and long-term sustainability goals may be.

By developing the technical rules that make safe innovation possible, classification societies play a unique role in shaping a better future for the shipping industry and the wider world.

We hope that this document will give the reader a solid starting point for further discussions with Bureau Veritas and industry experts. The developments are accelerating and we invite you to make contact with us for any further clarifications and discussions.

The clock is ticking down to 2050, and in a safe zero-carbon future, Bureau Veritas believes the maritime world will gain in prominence. Seaborne trade has long been the backbone of our global economy, strengthening relationships between nations and allowing humanity to thrive. Progress has been driven historically by the global exchange of goods in ever-more complex vessels.

The power of the open seas can be harnessed, contributing to the renewable energy needed to decarbonize our economy at scale. Either by transporting zero-carbon fuels or assisting in transporting liquefied CO_2 for definitive sequestration, the maritime industry will prove indispensable in reaching a net zero emission future.

Our future lies in the oceans. That is why Bureau Veritas is committed to shaping a better maritime world, and building a sustainable future for generations to come.

ABBREVIATIONS

AEC	Alkaline electrolyzer cells
AFID	Alternative Fuels Infrastructure Directive
BtL	Biomass-to-liquid
BC	Black carbon
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CII	Carbon intensity indicator
CO	Carbon monoxide
CO_{2e} / $CO2_{eq}$	CO_2 equivalent
CfD	Contract for difference
CSR	Corporate social responsibility
DCS	Fuel oil data collection system
DME	Dimethyl ether
DAC	Direct air capture
DO	Distillate oils
ECA	Emission control areas
EEXI	Energy Efficiency Existing Ship Index
EEDI	Energy Efficiency Design Index
ETD	Energy Taxation Directive
ETS	Emissions Trading System
EU MRV	Monitoring, reporting, verification
EUA	European Union allowances
EU	European Union
EJ	Exajoules
FAME	Fatty-acid methyl ester
FT	Fischer-Tropsch
GWP	Global warming potential
GHG	Greenhouse gas
GT	Gross tonnage
HFO	Heavy Fuel Oil
HPDF	High pressure dual fuel engine
HFCs	Hydrofluorocarbons
H_2	Hydrogen
HVO	Hydrotreated vegetable oil
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuel
ILUC	Indirect land use change
IFO	Intermediate fuel oils
IBC Code	International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IMO	International Maritime Organization
LCA	Life-cycle analysis
LBG	Liquid biogas
LPDF	Low pressure dual fuel engine
MDO	Marine diesel oil
MGO	Marine gasoil
MBM	Market-based measures
MARPOL	International Convention for the Prevention of Pollution from Ships
MWh	Megawatt hours
CH_4	Methane
CH_3OH	Methanol
MLC	Maritime Labor Convention
MSW	Municipal solid waste
NECA	NOx emission control area
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
N_2O	Nitrous oxide
NMVOCs	Non-methane volatile organic compounds
OPEX	Operating expenditure
OPS	On-shore power supply
PM	Particulate matter
ppm	Parts per million
PFCs	Perfluorocarbons
PtX	Power-to-X
PEM	Proton-exchanged membrane
RO	Recognized Organization
SAF	Sustainable aviation fuel
SECA	SOx emission control area
SGMF	Society for Gas as Marine Fuel
SEEMP	Ship energy efficiency management plan
SMR	Steam methane reforming
SOEC	Solid oxide electrolyzer cells
SOFC	Solid Oxide Fuel Cell
STCW	Standards of Training, Certification and Watchkeeping for Seafarers)
SO_2	Sulfur dioxide
SF_6	Sulfur hexafluoride
SOx	Sulfur oxides
SDGs	Sustainable Development Goals
SNG	Synthetic natural gas
TtW	Tank-to-wake
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VLCC	Very large crude carriers
VLSFO	Very Low Sulphur Fuel Oil
VOCs	Volatile organic compounds
H_2O	Water
WtT	Well-to-tank
WtW	Well-to-wake
WHO	World Health Organization

BUREAU VERITAS RULES AND GUIDELINES

NR 467	Rules for the Classification of Steel Ships
NR 529	Gas-Fuelled Ships
NR 620	LNG Bunkering Ship
NR 686	Rules for the Design and Certification of Membrane Type LNG Cargo Containment System
NR 670	Methanol & Ethanol Fuelled Ships
NR 671	Ammonia-Fuelled Ships - Tentative Rules
NR 547	Ships using Fuel Cells
NR 206	Wind Propulsion Systems

NI 618	Guidelines on LNG Bunkering
NI 654	Guidelines on Conversion to LNG as Fuel
NI 655	LNG Carrier Conversion to FSRU or FSU
NI 647	LPG-Fuelled Ships - Tentative Rules
NI 525	Risk-based Qualification of New Technology - Methodological Guidelines

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