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D2.1 Understanding the decarbonisation of maritime shipping

Sustainable Energy and Alternative Fuels from Advanced Intermediate Renewable Energy carrieR technology

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1. Introduction

1.1 Description as per Grant Agreement

This Deliverable, **D2.1 - Understanding the decarbonisation of maritime shipping**, is a public report under Work Package 2 (WP2: Identification and mapping of value chain requirements), led by Fundación Valenciaport (FVP), with a due date in month 6 (February 2025). According to the Grant Agreement, the Deliverable is intended to provide a report on the technical, environmental, and regulatory aspects of the decarbonisation of maritime shipping, including relevant regional, national, and international regulations and directives related to greenhouse gas emission reduction, as well as structural changes required for the implementation of sustainable biofuel value chains, including the utilisation of refinery infrastructures and the logistics and storage of biofuels. This deliverable is related to Task 2.2, which is described below:

- ***Task 2.2 Analysis of technical, environmental, and regulatory aspects of the decarbonisation of maritime shipping (Lead: FVP, Partners: DTU) [M01-M06]***. The objective of this task is to produce a report on the technical, environmental, and regulatory aspects of the decarbonisation of maritime shipping. Regional, national, and international regulations and directives with regards to reducing GHG emissions (e.g., FuelEU Maritime) will be considered, as well as structural changes required for the implementation of sustainable biofuel value chains, including the utilisation of refinery infrastructures, and logistics and storage of biofuels.

This deliverable is positioned within WP2, which addresses the identification and mapping of value chain requirements across technical, environmental and regulatory dimensions, and supports the wider SEAFAIRER objective of enabling the deployment of the VINTER value chain for renewable maritime biofuels. In this context, D2.1 provides an initial framework for understanding the external boundary conditions affecting maritime fuel decarbonisation, while also informing subsequent project activities related to stakeholder mapping, value chain simulation, infrastructure integration, sustainability assessment and future implementation pathway. The purpose of D2.1 is therefore to establish a common reference framework for the project regarding the main drivers, constraints and enabling conditions associated with the decarbonisation of maritime shipping. The report therefore reviews the technical characteristics of relevant fuel options, the environmental implications of alternative fuel pathways, and the evolving regulatory landscape shaping the transition of the maritime sector toward lower-carbon energy carriers.

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2. Executive Summary

The present Deliverable D2.1 provides an initial, state-of-the-art assessment of the technical, environmental and regulatory dimensions of maritime decarbonisation, with a particular focus on the role of sustainable biofuels and advanced bio-oil intermediates – such as the VINTER bio-oil – within emerging low- and zero-carbon fuel portfolios. It confirms that international shipping is a hard-to-abate sector with rising well-to-wake greenhouse gas emissions, increasingly exposed to policy drivers such as the IMO Strategy on Reduction of GHG Emissions from Ships, FuelEU Maritime and the inclusion of shipping in the EU Emissions Trading System. In this context, this report sets the framework for understanding how alternative fuels, and in particular biofuels and bio-oils, can contribute to compliance trajectories and long-term decarbonisation pathways – and this ties in to the objectives and work of SEAFAIRER.

From a fuel technology perspective, the analysis distinguishes between conventional fossil fuels, transitional lower-emission options (*e.g.*, LNG, LPG, methanol) and emerging zero-carbon candidates (*e.g.*, hydrogen, ammonia, e-fuels), while emphasising the specific potential of biofuels to deliver substantial well-to-wake GHG reductions. Biofuels and bio-oils are highlighted as particularly attractive because of their drop-in potential in existing marine engines and auxiliary systems, limited requirements for new bunkering infrastructure, and compatibility with established supply chains. At the same time, the report underlines key technical challenges, including fuel stability, cold-flow properties, blend behaviour, combustion characteristics, and impacts on engine wear, exhaust after-treatment systems and emissions of non-CO_2 climate forcers such as black carbon.

The environmental and regulatory sections adopt a life cycle-based perspective, considering well-to-tank and tank-to-wake contributions, sustainability of biomass feedstocks, and interactions with certification and reporting frameworks. The deliverable reviews how tightening GHG intensity targets and carbon pricing mechanisms shift the relative cost of different fuels and reinforce the value proposition of low-carbon alternatives, especially those that can satisfy emerging sustainability criteria and traceability requirements. Particular attention is given to the implications of FuelEU Maritime's well-to-wake approach, the interplay with EU ETS compliance costs, and the role of standards, guidelines and class rules in de-risking the uptake of novel fuels and fuel blends.

A central conclusion is that the structural changes required for the implementation of sustainable biofuel value chains can be significantly reduced when value chains are designed to interface with existing assets. The preliminary findings highlight the importance of direct integration with current maritime infrastructure, including the use of standardised storage solutions (*e.g.*, ISO tanks), established logistics and bunkering partners (*e.g.*, chemical bulk carriers and terminal operators), and, where appropriate, the utilisation of existing refinery and fuel upgrading infrastructure for co-processing or dedicated hydrotreating pathways, if required. This reinforces one of the key value propositions underpinning SEAFAIRER: that intermediate bio-oil streams, if properly specified, can be channelled through largely existing logistics and conversion infrastructure, thereby lowering CAPEX, shortening deployment timelines and facilitating scale-up – without requiring structural changes to existing marine infrastructure.

For SEAFAIRER, this report thus provides the technical and regulatory backdrop against which subsequent work on VINTER bio-oil characterisation, blend formulation, engine and component testing, sustainability assessment, value-chain modelling and techno-economic analysis will be carried out. It consolidates the main drivers, barriers and boundary conditions that will shape the design of the SEAFAIRER value chains, and it identifies key knowledge gaps to be addressed in later work packages. In doing so, it positions the project within the broader maritime decarbonisation landscape and clarifies the specific niche that VINTER-derived bio-oils and related biofuel pathways aim to occupy in future sustainable shipping scenarios.

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3. Background

3.1 Importance of the maritime sector in worldwide GHG emissions

The maritime sector is a cornerstone of global trade, responsible for transporting approximately 80% of the world's goods by volume and 70% by value (IMO, 2020). This cost-effectiveness and capacity to move vast quantities of cargo over long distances make shipping indispensable to the global economy. However, this essential role comes with significant environmental consequences, particularly in terms of greenhouse gas (GHG) emissions.

Recent assessments indicate that shipping accounts for about 3% of global GHG emissions annually (UNCTAD, 2023). In absolute terms, total GHG emissions from shipping increased from 977 million tonnes in 2012 to 1,076 million tonnes in 2018, a 9.6% rise (IMO, 2020) . This upward trend is driven by growing global trade and the sector's continued dependence on fossil fuels such as heavy fuel oil (HFO) and marine diesel oil (MDO). Although shipping is one of the most fuel-efficient modes per tonne-kilometre, the extensive use of these fuels results in significant emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O), along with pollutants like black carbon (BC), nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter (PM). While measures such as the IMO 2020 Sulphur Cap have reduced SO_x emissions, the overall carbon footprint of the industry remains a pressing concern.

Annually, around 120,000 merchant ships transport over 10 billion tonnes of cargo, connecting nearly 3,000 ports worldwide. In 2022, this activity was responsible for 1.4% of global GHG emissions, 13% of NO_x emissions, and 12% of SO_x emissions, figures comparable to the total emissions of major industrialised nations like Germany. Furthermore, a European report on the environmental impact of logistics highlights that maritime transport, while critical for trade (accounting for nearly 90% of global transport by volume), is the third-largest emitter of polluting gases (14%), behind road and air transport. In the EU context, shipping contributes approximately 3-4% of the total carbon footprint, significantly lower than road transport, which represents about 20.5%.

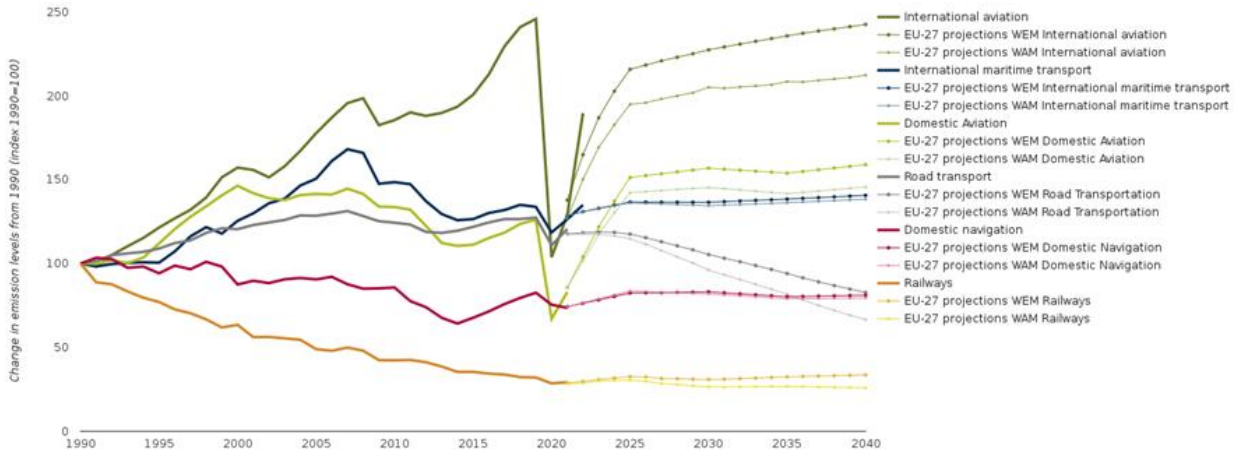

Figure 1. GHG emissions from transport in the EU, by mode and scenario. Source: (EEA, 2023).

Figure 1 visually illustrates the contribution of different transport modes to GHG emissions in the European Union. Although maritime transport plays a vital role in global trade, it contributes a smaller share to overall emissions compared to road transport, which accounted for approximately 72% of the EU's transport-related GHG emissions in 2022. This comparison underscores the need for comprehensive mitigation strategies across all transport sectors. As discussed in subsequent sections, further details will be provided regarding the strategies and regulatory measures being implemented to address these challenges. Recognising the urgency of the problem, the International Maritime Organisation (IMO) developed a comprehensive strategy to reduce GHG emissions. The IMO's Initial Strategy on GHG Emissions Reduction, adopted in 2018, outlines several key targets, including a 40% reduction in carbon intensity by 2030 compared to 2008 levels, a 50% reduction in total GHG emissions by 2050, and a long-term objective of achieving net-zero emissions by the end of the

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century (IMO, 2018). These targets align with the broader goals of the Paris Agreement, which aims to limit global temperature rise to below 2°C, with an ambition of keeping it at 1.5°C. In addition to the IMO's global efforts, regional policies, such as the European Union's inclusion of shipping in its Emissions Trading System (EU ETS) in 2024, further reinforce emissions control by imposing economic penalties on high-carbon vessels operating within European waters (European Commission, 2023).

The International Maritime Organisation (IMO), arguably the leading organisation in the maritime sector, is developing policies to reduce greenhouse gas emissions for international shipping. The first regulations, in particular, the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) entered force on January 1, 2023. One of the goals of these activities is to achieve by 2030 a 40% reduction in carbon emissions compared to the 2008 level. The goal is to reduce GHG emissions by increasing the energy efficiency of ships, as well as introducing new technologies and fuels with low or zero carbon content. These documents are expected to have a significant impact on the design and operation of all vessels. Although all ships must meet the IMO's minimum requirements, commercial pressure may push ship owners to take the lead in decarbonisation, as shipping companies with poor performance are expected to be less attractive in the shipping market and have problems accessing capital. The available GHG mitigation measures range from easily achievable operational measures to capital-intensive technical solutions. New builds will have more available options than ships in operation. The greatest potential to reduce GHG emissions is the use of alternative fuels and renewable energy, as shown in Figure 2.

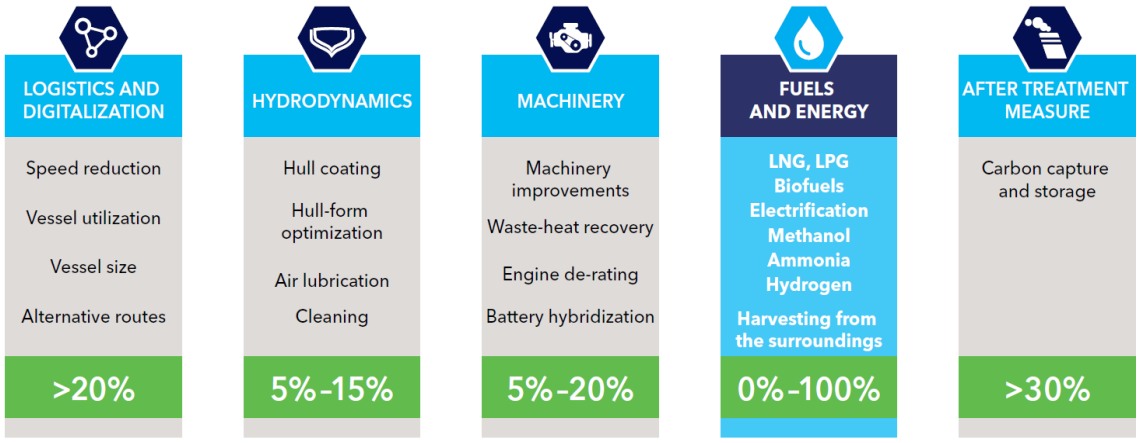

Figure 2. Available technologies to decarbonise shipping and their GHG emission reduction potential.

As global trade continues to expand, reducing emissions in the maritime sector is critical for achieving international climate objectives. Transitioning toward alternative fuels, enhancing energy-efficient technologies, and implementing stricter regulatory measures will be essential in mitigating the sector's environmental impact. While the path to decarbonisation presents technological and economic challenges, it also offers opportunities for innovation and long-term sustainability in the maritime industry. The development of low-carbon fuels, enhanced energy efficiency measures, and stricter emissions regulations will be crucial in steering the industry toward a greener future.

3.2 Brief description of the main GHG sources in the maritime sector

For contextualisation, it is useful to distinguish between two major types of emissions released into the atmosphere, as shown in Figure 3 atmospheric pollutants and greenhouse gases (GHGs). These two groups differ not only in their sources but also in the ways they affect human health and the environment.

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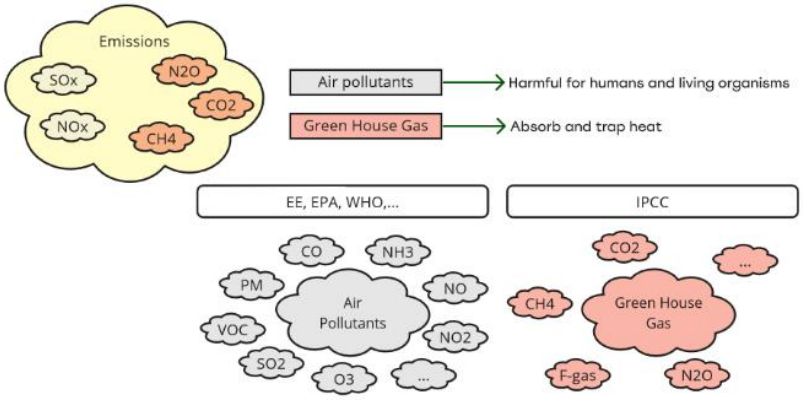

Figure 3. Atmospheric pollutants vs. greenhouse gases (GHG).

- Atmospheric pollutants: These are substances, particles or chemical compounds present in the atmosphere that can be harmful to human health and the environment. Depending on their origin, atmospheric pollutants are classified as primary or secondary. Primary pollutants are emitted directly into the atmosphere because of human activities such as fuel combustion, industry and transportation. Secondary pollutants are formed through chemical reactions between primary pollutants and other atmospheric compounds. Common examples of primary air pollutants include sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NOx) and particulate matter such as dust and soot. These pollutants are regulated by multiple entities, such as the European Environment Agency (EEA) and the U.S. Environmental Protection Agency (EPA).

- Greenhouse gases (GHGs): Greenhouse gases are a set of substances present in the Earth's atmosphere with the capacity to absorb radiation emitted by the Earth. This absorption breaks the balance between the heat received from the sun and the heat emitted by the Earth, resulting in the retention of heat in the atmosphere and contributing to the phenomenon known as the greenhouse effect. This phenomenon is fundamental to maintaining the Earth's temperature in a range suitable for life as we know it. However, when the levels of greenhouse gases increase due to human activities, the greenhouse effect intensifies, leading to global warming and significant climate changes. The United Nations Intergovernmental Panel on Climate Change (IPCC) is the authority responsible for defining which gases are considered greenhouse gases. The main greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor and fluorocarbons.

  Maritime transport is a highly carbon-intensive sector due to its extensive dependence on fossil fuels (IMO, 2015). Vessels rely on large internal combustion engines that burn petroleum-based fuels to generate energy for both propulsion and onboard operations. This combustion process is the primary source of greenhouse gas (GHG) emissions in the industry, with carbon dioxide (CO_2) accounting for roughly 98% of the total (IMO, 2018). However, the environmental impact of maritime activities extends beyond CO_2 emissions. The combustion of heavy fuel oil (HFO) and marine diesel oil (MDO) also emits smaller quantities of methane (CH_4) and nitrous oxide (N_2O), both of which have a significantly higher global warming potential than CO_2. According to the Intergovernmental Panel on Climate Change (IPCC, 2014), methane's global warming potential is estimated to be 28 to 36 times greater than that of CO_2 over a 100-year period. Additionally, the use of liquefied natural gas (LNG) can lead to "methane slip," where unburned methane is released into the atmosphere, further contributing to the overall GHG burden (IPCC, 2014). In addition to propulsion, ships require considerable energy for auxiliary systems such as electricity generation, navigation, cargo handling, and climate control. These functions are typically powered by diesel generators which, when operating under conditions of incomplete combustion, release black carbon. Although black carbon has a short atmospheric lifetime, it is a highly effective absorber of solar radiation and plays a significant role in accelerating Arctic ice melt (EPA, 2016). Maritime operations also produce nitrogen oxides (NO_x) and sulphur oxides (SO_x), compounds associated with acid rain, respiratory illnesses, and ocean

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acidification (EMSA, 2020). While regulations such as MARPOL Annex VI have successfully reduced SO_x and NO_x emissions within designated Emission Control Areas (ECAs) (IMO, 2015), comprehensive global measures addressing CO_2, CH_4, and N_2O emissions are still needed.

Understanding the classification of emissions, differentiating between primary and secondary atmospheric pollutants and greenhouse gases, is essential for assessing the environmental impact of maritime transport. Given the sector's heavy reliance on fossil fuels, it not only emits significant quantities of CO_2 but also contributes to the formation of various harmful pollutants. Consequently, effective mitigation strategies must target both local air pollutants and the greenhouse gases driving global climate change. This dual approach requires transitioning to low-carbon energy sources, such as biofuels, ammonia, hydrogen, and synthetic fuels, and implementing technological advancements that enhance energy efficiency. Furthermore, robust regulatory measures, including carbon pricing, improved emissions reporting, and stricter efficiency standards, are critical for meeting international climate targets and ensuring the long-term sustainability of the maritime industry.

3.3 Brief explanation of current implemented fuels in Europe and the world

The maritime sector is undergoing a significant transition toward lower-emission and alternative fuels as part of global decarbonisation efforts. Traditional heavy fuel oil (HFO) and marine diesel oil (MDO) remain the dominant fuels used in shipping, but stricter environmental regulations and international commitments, such as those from the International Maritime Organisation (IMO, 2020) and the European Union (European Commission, 2023), are driving the adoption of cleaner and more sustainable alternatives. The fuels currently implemented in Europe and worldwide can be grouped into conventional fossil fuels, transitional lower-emission fuels, and emerging zero-carbon options

3.3.1 Conventional fossil fuels

The HFO and MDO have long been the workhorses of the shipping industry, primarily due to their affordability and well-established supply chains. However, the high sulphur content of these fuels has raised significant environmental concerns. To address this, the IMO implemented the 2020 global sulphur cap, reducing the allowable sulphur content in marine fuels from 3.50% m/m to 0.50% m/m (IMO, 2020). In response, refiners have developed new fuel blends, such as Very Low Sulphur Fuel Oil (VLSFO), engineered to meet these tighter standards. Additionally, many shipowners have installed exhaust gas cleaning systems (scrubbers) that allow vessels to continue using higher-sulphur fuels while still complying with emission limits (IMO, 2020).

3.3.2 Transitional lower-emission fuels

To bridge the gap between conventional fossil fuels and future zero-emission technologies, the maritime industry is increasingly turning to transitional fuels that reduce harmful emissions while requiring only minor modifications compared to a complete switch to emerging zero-carbon options.

- **Liquified Natural Gas (LNG):** LNG is currently the most widely adopted alternative fuel in commercial shipping. It offers a 20–30% reduction in CO_2 emissions compared to HFO and significantly lowers emissions of sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (Bureau Veritas, 2022). The EU has invested heavily in LNG bunkering infrastructure, with major European ports, including Rotterdam, Barcelona, and Hamburg, offering LNG refueling facilities. However, LNG presents challenges such as methane slip, where unburned methane (which has a higher global warming potential than CO_2) is released into the atmosphere (IEA, 2021).

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- **Liquified Petroleum Gas (LPG):** LPG offers lower CO_2 emissions compared to both HFO and MDO. It is most commonly used by vessels designed as LPG carriers - vessels that can even utilise their cargo as fuel. LPG's relatively lower infrastructure requirements make it an attractive option for certain vessel types, though its availability for large-scale adoption remains limited (European Commission, 2023).

- **Methanol:** Methanol is gaining traction as an alternative marine fuel for several reasons. As a liquid at ambient temperature, it simplifies storage and bunkering operations compared to cryogenic fuels like LNG. Additionally, methanol can be produced from renewable resources, offering the potential for carbon neutrality when generated from biomass or renewable electricity. It can be used in gasoline engines, commonly blended with conventional fuels. Also, when used in diesel engines, methanol requires a small amount of diesel or an ignition improver to properly run. From an environmental perspective, there is no sulphur in the composition of methanol, eliminating SO_x generation. Furthermore, NO_x emissions are produced in a small amount, and there are no emissions of solid particles (PM). When converting ships to methanol, it is necessary to modify the engine, fuel tanks, pipelines and bunkering system. The use of methanol to produce fuels requires compliance with the current legislation, as methanol is a highly flammable liquid, highly poisonous of a nervous and vascular nature with a pronounced cumulative effect, similar in color, smell, and taste to ethyl (wine) alcohol. Along with its limited global supply, these factors pose barriers to widespread adoption. Despite these challenges, major shipping companies, such as Maersk, are investing in methanol-powered vessels, and ports such as Rotterdam and Gothenburg are actively developing methanol bunkering facilities (Bureau Veritas, 2022).

- **Biofuels:** Biofuels such as biodiesel and HVO provide an immediate reduction in lifecycle CO_2 emissions. A key advantage of biofuels is their compatibility with existing marine engines, which can operate on biofuel blends without significant modifications. Initiatives like the EU's Renewable Energy Directive (RED II) support their use (European Commission, 2023). However, challenges such as feedstock availability, higher costs, and competition with other industries remain barriers to large-scale adoption.

3.3.3 Emerging zero-carbon fuels

Looking further ahead, the industry is actively researching and testing emerging fuels that offer near-zero carbon emissions. Hydrogen and ammonia are leading candidates in this category. These fuels have the potential to drastically reduce or even eliminate carbon dioxide (CO_2) emissions during operation, provided they are produced using renewable energy sources. However, both hydrogen and ammonia face technical and infrastructural challenges, including storage, handling, and modifications to ship design. Despite these hurdles, they represent the cornerstone of long-term strategies for decarbonising maritime transport.

- **Green ammonia:** Ammonia (NH_3) is regarded as one of the most promising zero-carbon fuels for shipping because it contains no carbon and, when burned under proper conditions, produces no CO_2 emissions. When produced using renewable energy, so-called green ammonia, it could drastically reduce the carbon footprint of maritime operations. Companies like MAN Energy Solutions and Wärtsilä are developing ammonia-fueled engines, with the first orders for new vessels expected as early as 2025 and broader commercial adoption targeted for the 2030s (IMO, 2020). Despite these advantages, challenges such as ammonia's toxicity, corrosiveness, and the need for specialised storage and handling systems remain. Ammonia can be used as marine fuel in both internal combustion engines and fuel cells. Due to its high-auto ignition temperature, ammonia requires a higher compression ratio (35:1 and higher) than used in typical CI engines (16-23:1). It is difficult to design such an engine, so the addition of a second fuel, with lower auto-ignition temperature, can help to combust the mixture and

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allows for a more stable combustion. Ammonia has a high minimum ignition energy and a low flame speed, so mixtures of ammonia with other types of fuel are also used in engines with forced ignition. Ammonia positive-ignition engines are thought to be used for smaller vessels, while modified two-stroke (dual-fuel) diesel engines may be suitable for larger ships. Combustion of ammonia or ammonia mixtures can lead to emissions of nitrogen oxides (NO_x), nitrous oxide (N_2O) and direct emissions of ammonia (NH_3). However, to date, there is no experience of long-term operation of ship engines on ammonia. Therefore, there is not enough empirical data on emissions from burning this type of fuel. The first commercial ammonia engines became available in 2024.

- **Hydrogen (H_2):** Hydrogen is another key zero-emission fuel with significant potential for maritime applications, particularly in short sea shipping and inland waterways. Hydrogen can be used in fuel cells or burned in modified engines, producing only water as a by-product. However, its low volumetric energy density necessitates significant onboard storage modifications and robust handling infrastructure. Additionally, high production costs and energy losses during electrolysis currently limit its viability for deep-sea shipping (IEA, 2021).'

- **E-fuels (synthetic fuels; e-methanol, e-diesel, e-ammonia):** E-fuels are synthetic fuels produced by combining renewable hydrogen with captured CO_2, rendering them potentially carbon neutral. They can serve as drop-in replacements for conventional fossil fuels without requiring major engine modifications. Despite their compatibility with existing infrastructure, e-fuels face challenges such as high production costs and relatively low energy conversion efficiencies. Ongoing research and pilot projects aim to improve these metrics, with hopes of making e-fuels economically competitive on a commercial scale by mid-century (Bureau Veritas, 2022).

In this regard, Table 1 summarises the main properties of the alternative fuels explained in this section.

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Table 1. Summary of alternative fuel properties.

Fuel Category	Fuel/Type	Advantages	Challenges	Implementation/Status
Conventional fossil fuels	HFO, MDO, VLSFO	- Low cost and widespread availability - Established global supply chains	- High sulphur content leading to environmental and health risks - Significant GHG emissions - Requires scrubbers to meet IMO regulations	Still dominant in shipping, but subject to stringent sulphur cap (0.5% globally, 0.1% in ECAs per IMO 2020) and ongoing regulatory pressure
Transitional lower-emission fuels	LNG	- 20-30% reduction in CO_2 emissions - Significantly lowers SO_x, NO_x, and PM emissions - Extensive EU investments in LNG bunkering infrastructure	- Methane slip, with methane's high global warming potential - Requires vessel retrofitting and specialised cryogenic storage	Widely adopted in commercial shipping with major European ports offering LNG bunkering; emerging as a key alternative fuel in transition
Transitional lower-emission Fuels	LPG	- Lower CO_2 emissions compared to HFO/MDO - Simpler infrastructure requirements compared to LNG	- Limited availability for large-scale adoption across the maritime industry	Mainly used in LPG carriers where the cargo can also serve as fuel; not as broadly implemented as LNG
Transitional lower-emission Fuels	Methanol	- Liquid at ambient temperatures, easing storage and bunkering - Potential for carbon neutrality when produced from renewable sources	- Lower energy density than conventional fuels - Limited global supply and infrastructure	- Gaining traction; major shipping companies like Maersk are investing in methanol-powered vessels; ports like Rotterdam and Gothenburg are developing methanol bunkering facilities
Transitional lower-emission Fuels	Biofuels (biodiesel, HVO)	- Immediate reduction in lifecycle CO_2 emissions - Compatible with existing marine engines without major modifications	- Challenges with feedstock availability - Higher costs and competition with other sectors (*e.g.*, road transport)	Used in blends with conventional fuels and supported by policies such as the EU Renewable Energy Directive (RED III)
Emerging zero-carbon fuels	Hydrogen (H_2)	- Zero emissions at the point of use (produces only water) - High potential for short-sea and inland waterway applications	- Low volumetric energy density requiring significant storage modifications - High production costs and energy losses during electrolysis limit deep-sea applications	Actively researched; pilot projects underway, particularly in short-sea shipping; infrastructure and cost improvements needed for broader adoption

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Emerging zero-carbon fuels	Green ammonia (NH_3)	- Contains no carbon; when burned under proper conditions, produces no CO_2 emissions - Potentially major decarbonisation fuel when produced via renewable energy sources	- Toxicity, corrosiveness, and need for specialised storage and handling systems - Requires robust safety and bunkering protocols to prevent leaks	- Considered one of the most promising zero-carbon fuels; companies like MAN Energy Solutions and Wärtsilä are developing ammonia-fueled engines, with first orders expected around 2025 and broader adoption targeted for the 2030s
Emerging zero-carbon fuels	E-fuels (synthetic fuels: e-methanol, e-diesel, e-ammonia)	- Can be used as drop-in replacements for conventional fuels without major engine modifications - Potentially carbon-neutral if produced from renewable hydrogen and captured CO_2	- High production costs - Relatively low energy conversion efficiencies - Challenges in scaling up production to meet industry demand	- Under research and pilot projects; long-term potential remains significant, but commercial-scale adoption is expected mid-century

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3.4 Importance of alternative fuels for decarbonisation of maritime shipping

As discussed, the maritime sector is a significant contributor to global GHG emissions, due to the high consumption of conventional fossil fuels such as Heavy Fuel Oil (HFO) o Marine Diesel Oil (MDO). In this sense, entities such as the EU aim to progressively reduce their emissions, aiming to be climate-neutral by 2050, including the different economic sectors, from power generation to transportation (European Union, 2023).

For the maritime sector, IMO published the first version of its revised GHG strategy in 2023 (IMO, 2023), strengthening its ambitions for GHG reduction. Using 2008 as baseline year, IMO is aiming to reduce well-to-wake GHG emissions by 20% by 2030, 70% by 2040 and reach net-zero emissions around 2050. Additionally, by 2030, at least 5% of the energy used in international shipping should come from zero or near-zero GHG emission technologies, fuels, and energy sources, with a goal of striving for 10%.

In this regard, different strategies on ships can be applied to reduce emissions including technical and operational solutions such as hull modifications, fleet management, speed optimisation and changes in the propulsion system, as can be seen in Figure 4 (Bureau Veritas, 2022). It is seen that operational and technical solutions have the potential to reduce the emissions from 5-50%, achieving values near to 75% when the vessel speed is extensively optimised. Furthermore, it can be observed that the adoption of alternative fuels such as biofuels (90% reduction), hydrogen (80-100%) or bio-LNG (35%) have a remarkable effect on GHG reduction, highlighting their growing importance in the maritime industry. In this sense, Table 2 shows the Well-to-Wake (WtT) emissions of different fuels, fossil-based and alternative (biofuels and e-fuels). Here, the contribution of production, refining and transportation, (Well-to-Tank, WtT) emissions, as well as the emissions produced from the combustion process or (Tank-to-wake, TtW) are specified.

WtW emissions		WtT (gCO_2eq/MJ)	TtW (gCO_2eq /MJ)	WtW (gCO_2eq /MJ)	WtW reduction (referenced to MDO) (%)
Fossil	HFO	13.50	76.89	90.39	-
	LFO	13.20	76.85	90.05	-
	MDO	14.40	75.08	89.48	-
	LNG	18.50	56.01	74.51	17.57
	LPG	7.80	65.54	73.34	18.86
Biofuels	Biomethanol	-55.60	69.10	13.50	85.06
	Bioethanol	-42.75	70.85	28.10	68.91
	HVO	-58.90	70.80	11.90	86.83
	FAME	-31.09	76.59	45.50	49.66
	Bio-LNG	-17.01	56.01	39.00	56.85
E-fuels	e-methanol	-40.90	69.10	28.20	68.81
	e-LNG	-42.50	56.01	13.51	85.06
	e-H2	28.20	0.00	28.20	68.80
	e-Ammonia	28.20	0.00	28.20	68.80

Table 2. WtW GHG Emissions Intensity of Various Fuels for Ships. Source: (European Parliament and Council of the European Union, 2018).

It is seen that conventional maritime fuels have Well-to-Wake emissions around 90 gCO_2/MJ, with a carbon intensity associated with their extraction, refining and distribution representing nearly the 17% of the emissions. In the fossil-based classification it can be seen transition fuels such as Liquefied Natural Gas (LNG) and Liquified Petroleum Gas (LPG), whose emissions are 18% lower than MDO (taken as reference). While LNG is often promoted as a transitional fuel due to its lower combustion emissions (TtW = 56 gCO_2e/MJ), its

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production phase (WtT = 18.5 gCO_2e/MJ) and the risk of methane slip during transport and use limit its long-term sustainability benefits.

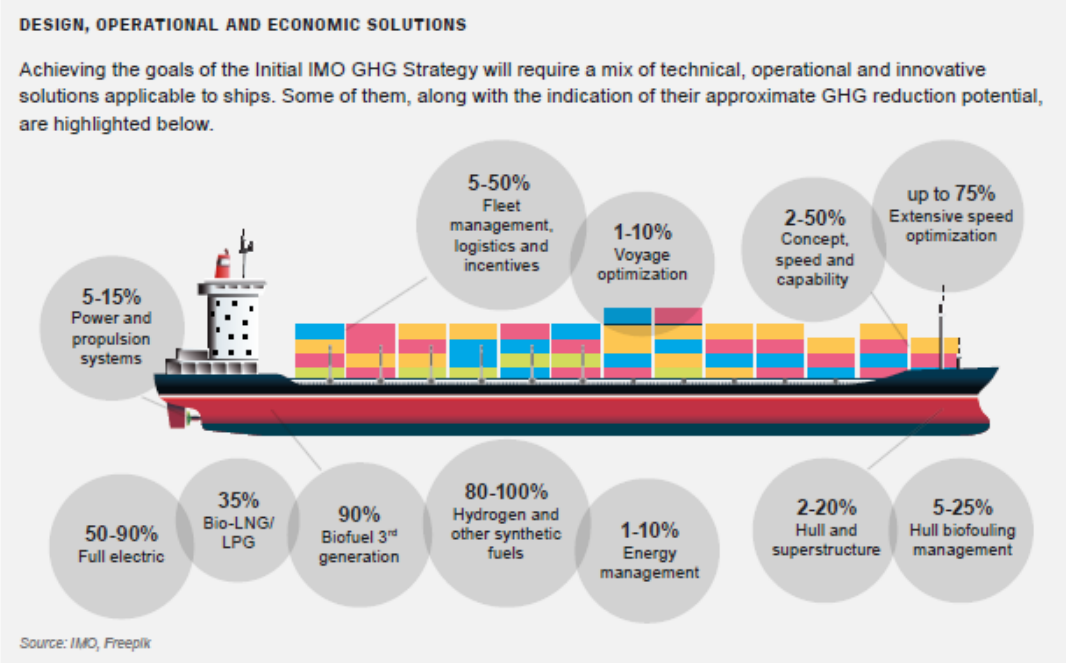

Figure 4. Design, operational and economic solutions to reduce GHG emissions in maritime applications. Source: (Bureau Veritas, 2022).

In contrast, the carbon emissions of biofuels are much lower due to the absorption of atmospheric CO_2 that comes from the biological processes in their production pathways, exhibiting negative WtT emissions. For instance, fuels such as HVO (Hydrotreated Vegetable Oil) or biomethanol achieve almost a 90% of reduction compared to conventional fuels. Additionally, e-fuels such as e-methanol and e-LNG are promising alternatives that use renewable electricity and CO_2 captured from the atmosphere or industrial sources, making their production carbon-neutral if powered entirely by renewables. As an example, e-LNG achieves a significant reduction compared to fossil LNG (48%). However, the feasibility of e-fuels depends on the availability of low-carbon electricity, as energy-intensive production processes can lead to higher emissions if fossil energy sources are implemented.

Finally, hydrogen and ammonia appear as fuels that eliminate Tank-to-Wake emissions due to the absence of carbon in their composition, making them a considerable alternative to zero-emission propulsion. Nonetheless, their production can represent significant carbon emissions if non-renewable electricity is used, for which the development of green hydrogen and ammonia supply chains that ensure low carbon in their entire lifecycle is necessary for their successful implementation in the maritime sector. Considering this, the adoption of alternative fuels provides a substantial and long-term reduction in emissions that can be complemented with operational or technical measures. While fossil-based options like LNG provide slight improvements, biofuels and e-fuels offer drastic reductions in WtW emissions. The transition towards these fuels will be critical for achieving decarbonisation in the maritime industry to meet global emissions reduction targets. In this sense, Figure 5 presents the forecasting of carbon emissions and the share of fossil-based and alternative fuels until 2070, showing the expected increase in the use of alternative fuels and the consequent reduction in CO_2 emissions. It is seen that as the share of alternative fuels increases, the carbon generation is reduced even if the energy requirements continue to rise. Regarding natural gas, it is expected to maintain its role as a transitional fuel, while the use of biofuels is expected to rise its participation after 2030. Additionally, zero-emission fuels, such as hydrogen or ammonia, are expected to gain prominence after 2040, becoming the dominant energy source in the maritime sector by 2070. As a result, a reduction of 80% in the emissions from 2019 to 2070 is expected due to the implementation of these fuels.

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In addition to this, the introduction of regulations with economic implications on fuel prices has increased interest in the adoption of alternative fuels. These regulations have been designed to ensure that maritime sector operators internalise the cost of their greenhouse gas emissions. The purpose of these regulations is to promote emission reductions and financing the transition towards more sustainable energy sources (European Union, 2023). In this context, it is noteworthy that there are two key regulations that impose additional costs on fuels: the EU Emissions Trading System (EU ETS) and the FuelEU Maritime regulation.

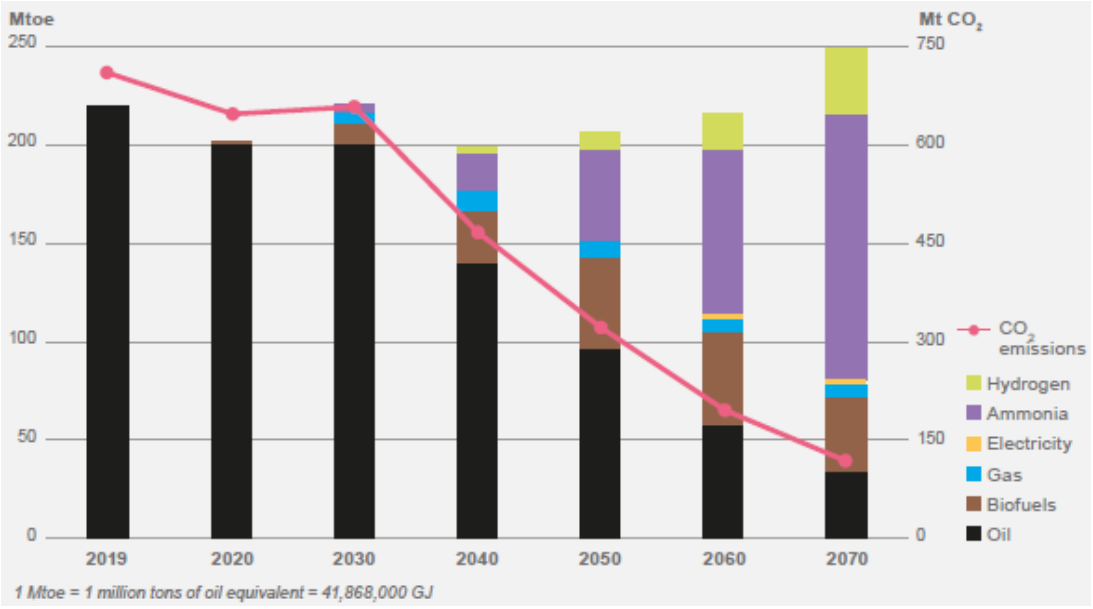

Figure 5. Global energy consumption and CO_2 emissions of international shipping. Source: (Bureau Veritas, 2022).

On the one hand, the EU ETS (European Union, 2023) is based on a "cap and trade" principle, where a limit is set on the total allowed emissions for each installation under the scope of the system. This cap is gradually reduced, ensuring a reduction in overall emissions over time. Within the limit, companies purchase or receive carbon allowances to cover all their annual emissions. Each allowance grants permission to emit one tonne of $CO_{2\,eq}$. The allowances are sold in auctions, and their price is determined by EU carbon market, which operates under a strict set of rules to ensure market stability.

On the other hand, FuelEU Maritime (European Commission, 2023) establishes maximum limits on the yearly average GHG intensity of the energy used by ships over 5,000 GT calling at EU ports. The regulation indicates a gradual reduction in fuel GHG intensity, starting with a 2% decreased by 2025 and reaching 80% by 2050. Unlike the EU ETS, which only considers Tank-to-Wake (TtW) emissions, FuelEU Maritime applies a Well-to-Wake (WtW) approach. The additional cost imposed by FuelEU Maritime depends on how much a vessel fuel exceeds the GHG intensity limit set for a given year. If the fuel used does not comply with the required target, the ship operator must pay a penalty, calculated based on the excess emissions per megajoule (MJ) of energy used. This means that fuels with a higher carbon footprint will result in higher penalties, while the use of low-emission fuels (such as biofuels, e-fuels, or hydrogen) will help avoid extra costs (European Commission, 2023).

Both regulations increase fuel costs for non-compliant fuels, reinforcing the shift towards low- and zero-emission alternatives. First, market fluctuations in the carbon market represent a fuel price volatility that affects operation costs, while there is an increase in the penalty due to the strengthening of the gradual GHG intensity limit, imposing an additional cost on fuels that do not meet the required targets. As a result, ship operators are motivated to adopt cleaner fuels to reduce financial penalties and meet regulatory requirements, accelerating the decarbonisation of the maritime sector. More details of these regulations are given in section 7, where an extended explanation of how these regulations affect fuel prices is given.

It can be concluded that the implementation of alternative fuels has effects in environmental, legislative and economic aspects, each one influencing the other. These fuels have an important part in reducing GHG emissions, aligning with decarbonisation objectives of the different governmental entities. These objectives

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come along with regulations such as the EU ETS and FuelEU Maritime that impose increasingly strict GHG limits and financial penalties, motivating the transition towards low and zero carbon alternatives. Compliance with these policies leads to higher costs for fossil-based fuels, increasing the interest in cleaner fuels that minimise operating expenses. The interaction between these factors accelerates the energy transition in the maritime sector, ensuring that sustainability goals are met while maintaining competitiveness in an evolving regulatory and market framework.

3.5 Environmental, regulatory and technical challenges of alternative fuels

The adoption of alternative fuels in the maritime industry is driving significant changes across multiple areas, requiring coordinated efforts among stakeholders of the fuel value chain to ensure an appropriate transition. These changes imply environmental challenges related to fuel production and consumption, technical and infrastructure developments, and regulatory challenges regarding the creation and enforcement of new polices. Addressing these aspects is essential for promoting the global adoption of alternative fuels. In this context, this section provides an overview of environmental, technical, and regulatory challenges associated with their implementation in the maritime sector.

- **Environmental:** Currently, the tightening of environmental regulations in the maritime sector has accelerated the development of new fuels. In this regard, regulatory bodies such as the International Maritime Organisation (IMO) have set greenhouse gas (GHG) reduction targets, as mentioned in previous sections, aiming for carbon-neutral operations by the end of the century. Additionally, the IMO has set limits in the sulphur content of marine fuels, with a maximum mass fraction of 0.1% when vessels operate within Emission Control Areas (ECAs) (Foretich, Zaimes, Hawkins, & Newes, 2021). These regulations have encouraged ship operators to explore ways to diversify their fuel portfolios, seeking options with low sulphur content and low-carbon alternatives. However, the adoption of alternative fuels could also bring environmental challenges, which vary depending on their nature (Foretich, Zaimes, Hawkins, & Newes, 2021). For transition fuels, such as LNG (Liquefied Natural Gas) and LPG (Liquefied Petroleum Gas), although these are mature technologies that have demonstrated a significant reduction in emissions, they still present certain environmental challenges that need to be addressed. In the case of natural gas, the main environmental challenge is methane slip, which must be avoided to prevent additional environmental impacts. Methane slip is a phenomenon inherent to the use of natural gas in internal combustion engines, occurring due to the incomplete combustion of the fuel (Bureau Veritas, 2022). There are post-treatment technologies that help reduce methane levels in exhaust gases. However, several challenges remain, particularly regarding methane conversion at low temperatures and the high degradation of catalysts used in this process. Further technological advancements are required to make these solutions more durable and efficient (Bureau Veritas, 2022). Similarly, a significant portion of methane leaks occur across the fuel value chain, which can surpass the methane slip observed in certain dual-fuel engines in some cases. This is a challenge that also needs to be addressed to further reduce the environmental impact associated with the use of natural gas (Bureau Veritas, 2022).

  For LPG, even on a smaller scale, one of its environmental challenges is fuel leakage associated with its production and combustion. While these emissions are less significant compared to natural gas, propane and butane, the main components of LPG, have a high global warming potential. Therefore, minimising these leaks is essential to reduce its environmental impact (Lloyd's Register, 2024; Foretich, Zaimes, Hawkins, & Newes, 2021). Furthermore, the implementation of biofuels, such as bio-oils like HVO or FAME (fatty acid methyl esters), presents challenges related to land use, as the growing demand for biofuels could lead to the global expansion of agricultural land, often resulting in increased deforestation. In this regard, many first-generation biofuels, which are produced from crops primarily intended for food, may create strong competition in food markets. Consequently, additional biofuel production would drive an increased demand for land (Bureau Veritas, 2022).

  In this sense, biofuel production must demonstrate long-term sustainability, with biomass, being the first step in the value chain, as the first element where sustainability should be verified. Moreover,

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issues related to water use must be carefully considered and certified by biofuel producers to enhance consumer confidence (Lloyd's Register, 2024).

Regarding e-fuels, they present a promising solution for emissions reduction. However, they require a high availability of renewable energy sources to be considered truly sustainable options. The production of these fuels, such as e-methanol, e-ammonia, or e-LNG, relies on the generation of e-H_2 as a key feedstock. This latter is produced through an electrolysis process, which is highly energy-intensive and requires large amounts of electricity. For this reason, using an electricity grid primarily powered by non-renewable sources, such as coal or natural gas, for e-fuel production can be counterproductive (Bureau Veritas, 2022).

In this sense, environmental challenges associated with fuels such as methanol or ammonia mainly arise from their production pathway and the subsequent modifications required to make their generation sustainable, especially what is related to hydrogen production. For methanol, approximately 65% of the current production is based on natural gas, while nearly the remaining 35% relies on coal gasification. Meanwhile, only about 0.2% of the production is generated using renewable sources (IRENA and Methanol Institute, 2021). In the case of ammonia, current production is mainly based on the production of hydrogen from natural gas and coal combined with nitrogen that is separated from air using electricity, while only 1% of the ammonia supply comes from near-zero-emission sources (Lloyd's Register, 2024). Therefore, it is important to promote the development of sustainable technologies to simplify production, reduce its costs and encourage shipowners to use these fuels.

- **Regulatory:** The adoption of alternative fuels involves facing challenges related to their use, transportation, and storage, as it requires modifications to engines and fuel distribution systems. Additionally, these fuels have specific conditions and requirements that must be met to ensure a reliable supply to end users. The adoption of LNG presents three main technical challenges to be addressed: Fuel storage and handling, boil-off gas and engine design. Regarding fuel storage and handling, LNG must be stored under cryogenic conditions (at -163ºC), requiring nearly twice the volume of conventional fuel. This imposes a high CAPEX for the fuel containment (Bureau Veritas, 2022). Compared to conventional fuels, additional elements are also to be considered such as a bunker station and transfer piping, a fuel gas supply system, a double-wall fuel gas distribution piping, gas valve unit, a nitrogen generating plant used for purging, pressurisation, inertisation and cooling and vent piping. These elements add significant complexity to vessel arrangements (ABS, 2022).

  About boil-off gas, it is produced due to heat absorption that causes evaporation on part of the gas. To handle this, a specialised installation is required to re-liquify the gas and maintain the tank pressure within acceptable levels (ABS, 2022). Furthermore, the adoption of LNG currently requires the implementation of dual-fuel engines that require a pilot injection of liquid fuel to ensure proper combustion. In this sense, there are two different injection technologies, each bringing some particularities to consider. The high-pressure injection technology implies an increase in the complexity and cost of the fuel gas supply while, the low-pressure methodology leads to a considerable methane slip. Therefore, a case-specific decision must be made to find a compromise between emissions reduction and system complexity (ABS, 2022).

  Regarding LPG, there are currently not commercially available four-stroke engines on the market. Moreover, propane, one of its main components, has a higher density than air, meaning that released vapours are expected to collect in low spaces. Likewise, LPG is a highly flammable gas, requiring special safety measures to prevent leaks, spills, and fire propagation. Similarly, further development is needed to expand bunkering capacity in the maritime sector. Additionally, in terms of storage, LPG requires 1.5 times the volume of conventional fuels to supply the operation of a given vessel (Foretich, Zaimes, Hawkins, & Newes, 2021; Bureau Veritas, 2022).

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With respect to methanol, one of its main challenges is its low energy content, which requires tank sizes approximately 2.5 times larger than those of conventional fuels to meet the energy demands of a given vessel (Bureau Veritas, 2022). Additionally, methanol has a low flash point and high toxicity, increasing the complexity of onboard safety systems. Safety measures like those required for natural gas are needed, such as double-walled piping and boil-off gas handling systems (MAN Energy Solutions, 2021). Furthermore, methanol exhibits highly corrosive behaviour, requiring specialised coatings and seals (MAN Energy Solutions, 2021). Likewise, special detectors are needed due to the nearly invisible flame produced when methanol burns (Bureau Veritas, 2022).

On the other hand, further development is needed in the methanol value chain, including production and bunkering infrastructure, which would help in a price reduction, which is an essential step for its medium-term adoption in the maritime sector (Bureau Veritas, 2022; MAN Energy Solutions, 2021). The same applies to ammonia, whose green value chain is still under development, with only 1% of its supply expected to come from near-zero-emission sources by 2025. Expanding the available infrastructure is essential to reducing costs and, consequently, lowering prices (Lloyd's Register, 2024). Additionally, ammonia has a low energy density, requiring three times the volume of conventional fuels to meet the energy demands of a given vessel (Lloyd's Register, 2024; Bureau Veritas, 2022). Furthermore, ammonia is a highly corrosive and toxic substance, even at low concentrations, making the implementation of specialised safety measures crucial to protect crew members and passengers (Bureau Veritas, 2022). Moreover, ammonia combustion must be carefully controlled to minimise NOx and N_2O emissions, the latter being a greenhouse gas with a global warming potential 273 times greater than CO_2 (Bureau Veritas, 2022; DNV, 2023; Lloyd's Register, 2024). To address this issue, engine manufacturers have integrated solutions such as Selective Catalytic Reduction (SCR) to eliminate NOx emissions (MAN Energy Solutions, 2024).

Additionally, ammonia requires a cryogenic installation for proper storage as a liquid, reducing its density and reducing the storage volume, complicating its application (Lloyd's Register, 2024). Also, like methanol, it also requires a dedicated storage and supply system with a specialised fuel valve unit, a venting system, a nitrogen supply, and other components (LR, 2024). Finally, due to its poor ignition characteristics, it requires a pilot fuel in engines that can be 5-15% of the total fuel injected during the operation, even though this amount depends on factors such as engine load and combustion technology. Consequently, CO_2 production and any emissions associated to the pilot fuel are still presented during ammonia application in engines (Bureau Veritas, 2022; DNV, 2023; Lloyd's Register, 2024).

Regarding hydrogen, it is a high inflammable and explosive fuel for which major safety risks come with its implementation. Also, it presents a critical logistical challenge due to its low volumetric density, requiring a significant onboard storage capacity (4-14 times the capacity of conventional fuels, depending on the storage technology), requiring a cryogenic installation to be properly stored. Additionally, its value chain is still in development (production, bunkering and storage facilities) where most of its production currently comes from natural gas while its supply at scale may be challenging for green hydrogen (Bureau Veritas, 2022).

Compared to other alternative fuels such as methanol, ammonia, and hydrogen, biofuel, especially bio-oils like HVO and FAME, present fewer technical and infrastructural barriers, making them a practical short-term solution for the maritime industry. Nonetheless, there are some technical challenges that need to be addressed regarding storage and consumption, with considerable potential for microbial contamination and oxidation risk. Additionally, special additives are required for the lubricating oil used in certain engine types. Furthermore, challenges regarding its production availability and prices are needed to be solved to fully adopt biofuels in maritime industry (Bureau Veritas, 2022; Lloyd's Register, 2024).

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4. Current state of biofuel uses and production

4.1 Definition of biofuels

Biofuels are renewable energy sources derived from organic materials, primarily plant or algal biomass and animal waste[1]. These sustainable alternatives to fossil fuels are designed to reduce greenhouse gas emissions and decrease dependence on non-renewable energy sources[2]. In its wider remit, the term "biofuel" encompasses a broad range of fuel types, including solid, liquid, and gaseous forms. However, in the context of transportation and energy production, biofuels are most referred to in their liquid or gaseous states, as these forms are more easily transportable and can be burned more cleanly[3].

According to the latest EU Renewable Energy Directive, biofuels are specifically defined as "**liquid fuels for transport produced from biomass**"[4]. This definition highlights the primary application of biofuels in the transportation sector, where they are often blended with conventional fossil fuels to reduce overall emissions, as is *e.g.* the case of SEAFAIRER with the production of biofuel from three selected feedstocks. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report provides a more comprehensive definition, describing biofuel as "**A fuel, generally in liquid form, produced from biomass**. Biofuels include bioethanol from sugarcane, sugar beet or maize, and biodiesel from canola or soybeans". This definition emphasises the diverse range of feedstocks that can be used to produce biofuels. It's important to note that the term "biomass" in the context of biofuels refers to organic material that is not fossilised or embedded in geological formations. This distinction explicitly excludes fossil fuels like coal and oil from the biofuel category, despite their organic origins. Biofuels are often categorised into generations based on their feedstock and production methods. First-generation biofuels, also known as conventional biofuels, are produced from food crops grown on arable land. Advanced biofuels, which include second and third-generation biofuels, are made from non-food feedstocks such as agricultural and forestry residues, waste products, and energy crops grown on marginal lands.

The definition and classification of biofuels continue to evolve as new technologies and feedstocks are developed. For instance, the concept of **Renewable Fuels of Non-Biological Origin (RFNBO)** has emerged, referring to synthetic fuels produced from renewable hydrogen and carbon dioxide captured from biogenic sources or air[5]. While these fuels are not strictly biofuels in the traditional sense, they represent an extension of the concept of renewable, low-carbon fuels. In the present document, we focus on "**feedstock-to-fuel**" production pathways when referring to **biofuels or bio-oils**. As such, the overview of different feedstock conversion routes below provides an overview of conventional and advanced **feedstock to marine biofuels** pathways.

[1] Source: https://www.epa.gov/risk/biofuels-and-environment.
[2] Source: https://www.britannica.com/technology/biofuel
[3] https://www.petro-online.com/news/biodiesel/183/breaking-news/what-is-biofuel-definition-advantages-examples-and-uses/54731
[4] https://www.eca.europa.eu/ECAPublications/SR-2023-29/SR-2023-29_EN.pdf
[5] https://blog.sintef.com/energy/status-of-biofuels-and-e-fuels-in-2023/

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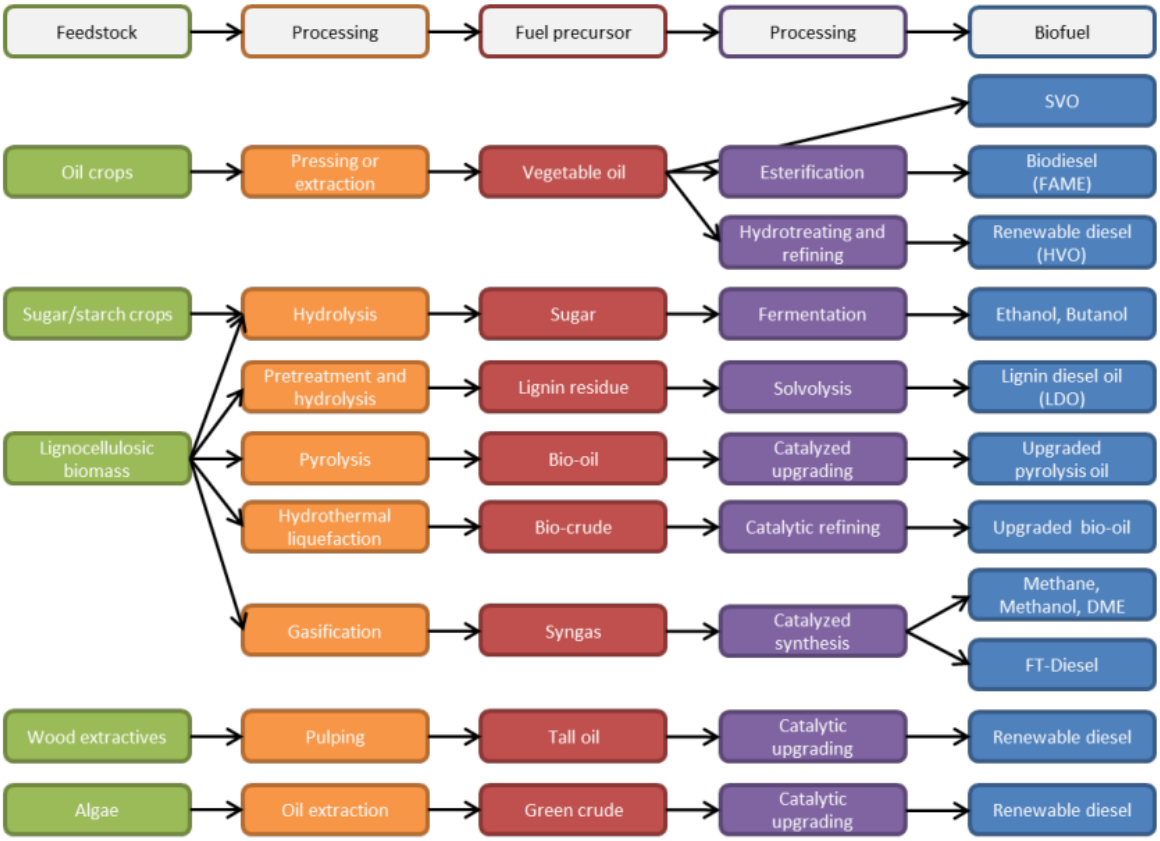

Figure 6. Feedstock-to-fuel pathways (source: International Energy Agency Task 38).

The main fuel properties of selected marine biofuels can be found in Table 3 below.

Table 3. Comparative table of properties of selected marine biofuels.

Properties	Biodiesel (FAME)	Renewable diesel (HVO)	FT diesel	FP bio-oil	Upgraded bio-oil	HtL biocrude
Specific gravity	0.88	0.78	0.765	1.1-1.3	0.84	1.1
Kinematic viscosity (at 40°C)	4-6	2-4	2	40-100		
Cetane number	47-65	>70	>70			
Lubricity, µm		650	371			
Lower heating value, MJ/kg	37.2	44.1	43	16		≈32
Cloud point, °C	-3-15	-5 to -34	-18			
Pour point, °C	-5-10			-9 to -36		
Water content, mass %	0	0	0	20-35	0.1	8

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Oxygen content, mass %	11	0	0	34-45	0.5	10–13
Sulphur content, mass %	<0.0015	<0.0005	<0.1	0–0.05	<0.005	0
Flammability limits (vol % in air)	0.88	0.78	0.765	1.1–1.3	0.84	1.1
Water solubility	4–6	2–4	2	40–100		

4.2 Most widespread biofuels and characteristics

The maritime sector is actively exploring alternative fuels to reduce greenhouse gas (GHG) emissions and align with global decarbonisation objectives. Among the most viable short-term options, biofuels have gained significant traction due to their compatibility with existing ship engines and infrastructure. **The two most widely used biofuels in maritime transport are Fatty Acid Methyl Esters (FAME) and Hydrotreated Vegetable Oil (HVO)**. FAME commonly referred to as biodiesel, are derived from vegetable oils, animal fats, or waste oils through a transesterification process. It is the most widely used biofuel in the maritime sector, particularly as a blend with conventional fuels. Currently, ships can already operate on various alternative fuels such as liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol and ammonia. An overview of the different physico-chemical characteristics is presented below in Table 4.

Table 4. Overview of alternative fuel properties.

Properties	Diesel fuel	LNG	Methane	Methanol	LPG
Molecular formula	$C_nH_{1,8n}$; C_8-C_{20}	C_nH_m; 90-99% CH_4	CH_4	CH_3OH	C_3H_8 ; C_4H_{10}
Carbon contents (wt %)	86.88	≈75	74.84	37.49	
Density at 16°C (kg/m^3)	833 to 881	431 to 464a	422.5a	794.6	505
Boiling point at 101.3 kPa (°C)b	163 to 399	-160 (-161)	-161.5	64.5	-42
Net heating value (MJ/kg)	42.5	49	50	20	47
Net heating value (GJ/m^3)	35	22		16	
Net heating value (GJ/m^3)	257	580	537	464	457
Auto-ignition temperature (°C)	52 to 96	-136		11	-60
Flashpoint (ºC)c	>40	0		5	
Cetane rating	1.0 to 5.0	4.2 to 16.0	1.4 to 7.6	6.72 to 36.5	2.1 to 9.6

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Flammability limits (vol % in air)	No		No	Complete	
Water solubility	Varies, <0.5 or < 0.1	< 0.06	0	0	

4.3 Current uses of biofuels in the maritime sector

Most liquid biofuels are consumed in the road transport sector, where many countries have implemented blending requirements with conventional fuels, enabling their use in diesel and gasoline engines in cars and trucks. On the other hand, the adoption of these fuels in the maritime sector is growing, although it is behind road transport. In this regard, the amount of biofuel used in the maritime sector in 2023 was estimated at approximately 0.7 Mtoe, representing only 0.6% of the global liquid biofuel consumption and merely 0.3% of the total energy consumed by marine vessels (IEA, 2024; DNV, 2025).

Considering the above, the most widely used biofuels in the maritime sector are FAME and HVO, with FAME being the predominant option. Additionally, there is an emerging use of ethanol, as well as reported bunkering operations with bio-LNG, along with the recent implementation of bio-methanol in some vessels. As in road transport, most of the biofuels consumed in vessels consist of FAME/HVO blends with conventional fuels, with volumetric proportions ranging between 20% and 30%. An example of this is the consumption of these fuels in two of the world's largest bunkering hubs: in Singapore, 99% of biofuel refueling operations consisted of 24% blends (B24), while in Rotterdam, the majority were B30. Similarly, vessels have been reported using other blend ratios, ranging from 5% to even 100% (DNV, 2025). MARPOL Annex II and the IBC Code limit FAME biofuel blends to a maximum of 25% when bunkered by oil tankers or barges. This explains why most biofuel bunkered in Singapore in 2023 was B24. For higher blends (B30, B50, B100), IMO Type 2 chemical tankers are required, creating a bottleneck for wider FAME adoption. Meanwhile, in Rotterdam, many bunkering operations are handled by inland waterway barges, which follow different regulations. This allows them to carry higher blends, like B30, without extra restrictions (DNV, 2025).

Considering this, Figure 7 presents the amount of biofuel bunkered (blended with conventional fuel) in the mentioned ports, showing significant growth from approximately 0.3 million tons in 2021 to 1.3 million tons in 2024 (with data available up to the end of the third quarter). Furthermore, the continued use of biofuels has been reported in over 60 ports starting in 2025, mostly located in East Asia and Europe. Additionally, more than 90 ports have stated that they have the capacity to supply biofuel globally (DNV, 2025).

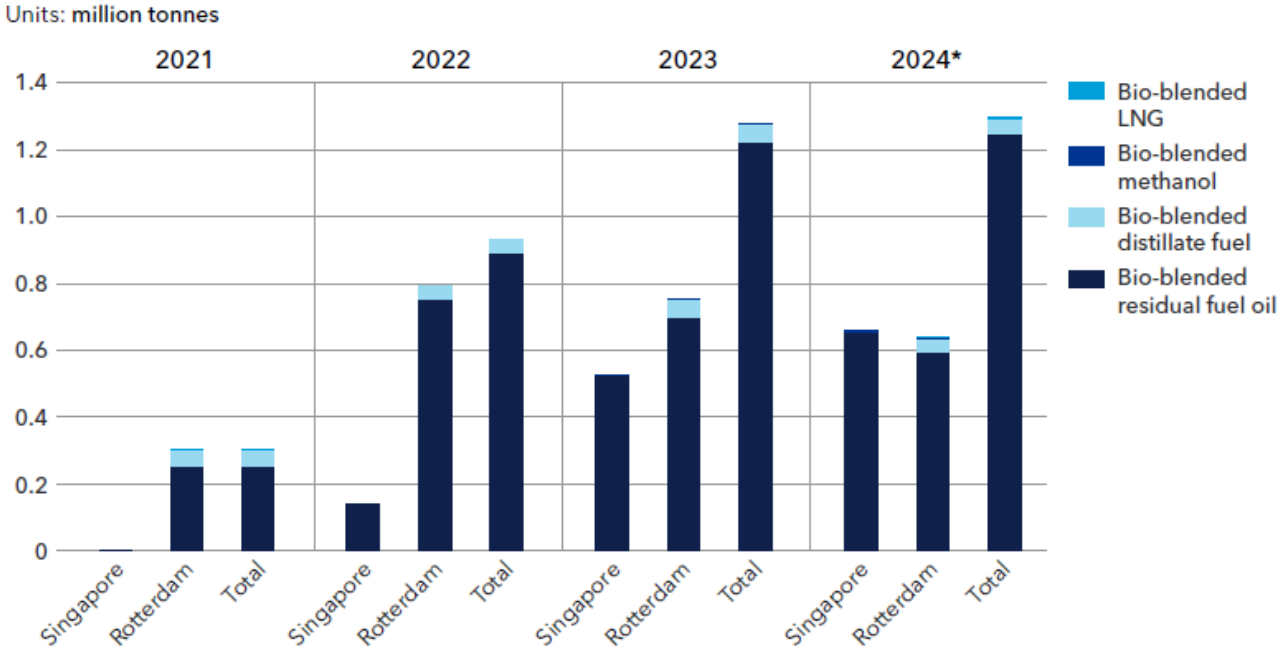

Figure 7. Biofuel bunkering in Singapore and Rotterdam. Source (DNV, 2025).

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In this regard, biofuel adoption in the maritime sector is influenced by the voluntary demand, GHG regulations, and supply constraints. The voluntary market, driven by cargo owners and green certification of supply chains, has been a key driver, with major shipping companies offering premium services for lower Scope 3 GHG emissions. Adoption is expanding to passenger shipping and green shipping corridors initiatives are being launched (DNV, 2025).

Meanwhile, GHG regulations are becoming stricter, with the EU ETS, FuelEU Maritime, and other policies increasing compliance requirements and further driving demand. However, supply challenges, including competition with other sectors, limited sustainable biofuels, and logistical barriers, are still important issues to the biofuel broader adoption. In this regard, new regulations are expected to complement the voluntary demand, ensuring GHG reductions beyond compliance while national and regional policies further support integration into maritime decarbonisation (DNV, 2025).

4.4 Production methods

The **Fuel Pathway Maturity Map** developed by the Mærsk McKinney Møller Center for Zero Carbon Shipping is a reference guide of the status of sustainable fuel production pathways in the maritime shipping industry, evaluating technological readiness from production to use aboard vessels. In its most recent update (2024), the Map has highlighted certain advancements on the different production methods/fuel types. Ammonia, for instance, has observed significant advancement with onboard energy storage and fuel conversion technology; similarly, methanol's global storage, logistics and bunkering infrastructure has risen due to the gradual implementation of dual-fuel methanol vessels (Maersk, 2024[6]). **Bio-oils** were also said to have improved, despite further work being needed "to achieve commercial viability for shipping". The fuels on the map have been shortlisted based on current expectations regarding scalability, sustainability, technology development, and commercial viability and displays fuel solutions that are considered to play a significant role by 2050.

Figure 8. Fuel Pathway Maturity Map (source: Mærsk McKinney Møller Center for Zero Carbon Shipping, 2024).

Merely based on the share of green ("mature") and yellow ("solutions identified") according to the map – which is not to be used as a commercial recommendation – the most market-ready fuels are **biodiesel, bio-methanol, e-diesel, e-methanol,** and **bio-methane**. For **bio-oils**, which relate closely with the VINTER bio-oil as a product, it is stated that the characterisation of these fuels' physical and chemical properties is not fully established. Therefore, the clear definition of a "bio-oil" category *per se* is not expected, but rather the establishment of marketable, **specific bio-oil types**, each with a tested, certified and unique set of physico-chemical properties.

[6] https://www.maersk.com/news/articles/2024/11/18/maersk-completes-first-large-container-vessel-conversion-to-dual-fuel-methanol-engine.

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5. Technical requirements for biofuel implementation

5.1 Overview

From an overarching perspective, **there is an evident, market-driven incentive to accelerate the technical readiness and availability of alternative fuel solutions**. For instance, as of June 2021, only 0.5% of ships in the world used alternative fuels, but at the same time, close to 12% of orders were for alternative fuel ships, particularly 6.1% of LNG orders, 3.85% on batteries, 1.51% on LPG, 0.3% on methanol, 0.06% on hydrogen and 0.02% on ammonia[7]. According to the International Certification and Classification Society DNV, the most common way to reduce emissions in water transport (Figure 9) is the use of scrubbers (ca. 5,000 ships) and only around 2,000 ships could use alternative fuels, of which 800+ ships LNG, approx. 250 ready to use LNG, 600+ electric batteries, 100+ LPG, 50+ methanol and approx. 10 hydrogen.

The implementation of bio-oils is generally well accepted from a technical perspective, due to their strong potential as drop-in fuels, allowing them to replace fossil fuels without significant structural modifications to propulsion systems while also reducing carbon emissions. In the maritime sector, ship engines are designed to operate with fuels that exhibit a wide range of properties, enabling them to run on biofuels without major modifications (EMSA, 2023). Considering the latter, this section presents the technical requirements for biofuel implementation in the maritime sector, focusing on the necessary engine adaptations as well as the adjustments required for storage and distribution to ensure proper integration. Additionally, the two main bio-oils, HVO and FAME are considered in this section. However, the insights made can be extended to other bio-oils according to their own particular properties.

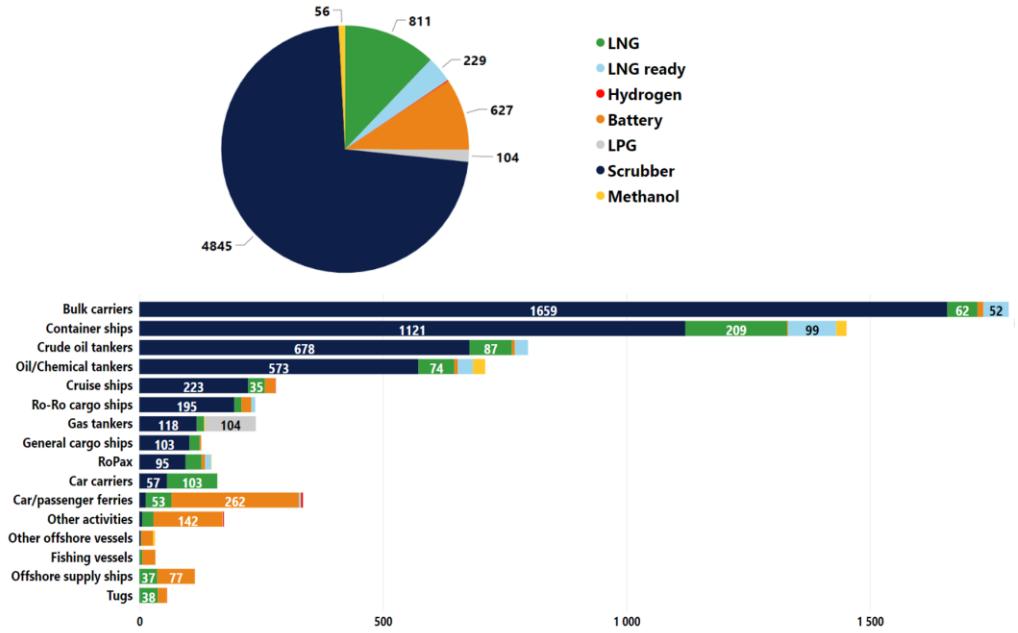

Figure 9. The number of vessels in operation and on order by types of alternative fuels and the use of scrubbers and their distribution by types.

5.2 Marine engines

One of the first issues that must be addressed when bio-oils are used in engines is the differences in viscosity with conventional fuels. This is a crucial issue for engine performance and fuel system integrity. Viscosity below 2 cSt may cause internal leaks in injector pumps, while levels below 1.5 cSt have been linked to increased wear

[7] https://afi.dnv.com/Statistics).

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on gear pumps (DNV, 2025). In this regard, HVO typically has a lower viscosity than conventional fuels, which can lead to leakages in pipe connections and engine components if not properly controlled (DNV, 2025). To mitigate this, fuel analysis should confirm compliance with specifications, and if necessary, a cooler can be used to increase viscosity (EMSA, 2023).

In contrast, FAME has a higher viscosity, comparable to conventional diesel, but an increment in it could create difficulties regarding fuel atomisation and combustion, especially in cold conditions. This can lead to coking of injector nozzles, deposits, ring sticking, and lube oil gelling, affecting engine reliability (EMSA, 2023). Considering this, a preheating system can be used to lower viscosity and maintain proper fuel flow. Despite these considerations, engine manufacturers permit the use of both HVO and FAME, if viscosity requirements at the engine inlet are met. Industry feedback indicates that no significant operational issues have been reported regarding viscosity variations (DNV, 2025).

In addition to this, another important aspect to consider is the change in the lower calorific value (LCV). The LCV of FAME is 10-14% lower than conventional fuels due to its high oxygen content (EMSA, 2023). Meanwhile, HVO has an LCV comparable to fossil fuels, making it a more suitable drop-in replacement. In this sense, higher fuel consumption has been observed when using FAME (EMSA, 2023; DNV, 2025). In this sense, manufacturers emphasise the importance of making engine adjustments to provide the correct energy content for a proper operation (DNV, 2025). In this regard, LCV of FAME blends decreases when its proportion increases. Thus, engine operation can be affected by mechanically controlled engines where there is not an automatic adjustment in the injection quantity. In contrast, providing the correct LCV to electronically controlled engines can potentially manage this through autotuning features. Furthermore, for engines where power limitation has been implemented, the maximum power output can be reduced when using a fuel blend with a lower LCV (DNV, 2025). In addition to this, studies indicate that higher density and viscosity values in FAME blends can also contribute to lower brake power and increased specific fuel oil consumption (SFOC) (Bilgili, Levent, 2023). Also, conflicting results regarding exhaust temperature variations suggest that biodiesel combustion behavior depends on factors such as blend ratio, engine type, and operating conditions (Bilgili, Levent, 2023).Considering the latter, one should highlight the importance of the required modifications in the fuel management strategies, particularly for engines where injection optimisation is less feasible.

Additionally, lubricity of biofuels is an important parameter to consider. The manufacturing precision of engine components, such as pumps and injectors, requires them to be adequately protected from scuffing and wear, which can affect their delivery characteristics (EMSA, 2023). HVO has lubricity issues due to the absence of sulphur and oxygen compounds, leading to an increase in wearing components such as pumps and fuel injectors. Thus, it is important to verify the lubricity of HVO as it may be lower than those of conventional fuels. In contrast, even though FAME can have low sulphur content, it enhances the lubricity properties within the engine. Additionally, it has been observed that FAME will be playing a role as lubricity additive when HVO is used, helping in the reduction of operative expenses (Vernados, Stathopoulos, & Kalligeros, 2023). In this regard, engine manufacturers must provide their own lubrication recommendations that should be strictly followed by the operators (DNV, 2025). Regarding the combustion performance, there are two main topics to attend. First, there is an increase in the cetane number, especially in HVO, while it is usually expected an increase in NOx emissions. First, both HVO and FAME have higher cetane numbers that result in a shorter ignition delay and, therefore, in earlier combustion relative to conventional fuels, enhancing the combustion efficiency (Bilgili, Levent, 2023; EMSA, 2023). Nonetheless, this difference requires some engine tuning adjustments to compensate for this earlier fuel ignition (EMSA, 2023).

With respect to NOx emissions, these are a product of the combustion process, primarily increasing as the combustion temperatures and the oxygen concentration in the combustion camera are higher. While HVO has shown similar or slightly lower NOx emissions than conventional fuel due to its higher cetane number and shorter ignition delay, FAME exhibit more variability (EMSA, 2023). In this sense, it has been reported both increments and reductions in NOx emissions while using FAME blends, remarking a considerable influence on the engine design and combustion system in the NOx presence in the exhaust gases (EMSA, 2023).

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Industry reports reveal that NOx emissions from biofuels generally remain within MARPOL Annex VI limits, even though some variations exist depending on different parameters such as blending ratio, engine type, and operating conditions (Lloyd's Register, 2022). In addition to this, two-stroke engines usually show higher NOx emissions at lower loads, while four-stroke engines have shown stable emissions or even some reduction while using biofuels. Also, some tests suggest that higher FAME content (nearly 100%) does not necessarily lead to an increment in NOx emissions, reinforcing the potential for biofuels to be used as drop-in fuels without significant modifications to engine settings (Lloyd's Register, 2022). However, testing NOx emissions during operation is still a complex effort, requiring specialised equipment and planning. Shipowners and engine manufacturers acknowledge that NOx variations are within expected ranges. Nonetheless, further studies are needed to better understand impacts in a long-term and emissions behavior for different engine types. As biofuels continue to be explored, more trials will be decisive in refining their emissions profile and operational feasibility (Lloyd's Register, 2022). Considering all the above, Table 5 summarises the properties of FAME and HVO compared to conventional fuels that affect engine operation.

	HVO	FAME
Viscosity	Lower	Higher
LHV	Higher (ca. 44-46 MJ/kg)	Lower (ca. 37-40 MJ/kg); presence of oxygen in molecular structure reduces its energy density
Lubricity	Very poor process (refining removes impurities that naturally enhance lubrication)	Good (higher content of polar compounds, which also reduce wear in engine components).
NO_x emissions	Lower (cleaner combustion process)	Higher (primarily due to higher oxygen content)
Oxygen content	Similar (0%)	Higher (ca. 10-12%)
Sulphur content	Similar	Similar

Table 5. HVO and FAME properties related to engine operation compared to conventional fuels. Sources: (EMSA, 2023; DNV, 2025)

In SEAFAIRER specifically, the compatibility of the advanced biofuel generated in the VINTER process with existing marine engine systems will be tested and validated by project partner FVTR, according to the steps described in Figure 10.

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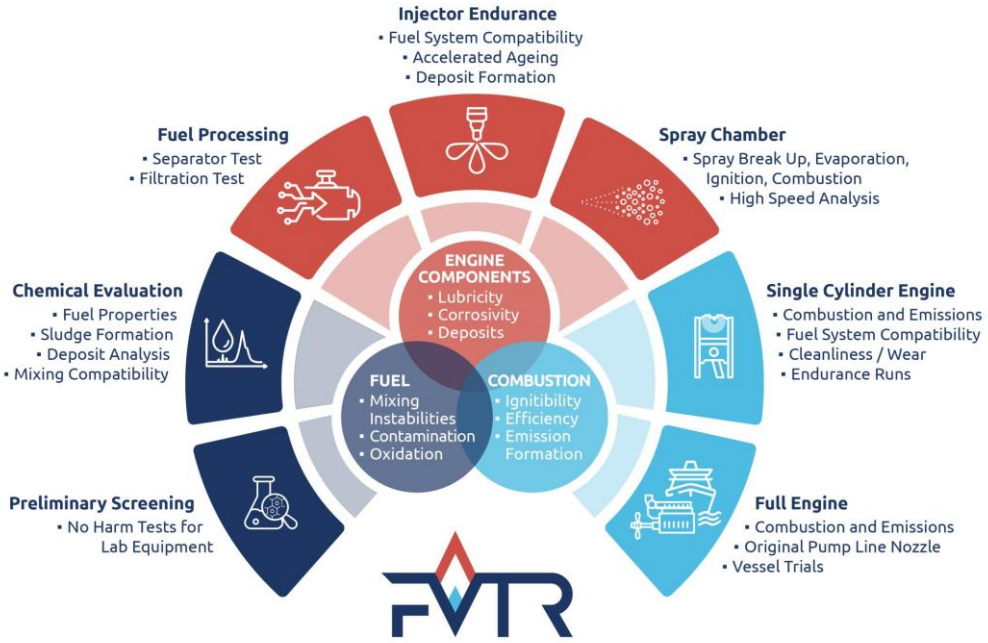

Figure 10. Testing and validation "wheel" - fuel, engine components and combustion. Source: FVTR.

5.3 Bunkering and logistics

Initially, for the implementation of bio-oils such as HVO or FAME, it is essential to consider the requirements for fuel blending and tank arrangements. In the case of HVO, no special storage measures are required, as it can be handled similarly to MDO/MGO (marine gasoil), without the need for tank cleaning when changing between these fuels. However, for vessels operating on HVO, blending with fossil fuels is kept to a minimum, aiming for an almost complete replacement of conventional fuels (DNV, 2025).

On the other hand, it is recommended that tanks where FAME are stored to be emptied, cleaned, and dried before storage. This is due to its solvent effect, which can dissolve or loosen deposits and sediments accumulated from conventional fuel use. In this regard, cleaning the storage system is essential to prevent blockages in the pipeline network (ABS, 2021; Lloyd's Register, 2024; DNV, 2025). Additionally, mixing fuels of different types or sources should be avoided unless necessary, with a recommended maximum ratio of 80:20 (DNV, 2025). Biofuels should not be mixed on board, whether with fossil fuels or other biofuels. However, this can be challenging, as factors like fuel origin, supplier consistency, and blend uniformity come into play. Vessel owners have previously faced compatibility issues due to the mixing of incompatible fuels onboard, a challenge that is expected to continue as more biofuels, blends, and different feedstocks are entering the market (ABS, 2021).

For FAME, industry feedback shows varied management practices. In this sense, some operators meticulously clean tanks to avoid fuel mixing, while others do not, relying on consistent suppliers, rapid consumption, and regular fuel quality testing (DNV, 2025). Given these variations, it is essential to assess each case individually, ensuring measures align with actual bunkering and operational conditions. The fuel supplier must ensure compliance with agreed standards and supply contracts, but vessel owners and crews remain responsible for ensuring compatibility, stability, and suitability of fuels with onboard systems (ABS, 2021). When mixing is unavoidable, compatibility test is recommended to prevent stability issues and ensure safe operations (DNV, 2025). Furthermore, among biofuels, HVO offers high chemical stability, with oxidation resistance comparable to conventional MGO, allowing for long-term storage under standard conditions (EMSA, 2023). In contrast, FAME have poor oxidative stability, making it prone degradation through chemical and biological processes. The latter leads to increased acidity, viscosity, and solid deposit formation, which also can clog filters and pipes, causing different engine issues (DNV, 2025). Thus, fuel additives can help improve stability, but it may not apply to all engines, depending on the amount of FAME that is used. Also, their high cost limits their use in

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marine applications, leading operators to explore alternative tank coatings or more frequent bunkering (EMSA, 2023).

In addition, solvent properties of FAME also add material compatibility challenges, particularly for copper, brass, lead, tin, zinc, rubber, and certain fuel system components, which can degrade over a prolonged exposure (ABS, 2021). This affects gaskets, hoses, fuel filters, injectors, and other machinery, requiring vessel owners to assess fuel system materials for compatibility (Lloyd's Register, 2024). Considering the latter, Table 6 shows the recommended materials for use with biofuels (Lloyd's Register, 2024).

Material	Recommended	Not recommended
Metals	Carbon steel, stainless steel, aluminium	Brass, bronze, copper, lead, Tin, Zinc
Elastomers	Fluorocarbon, Nylon, Teflon, Viton	Nitrite rubber, Neoprene, Chloroprene, Natural rubber, Hypalon Styrene, Butadiene rubber, Butadiene rubber
Polymers	Carbon filled acetal	Polyethylene, Polypropylene, Polyurethane, Polyvinylchloride
Others	Fibreglass	

Table 6. Recommended materials for biofuels use. Source: (Lloyd's Register, 2024).

Furthermore, regarding microbiological growth, it often occurs in ships that use conventional fuels. In this regard, ships with microbiological growth issues using MGO are prone to face this problem with biofuels (DNV, 2025). The presence of water in fuel storage systems significantly influences microbial growth, particularly in FAME, which is hygroscopic and absorbs more water than conventional fuels (Lloyd's Register, 2024). This water accumulation leads to favorable conditions for the proliferation of bacteria, yeast, and fungi. These biological deposits can clog filters and pipes, corrode tanks, and degrade fuel (DNV, 2025). Additionally, higher temperatures can accelerate microbial activity, increasing the risk of contamination during prolonged storage. As a preventive measure, water entrance should be minimised, and tank heating should only be used to maintain cold flow properties (DNV, 2025).

To mitigate these risks, frequent water drainage from fuel tanks is essential, besides regular monitoring for sludge accumulation (DNV, 2025). Additionally, emergency generators, lifeboat engines, and fire pumps, which store fuel for extended periods, should ideally be kept without FAME to avoid degradation related to microbial growth (Lloyd's Register, 2024). In some cases, biocides and antimicrobial additives can help control microbial growth, but proper fuel maintenance and filtering systems are still the most effective approach. Industry studies have shown that, when stored in clean, water-free conditions, FAME do not necessarily lead to microbial contamination (ABS, 2021). In addition to this, another challenge that is addressed when bio-oils are used are the flow properties at low temperatures. In this regard, HVO generally has good cold temperature tolerance when isomerisation is performed. This is an important step in HVO production that converts the n-alkanes, initially presented in the fuel, into more branched structures called iso-alkanes, significantly enhancing the low-temperature performance (EMSA, 2023).

On the other hand, FAME have poor cold flow properties, as its fatty acid composition, particularly saturated esters, makes it more prone to clouding and gelling at low temperatures (DNV, 2025). Compared to conventional fuels, which are typically stored at 2–5°C above the cloud point (CP), 10°C above the pour point (PP), and 10°C above the cold filter plugging point (CFPP), FAME require stricter temperature control, with recommended storage 10–15°C above the cloud point to maintain operability (ABS, 2021; EMSA, 2023). If temperatures drop below the pour point, FAME can form solid deposits, accelerate degradation and shorten shelf life (EMSA, 2023). To prevent fuel instability, clogging, and operational issues, temperature control is critical. A primary preventive action is the heating of fuel storage tanks, pipelines, and filters. However, in cases where heating is not feasible, cold-flow improvers can help maintain fuel fluidity (EMSA, 2023). Cold-flow additives can improve the operability of FAME and blends, but their treatment is complex, and application by fuel suppliers before delivery is recommended (Lloyd's Register, 2024). Additionally, studies have shown that biodiesel blends may require adjusted engine oil drain intervals, as biofuels can alter lubricating oil properties

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(ABS, 2021). Given these challenges, higher-percentage biofuel blends with poor cold flow behaviour should be avoided in uncontrolled temperature environments, ensuring stable fuel performance in maritime operations (ABS, 2021).

Finally, in some cases, fuel separators may require modifications to adapt biofuels with densities that differ from those originally used. HVO, with a lower density than traditional diesel, may impact on separator efficiency and require modifications. In contrast, FAME use does not imply the same challenge due to its similar density to conventional fuel (DNV, 2025). The user experience indicates that no major issues have been reported with FAME purification, though in some cases, control system upgrades have been required. For HVO, adjustments to older fuel separators, such as purifier replacements, have been necessary to accommodate their lower density (DNV, 2025).

Considering all the above, Table 7 summarises the properties of FAME and HVO compared to conventional fuels that affect the bunkering and logistics processes.

	FAME	HVO
Density	Comparable	Lower
Storage stability	Poor	Similar
Material compatibility	Incompatible with some materials	Comparable
Cold flow properties	Poor	Similar

Table 7. HVO and FAME properties related to bunkering and logistics compared to conventional fuels. Sources (EMSA, 2023; DNV, 2025).

6. Environmental aspects of biofuel usage and products

6.1 Feedstock sustainability

The sustainability of biofuel feedstocks represents a critical dimension in evaluating the environmental viability of biofuels for maritime shipping – and, evidently, influenced the feedstock selection in SEAFAIRER. Feedstock sustainability encompasses the entire lifecycle of biomass production, from land use practices and resource efficiency to GHG emissions and biodiversity impacts.

- *First- and second-generation feedstock*: Biofuel feedstocks are broadly categorised into first- and second-generation sources, each with distinct sustainability profiles. First-generation feedstocks are derived from food crops such as sugarcane, corn, and soybeans. While these crops are energy-dense and compatible with existing biofuel conversion technologies, their use raises significant sustainability concerns. The diversion of agricultural land for fuel production can exacerbate food-price volatility, drive deforestation, and intensify water and fertilizer use (Naik et al., 2010). For instance, palm oil-based biodiesel has faced criticism for its association with tropical deforestation in Southeast Asia, which undermines carbon sequestration efforts and threatens biodiversity (IEA, 2022). In contrast, second-generation feedstocks utilise non-food biomass, including agricultural residues (e.g., corn stover, wheat straw), forestry waste, and dedicated energy crops like switchgrass or miscanthus. These feedstocks minimise competition with food supplies and are often cultivated on marginal lands unsuitable for agriculture, reducing pressure on ecosystems. Advanced conversion technologies, such as enzymatic hydrolysis and gasification, enable the extraction of sugars and oils from lignocellulosic materials, though these processes remain energy-intensive and costly compared to first-generation methods. The sustainability advantage of second-generation feedstocks lies in their potential to utilise

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waste streams, thereby aligning with circular economy principles. For example, used cooking oil (UCO) and animal fats repurposed for biodiesel production avoid methane emissions from landfill decomposition while displacing fossil fuel use.

- *Certification schemes:* To mitigate the risks of unsustainable feedstock sourcing, certification systems such as the **International Sustainability and Carbon Certification (ISCC EU)** provide rigorous frameworks for verifying compliance with environmental and social criteria. The ISCC EU standard, recognised under the EU Renewable Energy Directive (RED II), mandates that feedstocks meet GHG reduction thresholds (minimum 50% savings compared to fossil fuels) and adhere to safeguards against deforestation, peatland degradation, and biodiversity loss. Key requirements include:

    - Land use restrictions: Feedstock cultivation must not occur on land with high carbon stock or biodiversity value post-January 2008;
    - **GHG accounting**: Life-cycle emissions from cultivation, processing, and transport must be transparently documented;
    - **Social sustainability**: Compliance with International Labour Organisation standards, including fair wages and safe working conditions (GUTcert, 2025)

- *Challenges in feedstock availability*: Despite advancements in certification and technology, feedstock sustainability faces persistent challenges. **Indirect land-use change (ILUC)** remains a contentious issue, particularly for first-generation biofuels. ILUC occurs when biofuel crop expansion displaces food production to previously uncultivated areas, indirectly driving deforestation and GHG emissions[3][4]. The European Commission's ILUC Directive (2015) seeks to address this by capping the contribution of food-based biofuels to renewable energy targets yet monitoring and enforcement remain complex[4]. **Biodiversity impacts** further complicate feedstock sustainability. Large-scale monocultures of energy crops, even if non-food, can fragment habitats and reduce species diversity. For instance, short-rotation coppice plantations may disrupt local flora and fauna if not managed with ecological safeguards. Conversely, agroecological practices such as intercropping energy crops with food crops can enhance biodiversity while maintaining soil health[7]. Additionally, competition for **waste and residue feedstocks** is another emerging challenge. With demand for UCO and animal fats outpacing supply, prices have surged, incentivising fraudulent practices such as the dilution of waste oils with virgin oils[4]. Strengthening traceability systems and expanding feedstock diversification, e.g., exploring algal biofuels or carbon-rich industrial off-gases, will be critical to avoiding supply bottlenecks.

- *Shifting toward a "sustainable feedstock" paradigm*: Achieving feedstock sustainability in hard-to-abate sectors requires a multi-faceted approach, covering the main factors outlined concerning feedstock sustainability. Firstly, there is a clear prioritisation of waste and advanced feedstock. Regulatory support for second-generation pathways, coupled with R&D investments in algae and synthetic biology, can reduce reliance on food crops. **Enhancing certification rigor**, such as expanding ISCC EU's scope to address ILUC risks, and incorporating real-time satellite monitoring for deforestation detection. **Promoting regenerative agriculture**: Incentivising cover cropping and agroforestry systems that integrate biofuel feedstock production with ecosystem restoration. As the International Energy Agency (IEA) notes, without systemic reforms, the biofuel industry risks a **"feedstock crunch" by 2027**, underscoring the urgency of sustainable feedstock strategies[4]. For the maritime sector, aligning biofuel procurement with certification standards and circular economy principles will be pivotal in reconciling decarbonisation goals with planetary boundaries. In sum, **second-generation biofuels made from waste and lignocellulosic biomass offer the most substantial GHG reductions,** ranging from approx. 70% to almost 100% well-to-wake GHG emission savings compared with Marine Gas Oil (MGO). That is due to their relatively small impact on land use, large biogenic carbon uptake, and modest use of fossil fuel energy for feedstock conversion. Other alternative fuels, such as DME and FT diesel made from cellulosic feedstocks also have particularly low GHG emissions. An overview of life cycle GHG emissions (100-year GWP) of the alternative liquid marine fuels and feedstocks analysed can be found below:

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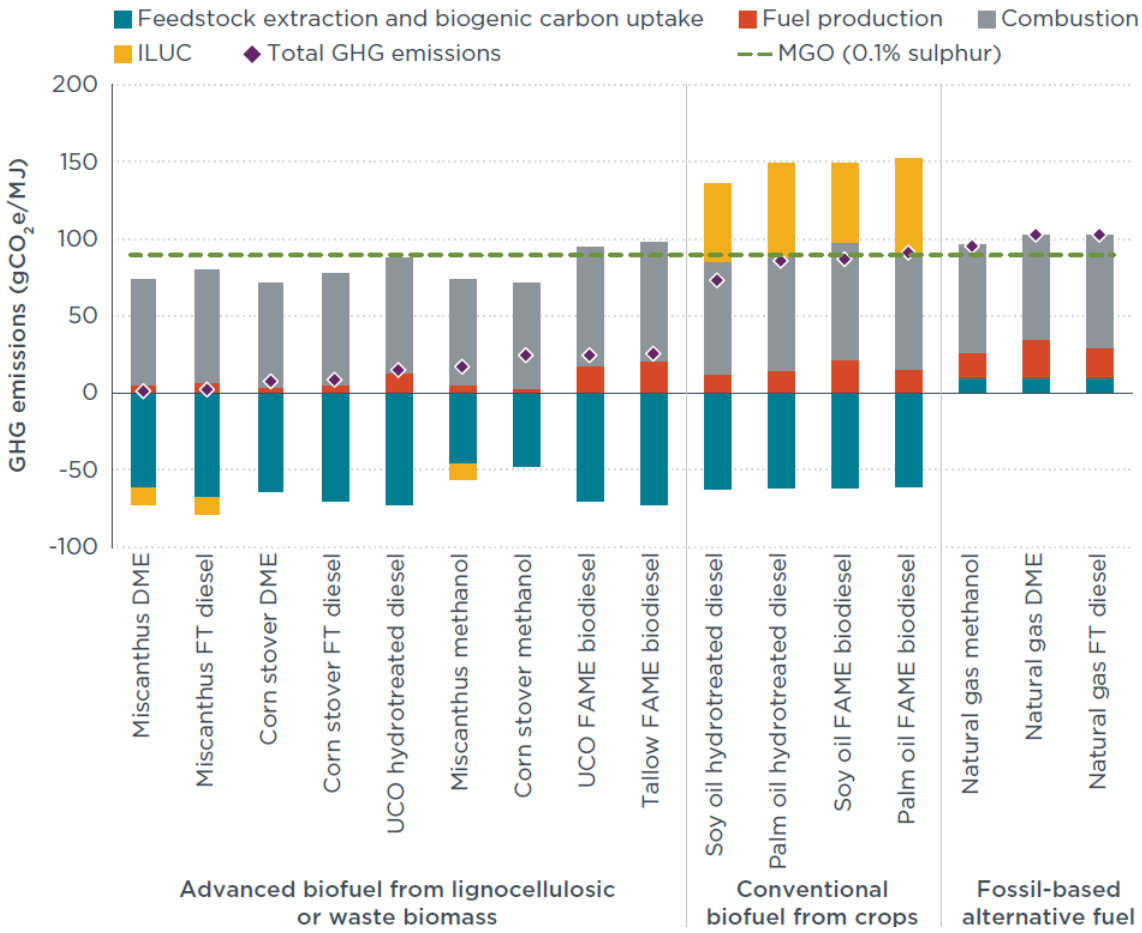

Figure 11. Life-cycle GHG emissions of alternative liquid marine biofuels (source: Zhou et al. (2021).

6.2 Feedstock sustainability

The adoption of biofuels in maritime shipping, however, introduces indirect emissions that extend beyond direct combustion-related greenhouse gas outputs. These emissions arise from upstream production processes, land-use changes, and accidental releases into marine ecosystems (*e.g.*, oil spills). Understanding these cascading effects is critical for evaluating the true environmental footprint of biofuels and ensuring they contribute meaningfully to maritime decarbonisation. This chapter examines three pivotal sources of indirect emissions: **nitrogen oxide (NOx) formation during combustion, indirect land-use change (ILUC) impacts**, and ecological consequences of **biofuel spills**.

- ***Nitrogen oxide (NOx) emissions in marine engines***: Biofuel combustion in maritime engines generates NOx, a potent air pollutant linked to acid rain, eutrophication, and respiratory health impacts. Unlike sulphur oxides (SOx), which are reduced in biofuels due to their lack of sulphur content, NOx emissions depend on combustion dynamics and fuel composition. Trials aboard a Kamsarmax bulk carrier burning a 50:50 blend of used cooking oil (UCO) biodiesel and marine gas oil (MGO) revealed marginal differences in NOx emissions compared to conventional low-sulphur MGO. Lloyd's Register's analysis of marine diesel engines further corroborates this, showing that NOx levels remained within baseline variability across load ranges when using waste-derived fatty acid methyl ester (FAME) biodiesel2. However, NOx profiles vary significantly by feedstock and engine type. First-generation biofuels derived from energy-dense crops like soy or palm oil can increase NOx emissions due to higher combustion temperatures and nitrogen content in the biomass1. For instance, rapeseed-based FAME biodiesel exhibited 23% lower lifecycle GHG emissions than fossil fuels but may elevate NOx output

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without engine recalibration. Advanced biofuels from lignocellulosic feedstocks or UCO mitigate this risk, as their lower nitrogen content and optimised cetane numbers stabilise combustion6. The maritime sector must therefore pair feedstock selection with engine compatibility studies to minimise NOx trade-offs.

- *Indirect Land-Use Change (ILUC) and carbon debt*: ILUC remains one of the most contentious indirect emission sources in biofuel production. When biofuel crop cultivation displaces food production or encroaches on forests and peatlands, it triggers carbon-intensive land conversions elsewhere. The International Council on Clean Transportation (ICCT) highlights that soybean- and palm oil-based FAME biodiesel can generate 25% higher lifecycle emissions than fossil fuels when ILUC is accounted for1. For example, palm expansion in Southeast Asia has driven deforestation at a rate of 0.4 million hectares annually, releasing 500–900 million tonnes of CO_2 equivalents through peat oxidation and biomass loss. Waste and residue-based feedstocks circumvent ILUC risks by utilising existing byproducts. UCO-derived hydrotreated vegetable oil (HVO) reduces lifecycle emissions by 80% compared to fossil diesel, as it avoids land competition and associated carbon debt. Regulatory frameworks like the EU Renewable Energy Directive (RED II) – and the upcoming RED III - now mandate ILUC assessments, penalising biofuels linked to deforestation. Nevertheless, monitoring remains challenging due to global commodity market complexities, necessitating satellite-based traceability systems and stricter certification protocols.

- *Marine ecosystem impacts from biofuel spills*: While biofuels are often marketed as environmentally benign, their spillage poses significant risks to marine ecosystems. Ethanol, a common biofuel additive, is highly toxic to aquatic life. A 2009 spill in Iowa caused 500,000 fish deaths due to oxygen depletion and direct toxicity. Even biodegradable fuels like UCO biodiesel can form toxic sheens and degrade water quality before breaking down. Friends of the Earth reports that biodiesel spills in marine environments exhibit similar acute toxicity to petroleum fuels, albeit with faster biodegradation rates. Operational challenges exacerbate these risks. Biofuels' hygroscopic nature increases microbial growth in fuel tanks, raising the likelihood of leaks from corroded infrastructure5. During the Kamsarmax trial, no spills occurred, but the study emphasised the need for revised storage protocols and spill response plans tailored to biofuel properties. The American Bureau of Shipping (ABS) recommends maintaining conventional spill containment measures, as biofuel blends still require mechanical recovery and dispersants despite their biodegradability.

7. Regulatory framework

7.1 Status of maritime fuels regulation

The maritime sector plays a vital role in global trade and economic development; however, its environmental footprint is increasingly under scrutiny. Shipping is responsible for nearly 3% of global greenhouse gas (GHG) emissions (IMO, 2020), prompting regulators at global, regional, and national levels to accelerate the transition toward cleaner fuels and more sustainable practices. The regulatory framework governing maritime fuels and emissions is continuously evolving as new policies are introduced to reduce emissions, incentivise cleaner technologies, and penalise non-compliance. To address climate change and mitigate its effects, institutions at all levels, global, European, and national, have developed strategies, policies, and regulations that both demonstrate their commitment to this issue and outline the steps needed to achieve the established objectives. The modern framework for addressing climate change was laid by early global agreements. The Kyoto Protocol (1997) was one of the first major international treaties to mandate GHG reductions by binding 36 industrialised nations and the European Union (EU) to individual emission reduction targets (UNFCCC, 1997). This set the stage for subsequent efforts such as the Paris Agreement (2015), which aims to limit global temperature increases to well below 2°C, with efforts to keep the rise to 1.5°C, through voluntary emission reduction commitments (UNFCCC, 2015). Complementing these treaties, the 2030 Agenda for Sustainable Development (2015) introduced 17 Sustainable Development Goals (SDGs), with SDG 13 specifically calling for urgent action to combat climate change and its impacts (UN, 2015).

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Given the international nature of maritime transport, it is essential that regulations and standards are adopted by consensus. The International Maritime Organisation (IMO), a specialised agency of the United Nations responsible for ensuring maritime safety and preventing marine pollution, has played a key role in developing these standards. In 2011, IMO adopted its first binding international measures to improve energy efficiency, marking the beginning of targeted regulatory action (IMO, 2011). This was followed by the initial GHG Strategy in 2018, reinforcing its commitment to reducing emissions from international shipping (IMO, 2018). Most recently, during the 2023 Marine Environment Protection Committee (MEPC 80) meeting under MARPOL, IMO members adopted the IMO 2023 Strategy on Reducing GHG Emissions from Ships. This strategy set ambitious targets such as achieving net zero GHG emissions by 2050, adopting alternative fuels with zero or near zero- GHG emissions by 2050, reducing emissions by 40% by 2030 and 70% by 2050 compared to 2008 levels, and following a CO_2 reduction trajectory consistent with the Paris Agreement (IMO, 2023). These regulatory steps are exhibited in Figure 12.

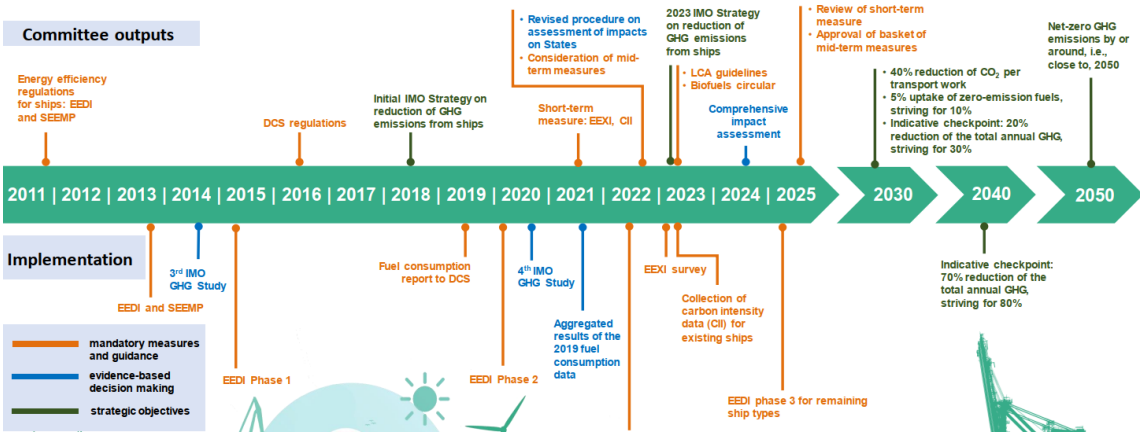

Figure 12. Key regulatory and implementation support steps by IMO and to reduce ship emissions. Source: IMO

In the same global context, the EU has led the response to the climate crisis since 1990, continuously evolving its legal framework. In 2008, the Energy and Climate Change Package 2013–2020 was approved with targets for renewable energy, energy efficiency, and emission reductions until 2020 (European Commission, 2008). This package was later extended and accompanied by a Roadmap toward a low-carbon economy by 2050. In 2019, the EU launched the European Green Pact, followed in 2020 by the Sustainable and Smart Mobility Strategy, which promotes sustainability in all transport modes through sustainable alternatives and transition incentives (European Commission, 2019; European Commission, 2020). To convert political commitment into legal certainty, the European Climate Law was adopted on June 30, 2021, setting a goal of carbon neutrality for the European economy and society by 2050, requiring a 90% reduction in transport emissions and an interim target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels (European Commission, 2021). To achieve these objectives, the European Commission launched the Fit for 55 Package in 2021, which reviews and updates legislation across industry, transport, construction, and agriculture. This package includes measures such as phasing out fossil fuels, promoting renewable energies, and improving energy efficiency (with the aim of reaching 40% of energy consumption from renewable sources by 2030), boosting investments, and facilitating cooperation among countries to develop smart grids (European Commission, 2021). For the maritime transport sector, the Fit for 55 package includes several specific measures that have a direct impact on decarbonisation of the sector, as shown in Figure 13:

- Emissions Trading System (EU ETS)
- Alternative Fuel Infrastructure Regulation (AFIR)
- FuelEU Maritime
- Energy Taxation Directive (ETD)

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- Renewable Energy Directive (RED)

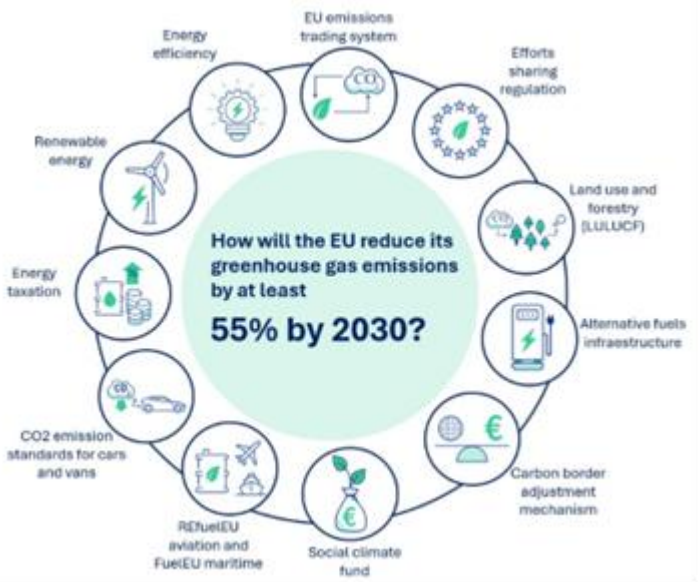

Figure 13. Fit for 55 measures package. Own elaboration based on information from the Council of the EU and the European Council.

- ***EU Emissions Trading System (EU ETS)***: Originally piloted in 2005 and expanded in 2008 and 2012, the EU ETS has evolved to cover a broader range of gases and sectors. The current phase (2021-2030) targets a 40% reduction in GHG emissions by 2030 compared to 1990, with proposals aiming for a 55% reduction. A revision published on May 16, 2023, now includes emissions from maritime transport, and starting from January 2024, this system will be gradually extended to maritime transport using a "cap and trade" mechanism. Each registered emitter will be required to purchase allowances through an auction system, with revenues generated per ton of emissions expected to partially finance the decarbonisation of shipping (European Commission, 2023).

- ***Alternative Fuel Infrastructure Regulation (AFIR):*** AFIR seeks to establish a complete network of alternative fuels infrastructure throughout the EU. Its key provisions require ports to install onshore power supply systems (OPS) for container ships and passenger vessels by 2030. Additionally, AFIR regulates the supply of Liquefied Natural Gas (LNG) and other alternative fuels by mandating that TEN-T ports have LNG refueling points by January 2025 and setting specific requirements for ports operating as multimodal hubs. The regulation reached a general approach on June 2, 2022, with a provisional agreement on March 28, 2023, and became effective on October 12, 2023. Deadlines include December 31, 2024, for Member States to submit drafts of national policy frameworks, and mandatory OPS provisions between December 31, 2024, and December 31, 2029, for inland and seaports within TEN-T (European Commission, 2023).

- ***FuelEU Maritime:*** FuelEU Maritime is a key initiative to reduce carbon emissions by promoting the use of renewable and low-carbon fuels. It sets a gradual reduction trajectory for the maximum intensity of GHG emissions from 2% by 2025 to 80% by 2050 and focuses on both vessel navigation and port operations. Specifically, from 2030 onward, containers and passenger vessels docking in AFIR-affected ports must meet their electrical needs by connecting to OPS. The FuelEU Maritime Regulation 2023/1805 was published in the EU Official Journal on September 22, 2023, became effective on October 12, 2023, and will be implemented starting January 1, 2025. As a regulation, it applies directly without the need for national transposition (European Commission, 2023).

- ***Energy Taxation Directive (ETD):*** The ETD establishes the framework for taxing energy products in the EU to discourage fossil fuel use and promote cleaner energy. Initially adopted in 2003 and currently under revision, the directive proposes higher taxes on the most polluting fuels and introduces a system of minimum rates based on the energy content of fuels, classifying them as fossil, low-carbon, or

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renewable. Although international maritime transport is excluded, the ETD will impact all bunker fuels used in intra-EU shipping, thereby encouraging more sustainable practices (European Commission, 2023).

- ***EU Renewable Energy Directive (RED):*** ETD establishes RED is designed to promote the use of renewable energy sources and reduce dependence on fossil fuels. Member States must choose between a binding target of a 14.5% reduction in transportation GHG intensity from renewable energy use by 2030 or ensuring that renewable energies account for at least 29% of final energy consumption in the transport sector by 2030. In addition, RED sets a specific sub-target for advanced biofuels and non-biological renewable fuels combined target of 5.5% by 2030, with a minimum requirement of 1% for non-biological renewable fuels. The revision of RED III, approved on October 9, 2023, and effective as of November 20, 2023, marks an important milestone toward greater energy sustainability (European Council, 2023). Additional initiatives complement these measures. In 2018, the IMO adopted a strategy to reduce GHGs, which was revised in 2023 to set net-zero emissions targets for 2050 and promote low-emission alternative fuels by 2030. This revised strategy aims to reduce GHG emissions by at least 20% by 2030 and 70% by 2040 compared to 2008 levels, even though carbon intensity was already reduced by 29% between 2008 and 2018 (IMO, 2018; 2023). The IMO has also implemented tools such as the Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency Design Index (EEDI) to enhance energy efficiency and reduce emissions. Complementary economic instruments at the European level, including European Funds 2021–2027, Next Generation EU, REPowerEU, the Connecting Europe Facility (CEF), and Horizon Europe, support investments in digital, transport, and energy infrastructure, as well as research and innovation (European Commission, 2021; European Commission, 2022). Together, these initiatives underscore the critical role of ports as strategic nodes in the global supply chain whose transformation can significantly reduce GHG emissions from the maritime sector.

7.2 Production, transportation, storage and use

Alternative fuel adoption in the maritime sector demands compliance with fuel standards to guarantee safe operation and quality control. The current regulation that regulates marine fuels is ISO 8217:2024 (ISO, 2024), which now includes biofuels, allowing the use of 100% FAME (B100) and paraffinic diesel fuels such as HVO. This update, replacing ISO 8217:2017 (ISO, 2017), refines energy content measurement (ASTM D240), oxidation stability, viscosity, and lubricity, ensuring compatibility with marine fuel systems and emissions regulations. Additionally, biofuel production and supply chains must comply with EU sustainability requirements, as outlined in Directive (EU) 2018/2001 (European Parliament and Council of the European Union, 2018).

First, biofuels must meet sustainability criteria and minimum greenhouse gas (GHG) savings limits. The directive establishes that biofuels must achieve at least 65% of GHG reduction, a threshold that ensures an effective contribution from biofuels to carbon reduction goals (European Parliament and Council of the European Union, 2018). Additionally, to prevent environmental damage, the directive limits the contribution of biofuels derived from food and feed crops to the renewable energy targets of the EU. High-risk indirect land-use change (ILUC) biofuels must be gradually phased out between 2023 and 2030, eliminating support for biofuels that contribute to deforestation and biodiversity loss (European Parliament and Council of the European Union, 2018).

Furthermore, EU member states are required to verify strictly to ensure that biofuels meet sustainability criteria. In this sense, the directive mentions the implementation of mass balance tracking systems to confirm the origin and sustainability of biofuel feedstocks, along with independent auditing for certification (European Parliament and Council of the European Union, 2018). Also, the directive recognises voluntary certification schemes, such as ISCC and RSB, as valid tools to demonstrate compliance with sustainability criteria. These schemes must be transparent, independent auditing processes to ensure integrity in biofuel certification (European Parliament and Council of the European Union, 2018).

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Finally, the directive mandates a review of sustainability criteria by 2026, assessing the effectiveness of current regulations and their impact on the biofuel market. This review will determine whether additional restrictions or incentives are necessary for further biofuel adoption (European Parliament and Council of the European Union, 2018). Regarding transportation and storage, it is known that FAME fuels are prone to oxidation and acidic degradation, for which they require monitoring of Acid Number (AN). ISO 8217:2024 does not correlate AN with corrosivity, but Strong Acid Number (SAN) testing helps assess the risk of inorganic acid-related corrosion. Engine manufacturers recommend fuel analysis for extended storage to prevent degradation.

In addition to this, SOLAS Chapter II-2 (IMO, 2002) stipulates a minimum fuel flashpoint of 60°C, easily meet by FAME. However, HVO may sometimes be close to or below this restriction, requiring flashpoint verification via Bunker Delivery Notes (BDN) and fuel analysis. It must be mentioned that, under MARPOL Annex I (IMO), conventional bunker tankers cannot transport FAME blends above B25, being classified under MARPOL Annex II and the IBC Code as noxious liquid substances. Industry discussions at IMO MEPC are exploring dual certification of Annex I bunker tankers, allowing them to carry both petroleum fuels and higher FAME blends, facilitating wider biofuel adoption (Lloyd's Register, 2024).

Regarding biofuel use, ISO 8217:2024 aligns biofuels with marine distillates, setting a minimum viscosity of 2 cSt and maximum of 6 cSt. This is important to address due to the low viscosity of HVO that potentially could cause leakages and pump wearing, while the high viscosity can impact fuel atomisation and combustion. Even more, regarding lubricity, HVO must comply with EN 15940 (CEN, 2016) (max. wear scar 400 µm), while FAME under ISO 8217:2024 is allowed up to 520 µm. Proper fuel-specific lubrication is essential to prevent premature wear of engine components such as injectors and fuel pumps. Finally, concerning NOx limits, biofuels must meet MARPOL Annex VI (IMO) fuel quality (Reg. 18) and NOx limits (Reg. 13). MEPC.1/Circ.795/Rev.7 allows biofuels to be used without flag-state exemptions, provided NOx emissions remain within limits. B30 blends are treated as fossil fuels, while higher blends can be used if NOx-critical components remain unchanged. Compliance is verified via Onboard Verification Procedures (OVP), reducing regulatory barriers for biofuel adoption. Considering these regulations, biofuels are presented as a viable decarbonisation pathway while ensuring safety, efficiency, and compliance in maritime operations.

7.3 Costs and incentives

While the measures described above primarily aim to improve sustainability, they also raise concerns about the potential impact of increased operational costs on end consumers. Increased costs can bring risks such as regulatory evasion or cargo diversion, where cargo is offloaded from one vessel to be transferred to another outside the European Union. This is particularly relevant for measures like FuelEU Maritime and the EU ETS, which have a direct impact on vessel operating costs. Although other indicators may influence clauses in charter parties, they do not have as direct an effect on cost.

There remain uncertainties regarding the management of ETS and FuelEU funds; however, it is crucial that these resources are used to drive the development of new decarbonisation technologies. Globally, emissions reported in the EU-MRV in 2022 totaled 8.4 million metric tons of CO_2 equivalent (European Commission, 2022). At the beginning of 2024, EU carbon permits were priced at approximately €80 per tonne, translating to roughly €7 billion per year for the ETS alone. Major shipping lines operating container ships have already calculated cost overruns, with estimates indicating an excess cost of around €90 per container per ton of CO_2 without reductions (Hapag-Lloyd, Maersk, & CMA-CGM, 2024). Although the use of energy efficiency and operational indicators aligns with the goal of achieving a carbon-neutral industry, significant progress is still needed. Certain aspects of the IMO Strategy, such as studying the supply of renewable energy from land to ships and developing infrastructure to support alternative low-carbon or zero-carbon fuels, are already in progress. To meet regulatory objectives, alternative fuels with low carbon emissions are essential. According to the European emission accounting, three technologies stand out as particularly promising: renewable hydrogen, ammonia, and renewable methanol with carbon capture and recycling. These options can potentially eliminate 100% of emissions (in contrast to natural gas, which reduces emissions by only 17%), with renewable methanol noted for its simpler management, lower investment requirements, and compatibility with existing combustion engines (European Commission, 2023).

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Both the maritime and energy sectors are focusing on developing and implementing low-emission fuels, though challenges exist at every level of the value chain that may slow the widespread adoption of alternative fuels. It is therefore crucial to support emissions reduction by implementing complementary, less disruptive measures in the short term. Such measures include electrification, improvements in onboard energy efficiency, installation of batteries to allow engine shutdown during port maneuvers, adoption of onshore power supply (OPS), and the use of renewable fuels and biofuels compatible with existing engines. These actions, which are already being implemented, reflect a strong commitment to accelerating decarbonisation. In this context, the carbon price, currently around €80 per tonne under the EU ETS, acts as a market-based incentive to internalise the environmental cost of emissions. As carbon prices increase, higher operating costs may be passed on to consumers or force shipping companies to make strategic adjustments. Ultimately, carbon pricing drives the transition to a low-carbon economy while providing funds necessary for both current compliance and future technological innovation (European Commission, 2023).

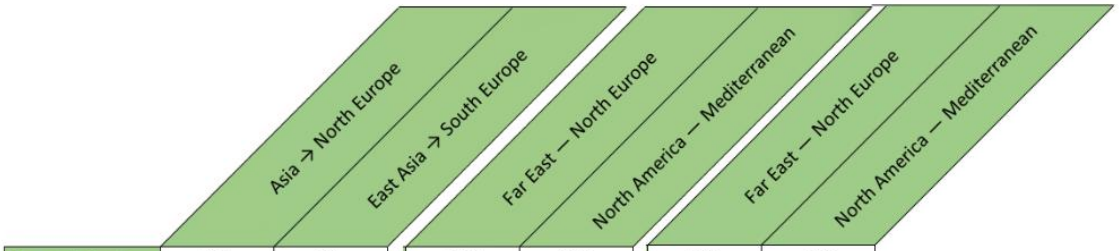

Table 8. Shipping companies' cost overruns due to ETS implementation8. Source: Own elaboration based on information provided by Hapag-Lloyd, Maersk and CMA-CGM shipping companies.

7.4 Compliance with emissions regulations

Ensuring adherence to emissions regulations is paramount to the success of decarbonisation efforts in the maritime industry. The compliance framework is multifaceted, involving rigorous monitoring, reporting, and verification systems enforced at global, regional, and national levels.

At the international level, the IMO requires vessels to submit regular reports on fuel consumption and emissions data as part of programmes such as the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII). These programmes mandate that shipowners continuously monitor their vessels' performance and implement corrective actions if emission targets are not met; non-compliance can result in significant financial penalties, operational restrictions, or even revocation of certification (IMO, 2020). A recent publication by DNV (2024) displays the FuelEU Maritime GHG intensity requirements from 2025 to 2050. The requirements, seen in Figure 14 below, are indicated as a share (%) relative to a baseline, which is 2020 GHG intensity.

[8] These estimates did not consider external circumstances, such as the cost overruns due to the crisis in the Red Sea and the Suez Canal, which have raised the cost of shipping by 300%. Fuel consumption for ships sailing around the Cape of Good Hope has increased, which has increased CO_2 emissions per voyage. However, the impact on inflation is expected to be moderate, as logistics represents only a small part of the final price of goods.

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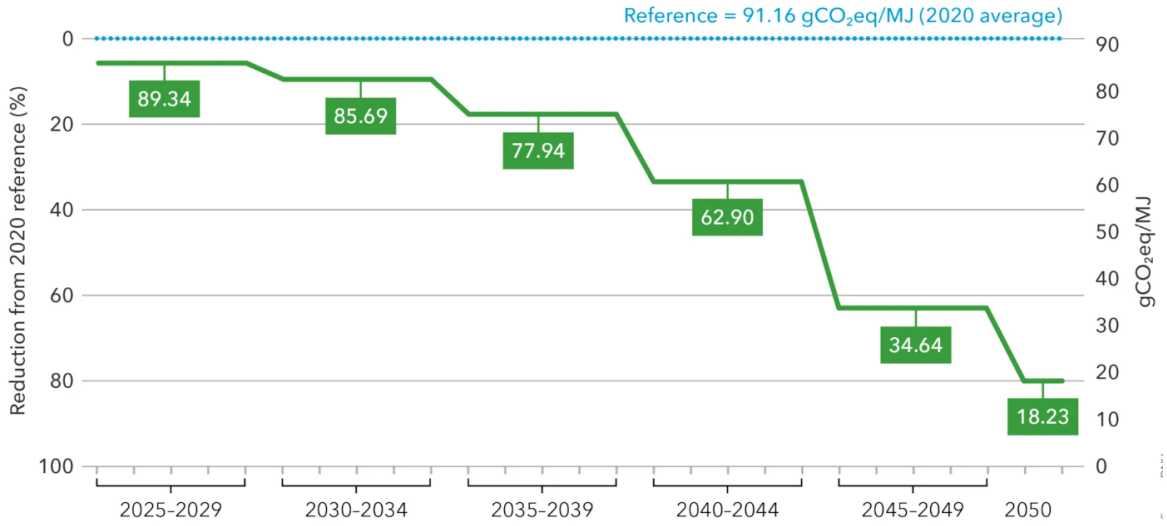

Figure 14. FuelEU Maritime GHG intensity requirements from 2025 to 2050. Source: DNV, 2024

- ***Energy efficiency and operational indicators:*** A key element of compliance is the use of both energy efficiency and operational indicators that serve as benchmarks for assessing vessel performance. Energy efficiency indicators evaluate a vessel's design characteristics and are typically calculated once, unless modifications occur, to establish a baseline standard. In contrast, operational indicators assess a vessel's real-time performance over its operational life. These indicators are periodically reported and compared against established baselines; if a vessel fails to meet its targets, financial penalties may be imposed, and a document of compliance is issued upon verification.

	Units	Developed by	Mandatory	Applicability	Applicability date	Target	Reporting Periodicity	Data reported to	Penalty	Compliance
EEXI EEDI	$\left[\frac{gCO_2}{ton \cdot mile}\right]$		Yes	Worldwide	1st Jan. 2023	Vessel (Shipowner)	Once	—	No	Statutory, IECC
CII	$\left[\frac{gCO_2}{ton \cdot mile}\right]$		Yes	Worldwide	1st Jan. 2024(*)	Vessel (Shipowner)	Annually	DCS	No	DCS Statement of Compliance
ETS	$\left[\frac{CO_2(eq)[t]}{year}\right]$		Yes	EU ports calls	1st Jan. 2025(*)	Vessel (Shipowner)	Annually	THETIS-MRV	Yes	Document of Compliance
FuelEU	$\left[\frac{CO_2(eq)[g]}{MJ \cdot year}\right]$		Yes	EU ports calls	1st Jan. 2026(*)	Vessel (Shipowner)	Annually	Verifier	Yes	Document of Compliance
ESI	$Air\ score\ [of\ 100]$	iaph	No	Worldwide	—	Vessel (Shipowner)	Once	—	—	—
Green Marine Europe	—		No	Worldwide	—	Shipowner, Port, Terminal, Shipyard	Once	—	—	—

Table 9. Energy efficiency and operational indicators. Source: Own elaboration based on information provided by IMO, EU, IAPH and Green Marine Europe.

As shown in Table 9, the various indicators differ regarding measurement frequency, mandatory application, and the types of emissions they consider. Furthermore, it is important to understand which substances are monitored by these indicators. Some indices, such as those used by the IMO and EU, focus primarily on greenhouse gases (*e.g.*, CO_2), while other indexes, like the Environmental Ship Index (ESI) by IAPH include additional pollutants that can affect human health, especially near urban areas surrounding major ports. The following table clearly outlines the specific pollutants and greenhouse gases tracked by each index.

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		CII	ETS	FuelEU	ESI	GWP [AR5]
CO2	Carbon dioxide	✓	✓	✓	✓	1
N2O	Nitrous Oxide	✗	✓	✓	✗	268
CH4	Methane	✗	✓	✓	✗	28
SOx	Sulphur Oxides	✗	✗	✗	✓	–
NOx	Nitrogenous Oxides	✗	✗	✗	✓	–

Table 10. Substances considered by each index. Source: Own elaboration based on information provided by IMO, EU and IAPH.

- ***Digital technologies and training:*** Advanced digital technologies play a crucial role in ensuring compliance. Modern ships are equipped with sophisticated sensors and monitoring systems that capture real-time data on fuel consumption and emissions. These data are transmitted via satellite to centralised databases, enhancing transparency and enabling regulators to promptly address any deviations from established targets. In addition, comprehensive training programmes, developed in collaboration with industry associations and academic institutions, ensure that seafarers and port workers acquire the necessary skills to manage new technologies and handle alternative fuels (e.g., LNG, hydrogen, and ammonia) safely. Continuous professional development and updated certification standards are critical components of maintaining a robust compliance regime (IMO, 2020).

- ***Integration of IMO and EU compliance systems:*** The IMO's Monitoring, Reporting, and Verification (MRV) system includes modules such as the Global Integrated Shipping Information System – Data Collection System (GISIS-DCS) and the Hybrid European Targeting and Inspections System (THETIS-MRV), developed by the European Maritime Safety Agency (EMSA). These systems facilitate the systematic collection and analysis of emissions data, with the extent of consumption data required varying between systems (EMSA, 2020). In addition to the mandatory IMO indicators (namely the EEXI/EEDI and CII), the European framework includes its own compliance mechanisms through FuelEU Maritime and the EU ETS. While the EU ETS employs a market-based cap-and-trade approach to regulate emissions from combustion, FuelEU Maritime addresses emissions from production to end-use by providing calculation factors based on fuel origin. Moreover, non-mandatory initiatives such as the Environmental Ship Index (ESI) by IAPH and measures promoted by Green Maritime Europe offer additional benchmarks and incentives for improved energy efficiency and emissions reduction. Figure 15 visually summarises the evolution of these measures over time and illustrates how various indicators and compliance tools are integrated to support decarbonisation efforts. Together, these indicators and compliance mechanisms ensure that the maritime sector maintains transparency and accountability in emissions reporting while steadily progressing toward decarbonisation.

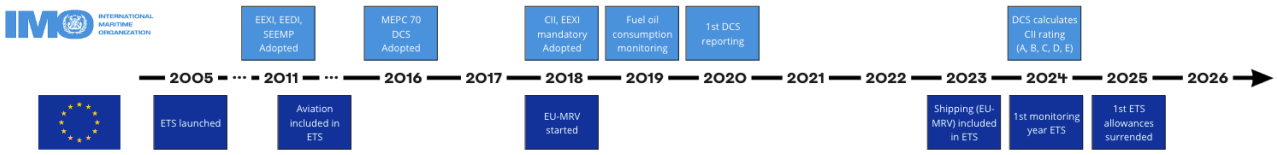

Figure 15. Energy efficiency initiatives in the maritime sector. Source: Own elaboration.

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8. Results

8.1 Summary and recommendations

The SEAFAIRER project has extensively analysed the feasibility, environmental impact, and regulatory challenges associated with the adoption of alternative fuels, particularly biofuels, in the maritime sector. The findings emphasise the following main conclusions:

- **Viability of biofuels**: The research confirms that biofuels, particularly second-generation fuels derived from non-food biomass, are a promising alternative for reducing greenhouse gas (GHG) emissions in maritime shipping. Compared to conventional marine fuels, biofuels can achieve up to 90% GHG emission reductions, aligning with global decarbonisation goals;

- **Technical readiness**: The current state of ship engines and fuel infrastructure allows for the integration of biofuels with minimal modifications. However, specific challenges related to fuel storage, viscosity, and combustion performance require further technological advancements to optimise fuel efficiency and engine compatibility;

- **Environmental impact**: While biofuels significantly reduce CO_2 emissions, indirect emissions such as NOx remain a concern. The sustainability of biofuel feedstocks, including land use and biodiversity impacts, must be carefully managed to ensure true environmental benefits:

- **Regulatory landscape**: Compliance with existing regulations, including MARPOL Annex VI and the EU's Renewable Energy Directive, FuelEU Maritime and the EU Emissions Trading Systems (for shipowners) is essential for the successful deployment of biofuels in maritime shipping. Current regulatory frameworks support biofuel adoption, but further standardisation and certification mechanisms are needed;

- **Economic and market considerations**: The cost of biofuel production remains a critical barrier. Incentives, subsidies, and carbon pricing mechanisms must be reinforced to encourage investment in biofuel production and infrastructure development;

- **Operational considerations**: Ensuring seamless integration of biofuels into the maritime supply chain requires improved bunkering logistics, enhanced cold-flow properties, and better fuel stability to prevent degradation over long storage periods.

With regards to **costs and incentives,** DNV (2025) has developed a case study which highlights significant cost disparities among different alternative fuel solutions. For example, even if using energy efficiency measures on ships and not sourcing alternative fuels at all, the pay penalty will result in a 60% higher expense than simply blending fossil-based fuel with bio-MGO (or other bio-options, albeit with slightly varying cost disparity). Penalty-only strategies are, evidently, the costliest due to compounding fees over time. This is illustrated in Figure 16.

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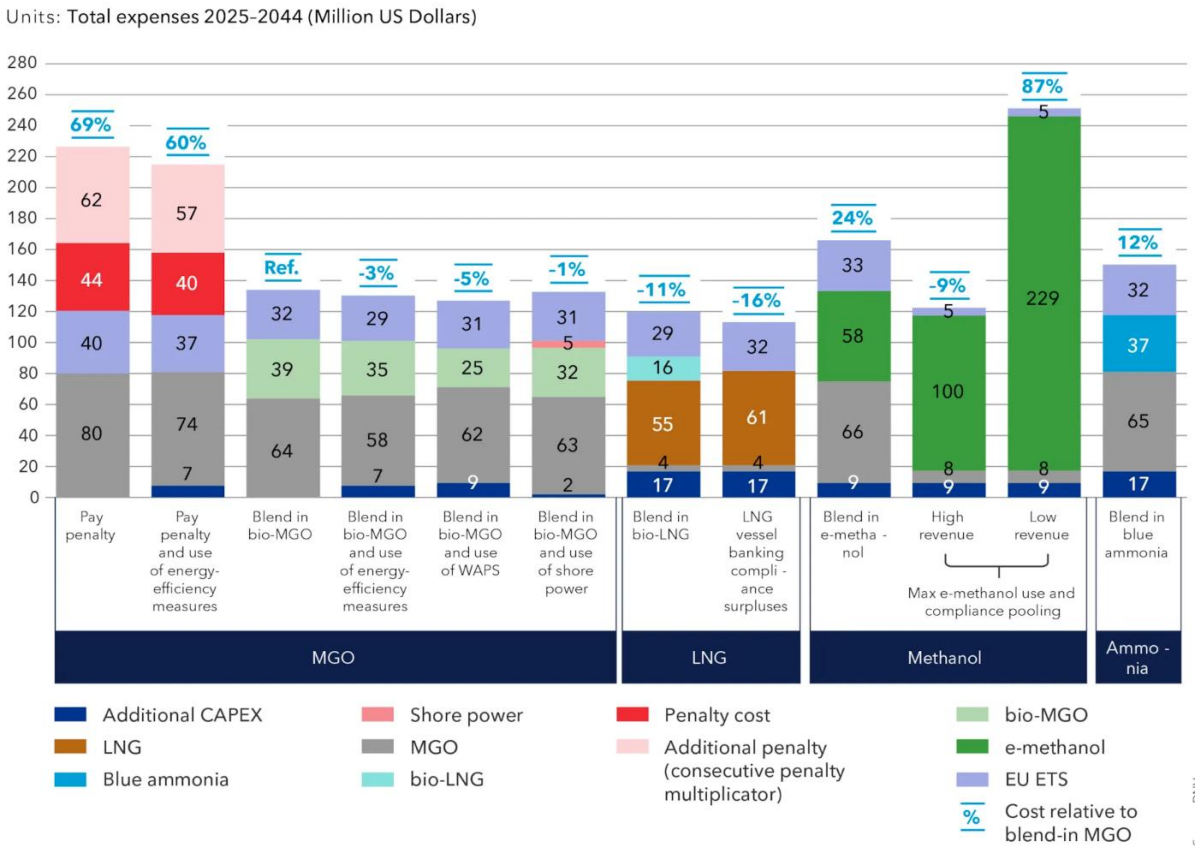

Figure 16. Comparison of total lifetime costs of each alternative fuel option (source: DNV, 2025).

8.2 Learnings for the SEAFAIRER project

Based on the understanding of maritime decarbonisation herein collected, SEAFAIRER will enact the following to, firstly, continuously monitor relevant development in policies, directives, and market/economic trends; and, secondly, to ensure the project's exploitation beyond its duration, delivering a commercially qualified marine biofuel solution:

- **Real-world case studies on the selected feedstocks**: agave bagasse (Mexico), biowaste sieving material (Germany) and rice husk (Spain) to prove techno-economic feasibility of SEAFAIRER's technology implementation. *Contributing partners*: Centro Mário Molina, Fraunhofer UMSICHT, DTU and SAGAVA;
- **Analysis of >20 sustainable feedstock sources** with no ILUC issues, with high availability for decentralised biofuel production in Europe and beyond, in line with RED II/RED III. *Contributing partners*: Centro Mário Molina, Fraunhofer UMSICHT, DTU, SAGAVA, UABIO;
- **Quantification of environmental benefits**: SEAFAIRER will perform a LCA following the IMO's Well-to-Wake methodology to quantify the GHG emissions and its reduction potential (CO_2-eq) with VINTER bio-oil. Contributing partners: DTU, Fraunhofer UMSICHT, SAGAVA, UABIO. • Comply with relevant product and value chain quality and sustainability thresholds: ISO 8217, ISCC EU, Carbon Standards International. *Contributing partners*: DTU, Fraunhofer UMSICHT, FVTR, SAGAVA;
- **Integration of biofuel** in (i) maritime ports and (ii) existing refinery infrastructure for SEAFAIRER's Pathway A (no upgrading) and Pathway B (minor upgrading at refinery). *Contributing partners:* Fraunhofer UMSICHT, FVP, FVTR, GALP;
- **Extensive biofuel and blends testing and validation in engines systems** at FVTR, which includes e.g., mixing compatibility, separator and filtration test, injector endurance and accelerated ageing, as well as engine endurance runs measuring combustion and emissions. *Contributing partners*: Fraunhofer UMSICHT, FVTR;

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- **Onboard performance and emission control** by FVTR on the test vessel to be commissioned in the port of Valencia in year 4 (2028). *Contributing partners*: Fraunhofer UMSICHT, FVP, FVTR;
- **EU roadmap for deployment**, which will guide the project's technology towards commercial implementation and continuously monitor relevant regulatory developments, as well as any trends in the marine biofuel market. *Contributing partners*: KPMG, FVP, SAGAVA, UABIO.

Ultimately, the goal of SEAFAIRER is to demonstrate the production of improved intermediate biofuels to deliver drop-in quality bio-oil for maritime transport. By successfully implementing these activities, which are foreseen in the project's Work Plan, SEAFAIRER aims to have a sustainable impact beyond its lifetime, i.e., bringing the biofuel production technology to market. At commercial scale, the intermediate biofuel, branches out into two market entry pathways that leverage existing refinery infrastructure: Pathway A is designed to cover the immediate biofuel needs of the industrial maritime shipping sector. This pathway will target direct blends (B10 to B30) of intermediate biofuel (VINTER bio-oil) on par with VSLFO according to the ISO 8217:2024 quality thresholds for marine fuels. Pathway B targets the medium- to long-term demands of the maritime industrial shipping sector. In this case, the intermediate biofuel will be upgraded via hydrodeoxygenation (HDO), targeting higher blending capacity up to pure drop-in fuel quality (B50 to B100), on par with ISO 8217:2024 quality thresholds for marine fuel.

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