

Beyond Climate: Environmental Implications of Green Shipping Fuels



Introduction

International shipping transports around 80-90% of global trade and as such is indispensable to the world economy.¹ At the same time, it contributes approximately 3% of global greenhouse gas emissions and is also a significant source of air pollution and marine contamination.² If maritime shipping were a country, it would be the sixth-largest climate polluter in the world.³

While the carbon intensity of the global fleet has declined over the past decade as ships have become more fuel-efficient, absolute emissions have continued to rise due to rapid growth in global maritime transport. In addition to CO₂, methane is another potent greenhouse gas associated with shipping. Methane emissions, largely resulting from methane slip, have increased more than 2.5-fold since 2016, linked to an increase of more than 80% in the use of liquefied natural gas (LNG) as a marine fuel over the same period.⁴

Apart from greenhouse gas emissions, shipping is also responsible for the emissions of air pollutants – nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) – which negatively affect air quality along shipping routes and in port areas. While sulphur dioxide (SO₂) emissions have fallen significantly following the introduction of IMO regulation in 2020, NO_x emissions from shipping remain high, at around 14% of all anthropogenic emissions.⁵

Aside from the harmful environmental impacts, these emissions also affect public health. Air pollution from global shipping has been estimated to contribute to approximately 265,000 premature deaths annually.⁶

Last but not least, shipping is a source of marine water pollution. Exhaust gas cleaning systems, known as scrubbers, allow ships to continue using high-sulphur fuel by removing sulphur oxides (SO_x) and other pollutants from the exhaust gas. In open-loop scrubbers, the resulting wash water is discharged directly into the sea, transferring part of the pollution from the air to the marine environment. Scrubber wash water is acidic and contains contaminants including heavy metals, polycyclic aromatic hydrocarbons (PAH's) and other harmful substances, which can poison marine life, destroy habitats, and disrupt the balance of ocean ecosystems.⁷

Shipping also contributes to water pollution through operational discharges and accidental releases, including oil and chemical spills, oily bilge water, sewage and waste. While major oil spills attract considerable attention,

routine operational discharges represent a more continuous source of pressure on the marine environment.

As the maritime sector seeks to reduce its climate impact, a range of alternative fuels – including methanol, ammonia, hydrogen and biofuels – have been proposed as replacements for conventional fossil marine fuels such as heavy fuel oil, marine diesel oil, marine gas oil or very low sulphur fuel oil.

Much of the current discussion has focused on the potential of these fuels to reduce greenhouse gas emissions. Comparatively less attention has been paid to their broader environmental implications. Every fuel has a unique environmental profile, affecting not only climate but also air quality, marine ecosystems, resource use and risks associated with production, transport and accidental spills.

This report provides a brief overview of the current state of knowledge regarding the environmental impacts of the most prominent alternative marine fuels. Rather than identifying a single "best" fuel, it highlights both the opportunities and the uncertainties that should inform future decisions.

Transition from fossil fuels to alternative fuels

For decades, the shipping industry has relied predominantly on fossil fuels, particularly heavy fuel oil, marine diesel oil and marine gas oil. Their high energy density, relatively low cost and well-established global supply infrastructure have made them well suited to long-distance maritime transport. However, this dependence on fossil fuels comes with substantial environmental and human-health costs. Their combustion releases carbon dioxide (CO₂), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter and black carbon, contributing to climate change, acidification, poor air and water quality and adverse health effects.

Improving the energy efficiency of ships can reduce fuel consumption and emissions, but efficiency improvements alone cannot eliminate the sector's dependence on fossil fuels. While the carbon intensity of international shipping has improved considerably, growth in maritime transport has partly offset these efficiency gains. A transition away from fossil fuels is therefore necessary if shipping is to

¹ <https://unctad.org/news/shipping-data-unctad-releases-new-seaborne-trade-statistics>

² <https://www.imo.org/en/ourwork/environment/pages/decarbonization%20of%20shipping.aspx>

³ <https://vitalsigns.edf.org/story/climate-pollution-global-shipping-growing-can-industry-clean-time>

⁴ https://theicct.org/wp-content/uploads/2025/04/ID-332-%E2%80%93Global-shipping_report_final.pdf

⁵ <https://essd.copernicus.org/articles/17/277/2025/index.html>

⁶ <https://www.sciencedirect.com/science/article/pii/S001393512201787X>

⁷ <https://www.emsa.europa.eu/emter-2025/full-report.html>

achieve substantial reductions in its overall greenhouse gas emissions.⁸

This transition is already beginning. A range of alternative fuels – including renewable methanol, ammonia, hydrogen and sustainable biofuels – are being introduced for maritime use. Their potential environmental benefits extend beyond climate mitigation. Depending on the fuel and technology used, they can substantially reduce or eliminate emissions of sulphur oxides, particulate matter and other pollutants associated with conventional fuels. Moving away from fossil fuels can therefore provide an opportunity to address several environmental pressures from shipping simultaneously.

However, alternative fuels come with their own set of challenges. Their environmental profiles differ considerably according to their feedstocks, production pathways, transport and storage requirements and behaviour in the event of an accidental release. For example, ammonia contains no carbon and can potentially achieve very low lifecycle greenhouse gas emissions when produced using renewable energy, but its toxicity presents a potential risk to marine ecosystems in the event of a spill. Similarly, renewable methanol can substantially reduce lifecycle greenhouse gas emissions, but its overall environmental performance depends on how the hydrogen and carbon used in its production are sourced.⁹

These challenges do not diminish the need to move away from fossil fuels. Rather, they underline the importance of managing the transition carefully. As new fuels and associated infrastructure are introduced at scale, potential environmental impacts should be identified early so that they can be prevented or mitigated through fuel sustainability criteria, technological development, regulation, safe handling practices and appropriate spill response measures.

The question is therefore not whether shipping should transition to alternative fuels, but how this transition can deliver the greatest possible climate and environmental benefits while minimising new risks. Assessing fuels from a lifecycle perspective – from feedstock and energy supply through production and transport to their use and eventual release into the environment – can help ensure that reducing one environmental pressure does not inadvertently increase another.

Environmental implications of different fuels

The environmental performance of alternative fuels depends not only on the fuel itself but also on how it is produced, transported and used. For example, methanol can be produced from natural gas, biomass or renewable

electricity and captured carbon dioxide, each with very different climate impacts. Likewise, the environmental footprint of biofuels depends heavily on the sustainability of the feedstocks used.

Table 1 summarises the main environmental characteristics of the fuels currently receiving the greatest attention in international shipping. It illustrates that no alternative fuel is environmentally neutral. Instead, each involves different trade-offs that must be evaluated across its entire life cycle and managed in order to gain the highest environmental benefits.

Table 1. Simplified overview of the climate and environmental implications of selected marine fuels

Fuel	Climate potential	Air pollution (point of use)	Marine spill behaviour	Main environmental concerns
 E-methanol CH ₃ OH	Potentially very low lifecycle GHG emissions when produced using renewable electricity and a sustainable CO ₂ source.	- No SO_x - Low particulate emissions - NO_x can still occur	Highly soluble; disperses and biodegrades relatively rapidly.	Renewable electricity demand; sustainability of CO ₂ source; aquatic toxicity at high concentrations.
 Bio-methanol CH ₃ OH	Potentially low lifecycle GHG emissions, depending strongly on feedstock and production pathway.	- No SO_x - Low particulate emissions - NO_x can still occur	Highly soluble; disperses and biodegrades relatively rapidly.	Sustainable biomass availability; possible land-use and biodiversity impacts.
 Ammonia NH ₃	No CO ₂ from combustion; potentially very low lifecycle GHG emissions when produced using renewable energy.	- No SO_x or carbon-based PM - NO_x and N₂O formation and ammonia slip are important concerns	Highly soluble in water; potentially acutely toxic to aquatic organisms.	Toxicity to humans and marine life; nitrogen pollution; N ₂ O and NO _x emissions; handling and safety concerns.
 Hydrogen H ₂	No CO ₂ at point of use; potentially very low lifecycle GHG emissions when produced using renewable electricity.	- Fuel cells produce no SO_x, PM or NO_x - Combustion can produce NO_x	Gas disperses rapidly following release; limited direct marine contamination.	Large renewable electricity demand; difficult storage and transport; leakage, fire and explosion risks.
 Sustainable biofuels	Potentially low, but highly dependent on feedstock, production and land-use effects.	- Generally low SO_x and PM - NO_x and CO₂ are still produced during combustion	Varies by fuel; many are biodegradable, but impacts differ substantially.	Biomass availability; land use; biodiversity; water, fertiliser and pesticide use for some feedstocks.
 LNG	Lower direct CO ₂ emissions than conventional oil fuels, but lifecycle benefit can be substantially reduced by methane leakage and slip.	- Very low SO_x and PM - NO_x generally lower in some engine types	LNG evaporates rapidly rather than forming a persistent oil slick.	Fossil-fuel dependence; upstream methane leakage and onboard methane slip.

Note: Environmental performance can vary substantially depending on feedstock, production pathway, electricity source, engine technology and operational conditions.

Key environmental considerations

The transition to alternative fuels can substantially reduce the climate and environmental impacts associated with conventional marine fossil fuels. However, the nature and location of these impacts will change. Some alternative fuels introduce new risks during production, storage or accidental release, while others may shift environmental pressures upstream to energy production, agriculture or other sectors. Understanding these differences is important as new fuel systems and infrastructure are being developed.

Marine pollution and accidental spills

Alternative fuels differ fundamentally from conventional oil products in how they behave when released into the marine environment. Heavy fuel oil is persistent and can form surface slicks, contaminate coastlines and sediments, and affect marine organisms for prolonged periods. Moving away from oil-based fuels could therefore significantly reduce the risk of this type of persistent marine pollution.

Alternative fuels, however, introduce different spill scenarios. Methanol is highly soluble in water and, unlike oil, does not form a persistent surface slick. Following a release, it is expected to disperse through the water

⁸ <https://www.transportenvironment.org/topics/ships>

⁹ <https://www.imo.org/en/ourwork/environment/pages/lifecycle-ghg-carbon-intensity-guidelines.aspx>

column and be relatively rapidly biodegraded. This considerably reduces its potential for long-term physical contamination compared with heavy fuel oil. Nevertheless, methanol is not harmless: sufficiently high concentrations can be toxic to aquatic organisms, particularly close to the point of release, and its biodegradation can increase biological oxygen demand. Expert assessment of methanol spills concludes that the environmental consequences will depend strongly on the size and location of the release, water exchange and local ecological conditions.¹⁰

Ammonia presents a potentially more acute environmental risk. It is highly soluble in water and does not create a persistent oil slick, but ammonia is toxic to aquatic organisms. Its toxicity depends on factors including concentration, pH, temperature and species sensitivity. A large release could therefore result in acute effects on fish and other marine organisms, particularly in enclosed environments such as ports, estuaries and coastal waters. Recent scientific reviews also identify possible indirect effects through changes in nitrogen cycling, microbial communities and algal growth, although these consequences are less well understood than acute toxicity.¹¹

These risks do not necessarily prevent ammonia from being used safely. Ammonia has long been transported by sea as a commodity and considerable experience already exists in its handling. However, its widespread use as a bunker fuel would increase the number of locations and operations in which ammonia is handled. EMSA therefore identifies toxicity as the principal hazard associated with ammonia as a marine fuel and stresses the importance of ship design, containment systems, operating procedures, crew training and release mitigation.¹²

Hydrogen poses comparatively little risk of persistent marine contamination because released hydrogen is a gas and disperses rapidly. Its primary hazards relate to its high flammability and the challenges associated with storage and handling. Biofuels are more difficult to generalise about because their chemical properties vary considerably. Many are biodegradable and less persistent than conventional bunker oil, but this does not mean that all biofuel spills are environmentally harmless.¹³

An important consequence of the fuel transition is therefore that spill preparedness will also need to evolve. Response strategies developed over decades for conventional oil spills may not be appropriate for highly soluble fuels such as methanol and ammonia. Environmental monitoring, emergency planning and spill

response procedures will need to reflect the different behaviour and toxicity of the fuels that become widely used.

Air quality

A major environmental advantage of moving away from conventional marine fuels is the potential to reduce air pollution. Heavy fuel oil and other petroleum fuels produce sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM), which contribute to poor air quality, acidification and adverse effects on human health.

Methanol, ammonia and hydrogen contain no sulphur and can therefore virtually eliminate fuel-related SO_x emissions. Methanol combustion also produces substantially less particulate matter than conventional oil fuels, while hydrogen used in fuel cells produces neither SO_x nor particulate matter. These benefits could be particularly important in ports and densely populated coastal areas with high exposure to shipping-related air pollution.

However, alternative fuels do not eliminate all emissions. NO_x remain an important consideration for combustion-based technologies. Methanol engines can still produce NO_x, while combustion of ammonia can produce both NO_x and nitrous oxide (N₂O). The latter is particularly important because it is a powerful greenhouse gas and even relatively small emissions can reduce ammonia's overall climate advantage. Unburned ammonia may also be emitted as ammonia slip, potentially contributing to air pollution and secondary particulate formation.¹⁴

Methanol combustion may also produce fuel-specific pollutants that require attention. In particular, unburned methanol and formaldehyde have been identified as important unregulated emissions from methanol-fuelled engines. Their emissions depend strongly on engine design and operating conditions and can be substantially reduced through appropriate exhaust after-treatment.¹⁵

Upstream impacts and resource use

Some of the most important environmental impacts of alternative fuels occur before the fuel reaches the ship.

Green hydrogen, e-methanol and e-ammonia all depend on renewable hydrogen produced through electrolysis. Their large-scale deployment would therefore require

¹⁰ <https://www.itopf.org/knowledge-resources/documents-guides/fate-behaviour-potential-damage-liabilities-arising-from-a-spill-of-methanol-in-the-marine-environment/>

¹¹ <https://www.sciencedirect.com/science/article/pii/S2772416626000987>

¹² <https://emsa.europa.eu/publications/reports/item/5264-study-investigating-the-safety-of-ammonia-as-fuel-on-ships.html>

¹³ <https://emsa.europa.eu/newsroom/latest-news/item/4834-update-on-potential-of-biofuels-for-shipping.html>

¹⁴ <https://www.sciencedirect.com/science/article/pii/S0196890423011949>

¹⁵ <https://www.sciencedirect.com/science/article/abs/pii/S1743967125001175>

substantial quantities of renewable electricity. E-methanol additionally requires a source of carbon, while electrolysis requires water and ammonia production requires nitrogen. Part of the environmental impact of these fuels thus depends on how their inputs are produced.

Even though alternative fuels have in general lower greenhouse gas emissions than conventional fuels, these too can vary depending on the source of energy. Hydrogen, ammonia and methanol can all be produced using fossil fuels as well as renewable energy. A fuel that produces little or no CO₂ on board can therefore still have substantial upstream greenhouse gas emissions. IMO has therefore adopted a well-to-wake approach to marine fuels for this reason, combining emissions associated with production and supply (well-to-tank) with those occurring on board (tank-to-wake).¹⁶

Biofuels raise a different set of upstream concerns. Their environmental performance depends strongly on the feedstock used. Fuels produced from genuine wastes and residues can potentially achieve large greenhouse gas reductions without requiring substantial additional land. By contrast, large-scale production from purpose-grown crops can create pressures through land use change, water consumption, fertiliser and pesticide use and habitat loss. Demand for biomass from shipping may also compete with its use in other sectors, as sustainable biomass feedstock is limited. EMSA has identified the availability of genuinely sustainable biofuels as a constraint on their large-scale use in shipping.¹⁷

The importance of a lifecycle perspective

These considerations illustrate why assessing alternative fuels only according to emissions from the ship can be misleading. Environmental pressures occur throughout the fuel chain – from energy and feedstock production to fuel synthesis, transport, bunkering, use and accidental release.

The IMO's lifecycle framework currently focuses primarily on greenhouse gas emissions, considering CO₂, methane (CH₄) and nitrous oxide (N₂O), but it also recognises broader sustainability dimensions associated with marine fuels.¹⁸ A comprehensive environmental assessment should therefore look beyond greenhouse gases to consider air pollution, toxicity, marine pollution, biodiversity, water and land use, and demand for renewable energy.

This broader perspective should not be interpreted as an argument for delaying the transition away from fossil fuels. The environmental and climate impacts of continued use of fossil fuels are severe and decarbonisation of shipping requires alternative energy

sources. Identifying the potential impacts of new fuels at an early stage creates an opportunity to manage them throughout the process.

The objective should therefore be to ensure that the transition away from fossil fuels delivers the greatest possible overall environmental benefit – not only lower greenhouse gas emissions.

Conclusion

Alternative fuels are essential for reducing greenhouse gas emissions from international shipping. However, no fuel is completely impact-free.

Alternative fuels in general improve air quality and can significantly reduce greenhouse gas emissions when produced sustainably. At the same time, they introduce new environmental considerations related to toxicity, resource use, production pathways and spill behaviour.

Rather than focusing solely on climate performance, future assessments of marine fuels should adopt a broader environmental perspective that considers impacts across the entire life cycle.

As the maritime transition accelerates, continued research and transparent environmental assessment will be essential to ensure that solutions to one environmental challenge do not unintentionally create others.

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¹⁶ <https://www.imo.org/en/ourwork/environment/pages/lifecycle-ghg--carbon-intensity-guidelines.aspx>

¹⁷ <https://emsa.europa.eu/newsroom/latest-news/item/4834-update-on-potential-of-biofuels-for-shipping.html>

¹⁸ <https://www.imo.org/en/ourwork/environment/pages/lifecycle-ghg--carbon-intensity-guidelines.aspx>