OPPORTUNITY GREEN

Ammonia as a shipping fuel: how can we avoid swapping one pollution problem for another?

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Executive summary

Shipping is responsible for 3% of global greenhouse gas (GHG) emissions every year, making a significant contribution to the climate crisis. Reducing the industry's GHG emissions is essential, and can partly be achieved by measures including demand reduction, energy efficiency improvements, use of wind-assisted propulsion, speed reduction and electrification. However, decarbonisation will also rely on replacing climate-damaging fossil fuels with lower emission alternative fuels.

Ammonia (chemical formula NH_3) is touted as one such alternative fuel, primarily because burning ammonia in ship engines does not produce CO_2. However, no alternative fuel is the perfect answer to shipping's pollution problems, with each posing unique challenges and opportunities. In this regard, ammonia is no exception.

This briefing demonstrates that while ammonia can meaningfully contribute to decarbonising the shipping industry, deep GHG emissions reductions are not guaranteed. Instead, these hinge on the use of green ammonia, produced with hydrogen sourced from water electrolysis powered by renewable electricity, as well as minimising direct and indirect emissions of nitrous oxide (N_2O), which is a GHG 273 times more potent than CO_2, throughout the fuel lifecycle. Furthermore, using ammonia as a shipping fuel could significantly increase global nitrogen pollution, creating a variety of additional risks. Leaks and spills of ammonia must be minimised to protect the environment, biodiversity and safety, while unburned ammonia and nitrogen oxide (NO_x) emissions must be controlled to reduce adverse impacts on air quality and to avoid potentially hundreds of thousands of additional premature deaths every year.

Effective policy and regulation are therefore urgently required. Efforts to decarbonise shipping have focused mostly on CO_2 emissions, but to truly deliver an effective, just and equitable transition, it is essential to look beyond CO_2 and avoid swapping one pollution problem for another.

To this end, industry and regional, national and international policymakers should ensure the following three conditions are in place when ammonia is rolled out as a shipping fuel to ensure it contributes meaningfully to reducing the industry's GHG emissions, while minimising adverse public health, environmental and biodiversity impacts:

Recommendations for using ammonia as a shipping fuel	Why?
The ammonia used should be green, and N_2O emissions, hydrogen leaks and reactive nitrogen leaks, spills and emissions must be minimised.	Without these conditions, the GHG emissions reductions achievable by using ammonia, compared with conventional fuels, are significantly reduced or even negated entirely.
Monitoring and reporting both GHG emissions and all forms of reactive nitrogen pollution across the ammonia fuel lifecycle must be mandatory and transparent.	To more accurately assess the magnitude of nitrogen pollution from the ammonia fuel lifecycle, and the associated impacts.
There must be a robust regulatory and policy framework which manages nitrogen pollution across the fuel life cycle.	To ensure the safe use of ammonia enables GHG emissions reductions and minimises adverse public health, environmental and biodiversity impacts.

This briefing focuses on the use of ammonia as a shipping fuel, with recommendations tailored to the shipping industry's unique governance structures. However, as outlined in the main text, these recommendations are also relevant for other industries which use ammonia (e.g., agriculture), and there needs to be a coordinated approach to policy and regulation across all ammonia use cases.

Briefing: ammonia as a shipping fuel

Introduction

The shipping industry is responsible for 3% of global greenhouse gas (GHG) emissions every year.[1] In 2023, a landmark agreement saw the sector pledge to reduce its emissions to net-zero by, or around, 2050.[2] Considerable emissions reductions can, and should, be achieved by measures like demand reduction, energy efficiency improvements, use of wind-assisted propulsion, speed reduction and electrification.[e.g., 3;4;5] However, it will also be essential to develop alternative fuels to replace the climate-damaging fossil fuels currently burned in ship engines.

Ammonia (chemical formula NH_3) is being developed as a candidate alternative shipping fuel, which can either be burned in ship engines, used in fuel cells or used as a hydrogen carrier for hydrogen-fuelled vessels.[e.g., 6;7] This briefing focuses on the use of ammonia in ship engines. At the time of writing, just three operational vessels use ammonia engines,[8] however, many more are on order[8;9] and studies have forecast that ammonia will power a significant proportion of the global fleet by 2050.[10]

Evidence suggests, however, that ammonia is not guaranteed to deliver GHG emissions reductions,[11;12;13;14;15] and could result in adverse health, environment and biodiversity impacts.[11;14;16;17]

No alternative fuel offers a perfect solution to shipping pollution – each presents unique challenges and opportunities, and ammonia is no exception. This briefing outlines the key challenges and opportunities associated with using ammonia as a shipping fuel. It then makes recommendations for industry and regional, national and international policymakers that would help ensure ammonia becomes a safe shipping fuel which contributes meaningfully to reducing the industry's GHG emissions, while minimising adverse public health, environmental and biodiversity impacts.

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[2] International Maritime Organization (IMO), 2023. 2023 IMO Strategy on Reduction of GHG Emissions from Ships. Retrieved 4 June, 2025 from https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx
[3] Seas at Risk, 2025. Wind First! Retrieved 21 May, 2025 from https://seas-at-risk.org/press-releases/wind-propulsion-key-to-cut-costs-and-carbon-in-shipping-shows-new-report/
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Ammonia, nitrogen pollution and the nitrogen cycle

In a chemical sense, ammonia is a type of reactive nitrogen. Comparatively unreactive nitrogen gas (N_2) makes up almost 80% of Earth's atmosphere, consisting of two nitrogen atoms held tightly together by a strong chemical bond. However, if that bond is broken, reactive nitrogen species like ammonia, nitrous oxide (N_2O) and nitrogen oxides (known as NO_x), can form. Reactive nitrogen transitions through a series of reactions to eventually form N_2 once more in what is known as Earth's nitrogen cycle.[18;19]

Flows of nitrogen, together with phosphorous, are essential for life and are one of nine key processes responsible for Earth's stability.[20] However, since the 20th century, production of ammonia for agricultural fertiliser and emissions of reactive nitrogen from burning fossil fuels have caused vast reactive nitrogen pollution, disrupting Earth's nitrogen cycle[18] and far exceeding the safe planetary boundary.[20]

Looking ahead, use of ammonia as a shipping fuel has the potential to cause further significant nitrogen cycle disruption.[11] Reactive nitrogen will inevitably be released into the environment throughout the ammonia fuel lifecycle (i.e., all of the processes between fuel production and use onboard ships).[11;15] Potential sources of reactive nitrogen release are shown in Table 1 and discussed in detail later. Estimates suggest that between 0.5% and 5% of the supply chain ammonia input could be released as reactive nitrogen,[14] a substantial amount given fuelling the 2018 global shipping fleet would have required four times as much ammonia as was produced, worldwide, in that year.[11]

Considering emissions across the fuel lifecycle is known as a "Well-to-Wake" (WtW) perspective, which involves two phases:

1. "Well-to-Tank" (WtT) emissions during fuel production, distribution, storage in port and bunkering (i.e., ship fuelling), up to the point fuel enters the ship's tank.
2. "Tank-to-Wake" (TtW) emissions from the storage and use of the fuel onboard the ship.

[18] Canfield, D.E., Glazer, A.N., Falkowski, P.G., 2010. The Evolution and Future of Earth's Nitrogen Cycle. Science 330, 192–196. https://doi.org/10.1126/science.1186120
[19] Stein and Klotz, 2016. The nitrogen cycle. Current Biology 26, R94–R98. https://doi.org/10.1016/j.cub.2015.12.021
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	Well-to-Tank				Tank-to-Wake	
Phase	Production	Distribution	Port storage	Bunkering	Storage on ship	Engine emissions
Ammonia leakage	Yes	Yes	Yes	Yes	Yes	Yes
Ammonia venting			Yes	Yes	Yes	
Direct NO_x emissions						Yes
Direct N_2O emissions						Yes

Table 1. Potential for emissions of reactive nitrogen species during different stages of the green ammonia fuel lifecycle, based on Esquivel-Elizondo et al. (2025) (their figure 1).[15] The fuel lifecycle can be split into the Well-to-Tank and Tank-to-Wake phases, as explained below. Ammonia leakage refers to unintentional leaks, spills or emissions. Ammonia venting refers to intentional release of ammonia to prevent overpressure damage. Bunkering refers to the process of transferring fuel to the ship's fuel tank.

Nitrogen pollution on this scale is the root of many of the challenges associated with using ammonia as a shipping fuel.[11] However, using ammonia also presents an opportunity to meaningfully reduce the industry's GHG emissions. The following sections review these challenges and opportunities, focusing on GHG emissions, the environment, biodiversity, health and safety.

Greenhouse gas emissions

Ammonia has been championed as a lower emission shipping fuel because it does not produce CO_2 when burned. However, two additional considerations are key for determining ammonia's climate impacts:

1. CO_2 is not the only GHG responsible for warming our planet: methane, nitrous oxide and various short-lived climate forcers (SLCFs) make substantial contributions as well.[21]
2. Combustion is only one stage in the ammonia fuel lifecycle, which also includes production, distribution and storage, as demonstrated in Table 1.

The following sections discuss the different GHG emissions that may be released at different stages of the ammonia fuel lifecycle, taking a WtW perspective.

Sources of Well-to-Tank GHG emissions

Ammonia production is currently a key source of GHG emissions. Since the early 20th century ammonia has been produced using the Haber-Bosch process, which reacts hydrogen with nitrogen. Today, around 185mn tonnes of ammonia are produced every

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[21] Intergovernmental Panel on Climate Change (IPCC), 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896

year in industrial plants around the world,[22] accounting for 2% of global final energy demand and direct GHG emissions equivalent to 450mn tonnes CO_2,[23] more than the total GHG emissions of the entire UK in 2023.[24]

These emissions arise because most ammonia produced today is "grey ammonia",[6] meaning natural gas is used as a source of hydrogen and reaction processes are powered by fossil fuels. Grey ammonia (and the "brown ammonia" equivalent also used today which adopts coal as a source of hydrogen) generates significant CO_2 emissions.[15;25;26]

Lower emission ammonia production must, therefore, be scaled up.[6] One option, termed "blue ammonia", is to reduce CO_2 emissions by pairing brown/grey ammonia production with Carbon Capture and Storage (CCS) technology. Another option, however, is to avoid using fossil fuels altogether and producing "green ammonia" with hydrogen sourced from electrolysis of water, and all reactions powered by electricity from renewable sources. While blue ammonia delivers GHG savings compared with brown/grey ammonia, emissions can remain significant, due to methane leaks in the natural gas supply chain and incomplete carbon capture.[e.g., 12;15;25;27] Conversely, green ammonia is capable of delivering deeper GHG emissions reductions.[12;15;25;26]

However, even green ammonia can have a climate impact during the WtT phase due to indirect N_2O emissions and hydrogen leaks, which occur regardless of the means of ammonia production.[11;14;15]

Firstly, N_2O is itself a potent GHG with a climate impact 273 times larger than CO_2 on a 100-year timescale.[21] In the WtT phase of the green ammonia lifecycle, while there are no direct sources of N_2O, indirect N_2O emissions can result when other reactive nitrogen species are released, for instance due to ammonia leaks during production, distribution and bunkering, or ammonia emissions from intentional venting (Table 1). While not GHGs themselves, reactive nitrogen species can later be converted to N_2O as part of the nitrogen cycle.[11;14;15] The amount of reactive nitrogen which gets converted to N_2O will vary depending on the environment and conditions it is released into.[15]

Secondly, hydrogen is an indirect GHG – when released to the atmosphere it extends the lifetime of GHGs such as methane, tropospheric ozone and stratospheric water vapour.[28] The climate effects of hydrogen are around 10 times larger than equivalent emissions of CO_2 on a 100-year timescale,[29] and recent research suggests that hydrogen leaks from the ammonia supply chain could contribute significantly to overall GHG emissions from ammonia as a shipping fuel.[15] While uncertainties remain

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[22] International Fertilizer Association (IFA), 2024. Production & Trade Tables by Region. Retrieved 13 February, 2025 from https://www.ifastat.org/supply/Nitrogen%20Products/Ammonia
[23] International Energy Agency (IEA), 2021. Ammonia Technology Roadmap. IEA, Paris. https://www.iea.org/reports/ammonia-technology-roadmap. Licence: CC BY 4.0.
[24] Department for Energy Security and Net Zero (DESNZ), 2025. Final UK greenhouse gas emissions statistics: 1990 to 2023. Retrieved 3 July, 2025 from https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-statistics-1990-to-2023
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regarding climate effects and rates of leakage, accounting for hydrogen emissions is clearly essential for assessing the benefits and risks of a hydrogen-based economy, of which ammonia used as a shipping fuel would form a constituent part. [27;28;30]

Sources of Tank-to-Wake emissions

Turning now to the TtW phase, while in theory burning pure ammonia produces only nitrogen and water, in reality ammonia combustion in ship engines will also produce other compounds including N_2O (a powerful GHG, as noted above).

The magnitude of these direct N_2O emissions from ammonia ship engines remains unclear, but at its worst may undermine ammonia's low emission credentials. Though ammonia engine manufacturers have asserted that N_2O emissions are "extremely low" and "negligible",[31] the same manufacturers are yet to publish detailed, publicly available emissions data (see below for more detail). The best available evidence, from experimental and modelling-based approaches, reveals a wide spread of N_2O emissions, ranging from negligible emissions in optimised models to values which cancel out much of the climate benefit of using ammonia altogether.[12;13;15] In part, the breadth of this spread is because direct N_2O emissions depend on a variety of factors, including engine configuration and conditions (e.g., ammonia injection pressure, combustion temperature and engine load).[e.g., 32;33;34] Controlling these emissions in real-world scenarios, in which engine design and conditions may not always be optimised for minimising N_2O emissions, will be crucial to ensuring ammonia can deliver deep and meaningful emissions reductions.[11;12;13;14;15]

As during the WtT phase, TtW N_2O emissions can also arise indirectly due to release of other reactive nitrogen species. Reactive nitrogen will be released by venting ammonia from onboard storage tanks, while unburned ammonia (termed "ammonia slip") and NO_x will also be emitted from ship exhausts.[15] Finally, CO_2 emissions may also occur during ammonia combustion if a fossil fuel is used as a "pilot fuel" – a potentially necessary addition to initiate combustion due to ammonia's chemical properties.[35;36;37] Pilot fuels are often assumed to be around 5% of the total fuel.[e.g., 15]

Overall Well-to-Wake GHG emissions

Generally, only some of the sources of GHG emissions released across the ammonia fuel lifecycle are included in studies of ammonia's climate impact. Most studies, for instance, do not account for warming contributions from indirect N_2O and hydrogen.

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[30] Esquivel-Elizondo, S., Hormaza Mejia, A., Sun, T., Shrestha, E., Hamburg, S.P., Ocko, I.B., 2023. Wide range in estimates of hydrogen emissions from infrastructure. Front. Energy Res. 11, 1207208. https://doi.org/10.3389/fenrg.2023.1207208
[31] For example, see: MAN Energy Solutions, 2024. Ammonia as a fuel for two-stroke powered vessels. Unlocking the potential. Retrieved 10 June, 2025 from https://ammoniaenergy.org/wp-content/uploads/2024/11/E-Wilche-2024.pdf
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[37] Scharl and Sattelmayer, 2022. Ignition and combustion characteristics of diesel piloted ammonia injections. Fuel Communications 11, 100068. https://doi.org/10.1016/j.jfueco.2022.100068

Despite this, analyses of WtW emissions clearly reveal that grey/brown ammonia results in more GHG emissions than conventional shipping fuels. Grey/brown ammonia is therefore not a viable option for cutting maritime emissions.[15;25;26]

Similarly, the emissions reductions achievable using blue ammonia are relatively small. According to the most comprehensive study to date, blue ammonia can deliver at best 30% GHG emissions reductions compared with conventional fuels. At worst, for example in non-ideal conditions with high emissions of direct and indirect N_2O, blue ammonia can produce more GHG emissions on a WtW basis than conventional shipping fuels.[12;15]

Green ammonia is therefore the best option if ammonia is to deliver meaningful decarbonisation of the maritime sector, as estimates suggest green ammonia can significantly reduce WtW GHG emissions compared with conventional shipping fuels.[25;26;35;38] But these emission reductions from green ammonia are not guaranteed and are highly dependent on (1) the extent of direct N_2O emissions produced by burning ammonia in ship engines and (2) reactive nitrogen release throughout the ammonia fuel lifecycle and rates of conversion to indirect N_2O.[12;15]

In a scenario in which direct N_2O emissions and reactive nitrogen release are tightly controlled, one robust study calculates maximum potential WtW GHG emissions reductions for green ammonia of 68-80%, compared with conventional fuel oil.[15] However, under a higher emissions scenario, the same study finds that the achievable GHG emissions reductions fall to less than 25%, and could even be negated entirely if high rates of reactive nitrogen-N_2O conversion occur.[15] Including the impacts of hydrogen emissions would also further reduce GHG savings.[15]

Therefore, unless tightly controlled, direct and indirect N_2O, as well as hydrogen, emissions could significantly offset, or even negate entirely, the climate benefits of moving to ammonia as a shipping fuel:[11;12;13;14;15]

Recommendation 1

The ammonia used should be green, and N_2O emissions, hydrogen leaks and reactive nitrogen leaks, spills and emissions must be minimised.

- Without these conditions, the GHG emissions reductions achievable by using ammonia, compared with conventional fuels, are significantly reduced or even negated entirely.

[38] Dong, D.T., Schönborn, A., Christodoulou, A., Ölcer, A.I., González-Celis, J., 2024. Life cycle assessment of ammonia/hydrogen-driven marine propulsion. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 238, 531–542. https://doi.org/10.1177/14750902231207159

Environment and biodiversity

Aside from GHG emissions, other issues may stem from using ammonia as a shipping fuel. Environmental degradation and biodiversity impacts are of particular concern.

One risk arises from the fact that ammonia is **highly toxic** to marine and aquatic organisms. Ammonia spills or leaks from ships could therefore have fatal consequences for nearby marine life. [e.g., 39]

Additionally, leaks, spills and emissions of ammonia and other reactive nitrogen species (like N_2O and NO_x) will also contribute to **nitrogen pollution** of the environment, one potential outcome of which is **eutrophication**. Defined as an excess of nutrients, eutrophication can cause rapid growth of plants and algae in marine and aquatic environments. When these die, they can be decomposed by oxygen-consuming microorganisms, stripping oxygen from the water. This creates low-oxygen (known as hypoxic) conditions with potentially deadly consequences for marine life.[40]

This process may also contribute to **ocean darkening**, whereby an increase in surface ocean biomass reduces availability of light at depth, with potentially severe consequences for marine ecosystems.[41]

More widely, nitrogen pollution from shipping has been linked to **ocean acidification**.[42] Acidification threatens organisms which build calcium carbonate shells and skeletons.[43] Furthermore, N_2O is recognised as an **ozone depleting** substance,[44] yet is not currently regulated by the Montreal Protocol,[45] which mandated the phase-out of chlorofluorocarbons to address depletion of the Earth's ozone layer.

Finally, the environmental impacts of nitrogen pollution can also have knock-on **consequences for efforts to mitigate and adapt to climate change**. Both ocean acidification and hypoxia can increase environmental N_2O emissions from the ocean to the atmosphere.[46;47]

Furthermore, **coastal ecosystems** that play an important role in sequestering CO_2 and locking it away in so-called "blue carbon" stores,[48] such as estuaries, mangroves and wetlands, are particularly sensitive to ammonia spills.[39] Damaging these habitats risks reducing their carbon sink potential, as well as the climate adaptation benefits, such as coastal flood protection, they provide.[49;50]

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[39] Dawson, L., Ware, J., Vest, L., 2022. Ammonia as a Shipping Fuel: Impacts of large spill scenarios. Retrieved 4 June, 2025 from https://www.edf.org/media/environmental-defense-fund-lr-and-ricardo-launch-report-examining-ecological-impact-ammonia

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[41] Davies, T.W., Smyth, T., 2025. Darkening of the Global Ocean. Global Change Biology 31, e70227. https://doi.org/10.1111/gcb.70227

[42] Hassellöv, I. Turner, D. Lauer, A. Corbett, J., 2013. Shipping contributes to ocean acidification. Geophysical Research Letters. https://agupubs.onlinelibrary.wiley.com/doi/10.1002/grl.50521

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[44] Ravishankara, A.R., Daniel, J.S., Portmann, R.W., 2009. Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. Science 326, 123–125. https://doi.org/10.1126/science.1176985

[45] Vienna Convention for the Protection of the Ozone Layer, 1987. The Montreal Protocol on Substances that Deplete the Ozone Layer. Retrieved 4 June, 2025 from https://ozone.unep.org/treaties/montreal-protocol

[46] Breider, F., Yoshikawa, C., Makabe, A., Toyoda, S., Wakita, M., Matsui, Y., Kawagucci, S., Fujiki, T., Harada, N., Yoshida, N., 2019. Response of N_2O production rate to ocean acidification in the western North Pacific. Nat. Clim. Chang. 9, 954–958. https://doi.org/10.1038/s41558-019-0605-7 4

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[48] Lovelock, C.E., Duarte, C.M., 2019. Dimensions of Blue Carbon and emerging perspectives. Biol. Lett. 15, 20180781. https://doi.org/10.1098/rsbl.2018.0781

[49] Deegan, L.A., Johnson, D.S., Warren, R.S., Peterson, B.J., Fleeger, J.W., Fagherazzi, S., Wollheim, W.M., 2012. Coastal eutrophication as a driver of salt marsh loss. Nature 490, 388–392. https://doi.org/10.1038/nature11533

[50] Climate Change Committee, 2022. Briefing: Blue Carbon. Retrieved 4 March, 2025 from https://www.theccc.org.uk/publication/briefing-blue-carbon/

Air quality and public health

It's estimated that shipping pollution contributes to tens or even hundreds of thousands of premature deaths worldwide every year, with the health burden shouldered by those living close to ports or shipping lanes.[51;52;53] Some of the main contributors to this air pollution are sulphur oxides (SO_x) and NO_x, which contribute to the formation of fine particulate matter (PM2.5) and ground-level ozone.[54] Exposure to these pollutants causes health risks, including respiratory and cardiovascular diseases.[55]

Looking ahead, these risks could be worsened by the widespread adoption of ammonia as a shipping fuel. Specifically, ammonia itself is a harmful air pollutant, contributing to the formation of PM2.5.[54] When used as a shipping fuel, ammonia could be released to the atmosphere by venting (Table 1) and through unburned ammonia emissions. Since ammonia emissions from ships are currently unregulated, switching the entire global shipping fleet to run on pure ammonia without strengthening air pollution regulations could result in hundreds of thousands of additional premature deaths worldwide every year.[16]

However, exacerbating this major global health problem is not an inevitable consequence of deploying ammonia as a shipping fuel. With strict, global limits on allowable NO_x and ammonia emissions, ammonia could deliver public health benefits compared to the situation today, owing to reduced SO_x, and potentially NO_x, emissions compared with conventional fuels.[16]

Safety

The toxicity of ammonia is not just a challenge for the environment and biodiversity, but also creates safety risks throughout the fuel lifecycle for production workers, port staff, seafarers and communities close to ammonia infrastructure. Even at low concentrations exposure to ammonia is dangerous to health, while at high concentrations (> 300ppm) it can be fatal.[56]

There are a variety of mitigating measures which can be put in place to address safety concerns, and progress has been made in this regard. The International Maritime Organization (IMO) adopted interim guidelines for the safety of ships using ammonia as fuel in December 2024,[57] while a recent study documented an operational trial of ammonia bunkering.[58] Furthermore, ammonia has been produced and used in various

[51] Zhang, Y., Eastham, S.D., Lau, A.K., Fung, J.C., Selin, N.E., 2021. Global air quality and health impacts of domestic and international shipping. Environ. Res. Lett. 16, 084055. https://doi.org/10.1088/1748-9326/ac146b
[52] E.g., see review in: Kiihamäki, S.-P., Korhonen, M., Kukkonen, J., Shiue, I., Jaakkola, J.J.K., 2024. Effects of ambient air pollution from shipping on mortality: A systematic review. Science of The Total Environment 945, 173714. https://doi.org/10.1016/j.scitotenv.2024.173714
[53] Mueller, N., Westerby, M., Nieuwenhuijsen, M., 2023. Health impact assessments of shipping and port-sourced air pollution on a global scale: A scoping literature review. Environmental Research 216, 114460. https://doi.org/10.1016/j.envres.2022.114460
[54] Megaritis, A.G., Fountoukis, C., Charalampidis, P.E., Pilinis, C., Pandis, S.N., 2013. Response of fine particulate matter concentrations to changes of emissions and temperature in Europe. Atmos. Chem. Phys. 13, 3423–3443. https://doi.org/10.5194/acp-13-3423-2013
[55] Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., Van Dingenen, R., Van Donkelaar, A., Vos, T., Murray, C.J.L., Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. The Lancet 389, 1907–1918. https://doi.org/10.1016/S0140-6736(17)30505-6
[56] European Maritime Safety Agency (EMSA), 2023. Study Investigating the Safety of Ammonia as Fuel on Ships. EMSA, Lisbon. Retrieved 12 May, 2025 from https://emsa.europa.eu/publications/item/5264-safety-of-ammonia-for-use-in-ships-part-1-ammonia-properties,-regulations-and-accidents-review.html
[57] International Maritime Organization (IMO), 2025. MSC.1/Circ.1687. INTERIM GUIDELINES FOR THE SAFETY OF SHIPS USING AMMONIA AS FUEL. Retrieved 31 March, 2025.
[58] Global Centre for Maritime Decarbonisation (GCMD), 2025. Path to zero-carbon shipping: Insights from ammonia transfer trial in the Pilbara. Retrieved 16 June, 2025 from https://gcformd.org/our-publications/?report-id=8205

other sectors for almost a century, meaning industry has developed safety measures in the context of ammonia production, transport and storage.

Nevertheless, with comparatively little practical experience of using ammonia as a fuel at sea, it is widely recognised that more work needs to be done.[56] In this regard, workforce training represents a particular challenge. A recent survey found that while a majority of seafarers and onshore personnel would sail on, or work with, ammonia vessels, their acceptance of ammonia depends on comprehensive training.[59]

A truly just transition to alternative fuels like ammonia must consider safety issues, as well as the training and rights of workers, as central issues. It has been reported that a majority of seafarers do not think that the transition to net-zero will bring benefits for their working conditions.[60] The safety challenges posed by ammonia as a shipping fuel, while not insurmountable, emphasise the importance of putting workers and communities at the heart of technical, policy and regulatory developments.

Monitoring and addressing uncertainty

The above review illustrates the importance of addressing the climate, environmental, biodiversity, health and safety issues associated with using ammonia as a shipping fuel. It is important to highlight that successfully addressing these issues requires a full understanding of the extent of nitrogen pollution across the ammonia fuel lifecycle. As outlined above, however, significant uncertainties remain with wide ranges reported for direct N_2O emissions from ammonia engines,[13] uncertainty in the extent of ammonia leaks, spills and venting,[14;15] and uncertainty and environmental variability in the conversion rate of reactive nitrogen to indirect N_2O.[15]

As industry first-movers adopt ammonia-fuelled vessels, it is therefore essential that comprehensive, accurate and transparent data regarding reactive nitrogen emissions throughout the ammonia fuel lifecycle are made publicly available. Currently, this is not happening. Ammonia engine manufacturers, for example, are yet to provide publicly available engine emissions data in a format which can be directly compared with other scientific and industry data. This would entail providing granular emissions data, in standard units (e.g., g/kWh, or as a percentage of fuel consumption) across the full range of engine load factors - instead, engine manufacturers have thus far reported relative, or percentage, emissions reductions covering only some engine load factors.[e.g., 31;61;62] This is despite a call for transparency issued by a number of nonprofit organisations,[63] and makes it difficult to assess the likely magnitude of direct N_2O emissions from operational ammonia ship engines. More broadly, robust, publicly available data is essential to enable more accurate assessments of the scale of

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[59] Boulay, A., Iwamoto, S., Nieuwenhuijs, T., 2024. Investigating maritime community perceptions of ammonia as a marine fuel. Retrieved 12 May, 2025 from https://www.zerocarbonshipping.com/publications/investigating-maritime-community-perceptions-of-ammonia-as-a-marine-fuel/

[60] Nautilus Federation, 2024. Mapping Our Maritime Future Survey. Retrieved 12 May, 2025 from https://www.nautilusint.org/en/news-insight/resources/nautilus-reports/mapping-our-maritime-future-survey/

[61] WinGD, 2025. Press release: WinGD delivers exceptional results in full-load X-DF-A ammonia engine test. Retrieved 21 May, 2025 from https://wingd.com/news-media/news/wingd-delivers-exceptional-results-in-full-load-x-df-a-ammonia-engine-test

[62] WinGD, 2025. WinGD Dual-fuel Ammonia Engine Webinar. Retrieved 21 May, 2025 from https://www.youtube.com/watch?v=-MFu_9HlXpg

[63] Environmental Defense Fund et al., 2024. Open letter to marine engine manufacturers for transparency on N_2O & NH_3 emissions from ammonia engines. Retrieved 21 May, 2025 from https://www.edf.org/media/calling-marine-engine-manufacturers-transparency-emissions-data

nitrogen pollution from ammonia ships, as well as the design of technological, regulatory and/or policy measures to address those issues:

Recommendation 2

Monitoring and reporting both GHG emissions and all forms of reactive nitrogen pollution across the ammonia fuel lifecycle must be mandatory and transparent.

- This is to more accurately assessing the magnitude of nitrogen pollution from the ammonia fuel lifecycle, and the associated impacts.

Mitigating measures: policy, regulation and technology

Turning now to measures to address the issues associated with using ammonia as a shipping fuel, a number of these issues, though not all, can be tackled by minimising leaks, spills and emissions of reactive nitrogen species, necessitating additional policy and regulatory interventions.

There are a variety of interventions which could help minimise reactive nitrogen release throughout the ammonia fuel lifecycle, many of which can be categorised simply as “good housekeeping” – monitoring and addressing leaks in ammonia production, distribution and storage facilities, for example.

Technical interventions can also help. These include optimising the design and operation of ammonia ship engines by, for example, adjusting the ammonia injection pressure and combustion temperature,[34] and the relative angles and timing of pilot fuel and ammonia injection.[37]

Reactive nitrogen may also be removed from ship exhaust gases by exhaust gas after-treatment systems. Selective catalytic reduction (SCR) is already commonly used to reduce NO_x emissions from conventional ship engines. Ammonia oxidation catalysts (AOC) could additionally be applied to remove unburned ammonia slip.[64] However, as for conventional ships, the use of exhaust gas after-treatment systems onboard ammonia ships could create challenges: modelling suggests that AOC can increase N_2O emissions,[64] while the discharge of any effluent containing forms of reactive nitrogen would increase nitrogen pollution.

[64] Voniati, G., Dimaratos, A., Koltsakis, G., Ntziachristos, L., 2023. Ammonia as a Marine Fuel towards Decarbonization: Emission Control Challenges. Sustainability 15, 15565. https://doi.org/10.3390/su152115565

Many of these strategies are yet to be demonstrated in commercial ship engines. There is an urgent need to incentivise their demonstration, development and uptake and, more generally, to promote responsible and sustainable practices throughout the ammonia fuel lifecycle. To this end, effective policy and regulation will be essential:

Recommendation 3

There must be a robust regulatory and policy framework which manages nitrogen pollution across the fuel lifecycle.

- This is to ensure the safe use of ammonia enables GHG emissions reductions and minimises adverse public health, environmental and biodiversity impacts.

"Robust regulatory framework" is easily written, but what might this look like in practise? The following sections outline how key components of the regulatory and policy framework could be adapted to address GHG emissions and tackle nitrogen pollution.

Component 1: measures to reduce GHG emissions

A variety of policy and regulatory approaches have been, or are being, developed to reduce the shipping industry's GHG emissions.[65] Examples of these are the IMO's Net-Zero Framework, approved in April 2025, the EU's FuelEU Maritime Regulation, and the EU's Emissions Trading Scheme (the EU ETS), which has incorporated maritime emissions since 2024.

The **IMO's Net-Zero Framework** aims to reduce international shipping emissions with a two-tiered global fuel standard (learn more in our explainer[66]). Many of the details of the Framework are still to be decided, but each year ships will be given two target levels for their GHG emissions per unit of energy used (also known as Greenhouse Gas Fuel Intensity, or GFI). These two targets are a lower, base target and a higher, direct compliance target. Emissions over the lower target will be priced at a lower level, while those above the higher target will be priced at a higher level. Rewards will also be offered for ships using certain technologies, fuels or energy sources, although the details of this reward mechanism are yet to be decided.

Meanwhile, the EU has already adopted GHG intensity (i.e., GFI) limits, as well as other decarbonisation measures, via the **FuelEU Maritime Regulation**.[67] Additionally, the **EU ETS** puts a price on emissions, aiming to incentivise industry to reduce emissions. Ship

[65] The policy and regulatory schemes mentioned in this paper have their own advantages and disadvantages, including shortcomings with respect to their scopes and targets. However, discussion of these is beyond the scope of the present paper.
[66] Opportunity Green, 2025. The IMO Net-Zero Framework: what is it and how does it work? Retrieved 13 May, 2025 from https://www.opportunitygreen.org/factsheet-imo-net-zero-framework
[67] Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance). Retrieved 19 May, 2025 from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1805

operators must monitor, verify and report their emissions, and buy or trade allowances to cover them. In the coming years, other countries are expected to follow suit. The UK, for instance, recently renewed its pledge to incorporate shipping into the UK ETS from 2026.[68]

The IMO's Net-Zero Framework and EU ETS provide examples of how policy and regulation could incentivise GHG emission reductions. To maximise GHG emissions reductions from ammonia as a shipping fuel, any future measures should:

1. **Apply to emissions calculated on a WtW basis**, meaning that emissions associated with ammonia production, distribution, transport and bunkering are accounted for. The EU ETS already adopts a WtW approach, and this has been agreed for the IMO's Net-Zero Framework.

2. **Account for direct N_2O**. The EU ETS has included maritime CO_2 emissions since 2024 and is scheduled to incorporate maritime methane and N_2O emissions from 2026. Any future framework must also include direct N_2O emissions from the outset.

3. **Use Continuous Emissions Monitoring**. ETS schemes, for instance, generally give operators the option to measure their own emissions, or calculate them using default emission factors. Given the uncertainty in N_2O emissions from ammonia engines, operators should use Continuous Emissions Monitoring wherever possible. Default emission factors should be set to conservative (high) values to minimise the risk of under-reporting.

4. **Consider hydrogen and indirect N_2O emissions**. Although their climate change contributions are more uncertain than those of CO_2, direct N_2O and methane, there is no doubt that these substances make a material contribution to ammonia's GHG footprint.[15]

Component 2: measures to control air pollution

Currently, air pollution from shipping is regulated by **Emission Control Areas (ECAs)** – areas of sea in which limits on emissions of air pollutants including NO_x and SO_x apply.[69] Limits on NO_x are applied in a tiered approach, with Tier I being the least stringent and applying to the oldest vessels, and Tier III being the most stringent and applying to the newest vessels.[70] Most recently, the North-East Atlantic ECA was approved by IMO member states in April 2025.[71]

ECAs were designed to limit emissions of air pollutants from fossil-fuelled vessels, and air pollution control will need to be adapted to address the novel issues posed by

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[68] Department for Transport, 2025. Maritime decarbonisation strategy. Retrieved 13 May, 2025 from https://www.gov.uk/government/publications/maritime-decarbonisation-strategy
[69] International Maritime Organisation (IMO), 2025. Emission Control Areas (ECAs) designated under MARPOL Annex VI. Retrieved 19 May, 2025 from https://www.imo.org/en/OurWork/Environment/Pages/Emission-Control-Areas-(ECAs)-designated-under-regulation-13-of-MARPOL-Annex-VI-(NOx-emission-control).aspx
[70] International Maritime Organisation (IMO), 2025. Nitrogen Oxides (NOx) – Regulation 13. Retrieved 19 May, 2025 from https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx
[71] International Council on Clean Transportation (ICCT), 2025. Press release: International Maritime Organization approves world's largest Emission Control Area in the North-East Atlantic Ocean. Retrieved 14 May, 2025 from https://theicct.org/pr-imo-approves-worlds-largest-eca-in-north-east-atlantic-ocean/

alternative fuels like ammonia. Specifically, ammonia emissions from ships are currently unregulated – controls on ammonia venting and unburned ammonia emissions will likely be required to minimise adverse health, environmental and biodiversity impacts.[16]

Limits on ammonia emissions could be introduced, for instance by expanding the scope of ECAs.[16] In combination with extending ECAs more widely, these limits could provide safeguards not just for public health but also climate, the environment and biodiversity. On a national level, policy and regulation could also be leveraged to reduce emissions within ports. The FuelEU maritime regulation, for example, mandates the use of electric on-shore power supply or zero-emission technologies for vessels at berth or moored in certain ports by 2030.[67]

Component 3: developing the safety regulatory framework

The toxicity of ammonia as a shipping fuel demands robust safety measures be put in place. In response, the IMO's Maritime Safety Committee adopted interim guidelines for the safety of ships using ammonia as fuel in December 2024.[57]

The IMO's interim guidelines include a suite of measures, both technical and procedural, to mitigate safety hazards from using ammonia as fuel. There are clear overlaps between these measures and those which will be required to address climate, health and environmental issues – ensuring the safe operation of ammonia ships relies in part on minimising the release of ammonia from the closed fuel system to the environment, which is also essential for mitigating climate, health and environmental issues. The impacts of nitrogen pollution will also depend on the required extent of safety procedures such as ammonia venting. Therefore, there is a need to ensure:

1. Safety measures include a comprehensive, robust and transparent monitoring, evaluation, verification and reporting scheme for N_2O, NO_x and NH_3 spills, leaks and emissions.

2. Safety guidelines explicitly recognise the importance of minimising reactive nitrogen leaks, spills and emissions, and potential strategies to do so.

Component 4: cross-sectoral and consistent policy and regulation

Beyond the above non-exhaustive review of potential policies to regulate ammonia as a shipping fuel, ammonia is today predominantly used by the agriculture sector, and in the future may also be used in the energy sector as a hydrogen carrier.[14] Policymakers should have an eye to ensuring ambitious policy and regulation is harmonised across different ammonia use cases, be that through cross-sectoral or bespoke, sector-specific measures.

Environmental and biodiversity ambitions, policies and regulations are examples of cross-sectoral measures relevant to a range of ammonia use cases. At a global level, the United Nations Environment Assembly adopted a resolution in 2022 which "encourages Member States to accelerate actions to significantly reduce nitrogen waste globally by 2030",[72] while the 2019 Colombo Declaration called for ambition to halve nitrogen waste by the same date.[73] Aside from ambition, specific examples of relevant policy and regulation include the EU's Marine Strategy Framework Directive, which recognises reduced eutrophication as a descriptor for Good Environmental Status in the EU's marine area.[74] Meanwhile in England, the Environmental Targets Regulations[75] set out legally binding targets for reducing nitrogen pollution of the water environment (which includes coastal environments) by agricultural activities, but do not encompass other sources of nitrogen pollution.

This illustrates how existing, cross-sectoral, commitments, policies and regulations must be adhered to as the shipping industry adopts ammonia-fuelled vessels. New and adapted policy and regulation will also be needed to limit the risks of nitrogen pollution from the use of ammonia as a shipping fuel.

Summary

Decarbonising shipping will in part rely on replacing conventional fossil fuels with lower emission alternative fuels. However, each alternative fuel poses unique climate, safety, environmental, biodiversity and social (e.g., health) challenges.

The shipping industry's energy requirements should therefore be met in the first instance by demand reduction, improvements in energy efficiency, increased use of wind-assisted propulsion, reduced speeds and electrification to the fullest extent possible. Despite this, for some applications, alternative fuels will be required to meet the industry's energy demands. Future projections tend to assume that the fuel mix of a decarbonised shipping industry will include a range of fuels, with potential contributions from ammonia, methanol, hydrogen and biofuels.[e.g., 10]

Of these, ammonia can be a safe fuel that delivers meaningful GHG emissions reductions. However, reactive nitrogen release throughout the ammonia fuel lifecycle creates a number of risks. Efforts to decarbonise shipping have focused mostly on CO_2 emissions. However, to truly deliver an effective, just and equitable transition, it is essential to look beyond CO_2 and avoid swapping one pollution crisis with another. In order to ensure that ammonia becomes a safe shipping fuel which contributes meaningfully to reducing the industry's GHG emissions, while minimising adverse public health, environmental and biodiversity impacts, we make three key recommendations, summarised in Table 2 below.

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[72] United Nations Environment Assembly of the United Nations Environment Programme, 2022. UNEP/EA.5/Res.2. Sustainable nitrogen management. Retrieved 4 June, 2025 from https://www.unep.org/nitrogen-management-WG

[73] United Nations Environment Programme, 2019. Press release. Colombo Declaration calls for tackling global nitrogen challenge. Retrieved 4 June, 2025 from https://www.unep.org/news-and-stories/press-release/colombo-declaration-calls-tackling-global-nitrogen-challenge

[74] Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) (Text with EEA relevance). Retrieved 19 May, 2025 from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0056

[75] The Environmental Targets (Water) (England) Regulations 2023. Retrieved 21 May, 2025 from https://www.legislation.gov.uk/uksi/2023/93/made

Recommendations for using ammonia as a shipping fuel	Why?
The ammonia used should be green, and N_2O emissions, hydrogen leaks and reactive nitrogen leaks, spills and emissions must be minimised.	Without these conditions, the GHG emissions reductions achievable by using ammonia, compared with conventional fuels, are significantly reduced or even negated entirely.
Monitoring and reporting both GHG emissions and all forms of reactive nitrogen pollution across the ammonia fuel lifecycle must be mandatory and transparent.	To more accurately assess the magnitude of nitrogen pollution from the ammonia fuel lifecycle, and the associated impacts.
There must be a robust regulatory and policy framework which manages nitrogen pollution across the fuel life cycle.	To ensure the safe use of ammonia enables GHG emissions reductions and minimises adverse public health, environmental and biodiversity impacts.

Table 2. Summary of recommendations made in this briefing. This briefing focuses on the use of ammonia as a shipping fuel, with recommendations tailored to the shipping industry's unique governance structures. However, as outlined in the main text, these recommendations are also relevant for other industries which use ammonia (e.g., agriculture), and there is a need for a coordinated approach to policy and regulation across all ammonia use cases.

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Legal disclaimer

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