INTERNATIONAL MARITIME ORGANIZATION

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INTERSESSIONAL MEETING OF THE WORKING GROUP ON REDUCTION OF GHG EMISSIONS FROM SHIPS
21st session
Agenda item 3

ISWG-GHG 21/3/20
6 March 2026
ENGLISH ONLY
Pre-session public release: ☒

FURTHER CONSIDERATION OF THE DEVELOPMENT OF THE IMO LIFE CYCLE GHG ASSESSMENT (LCA) FRAMEWORK

Accounting for the climate impacts of hydrogen and reactive nitrogen emissions

Submitted by Pacific Environment and EDF

SUMMARY

Executive summary:	There is a range of substances that influence Earth's climate. GHGs like CO_2 do so directly, while other substances change the global carbon cycle and/or atmospheric chemistry to warm the planet indirectly. Some of these substances are not currently targeted by IMO climate measures, and recent work has highlighted the importance of considering the climate impacts of shipping's hydrogen and reactive nitrogen emissions. This document summarizes the evidence regarding the indirect climate impacts of hydrogen and reactive nitrogen emissions from shipping. Though uncertain, these impacts currently arise from the use of conventional fossil fuels in ship engines and may result from the use of alternative fuels in the future. The associated public health, environmental, biodiversity and safety impacts of some of these emissions strengthen the case for action to control them.
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 57
Related documents:	MEPC 84/7/15; MSC 110/6/1, MSC 110/6/8; ISWG-GHG 20/4 and ISWG-GHG 18/3

Introduction

1 The *2023 IMO Strategy on Reduction of GHG Emissions from Ships* (2023 IMO GHG Strategy) sets out the ambition for greenhouse gas (GHG) emissions from international shipping to meet net zero by around 2050. Reflecting this, IMO is continuing to develop measures or tools to monitor and reduce shipping's GHG emissions. Examples of relevant measures or tools include the five-yearly IMO GHG studies, the *2024 Guidelines on life cycle GHG intensity of marine fuels* (2024 LCA Guidelines) (resolution MEPC.391(81)) and the development of the IMO Net-Zero Framework.

2 IMO efforts to reduce shipping's GHG emissions focus on the GHGs carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Cutting these emissions is the priority in shipping's decarbonization journey, and will require action including energy efficiency improvements, widespread electrification and replacement of fossil fuels with lower emission alternatives, such as green hydrogen-derived electro-fuels (herein referred to as e-fuels).[1]

3 Beyond CO_2, CH_4 and N_2O, IMO also works to track and, in some cases, reduce, emissions of other climate-relevant substances. For instance, action is ongoing to reduce emissions of Black Carbon, while the GHG Studies track emissions including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), particulate matter (PM) and sulphur oxides (SO_x).

4 More generally, a range of substances influences Earth's climate, via direct and indirect, warming and cooling impacts.[2] Some of these substances are classed as "indirect GHGs", meaning they do not cause planetary warming directly. Instead, they change the global carbon cycle and/or atmospheric chemistry, in turn increasing the concentration of GHGs and resulting in warming. Not all indirect GHGs are currently addressed by IMO climate measures, including hydrogen, which increases the concentrations of CH_4 and other GHGs in the atmosphere, and reactive nitrogen species like ammonia (NH_3) and NO_x (note the latter is monitored by the IMO GHG studies)—which are converted into N_2O (and other reactive nitrogen species) in the environment[3] and the atmosphere.[4]

5 Hydrogen and reactive nitrogen leaks and emissions may occur throughout the value chains of various fuels, including, but not limited to, e-fuels and biofuels, and research is clear that minimizing these emissions is crucial for maximizing e-fuel climate benefits.[5] Reflecting this, document ISWG-GHG 20/4 (CLIA et al.) called for "inclusion of (…) relevant substances from low- and zero-carbon marine fuels in the Fifth IMO GHG Study emissions inventory", referencing the indirect climate impacts of hydrogen and reactive nitrogen species specifically.[6] Similarly, document ISWG-GHG 18/3 (RINA) called for the addition of a complementary metric to the 2024 LCA Guidelines accounting for the indirect climate impacts of NH_3 emissions.[7]

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1 Phillips J and others, 'Fuelling nature: how e-fuels can mitigate biodiversity risk in EU aviation and maritime policy' (2024). Retrieved 17 November 2025 from https://www.sashacoalition.org/biodiversity-risks-eu-aviation-maritime-policy.

2 Szopa S and others, 'Short-Lived Climate Forcers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change' (2021) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 817–922, doi: 10.1017/9781009157896.008.

3 Denier Van Der Gon H and Bleeker A, 'Indirect N_2O Emission Due to Atmospheric N Deposition for the Netherlands' (2005) 39 Atmospheric Environment 5827.

4 Pai SJ, Heald CL and Murphy JG, 'Exploring the Global Importance of Atmospheric Ammonia Oxidation' (2021) 5 ACS Earth and Space Chemistry 1674.

5 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

6 CLIA and others, 'ISWG-GHG 20/4. Inclusion of other relevant substances from low- and zero-carbon marine fuels in the Fifth IMO GHG Study emissions inventory' (2025).

7 RINA, 'ISWG-GHG 18/3. Advancing environmental sustainability metrics: a pathway to robust fuel certification for maritime decarbonization' (2024).

6 However, the climate impacts of indirect GHGs, and especially reactive nitrogen species, are not unique to low- and zero-carbon fuels, and currently arise from the use of fossil fuels. What is needed is a holistic and consistent approach to manage these emissions from all fuels, both conventional and alternative.

7 More generally, there is currently a lack of consensus on how IMO should account for and address the indirect climate impacts of substances like hydrogen and reactive nitrogen. For example, on the topic of indirect N_2O climate impacts arising from NH_3 emissions, the report of the second meeting of the GESAMP-LCA Working Group (MEPC 84/7/15) states that "while it is well documented that ammonia used in fertilizers on soil contributes to N_2O emission (…) the Group was not aware of any scientific report regarding indirect emissions of N_2O from ammonia in the air".[8]

8 To provide further information on this topic, this document summarizes the state of scientific knowledge regarding the indirect climate impacts of hydrogen and reactive nitrogen emissions, and their current and future contribution to shipping's overall climate footprint. The co-sponsors also briefly summarize the wider safety, air quality, environmental and biodiversity impacts of reactive nitrogen emissions. Finally, the co-sponsors make recommendations for monitoring these emissions and highlight potential measures to control these via a range of interventions. This document is relevant to the development of the life cycle assessment (LCA) framework (agenda item 3), but also includes a proposal related to agenda item 4, and the finalization of the draft terms of reference for the Fifth IMO GHG Study.

Indirect climate impacts of hydrogen and reactive nitrogen species

Hydrogen

9 When hydrogen is emitted to the atmosphere, it reacts with hydroxyl radicals (OH) to form water vapour. OH is the main oxidizing agent in the atmosphere, responsible, for example, for the oxidation of methane. Therefore, increasing atmospheric hydrogen concentrations reduces OH concentrations, and, in turn, increases the atmospheric lifetime and concentration of methane. Hydrogen emissions also increase concentrations of tropospheric ozone and water vapour, both of which are short-lived GHGs.[9, 10, 11]

10 As a result, hydrogen is an indirect GHG with a 100-year Global Warming Potential (GWP) of around 10, with recent estimates spanning values from 8.8 to ~ 12.[12, 13, 14] However,

8 IMO Secretariat, 'MEPC 84/7/15. Report of the second meeting of GESAMP-LCA Working Group' (2025).

9 Derwent R and others, 'Global Environmental Impacts of the Hydrogen Economy' (2006) 1 International Journal of Nuclear Hydrogen Production and Applications 57.

10 Warwick NJ and others, 'Atmospheric Composition and Climate Impacts of a Future Hydrogen Economy' (2023) 23 Atmospheric Chemistry and Physics 13451.

11 Sun T and others, 'Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales' (2024) 58 Environmental Science & Technology 5299.

12 Yang LH and others, 'Assessment of Hydrogen's Climate Impact Is Affected by Model OH Biases' (2025) 52 Geophysical Research Letters e2024GL112445.

13 Warwick NJ and others, 'Atmospheric Composition and Climate Impacts of a Future Hydrogen Economy' (2023) 23 Atmospheric Chemistry and Physics 13451.

14 Sand M and others, 'A Multi-Model Assessment of the Global Warming Potential of Hydrogen' (2023) 4 Communications Earth & Environment 203.

as a short-lived molecule, its 20-year GWP is around three times higher (GWP20 ~ 30 to 40).[15, 16, 17]

11 The range in estimates of hydrogen's GWP demonstrates the uncertainties around its exact climate impacts, however there is scientific consensus that hydrogen is an indirect GHG.[18, 19] The concentration of hydrogen in the atmosphere is a balance between sources (which add hydrogen to the atmosphere) and sinks (which remove hydrogen from the atmosphere). While hydrogen sinks are dominated by soil uptake, sources are driven by oxidation of CH_4 and volatile organic compounds, nitrogen fixation, and leakage from hydrogen production and use, which is likely to grow rapidly under hydrogen-economy scenarios.[20] Accordingly, as a leak-prone molecule, hydrogen emissions must be minimized if the potential climate benefits of shifting to a hydrogen economy are to be fully realized.

12 For instance, when hydrogen leak rates are low (e.g. 1% across the value chain), using green hydrogen as a fuel can reduce 100-year climate impacts by 90 to 95% compared with using fossil fuels, across a wide range of sectors.[21, 22] Research suggests that at higher leakage rates (e.g. 10%), climate benefits remain significant but are reduced. For example, one study suggests that green hydrogen with 10% hydrogen leakage can result in 85% emissions reductions, compared with fossil fuels.[23] The reduction in climate benefits due to hydrogen leakage is also heightened when considering climate impacts on shorter timescales (e.g. 10 to 20 years).

13 Hydrogen leakage is also an important consideration in the life cycle climate impacts of e-fuels like e-methane, e-methanol and e-NH_3.[24]

15 Warwick NJ and others, 'Atmospheric Composition and Climate Impacts of a Future Hydrogen Economy' (2023) 23 Atmospheric Chemistry and Physics 13451.

16 Sand M and others, 'A Multi-Model Assessment of the Global Warming Potential of Hydrogen' (2023) 4 Communications Earth & Environment 203.

17 Ocko IB and Hamburg SP, 'Climate Consequences of Hydrogen Emissions' (2022) 22 Atmospheric Chemistry and Physics 9349.

18 Maria Sand and others, 'A Multi-Model Assessment of the Global Warming Potential of Hydrogen' (2023) 4 Communications Earth & Environment 203.

19 Zutao Ouyang and others, 'The Global Hydrogen Budget' (2025) 648 Nature 616.

20 Zutao Ouyang and others, 'The Global Hydrogen Budget' (2025) 648 Nature 616.

21 Sun T and others, 'Climate Impacts of Hydrogen and Methane Emissions Can Considerably Reduce the Climate Benefits across Key Hydrogen Use Cases and Time Scales' (2024) 58 Environmental Science & Technology 5299.

22 Ocko IB and Hamburg SP, 'Climate Consequences of Hydrogen Emissions' (2022) 22 Atmospheric Chemistry and Physics 9349.

23 Ocko IB and Hamburg SP, 'Climate Consequences of Hydrogen Emissions' (2022) 22 Atmospheric Chemistry and Physics 9349.

24 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

Reactive nitrogen species

14 Reactive nitrogen species, secondly, include N_2O, NO_x and NH_3. N_2O is a potent GHG with a climate impact 273 times larger than CO_2 on a 100-year timescale.[25] N_2O is emitted directly from ship engines when fossil fuels are burned. These direct N_2O emissions accounted for ~1.5% of international shipping's total climate impact in 2018.[26] Direct N_2O emissions are already accounted for in the IMO GHG studies and are the subject of proposed measures in the IMO Net-Zero Framework (e.g. direct N_2O emissions are included in fuel emission factors).

15 Additionally, reactive nitrogen species can also cause indirect climate impacts. Both NO_x and NH_3 can also cause indirect climate warming by increasing the atmospheric concentration of N_2O. When emitted to the environment, NH_3 and NO_x can transition through a range of chemical reactions as part of the nitrogen cycle, also referred to as the nitrogen cascade, eventually forming "indirect N_2O".[27, 28] This can occur both by oxidation of NH_3 in the atmosphere, and by conversion of reactive nitrogen to N_2O after deposition on soils and waters.[29, 30] These indirect N_2O emissions are addressed by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*[31] (see details in paragraph 19) but not currently accounted for by the IMO GHG studies, nor are they addressed by proposals as part of the IMO Net-Zero Framework.

16 Understanding of the climate impacts of indirect N_2O is developing. Specifically, uncertainty remains regarding the rate of NO_x and NH_3 conversion to indirect N_2O, which varies owing to environmental conditions.[32, 33] Most evidence comes from agricultural contexts, where conversion rates ranging from 0.1 to 24% have been documented.[34]

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25 Intergovernmental Panel On Climate Change (IPCC), 'Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change' (1st edn, Cambridge University Press 2023). Retrieved 17 November 2025 from https://www.cambridge.org/core/product/identifier/9781009157896/type/book.

26 International Maritime Organization, 'Fourth IMO GHG Study 2020' (2020). Retrieved 17 November 2025 from https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx.

27 Denier Van Der Gon H and Bleeker A, 'Indirect N_2O Emission Due to Atmospheric N Deposition for the Netherlands' (2005) 39 Atmospheric Environment 5827.

28 Pai SJ, Heald CL and Murphy JG, 'Exploring the Global Importance of Atmospheric Ammonia Oxidation' (2021) 5 ACS Earth and Space Chemistry 1674.

29 Gillenwater M, Saarinen K and Ajavon A, '2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 7 PRECURSORS AND INDIRECT EMISSIONS' (2006). Retrieved 4 March 2026 from https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html.

30 Pai SJ, Heald CL and Murphy JG, 'Exploring the Global Importance of Atmospheric Ammonia Oxidation' (2021) 5 ACS Earth and Space Chemistry 1674.

31 Hergoualc'h K and others, '2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 11 N_2O EMISSIONS FROM MANAGED SOILS, AND CO_2 EMISSIONS FROM LIME AND UREA APPLICATION' (2019). Retrieved 4 March 2026 from https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.

32 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

33 Short MD and others, 'Marine Nitrous Oxide Emissions: An Unknown Liability for the International Water Sector' (2013) 33 Environmental Science & Policy 209.

34 See review and references in Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

17 Meanwhile, evidence regarding the conversion of ship-emitted reactive nitrogen, including in marine environments, highlights that the fate of ship-emitted reactive nitrogen depends on atmospheric transport, the site of deposition, whether in terrestrial or marine environments, and subsequent biogeochemical transformation. Both NH_3 and NO_x can be transported hundreds or thousands of kilometres before deposition, but as a result of its shorter atmospheric lifetime, NH_3 emissions are typically deposited comparatively close to their source, compared with NO_x emissions, potentially creating more localized deposition hot spots.[35] Depending on where deposition occurs, these reactive nitrogen species subsequently enter either marine or terrestrial biogeochemical cycles, where they may form indirect N_2O. In marine environments, the location and timing of deposition is a key factor in determining conversion to N_2O: in oxygenated waters reactive nitrogen deposition enhances phytoplankton productivity, while in oxygen-deficient regions microbial processes form N_2O.[36, 37]

18 This evidence highlights that the conversion of reactive nitrogen species to indirect N_2O varies in time and space, in both marine and terrestrial environments.[38] Despite the need for more research to constrain NO_x and NH_3 conversion rates to N_2O in marine environments, there is clear evidence that marine fuel life cycle reactive nitrogen emissions will lead to indirect N_2O production, with documented examples of marine N_2O production due to deposition of reactive nitrogen emissions in marine environments.[39, 40]

19 IPCC guidance exists for calculating indirect N_2O emissions due to atmospheric reactive nitrogen (NO_x and NH_3) deposition from processes like fuel combustion and industrial waste, [41] as well as specific guidance for indirect N_2O resulting from land use and agricultural activities.[42] This guidance suggests that ~1% of reactive nitrogen is converted to indirect N_2O and is applied in various contexts. The United Kingdom, for example, reports indirect N_2O emissions to the UNFCCC as a memo item, as part of its annual GHG reporting.[43]

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35 Willem AH Asman, Mark A Sutton and Jan K Schjørring, 'Ammonia: Emission, Atmospheric Transport and Deposition' (1998) 139 New Phytologist 27.

36 SWA Naqvi and others, 'Marine Hypoxia/Anoxia as a Source of CH_4 and N_2O' (2010) 7 Biogeosciences 2159.

37 Parvadha Suntharalingam and others, 'Quantifying the Impact of Anthropogenic Nitrogen Deposition on Oceanic Nitrous Oxide' (2012) 39 Geophysical Research Letters 2011GL050778.

38 Klaus Butterbach-Bahl and others, 'Nitrous Oxide Emissions from Soils: How Well Do We Understand the Processes and Their Controls?' (2013) 368 Philosophical Transactions of the Royal Society B: Biological Sciences 20130122.

39 Parvadha Suntharalingam and others, 'Quantifying the Impact of Anthropogenic Nitrogen Deposition on Oceanic Nitrous Oxide' (2012) 39 Geophysical Research Letters 2011GL050778.

40 RA Duce and others, 'Impacts of Atmospheric Anthropogenic Nitrogen on the Open Ocean' (2008) 320 Science 893.

41 Gillenwater M, Saarinen K and Ajavon A, '2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 7 PRECURSORS AND INDIRECT EMISSIONS' (2006). Retrieved 17 November 2025 from https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html.

42 Hergoualc'h K and others, '2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 11 N_2O EMISSIONS FROM MANAGED SOILS, AND CO_2 EMISSIONS FROM LIME AND UREA APPLICATION' (2019). Retrieved 17 November 2025 from https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.

43 Brown P and others, 'UK Greenhouse Gas Inventory, 1990 to 2022. Annual Report for Submission under the Framework Convention on Climate Change' (2024). Retrieved 17 November 2025 from https://naei.energysecurity.gov.uk/reports/uk-greenhouse-gas-inventory-1990-2022-annual-report-submission-under-framework-convention.

20 Separately, previous studies have also identified that NO_x and NH_3 emissions cause short-term radiative forcing, as has been specifically recognized for the shipping industry.[44, 45, 46] NO_x emissions result in short-term climate impacts via complex nonlinear chemistry, resulting in indirect cooling effects from methane reductions and indirect warming effects from ground-level (tropospheric) ozone and aerosol ($PM_{2.5}$) enhancements. Presently, the combination of these processes is thought to result in overall short-term cooling impacts.[47] However, it is worth noting that the IPCC and other literature have consistently highlighted the uncertainty and context-dependence of the short-term radiative forcing impacts of NO_x, due to its high reactivity, nonlinear chemistry, and heterogeneous emission patterns.[48, 49, 50, 51, 52] NH_3 emissions also result in short-term impacts, mainly through the formation of secondary aerosols ($PM_{2.5}$) that scatter sunlight (cooling) and act as cloud-condensation nuclei with warming or cooling impacts depending on cloud properties. These effects are similarly difficult to quantify and are associated with large uncertainties.[53]

21 The best-estimate effective radiative forcing values for both NO_x and NH_3 reported by the IPCC currently only include the short-term climate impacts of these species, and do not include the climate impacts of indirect N_2O.[54] Whereas the short-term climate impacts of both NO_x and NH_3 are highly uncertain, as outlined above, it is unequivocal that the conversion of NO_x and NH_3 to form indirect N_2O causes long-term (i.e. hundreds of years) climate warming. Given this, recent research has highlighted that it is critical to consider both the short-term cooling effects of NO_x and NH_3 and the long-term warming effects of indirect N_2O when

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44 Fuglestvedt J and others, 'Shipping Emissions: From Cooling to Warming of Climate—and Reducing Impacts on Health' (2009) 43 Environmental Science & Technology 9057.

45 Holmes CD, Prather MJ and Vinken GCM, 'The Climate Impact of Ship NO_x Emissions: An Improved Estimate Accounting for Plume Chemistry' (2014) 14 Atmospheric Chemistry and Physics 6801.

46 Cheng Gong and others, 'Global Net Climate Effects of Anthropogenic Reactive Nitrogen' (2024) 632 Nature 557.

47 Szopa S and others, 'Short-Lived Climate Forcers' (2021). In Masson-Delmotte, V and others (eds.), 'Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'.

48 Myhre G and others, 'Anthropogenic and Natural Radiative Forcing' (2013). In Stocker T and others (eds.), 'Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change'.

49 Szopa S and others, 'Short-Lived Climate Forcers' (2021). In Masson-Delmotte, V and others (eds.), 'Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'.

50 Cheng Gong and others, 'Global Net Climate Effects of Anthropogenic Reactive Nitrogen' (2024) 632 Nature 557.

51 Øivind Hodnebrog and others, 'Uncertain Climate Effects of Anthropogenic Reactive Nitrogen' (2025) 646 Nature E4.

52 Cheng Gong and others, 'Reply to: Uncertain Climate Effects of Anthropogenic Reactive Nitrogen' (2025) 646 Nature E10.

53 Szopa S and others, 'Short-Lived Climate Forcers' (2021). In Masson-Delmotte, V and others (eds.), 'Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'.

54 Szopa S and others, 'Short-Lived Climate Forcers Supplementary Material' (2021). In Masson-Delmotte, V and others (eds.), 'Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'.

calculating the overall climate impacts of reactive nitrogen species.[55] This underscores the need for robust monitoring and measurement of NO_x, NH_3, and N_2O across fuel value chains.

Case studies of the climate impacts of indirect N_2O

22 Although indirect N_2O is not currently monitored in IMO GHG studies or incorporated into proposed measures in the IMO Net-Zero Framework, it contributes to shipping's climate impact today and may do so in the future. Here, the co-sponsors outline four case studies demonstrating this, focusing on indirect N_2O emissions from the use of fossil fuels in ships today, and from the use of NH_3 (ammonia) and biofuels in the future. Reflecting the estimated range of reactive nitrogen to indirect N_2O conversion rates (0.1 to 24%), all of the following calculations use a conservative 1% conversion rate, in line with IPCC guidelines.[56] It is important to note that the following case studies are not exhaustive, and the principles they highlight will be more widely applicable to other fuels.

Case study 1: NO_x emissions from international shipping in 2018

23 The Fourth IMO GHG Study showed that in 2018, NO_x emissions from international shipping totalled 17.1 Mt.[57] If 1 % of the reactive nitrogen released to the environment by these NO_x emissions were converted to indirect N_2O (see paragraphs 15 through 19), these emissions would total some 33 $MtCO_2eq$,[58] roughly equivalent to the annual emissions of a country like Slovakia (34 $MtCO_2eq$ in 2021).[59]

24 This is equivalent to 4% of international shipping's 2018 total GHG emissions (including CO_2, N_2O, CH_4 and Black Carbon), representing a larger share than methane and direct N_2O together (1.8% of the total). It is important to note that since the Fourth IMO GHG Study calculated shipping's 2018 emissions, the contribution of methane today could be much larger, owing to there being more than 800 operational LNG ships in 2025, compared to ~120 in 2018.[60]

25 Including NO_x-derived indirect N_2O in the Fourth IMO GHG Study would have increased total GHG emissions from international shipping in 2018 from 810 to 844 $MtCO_2eq$.

55 Pai SJ, Heald CL and Murphy JG, 'Exploring the Global Importance of Atmospheric Ammonia Oxidation' (2021) 5 ACS Earth and Space Chemistry 1674.

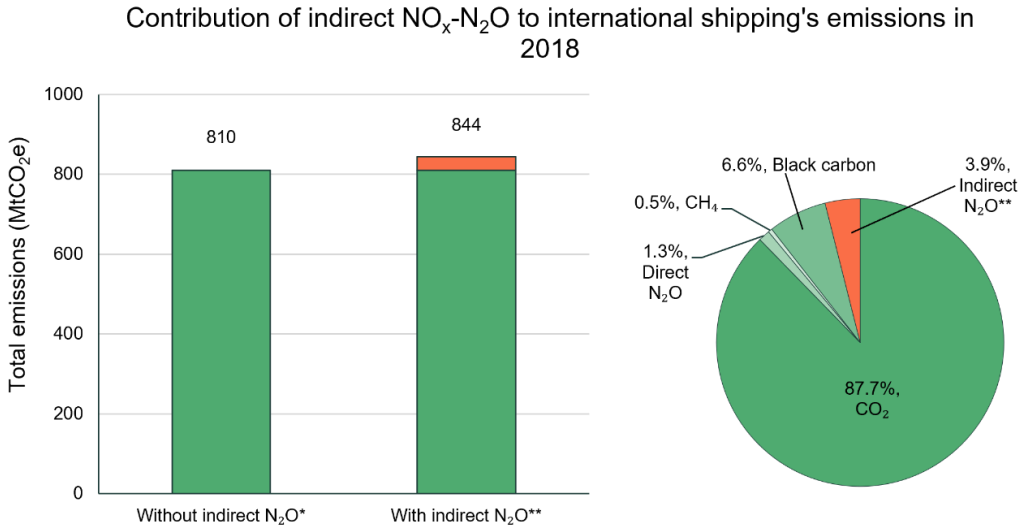
56 Conversion rate is moles of nitrogen in a given reactive nitrogen species converted to nitrogen in N_2O (indirect N_2O-N).

57 International Maritime Organization, 'Fourth IMO GHG Study 2020' (2020). Retrieved 17 November 2025 from https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx.

58 Assumes N_2O GWP-100 = 265, consistent with the 4th IMO GHG Study. All other calculations in this document use N_2O GWP-100 = 273, consistent with most recent estimates. Calculations assume all NO_x is present as NO.

59 EU Emissions Tracker (2025). Retrieved 25 November 2025 from https://emission-tracker.eu/?country=AT.

60 DNV, 'Alternative Fuels Insight' (2025). Retrieved 8 December, 2025 from https://www.dnv.com/services/alternative-fuels-insights-afi--128171/.



*Includes CO_2, CH_4, direct N_2O and black carbon. Data from 4th IMO GHG Study
**Indirect N_2O calculations assume 1% conversion of NO_x-N to N_2O-N

Figure 1: Shipping's climate impacts with and without indirect N_2O. Data taken from the Fourth IMO GHG Study.[61]

Case study 2: conventional fuel emission factors and air pollution controls

26 As demonstrated by case study 1, conventional shipping fuels produce GHG emissions which are dominated by CO_2. These fuels produce life cycle CO_2 equivalent direct GHG emissions (including CO_2, CH_4 and direct N_2O) of 83 to 118 gCO_2eq/MJ.[62] Indirect N_2O emissions are not included in these emissions factors.

27 Using conventional marine fuels results in emissions of NO_x during fuel combustion. NO_x emissions are limited by the requirements set out in the NO_x Technical Code 2008, which become more stringent from Tier I to Tier III.[63]

28 The impact of indirect N_2O emissions associated with a ship operating at the NO_x Tier I and Tier III limits (which vary by engine speed) on GHG emission factors are shown in Figure 2. For a vessel using fuel with a representative initial GHG intensity of 90 gCO_2eq/MJ, indirect N_2O resulting from NO_x emissions at the Tier III limit add just 1-2 % to the total emission factor. However, operating in accordance with the Tier I limit adds 6-11%.

29 Crucially, this case study illustrates how effective air pollution policy can minimize indirect climate impacts, which more broadly highlights that a range of measures are available to help reduce these impacts.[64]

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61 International Maritime Organization, 'Fourth IMO GHG Study 2020' (2020). Retrieved 17 November 2025 from https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx.

62 European Commission Joint Research Centre, 'Quantifying Emissions in the European Maritime Sector: A Review on Life Cycle Assessments of Maritime Systems Combined with an Analysis of the THETIS MRV Portal' (2022). Retrieved 17 November 2025 from https://data.europa.eu/doi/10.2760/496363.

63 International Maritime Organization (IMO), 'Nitrogen Oxides (NO_x) – Regulation 13' (no date) and references therein. Retrieved 8 December 2025 from https://www.imo.org/en/ourwork/environment/pages/nitrogen-oxides-(nox)-%E2%80%93-regulation-13.aspx.

64 E.g., Kershaw J, 'Policy briefing on ammonia as a shipping fuel' (2025). Retrieved 17 November 2025 from https://www.opportunitygreen.org/publication-policy-briefing-ammonia-shipping-fuel.

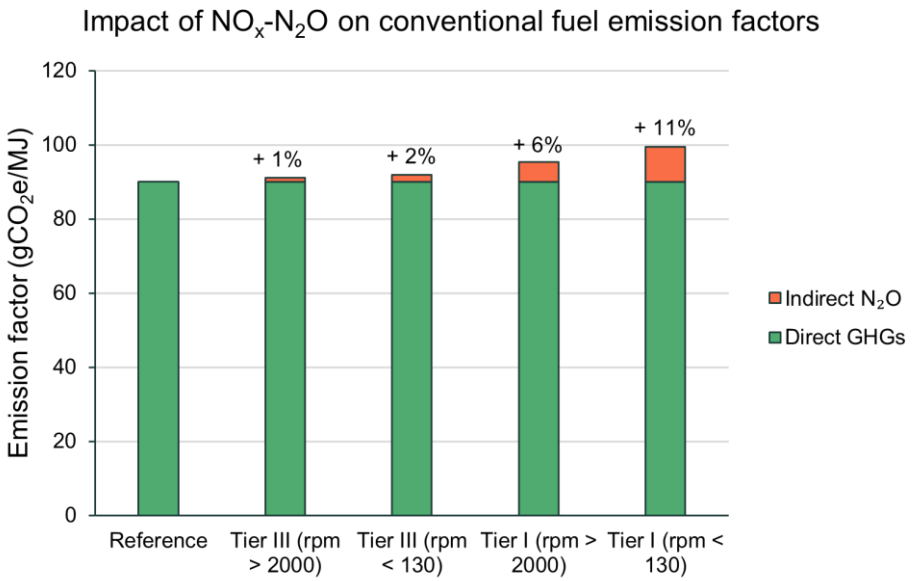


Figure 2: The impact on conventional oil emission factors, if including indirect N_2O derived from NO_x emissions. Calculations are shown for NO_x emissions equivalent to the Tier I and Tier III limits, as set out in the NO_x Technical Code 2008.

Case study 3: e-NH_3 emission factors

30 Turning now to alternative fuels, recent research has studied the impacts of indirect N_2O on the climate benefits of using NH_3 as a shipping fuel.[65, 66] NH_3 leaks and other emissions can occur at all stages of the fuel value chain, from NH_3 production through to end use on ships.[67, 68, 69] As well as unburned NH_3, emissions of direct N_2O and NO_x can also occur during NH_3 combustion in ship engines.

31 Published data reveal a wide range in direct N_2O emissions from NH_3 engines, highlighting the need for appropriate measures to address these.[70] If direct N_2O emissions are effectively controlled, well-to-wake (WtW) direct GHG emissions from using e-NH_3 (that is, NH_3 produced using hydrogen made from electrolysis of water, with all reactions powered by renewable electricity) as a marine fuel are low enough to meet the threshold for NH_3 to qualify within the zero or near-zero emission fuels, technologies or energy sources (ZNZ) category

65 Wolfram P and others, 'Using Ammonia as a Shipping Fuel Could Disturb the Nitrogen Cycle' (2022) 7 Nature Energy 1112.

66 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

67 Wolfram P and others, 'Using Ammonia as a Shipping Fuel Could Disturb the Nitrogen Cycle' (2022) 7 Nature Energy 1112.

68 Bertagni MB and others, 'Minimizing the Impacts of the Ammonia Economy on the Nitrogen Cycle and Climate' (2023) 120 Proceedings of the National Academy of Sciences e2311728120.

69 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

70 Pacific Environment, CSC and EDF 'MEPC 83/7/23 Review of current literature on tank-to-wake nitrous oxide emissions from ammonia-fueled engines' (2024).

(<19 gCO_2eq/MJ), delivering substantial emissions reductions compared to conventional fuels.[71]

32 However, delivering e-NH_3's potentially substantial climate benefits also relies on effectively minimizing indirect N_2O formed owing to leakage and emissions of NH_3 and NO_x throughout the NH_3 supply chain.[72]

33 Under a low NO_x and NH_3 emissions scenario (corresponding to the lower Tier III NO_x limit and minimized supply chain NH_3 leaks and emissions[73]), research shows that e-NH_3 can still deliver ~80% life cycle emissions reductions, compared to conventional fuels, assuming a 1% reactive nitrogen-indirect N_2O conversion rate.[74, 75]

34 However, under higher NO_x and NH_3 emissions scenarios, those benefits are reduced (Figure 3).[76] These higher emissions scenarios are plausible, being based on rates of leaks and emissions which could occur in the absence of robust controls (e.g. the medium scenario uses NO_x emissions corresponding to high-end Tier III limits (0.94 gNO_x/MJ), while the high scenario assumes NO_x emissions which fall within Tier I limits (4.21 gNO_x/MJ)).[77]

35 What's more, reactive nitrogen emissions are particularly relevant when considering the climate benefits associated with blue NH_3, which is produced by coupling fossil fuel-based NH_3 production methods with carbon capture technology. When accounting for indirect N_2O emissions, it's estimated that blue NH_3 can deliver emissions reductions of at most ~30%, compared with conventional fossil fuels, under a low reactive nitrogen emissions scenario.[78] This highlights that blue NH_3 is not a viable option for delivering deep emissions reductions.

36 Research is clear that using e-NH_3 as a shipping fuel can deliver substantial GHG reductions compared with fossil fuels, if reactive nitrogen emissions are controlled throughout the NH_3 life cycle.[79, 80] It is therefore crucial that ship and engine emissions of N_2O, NO_x and

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71 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

72 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

73 For all assumptions and full methods, see Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

74 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

75 Benefits reduce at higher reactive nitrogen-indirect N_2O conversion rates. For instance, at a conversion rate of 10%, green ammonia can achieve a 68% emissions reduction compared with conventional fossil fuels.

76 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

77 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

78 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

79 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

80 Kershaw J, 'Policy briefing on ammonia as a shipping fuel' (2025). Retrieved 17 November 2025 from https://www.opportunitygreen.org/publication-policy-briefing-ammonia-shipping-fuel.

NH_3 are tightly monitored and controlled, and that NH_3 emissions and leaks through NH_3 production, distribution, storage and bunkering are minimized.[81, 82, 83]

[81] Wolfram P and others, 'Using Ammonia as a Shipping Fuel Could Disturb the Nitrogen Cycle' (2022) 7 Nature Energy 1112.

[82] Bertagni MB and others, 'Minimizing the Impacts of the Ammonia Economy on the Nitrogen Cycle and Climate' (2023) 120 Proceedings of the National Academy of Sciences e2311728120.

[83] Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

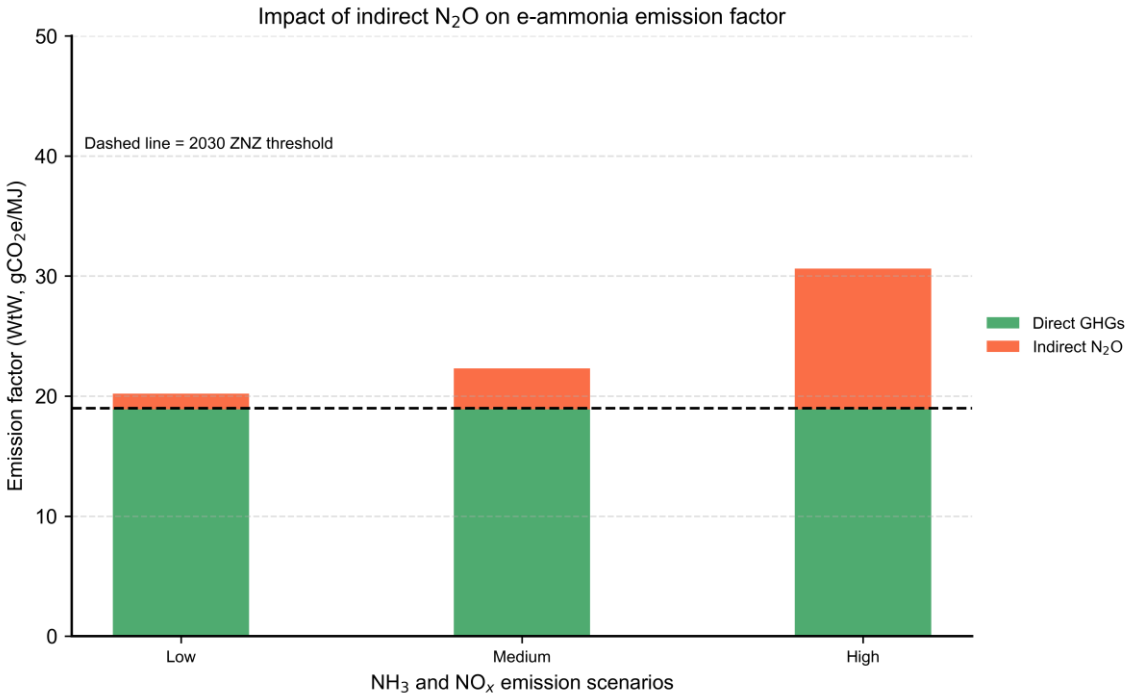


Figure 3: Impact of indirect N_2O on e-NH_3 emission factor under low, medium and high emission scenarios.

Note: For full description of scenarios, see text and Esquivel-Elizondo et al. (2025).[84] Representative estimates of direct GHG emissions are taken from Esquivel-Elizondo et al. (2025), broadly consistent with the midpoint of the range of e-NH_3 default emission factor values represented in documents submitted to MEPC 84 (which at the time of writing fall between 12.5 gCO_2eq/MJ and 26.2 gCO_2eq/MJ).[85, 86]

Case study 4: indirect N_2O from biofuel production

37 Indirect N_2O formation is also relevant for the life cycle assessment of crop-derived biofuels, as recognized by the 2024 LCA Guidelines (annex 4, table 1).[87] In this regard, the use of nitrogen-based fertilizers in biofuel production is a particularly important consideration.

38 The use of nitrogen-based fertilizers in biofuel production, and agriculture more generally, is a well-documented strategy for stimulating crop growth and improving yields, because addition of reactive nitrogen to soils provides nutrients for crop growth. Generally, however, only some of the added reactive nitrogen is taken up during crop growth, with the remainder lost to the environment. Use of nitrogen-based fertilizer is currently the major source of additional reactive nitrogen to the environment (112 Tg (or million tons) of reactive nitrogen

84 Esquivel-Elizondo S and others, 'Climate Impact of Direct and Indirect N_2O Emissions from the Ammonia Marine Fuel Value Chain' (2025) Environmental Science & Technology acs.est.4c13135.

85 United Kingdom, 'MEPC 84/7/4 Well-to-tank and tank-to-wake proposed default GHG emission factors for ammonia fuel pathways submission to GESAMP-LCA WG' (2025).

86 Norway, 'MEPC 84/7/1 Well-to-tank and tank-to-wake proposed default GHG emission factors for LNG and ammonia fuel pathways submission to the GESAMP-LCA WG' (2025).

87 International Maritime Organization, 'Resolution MEPC.391(81). 2024 Guidelines on life cycle GHG intensity of marine fuels' (2024).

per year[88]), and is the primary reason that current inputs of reactive nitrogen to the environment far exceed the safe planetary boundary, set at 62 to 82 Tg nitrogen per year.[89, 90]

39 Increased production of crop-based biofuels, for instance corn- and sugarcane-based ethanol, could increase reactive nitrogen release to the environment. Some of the reactive nitrogen added to the environment by nitrogen-based fertilizer application will be converted to indirect N_2O, as outlined in paragraphs 15 to 16. Research and IPCC guidance highlights that accounting for indirect N_2O, resulting from the use of nitrogen-based fertilizers, is an important part of accurately characterizing the life cycle emissions associated with biofuels.[91, 92, 93, 94]

40 More broadly, this case study emphasizes the importance of considering reactive nitrogen release throughout marine fuel value chains, including both well-to-tank (WtT) and tank-to-wake (TtW) reactive nitrogen sources.

Reactive nitrogen species: safety, air pollution, environmental and biodiversity impacts

41 Emissions of some indirect GHGs can also have wide-ranging negative impacts on safety, air pollution, the environment and biodiversity. This is especially true for reactive nitrogen, anthropogenic release of which from agricultural activities and burning fossil fuels has already altered the global nitrogen cycle beyond the safe "planetary boundary".[95, 96]

42 Reactive nitrogen pollution from shipping has caused profound environmental impacts including eutrophication, ocean acidification, biodiversity loss and ecosystem damage.[97, 98, 99,

88 Richardson K and others, 'Earth beyond Six of Nine Planetary Boundaries' (2023) 9 Science Advances eadh2458 https://doi.org/10.1126/sciadv.adh2458.

89 Canfield DE, Glazer AN and Falkowski PG, 'The Evolution and Future of Earth's Nitrogen Cycle' (2010) 330 Science 192.

90 Sakschewski B, Caesar L and others, 'Planetary Health Check 2025' (2025). Retrieved 17 November 2025 from https://www.planetaryhealthcheck.org/#reports-section.

91 Hergoualc'h K and others, '2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 11 N_2O EMISSIONS FROM MANAGED SOILS, AND CO_2 EMISSIONS FROM LIME AND UREA APPLICATION' (2019). Retrieved 17 November 2025 from https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.

92 L and others, 'Nitrogen Fertilization Challenges the Climate Benefit of Cellulosic Biofuels' (2016) 11 Environmental Research Letters 064007 https://doi.org/10.1088/1748-9326/11/6/064007.

93 Erisman JW and others, 'Nitrogen and Biofuels; an Overview of the Current State of Knowledge' (2010) 86 Nutrient Cycling in Agroecosystems 211 https://doi.org/10.1007/s10705-009-9285-4.

94 Smith KA and others, 'The Role of N_2O Derived from Crop-Based Biofuels, and from Agriculture in General, in Earth's Climate' (2012) 367 Philosophical Transactions of the Royal Society B: Biological Sciences 1169 https://doi.org/10.1098/rstb.2011.0313.

95 Canfield DE, Glazer AN and Falkowski PG, 'The Evolution and Future of Earth's Nitrogen Cycle' (2010) 330 Science 192.

96 Sakschewski B, Caesar L and others, 'Planetary Health Check 2025' (2025). Retrieved 17 November 2025 from https://www.planetaryhealthcheck.org/#reports-section.

97 Hassellöv I and others, 'Shipping Contributes to Ocean Acidification' (2013) 40 Geophysical Research Letters 2731.

98 Gray J, Wu R and Or Y, 'Effects of Hypoxia and Organic Enrichment on the Coastal Marine Environment' (2002) 238 Marine Ecology Progress Series 249.

99 Sakschewski B, Caesar L and others, 'Planetary Health Check 2025' (2025). Retrieved 17 November 2025 from https://www.planetaryhealthcheck.org/#reports-section.

[100, 101] Furthermore, NO_x is a powerful air pollutant, with air pollutant emissions from international shipping estimated to contribute to tens of thousands of premature deaths, globally, each year.[102]

43 Looking ahead, the potential use of fuels like biofuels and NH_3 could also result in significant reactive nitrogen pollution and related impacts, unless effective controls are introduced.[103] For NH_3, for instance, the range of potential safety, air quality, and environmental impacts are reviewed in detail in document MSC 110/6/1 (Pacific Environment and EDF).[104] To provide a brief example, using NH_3 instead of conventional fuels eliminates some air pollutant emissions, including sulphur oxides (SO_x) and carbon-based pollutants. However, air quality benefits could be undermined by NO_x emissions, as well as vented and unburned NH_3, which itself is an air pollutant. Public health benefits can be achieved by the transition from conventional shipping fuels to NH_3, but this relies on tightly controlling reactive nitrogen emissions.[105] Similarly, NH_3 is highly toxic and harmful to health, even at low concentrations (~30 ppm), while exposure to higher concentrations can be fatal.[106] Addressing safety concerns therefore relies on minimizing NH_3 leaks and emissions.

44 This example reveals how minimizing leaks and emissions of reactive nitrogen from the NH_3 value chain, would address indirect climate impacts, air pollution and safety concerns. More broadly, this illustrates the need for a coordinated approach to tackling indirect GHG emissions, taking into account that a range of impacts can share the same cause.

Current measures to control hydrogen and reactive nitrogen emissions

45 Current and planned measures to reduce shipping's climate impacts do not specifically address the indirect climate impacts of hydrogen and reactive nitrogen species. However, there are examples of policy and regulation which, although directed towards other outcomes, simultaneously serve to reduce these climate impacts.

46 For instance, ship NO_x emissions are regulated by MARPOL Annex VI according to the requirements set out in the NO_x Technical Code 2008. As shown in case study 2 of this document, there is a significant difference between the indirect climate impacts of more stringent (Tier III) and less stringent (Tier I) NO_x requirements, underscoring the importance of strengthening and expanding NO_x emission controls, as well as ensuring that air pollution regulations are adapted to regulate NO_x emissions from alternative fuels.

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100 Howarth RW, 'Coastal Nitrogen Pollution: A Review of Sources and Trends Globally and Regionally' (2008) 8 Harmful Algae 14.

101 Ngatia L, Grace III J and Moriasi D, 'Nitrogen and phosphorus eutrophication in marine' (2019) Monitoring of marine pollution.

102 Decker T, Meng Z and Comer B, 'Health and air pollution benefits of a global 0.1% fuel sulfur limit on marine fuels' (2025). Retrieved 17 November 2025 from https://theicct.org/publication/health-and-air-pollution-benefits-of-a-global-fuel-sulfur-limit-on-marine-fuels-jul25/.

103 Wolfram P and others, 'Using Ammonia as a Shipping Fuel Could Disturb the Nitrogen Cycle' (2022) 7 Nature Energy 1112.

104 Pacific Environment and Environmental Defense Fund, 'MSC 110/6/1. Coordinating efforts to address safety concerns and GHG emissions from ammonia as a shipping fuel' (2025).

105 Wong AYH and others, 'Climate and Air Quality Impact of Using Ammonia as an Alternative Shipping Fuel' (2024) 19 Environmental Research Letters 084002.

106 Laursen R and others, 'Safety of Ammonia For Use in Ships' (2024). Retrieved 17 November 2025 from https://www.emsa.europa.eu/publications/reports/item/5264-safety-of-ammonia-for-use-in-ships-part-1-ammonia-properties,-regulations-and-accidents-review.html.

47 NH_3 is also a powerful air pollutant, but is not currently regulated by MARPOL Annex VI. However, IMO has already initiated work to control NH_3 emissions from a safety perspective, with measures to detect and minimize NH_3 leaks included in the interim guidelines for the safety of ships using NH_3 as fuel.[107] As shown in case study 3 in this document, there are substantial differences between the climate impacts of more or less stringent controls on NH_3 emissions from, for example, bunkering infrastructure, highlighting how practices designed to ensure the safe operation of NH_3 ships could be adapted to simultaneously effectively mitigate indirect GHG emissions (see document MSC 110/6/1).[108]

48 These two examples illustrate firstly the importance of a coordinated and holistic approach to pollution management, with alignment across IMO instruments in order to address climate, safety, air pollution, environmental and biodiversity challenges most effectively. Secondly, these examples emphasize the range of potential policy and regulatory levers which could be employed to mitigate the indirect climate impacts of reactive nitrogen species.[109]

Summary and mitigation options

49 Mitigating emissions of CO_2, CH_4 and direct N_2O by replacing fossil fuels like oil and LNG with lower emissions alternatives like hydrogen-derived e-fuels must remain the priority in shipping's decarbonization journey.

50 Document ISWG-GHG 20/4 highlighted that indirect climate impacts will be associated with alternative fuels.[110] Maximizing the climate benefits of shipping's defossilization will require controlling emissions of indirect GHGs like hydrogen, NO_x and NH_3. However, indirect GHGs already contribute to shipping's overall climate impact, as a result of the use of fossil fuels in ship engines. Therefore, it is clear that action to address these emissions must be applied consistently across all pollutants and fuels, as illustrated in this document by case studies covering fossil fuels, NH_3 and biofuels.

51 Scientific understanding of the indirect climate impacts of hydrogen and reactive nitrogen species is still developing, illustrated by the uncertainty associated with hydrogen's GWP and in the environmental conversion rate of reactive nitrogen to indirect N_2O. However, uncertainty is not unusual in environmental science and does not necessarily preclude action. Using best estimates to guide action while improving evidence and understanding is a fundamental principle of policymaking, reflected in, for example, updates to the best estimate N_2O GWP-100 values over the past 15 years.[111]

52 Indeed, it is widely accepted that hydrogen emissions, and the environmental conversion of NO_x and NH_3 emissions to form indirect N_2O, lead to long-term warming impacts. While the short-term climate impacts of NO_x and NH_3 emissions remain highly uncertain, there is scientific consensus that reducing the climate impacts of conventional fuels, and maximizing

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107 International Maritime Organization, 'MSC.1/Circ.1687. Interim guidelines for the safety of ships using ammonia as fuel' (2025).

108 Pacific Environment and Environmental Defense Fund, 'MSC 110/6/1. DEVELOPMENT OF A SAFETY REGULATORY FRAMEWORK TO SUPPORT THE REDUCTION OF GHG EMISSIONS FROM SHIPS USING NEW TECHNOLOGIES AND ALTERNATIVE FUELS' (2025).

109 Kershaw J, 'Policy briefing on ammonia as a shipping fuel' (2025). Retrieved 17 November 2025 from https://www.opportunitygreen.org/publication-policy-briefing-ammonia-shipping-fuel.

110 CLIA and others, 'ISWG-GHG 20/4. Inclusion of other relevant substances from low- and zero-carbon marine fuels in the Fifth IMO GHG Study emissions inventory' (2025).

111 In 2007, the IPCC 4th Assessment Report used an N_2O GWP-100 of 298, which was updated to a value of 273 in the 2021 6th Assessment Report.

the climate benefits of alternative fuels, while mitigating environmental, biodiversity, public health and safety impacts, relies on minimizing emissions of hydrogen and indirect N_2O precursors.

53 Various mitigation options are available to achieve this. Firstly, given the certainty that they lead to long-term climate warming, hydrogen emissions and the environmental conversion of NO_x and NH_3 emissions to form indirect N_2O could be incorporated into IMO estimates of shipping's climate impacts, and measures aimed at tackling these, such as the life cycle assessment (2024 LCA guidelines). It is important that measures of this type are applied consistently across all pollutants and fuels, both conventional and alternative. These measures must also include careful consideration of uncertainties and retain the flexibility to incorporate new evidence as it becomes available, for instance related to the short-term climate impacts of NO_x and NH_3, which likely remain too uncertain for inclusion in the 2024 LCA Guidelines at this stage.

54 Secondly, where relevant, policy and regulatory levers related to safety, air pollution, the environment and biodiversity could also be developed or adapted with explicit consideration of how these could simultaneously and effectively control indirect climate impacts.

55 IMO and shipowners must also play active roles in addressing the uncertainties around indirect GHGs including hydrogen and reactive nitrogen species, through development and application of robust monitoring, reporting and verification procedures.

Proposal

56 Based on the information provided above, the co-sponsors propose that either;

.1 the terms of reference (ToR) for the Fifth IMO GHG Study are updated to include robust and accurate provisions for monitoring the climate impacts of hydrogen, NH_3, and NO_x, including the formation of NO_x- and NH_3-derived indirect N_2O, both for WtT and TtW fugitive emissions and nitrogen deposition, and TtW post-combustion by-products and unburnt fuel slip. For the group's convenience, proposed amendments to the ToR are attached in the annex to this document; or

.2 intersessional work is undertaken either through a new correspondence group, or through the "Correspondence Group on the Further Development of the LCA Framework", should it be re-established, or through the GESAMP-LCA Working Group, to review the evidence base related to the climate impacts of hydrogen, NO_x and NH_3, explicitly including NO_x- and NH_3-derived indirect N_2O emissions, both for WtT and TtW fugitive emissions and nitrogen deposition, and TtW post-combustion by-products and unburnt fuel slip, and consider how these could be addressed within the 2024 LCA Guidelines.

Action requested of the Working Group

57 The Group is invited to consider the information provided in this document, in particular the proposal in paragraph 56, and take action as appropriate.

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ANNEX

PROPOSED AMENDMENTS TO PARAGRAPH 1.1 OF THE DRAFT TERMS OF REFERENCE FOR THE FIFTH IMO GHG STUDY

Proposed amendments are made to the text of the draft terms of reference for the Fifth IMO GHG Study set out in annex 1 to document MEPC 84/7/14 (Secretariat). New text is shown in grey shading while deleted text is shown with red shading and strikethrough.

Paragraph 1.1.4 is suggested to be amended as follows:

1.1.4 The inventory should include current global emissions of GHGs and relevant substances emitted from ships of 100 GT and above engaged in international voyages as follows, breaking down the emissions at least in the size categories 100 – 399 GT; 400-4,999 GT; and 5,000 GT and above [,including a categorization by their type, size, and average age,]:

.1 GHGs should be defined as the six gases initially considered under the UNFCCC process: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), subject to data availability;

.2 [other relevant substances that may contribute to climate change include:

.1 nitrogen oxides (NO_x) [~~as well as the conversion of ammonia (NH3) and NO_x~~], non-methane volatile organic compounds (NMVOCs) [including but not limited to formaldehyde], carbon monoxide (CO), particulate matter (PM) and sulphur oxides (SO_x), subject to data availability; [~~and~~]

.2 Black Carbon (BC), subject to data availability and recognizing the complexity of providing accurate estimates; [and]

.3 [ammonia (NH_3), ~~and~~ hydrogen (H_2)~~,~~ and N_2O formed indirectly through the atmospheric conversion and deposition of NO_x and NH_3, both for WtT and TtW fugitive emissions and nitrogen deposition, and TtW post-combustion by-products and unburnt fuel slip, subject to data availability and recognizing the complexity of providing accurate estimates with sole aim to quantifying these emissions at this stage.]]