Health and air pollution benefits of a global 0.1% fuel sulfur limit on marine fuels

Tom Decker, Zhihang Meng, and Bryan Comer

INTRODUCTION

Pollution from maritime shipping has major consequences for public health. The ICCT previously estimated that air pollution from international maritime shipping contributed to 60,000 premature deaths in 2015, with other studies estimating even greater impacts.[1] The International Maritime Organization (IMO) 2020 regulation, which took effect on January 1 of that year, reduced the global limit on marine fuel sulfur from 3.5% mass by mass (m/m) to 0.5% m/m.[2] Nonetheless, a 2018 study projected that global shipping would be responsible for approximately 266,000 annual premature deaths from cardiovascular disease and lung cancer even with the 0.5% fuel sulfur limit.[3] Air pollution causes additional non-fatal public health and economic impacts not measured in these estimates, including illness-related productivity losses.

This brief examines how further reducing the global maximum allowable fuel sulfur content from 0.5% to 0.1% could affect air pollution emissions and premature mortality from fine particulate matter ($PM_{2.5}$). We analyze four scenarios. In the Baseline scenario, which is based on 2023 ship activity data, vessels comply with the global 0.5% fuel sulfur limit and

1 Dan Rutherford and Josh Miller, "Silent but Deadly: The Case of Shipping Emissions," *ICCT Staff Blog*, March 22, 2019, https://theicct.org/silent-but-deadly-the-case-of-shipping-emissions/; Yiqi Zhang et al., "Global Air Quality and Health Impacts of Domestic and International Shipping," *Environmental Research Letters* 16, no. 8 (August 1, 2021), https://doi.org/10.1088/1748-9326/ac146b.

2 International Maritime Organization, "IMO 2020 - Cleaner Shipping for Cleaner Air," press release, December 20, 2019, https://www.imo.org/en/MediaCentre/PressBriefings/pages/34-IMO-2020-sulphur-limit-.aspx.

3 Mikhail Sofiev et al., "Cleaner Fuels for Ships Provide Public Health Benefits with Climate Tradeoffs," *Nature Communications 9*, no. 1 (February 6, 2018): 406, https://doi.org/10.1038/s41467-017-02774-9.

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0.1% limits in effect in designated emission control areas (ECAs). The other scenarios assume a global 0.1% fuel sulfur limit with varying compliance approaches:

» Scrubber Max: Ships that use very-low sulfur fuel oil (VLSFO) switch to high-sulfur heavy fuel oil (HFO) with exhaust gas cleaning systems—commonly known as scrubbers—to comply.

» Scrubber Allowed: Ships that use VLSFO switch to marine gas oil (MGO) to comply.

» Distillate Only: Ships that use HFO and scrubbers or VLSFO switch to MGO to comply.

For these three scenarios, we estimate the avoided premature deaths attributable to $PM_{2.5}$ and the monetized health benefits compared with the Baseline scenario. We also discuss how shipowners' optional or mandatory use of distillate fuels for compliance with a 0.1% sulfur limit could increase the baseline marine fossil fuel price and thereby close the price gap between fossil fuels and zero or near-zero (ZNZ) greenhouse gas (GHG) emission fuels when paired with GHG pricing.

BACKGROUND

The IMO has progressively tightened global limits on the sulfur content of marine fuels to protect human health and the environment. An initial 4.5% sulfur m/m limit, which entered into force in 2005, was lowered to 3.5% in 2012.[4] As noted above, the IMO lowered the limit again in 2020, to 0.5%.

Fuel sulfur limits are stricter in ECAs, which aim to further restrict air emissions in designated areas. The IMO lowered the fuel sulfur limit in ECAs from 1.0% to 0.1% in 2015.[5] There are existing ECAs in the Baltic Sea, Caribbean Sea, Mediterranean Sea, North Sea, and off the coasts of Canada and the United States. New ECA fuel sulfur limits are due to enter into force in the Norwegian Sea and Canadian Arctic in March 2027. The IMO also has approved a North-East Atlantic ECA (AtlECA), which will come into force in January 2027; based on past regulatory procedure, AtlECA sulfur limits are expected to be enforced starting in January 2028.[6]

All ships must adhere to the global 0.5% fuel sulfur limit and the 0.1% ECA limits unless they use scrubbers, which enable ships to continue to use HFO by removing a portion of sulfur oxide (SO_x) emissions from the exhaust gas. While the use of scrubbers reduces SO_x emissions to within regulatory limits, previous ICCT studies have found that ships using scrubbers together with HFO emit more PM and black carbon (BC) emissions than those using MGO.[7] Furthermore, scrubber washwater contains harmful contaminants that are removed from the exhaust gas and discharged overboard,

4 International Maritime Organization, "Sulphur Oxides (SOx) and Particulate Matter (PM) – Regulation 14," https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx.

5 International Maritime Organization, "Ships Face Lower Sulphur Fuel Requirements in Emission Control Areas from 1 January 2015," press release, December 23, 2024, https://www.imo.org/en/MediaCentre/PressBriefings/Pages/44-ECA-sulphur.aspx. This ECA 0.1% sulfur limit for marine fuel is still relatively high compared with other transport modes. In Canada and the United States, the maximum allowable sulfur content in on-road diesel fuel is 15 ppm (0.0015%), and in the European Union, the limit is 10 ppm (0.001%).

6 International Council on Clean Transportation, "International Maritime Organization Approves World's Largest Emission Control Area in the North-East Atlantic Ocean," press release, April 11, 2025, https://theicct.org/pr-imo-approves-worlds-largest-eca-in-north-east-atlantic-ocean/. See also Liudmila Osipova et al., *Environmental and Health Benefits of a Designated North Atlantic Emission Control Area* (International Council on Clean Transportation, 2024), https://theicct.org/publication/environmental-and-health-benefits-of-a-designated-north-atlantic-emission-control-area-nov24/.

7 Bryan Comer, Elise Georgeff, and Liudmila Osipova, *Air Emissions and Water Pollution Discharges from Ships with Scrubbers* (International Council on Clean Transportation, 2020), https://theicct.org/publication/air-emissions-and-water-pollution-discharges-from-ships-with-scrubbers/.

which can worsen water quality.[8] If a global 0.1% fuel sulfur limit is proposed, the extent to which scrubbers may be allowed for compliance could thus be a subject for consideration by the IMO.

METHODS

We estimated air pollution emissions from the global shipping sector under a Baseline scenario, reflecting ship activity from 2023, and three global 0.1% fuel sulfur limit compliance scenarios. To assess potential health impacts, we partnered with researchers at the George Washington University and the University of Colorado Boulder to model reductions in SO_x, PM, and BC emissions from ships under the compliance scenarios. We then evaluated the avoided premature mortalities associated with ambient $PM_{2.5}$ exposure in each scenario and estimated the economic valuation of these avoided premature mortalities using the value of a statistical life (VSL).

SCENARIO ASSUMPTIONS

The assumptions of each of the four scenarios we modeled are detailed here and summarized in Table 1, below:

Baseline: In the Baseline scenario, ships comply with the current global fuel sulfur limit of 0.5% and the ECA limit of 0.1%. We assumed that ships with scrubbers used them to comply with sulfur limits when applicable. Ships using residual fuel without scrubbers were assumed to use VLSFO with a sulfur content of 0.5% outside of ECAs and MGO fuel when inside an ECA to comply with the 0.1% sulfur limit. Ships using other fuels such as liquefied natural gas (LNG) or methanol were assumed to continue to use these fuels.

The following three scenarios all assumed a global fuel sulfur limit of 0.1%.

Scrubber Max: In this scenario, any ship running primarily on residual fuel (HFO or VLSFO) was assumed to use HFO in combination with a scrubber to comply with the global 0.1% fuel sulfur limit. Ships using other fuels such as distillate (e.g., MGO), LNG, or methanol for compliance were assumed to continue to use these fuels.

Scrubber Allowed: In this scenario, we assumed ships with scrubbers used them to comply with the global 0.1% fuel sulfur limit. Ships without scrubbers that normally used VLSFO were instead modeled to use MGO. Ships using other fuels such as LNG or methanol were assumed to continue to use these fuels. This scenario can be considered the most likely compliance pathway under existing regulations because scrubbers are currently allowed as an alternative means of complying with IMO fuel sulfur regulations except in national or sub-national jurisdictions where scrubbers are restricted.

Distillate Only: In this scenario, we assumed that scrubbers were not allowed. All ships running primarily on residual fuel were modeled to use MGO whether they had a scrubber or not. Ships using other fuels such as LNG or methanol were assumed to continue to use these fuels.

8 Liudmila Osipova, Elise Georgeff, and Bryan Comer, *Global Scrubber Washwater Discharges under IMO's 2020 Fuel Sulfur Limit* (International Council on Clean Transportation, 2021), https://theicct.org/publication/global-scrubber-washwater-discharges-under-imos-2020-fuel-sulfur-limit/.

Table 1

Assumptions for the Baseline emissions scenario and the three scenarios to meet a 0.1% fuel sulfur limit

<table>
<tr><th>Scenario</th><th>Global sulfur limit</th><th>ECA sulfur limit</th><th>Ships with scrubbers</th><th>Residual fuel</th><th>Additional considerations</th></tr>
<tr><td>Baseline</td><td>0.5%</td><td>0.1%</td><td rowspan="3">Ships with scrubbers were assumed to use them to comply with the 0.1% fuel sulfur ECA limit</td><td>Ships without scrubbers that use residual fuel as their main fuel type were assumed to use VLSFO outside of ECAs and MGO inside ECAs</td><td>This scenario is based on 2023 ship activity data. All existing ECAs, plus the upcoming Norwegian Sea and Canadian Arctic ECAs, were assumed to be in effect[a]</td></tr>
<tr><td>Scrubber Max</td><td colspan="2" rowspan="3">0.1%</td><td>Ships without scrubbers that use residual fuel as their main fuel type were assumed to switch from VLSFO to HFO in combination with scrubbers to comply with the global 0.1% fuel sulfur limit</td><td>Ships using other fuel types (MGO, LNG, methanol) continue to use those fuels</td></tr>
<tr><td>Scrubber Allowed</td><td rowspan="2">Ships without scrubbers that use residual fuel as their main fuel type were assumed to switch from VLSFO to MGO to comply with global 0.1% fuel sulfur limit</td><td rowspan="2">Ships using other fuel types (LNG, methanol) continue to use those fuels</td></tr>
<tr><td>Distillate Only</td><td>Ships with scrubbers were modeled to switch to MGO to comply with the global 0.1% fuel sulfur limit</td></tr>
</table>

[a] These ECAs will soon be implemented, so excluding them from the analysis would inflate the potential emission reductions and health benefits of a global 0.1% fuel sulfur limit.

EMISSION ESTIMATES

Baseline carbon dioxide (CO_2), nitrogen oxide (NO_x), SO_x, PM, and BC emissions data and fuel consumption were estimated using the ICCT's Systematic Assessment of Vessel Emissions (SAVE) model, based on 2023 ship activity data.[9] The SAVE model matches Automatic Identification System ship activity data from Spire with ship characteristic data from S&P Global to estimate fuel consumption and emissions.[10] The model accounts for existing ECA emission limits based on ship location; to account for planned ECAs in the Norwegian Sea and Canadian Arctic, we also assumed ships in these areas met the 0.1% sulfur limit requirements in the Baseline scenario. The AtlECA was excluded from the Baseline because it had not yet been approved by the IMO at the time of our analysis.

The emission factors and accompanying assumptions for ships without scrubbers were consistent with those used in the *Fourth IMO GHG Study* with some updates, as explained in the SAVE documentation.[11] For ships equipped with scrubbers, we assigned SO_x emission factors associated with exactly achieving the applicable fuel sulfur equivalence for each scenario, as shown in Table 2. For example, in the Baseline scenario, we assumed ships with scrubbers achieved 0.5% fuel sulfur equivalence outside of ECAs and 0.1% sulfur equivalence inside of ECAs.

9 Naya Olmer et al., *Greenhouse Gas Emissions from Global Shipping, 2013–2015* (International Council on Clean Transportation, 2017), https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015; Xiaoli Mao et al., *Systematic Assessment of Vessel Emissions (SAVE) v2025.1 Documentation* [Computer software], International Council on Clean Transportation, https://theicct.github.io/SAVE-doc/.

10 This brief includes content supplied by S&P Global; Copyright © S&P Global, 2023. All rights reserved.

11 Mao et al., *SAVE Documentation;* Jasper Faber et al., "Fourth IMO Greenhouse Gas Study 2020" (International Maritime Organization, 2020), https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx.

For the scenarios in which scrubbers were included (Scrubber Allowed and Scrubber Max), scrubber-equipped ships achieved 0.1% sulfur equivalence globally. This approach differs from the recommended SO_x emission factors published in a 2020 ICCT report conducted for Environment and Climate Change Canada, in which ships with scrubbers were expected to achieve very low SO_x emissions based on the available literature.[12] In this analysis, we assumed that ships with scrubbers reduce SO_x emissions only as much as required to achieve compliance with sulfur limits while not overachieving. This assumption is consistent with Canada's approach in an analysis submitted to the IMO's 12th Pollution Prevention and Response Subcommittee.[13]

Table 2

Sulfur oxide emission factors for ships using 2.6% sulfur heavy fuel oil in combination with scrubbers, (g/kWh)

Engine type	Engine age	SO_x (Comer et al., 2020)[a]	Current analysis	
			SO_x (0.5% sulfur equivalent)	SO_x (0.1% sulfur equivalent)
Slow speed diesel	pre-1984	0.19	2.00	0.40
	1984–2000	0.17	1.81	0.36
	2001+	0.16	1.71	0.34
Medium speed diesel	pre-1984	0.20	2.10	0.42
	1984–2000	0.18	1.91	0.38
	2001+	0.17	1.81	0.36

[a] Comer et al. (2020) assumed that SO_x emissions were the same no matter the applicable maximum fuel sulfur limit, as they did not model the impacts of optimizing scrubber performance to achieve 0.1% or 0.5% sulfur equivalence.

HEALTH IMPACTS MODELING

The GEOS-Chem adjoint v35n global chemical transport model simulates global pollutant concentrations and calculates the sources and sinks of nitrogen dioxide, ozone, $PM_{2.5}$, and their precursors using meteorological data and both anthropogenic and non-anthropogenic emissions data. In our analysis, we replaced their existing shipping sector emission estimates with our scenario emissions.[14] The GEOS-Chem model provided global pollutant concentrations for each scenario, and we compared the results for the three 0.1% sulfur fuel limit compliance scenarios with the Baseline to show the estimated impacts on global air pollution concentration.

After the pollutant concentrations were calculated, we estimated the premature deaths in 2023 associated with long-term exposure to $PM_{2.5}$ in each scenario. To do so, we used the methodology of the *Global Burden of Disease 2019* to estimate how exposure to $PM_{2.5}$ in each scenario affected the incidence of ischemic heart disease, stroke, chronic obstructive pulmonary disease, lower respiratory illness, type 2 diabetes, and lung cancer, considering a range of factors that include country-specific baseline mortality rates and age-stratified population data.[15]

12 Comer, Georgeff, and Osipova, *Air Emissions and Water Pollution*.

13 Canada, "Air quality and health impacts of using EGCS (scrubbers) in Canadian waters" (International Maritime Organization, 2024), submitted as document PPR 12/INF.15.

14 Isabelle Bey et al., "Global Modeling of Tropospheric Chemistry with Assimilated Meteorology: Model Description and Evaluation," *Journal of Geophysical Research: Atmospheres* 106, no. D19 (October 16, 2001): 23073–95, https://doi.org/10.1029/2001JD000807.

15 Christopher Murray et al., "Global burden of 87 risk factors in 204 countries and territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019," *The Lancet* (2020) https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)30752-2/fulltext.

MONETIZED HEALTH BENEFITS OF EACH SCENARIO

Using the premature death estimates from each scenario, we calculated the corresponding monetized health benefits following an approach based on the methodology in a World Bank study on valuing the health impacts of air pollution.[16] This methodology scaled 2011 country-specific VSL values by the growth rate in per capita gross domestic product (purchasing power parity) from the International Monetary Fund, in 2023 constant U.S. dollars. This approach omits non-fatal health effects of air pollution, meaning the results of this analysis should be understood as a high-level indicator of the health impacts in each scenario. The monetized benefits are expected to increase over time as per capita income grows, which increases the VSL.

RESULTS

We present the absolute emissions and percent change compared with the Baseline, avoided premature deaths, and the monetized health benefits of the avoided deaths under the three 0.1% fuel sulfur limit compliance scenarios. We also consider how optional or required uptake of distillate fuels by shipowners combined with pricing of GHG emissions could close the price gap between fossil fuels and ZNZ GHG emission fuels.

EMISSIONS COMPARISON

Table 3 shows the estimated absolute emissions in each scenario and the percentage change compared with the Baseline. We found that implementing a global 0.1% fuel sulfur limit could reduce shipping-attributable SO_X emissions by 75%–85%, $PM_{2.5}$ by 46%–66%, and BC by 27%–41% compared with the Baseline, depending on the compliance scenario.

Except for CO_2 emissions, which were similar across all four scenarios, the three 0.1% fuel sulfur limit scenarios resulted in large emission reductions from the Baseline. The Scrubber Max scenario yielded an estimated 75% reduction in SO_X, 46% reduction in $PM_{2.5}$, and 27% reduction in BC. The Scrubber Allowed scenario yielded an estimated 82% reduction in SO_X, 61% reduction in $PM_{2.5}$, and 36% reduction in BC. Finally, the Distillate Only scenario had the lowest estimated absolute emissions of all scenarios, with an 85% reduction in SO_X, 66% reduction in $PM_{2.5}$, and 41% reduction in BC compared with the Baseline scenario.

Table 3

Absolute emission estimates (thousand tonnes) and percent change compared with the Baseline in each scenario

Scenario	CO_2	SO_X	PM_{10}	$PM_{2.5}$	BC
Baseline	795,000	1,800	640	590	71
Scrubber Max	797,000 (+0.31%)	450 (-75%)	350 (-46%)	320 (-46%)	52 (-27%)
Scrubber Allowed	784,000 (-1.4%)	320 (-82%)	250 (-61%)	230 (-61%)	45 (-36%)
Distillate Only	778,000 (-2.1%)	270 (-85%)	220 (-66%)	200 (-66%)	42 (-41%)

The Scrubber Allowed scenario is the most plausible under current regulations, as scrubbers are permitted for the purpose of meeting IMO fuel sulfur limits in most

16 Urvashi Narain and Chris Sall, *Methodology for Valuing the Health Impacts of Air Pollution* (World Bank, 2016), https://doi.org/10.1596/24440.

national and subnational jurisdictions. The Distillate Only and Scrubber Max scenarios are less likely but are included to demonstrate that health benefits increase as more vessels use MGO and decrease as more ships use HFO in combination with scrubbers.

AVOIDED PREMATURE DEATHS

Global shipping is estimated to be responsible for nearly 36,000 $PM_{2.5}$-attributable premature deaths in the Baseline scenario. This estimate is lower than the ICCT's previous estimate of 60,000 premature deaths in 2015, primarily due to the decrease in the global fuel sulfur limit from 3.5% to 0.5% m/m, which significantly reduced absolute SO_x emissions. The difference can also partially be attributed to the inclusion of ECAs in this report that were not accounted for in the previous ICCT estimate.

Our estimate is also considerably lower than the 266,000 premature deaths in 2020 projected by Sofiev et al.[17] A methodological difference accounts for most of this gap. Our analysis uses log-linear concentration-response functions, consistent with the methods of the *Global Burden of Disease 2019* study. Sofiev et al. used linear functions relating pollutant concentration to human health effects; the article's supplemental material reports 64,000 premature deaths in 2020 using log-linear concentration-response functions. As above, the inclusion of additional ECAs in our study may account for much of the remaining difference between estimates.

We estimate that implementing a global 0.1% fuel sulfur limit would avoid approximately 3,900–4,500 $PM_{2.5}$-attributable premature deaths each year, depending on the compliance scenario. The greatest health benefits accrue from the Distillate Only scenario, whereas the least accrue from the Scrubber Max scenario. Expanding our analysis to include the AtlECA, which this study did not consider, would close part of the mortality estimate gap between the Baseline and global 0.1% scenarios, as it would reduce emission levels and the number of premature deaths in the Baseline. The ICCT has estimated that the AtlECA could avoid 118–179 $PM_{2.5}$-attributable premature mortalities each year.[18] That study also found that the greatest health benefits would occur in a scenario in which scrubbers are prohibited and vessels running on residual fuels switch to MGO.

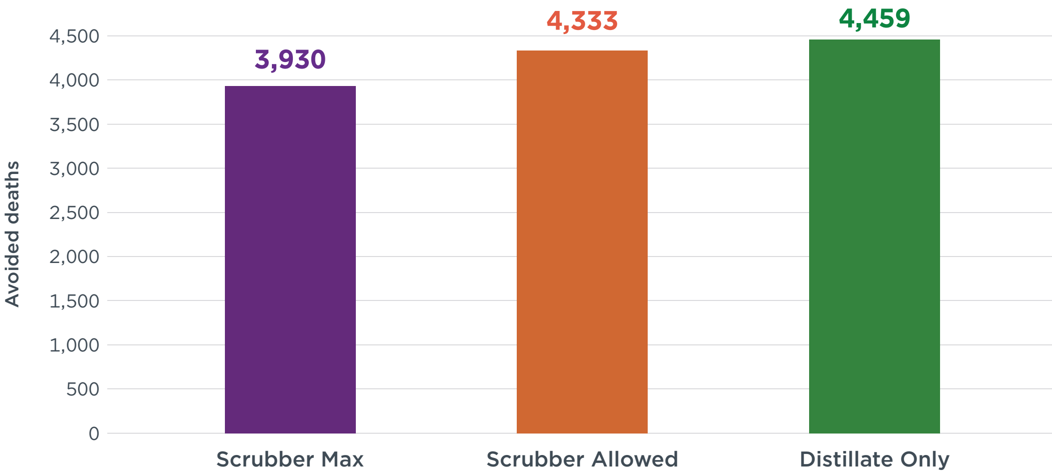
Figure 1 shows the estimated avoided premature $PM_{2.5}$-attributable deaths associated with each global 0.1% fuel sulfur limit scenario compared with the Baseline. In each case, the 0.1% sulfur limit lowers $PM_{2.5}$ emissions from ships and results in more than a 10% reduction in $PM_{2.5}$-attributable premature deaths. The Distillate Only scenario avoids nearly 4,500 $PM_{2.5}$-attributable premature deaths, the most of any scenario we modeled. The Scrubber Allowed scenario avoids more than 4,300 premature deaths, and the Scrubber Max scenario avoids more than 3,900.

17 Sofiev et al., "Cleaner Fuels."

18 Osipova et al., *Environmental and Health Benefits.*

Figure 1

Annual avoided $PM_{2.5}$-attributable premature deaths from three scenarios under a global 0.1% fuel sulfur limit



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MONETIZED HEALTH BENEFITS

Given our Baseline estimate of approximately 36,000 premature $PM_{2.5}$-attributable deaths from global shipping emissions, we estimate that global shipping emissions are responsible for more than $160 billion in premature death-related costs annually. Table 4 shows the monetized health benefits of each scenario compared with the Baseline.

Table 4

Monetized health benefits of avoided $PM_{2.5}$-attributable premature deaths from each scenario compared with the Baseline scenario

Scenario	Monetized benefits
Scrubber Max	$9.3 billion
Scrubber Allowed	$10.5 billion
Distillate Only	$10.9 billion

In the Scrubber Max scenario, in which ships install scrubbers to continue using lower-cost high-sulfur HFO, the avoided $PM_{2.5}$-attributable premature deaths resulted in an estimated economic benefit of $9.3 billion. The Scrubber Allowed scenario, in which ships equipped with scrubbers continue to use them while ships without switch to MGO, yielded an economic benefit of $10.5 billion; as noted above, this is the most likely compliance pathway assessed in this study. Finally, the Distillate Only scenario, requiring all ships to switch to MGO, yielded the greatest estimated monetized health benefit, of almost $11 billion in avoided costs.

The avoided health costs in this analysis only account for reductions in premature mortality and do not include other public health benefits, such as reduced illness-related productivity losses. All global 0.1% fuel sulfur limit scenarios yielded health benefits compared with the Baseline even if we only included avoided mortality. There would likely be higher monetized health benefits if avoided morbidity was considered.

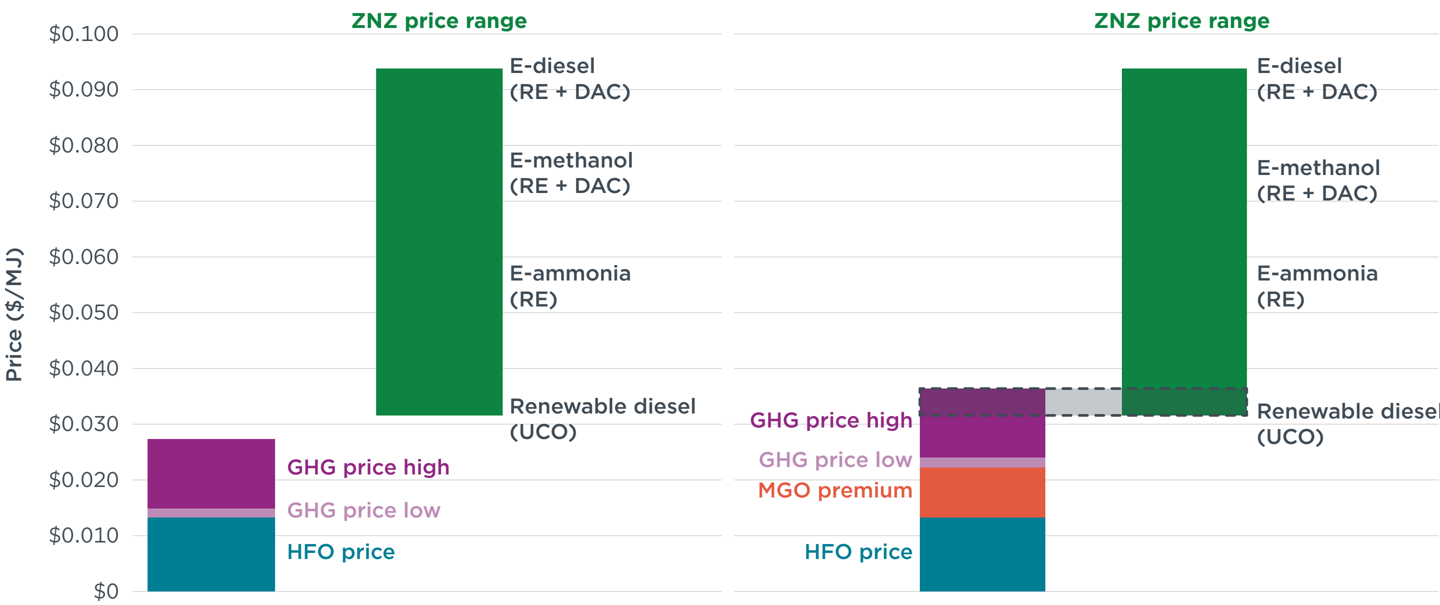
FUEL COSTS AND IMPLEMENTING A GHG PRICE

A global 0.1% sulfur limit, if it promoted the use of distillate fuel, could result in a higher baseline fossil fuel cost. When accompanied by a GHG price per tonne of well-to-wake CO_2-equivalent (CO_2e) emissions, the limit may also help accelerate cost parity between fossil fuels and ZNZ fuels.

In 2024, a coalition of IMO Member States and the International Chamber of Shipping submitted a proposal to the IMO to establish a GHG pricing scheme with a cost ranging from $18.75 to $150 per tonne of well-to-wake CO_2e emissions, equivalent to $0.002–$0.014/MJ.[19] Figure 2 models the estimated effect of this GHG price range (in purple) on the cost of fossil fuels. These estimates are based on average 2023 fossil fuel prices from Ship & Bunker compared with ZNZ fuel prices reported in a previous ICCT analysis under two different scenarios.[20] The ZNZ fuels considered in this analysis are renewable diesel from used cooking oil (UCO), e-ammonia from renewable electricity (RE), e-methanol from RE and direct air capture (DAC), and e-diesel from RE and DAC. The panel on the left shows that if the IMO continues to allow HFO, even if the GHG price is on the higher end of the proposed range, the estimated fossil fuel cost will not overlap with the low end of ZNZ fuel costs, and it would still be cheaper to use HFO. The figure on the right shows that when we account for the additional cost per MJ of switching from HFO to MGO under a global 0.1% sulfur limit, referred to as the MGO premium, the GHG price can result in overlap between fossil fuel and ZNZ fuel costs.

Figure 2

Cost ($/MJ) of fossil fuels versus zero or near-zero GHG emission fuels without (left) and with (right) a global 0.1% sulfur limit and a proposed GHG price range equivalent to $0.002–$0.014/MJ



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19 Austria et al., "Consolidation of the Proposals for an Economic Element of the Mid-Term Measures Based on a GHG Levy/Contribution" (December 20, 2024), submitted as document ISWG-GHG 18/2/5; available at the International Chamber of Shipping website at https://www.ics-shipping.org/wp-content/uploads/2025/01/ISWG-GHG-18_2_5-Consolidation-of-the-proposals-for-an-economic-element-of-the-mid-term-measures-based-on-a-GHG-levy_contribution-as-at-9-Jan.pdf.

20 Ship & Bunker, "Global Average Bunker Price Bunker Prices," 2025, https://shipandbunker.com/prices/av/global/av-glb-global-average-bunker-price; Daniel Rutherford et al., *Feasibility Study of Future Energy Options for Great Lakes Shipping* (International Council on Clean Transportation, 2024), https://theicct.org/publication/feasibility-study-of-future-energy-options-for-great-lakes-shipping-march24/.

In April 2025, the IMO approved the Net-Zero Framework, a set of legally binding measures that aim to reduce GHG emissions from the international shipping sector.[21] The Framework includes a GHG pricing scheme that differs from the range proposed in 2024. Specifically, it consists of a base annual GHG fuel intensity target and a more ambitious direct compliance target that vessels are expected to meet starting in 2028. Vessels that do not meet the targets can offset excess emissions by purchasing remedial units (RUs) that cost $100 (Tier 1) or $380 (Tier 2) per tonne of excess well-to-wake CO_2e based on compliance level. If a ship meets the base target but not the direct compliance target, it must buy Tier 1 RUs. If it does not meet either target, it must also acquire Tier 2 RUs. Ships that do not meet either target can purchase Tier 2 RUs, use previously acquired and unused units, or transfer surplus units from other ships to offset the Tier 2 compliance deficit.

The GHG pricing scheme in the Net-Zero Framework may not spur cost parity between fossil and ZNZ fuels as quickly as the pricing scheme in the 2024 proposal assuming a cost of $150 per tonne of well-to-wake CO_2e. According to ICCT modeling that will be published in a forthcoming publication, the Net-Zero Framework is estimated to result in an effective carbon price of approximately $42/t CO_2e for ships that use HFO and $46/t CO_2e for ships that use MGO in 2030. The effective carbon price is not projected to exceed $150/t CO_2e until after 2035, unless the price of Tier 1 and/or Tier 2 RU were increased. For example, increasing the Tier 1 RU to $150/t CO_2e and the Tier 2 RU to $600/t CO_2e would result in an effective GHG price of $150/t CO_2e by approximately 2033 for both HFO and MGO. A GHG price near this higher level would result in some overlap between the price of MGO and the low-end cost ZNZ fuels.

Moreover, additional incentives to support ZNZ fuel adoption could further accelerate cost parity between fossil and ZNZ fuels. While ZNZ fuels may not be entirely zero emission, these incentives could outweigh the potential cost of GHG pricing imposed on these fuels due to their comparatively low life-cycle GHG emissions.

Global ZNZ fuel prices also may vary from our estimates. The reported ZNZ fuel prices considered in this analysis did not account for the cost of regulations, such as hourly zero-emission electricity source matching. Requiring hourly matching can help ensure that fossil electricity is not used for clean hydrogen production during high demand hours.[22] Hourly matching regulations would likely increase the final ZNZ fuel costs.[23] Other factors will also affect the final fuel price, such as supply-demand impacts and the relative costs of producing fuels in different regions.[24]

CONCLUSION

This study found that lowering the global sulfur limit for marine fuels from 0.5% to 0.1% could reduce air pollution emissions and yield significant health and economic

21 International Maritime Organization, "IMO Approves Net-Zero Regulations for Global Shipping," press release, April 11, 2025, https://www.imo.org/en/MediaCentre/PressBriefings/pages/IMO-approves-netzero-regulations.aspx.

22 "ICCT Comments on Proposed Regulations Relating to the Credit for Production of Clean Hydrogen," International Council on Clean Transportation, February 26, 2024, https://theicct.org/comments-on-proposed-regulations-relating-to-the-credit-for-production-of-clean-hydrogen-feb24/.

23 Wilson Ricks, Qingyu Xu, and Jesse D. Jenkins, "Minimizing Emissions from Grid-Based Hydrogen Production in the United States," *Environmental Research Letters* 18, no. 1 (January 2023): 014025, https://doi.org/10.1088/1748-9326/acacb5.

24 UCL Shipping and Oceans Research Group, "Renewable Energy-Rich Developing Nations Priced out of Shipping's $1.6 Trillion Energy Transition Opportunity," March 19, 2025, https://www.shippingandoceans.com/post/renewable-energy-rich-developing-nations-priced-out-of-shipping-1-6-trillion-energy-transition.

benefits. Shipping emissions currently cause an estimated 36,000 $PM_{2.5}$-attributable premature deaths annually, with a corresponding global health cost of $160 billion. Relative to a Baseline scenario based on 2023 ship activity data, reducing the sulfur content of marine fuels as in the global 0.1% fuel sulfur limit scenarios modeled in this study would:

- **Mitigate air pollution**. Across our three 0.1% fuel sulfur limit compliance scenarios, shipping-attributable SO_x emissions are estimated to fall by 75%–85%, $PM_{2.5}$ by 46%–66%, and BC by 27%–41%. The Distillate Only scenario, in which the use of scrubbers is not allowed, yields the highest estimated emission reductions.
- **Reduce premature deaths**. The three scenarios avoid between 3,900 and 4,500 premature deaths annually, with the most significant reductions achieved under the Distillate Only scenario.
- **Deliver substantial economic benefits**. Relative to the Baseline, health-related economic benefits are estimated to range from $9.3 billion to $11 billion annually, depending on the compliance pathway.
- **Incentivize the use of ZNZ GHG fuels**. A global 0.1% sulfur standard that incentivizes the uptake of distillate fuel would increase the baseline price of fossil marine fuels and reduce the price gap between fossil and ZNZ fuels. Establishing a GHG price more ambitious than the IMO Net-Zero Framework, as proposed in 2024, could further close the price gap.

While the Scrubber Allowed scenario is the most likely compliance pathway, the Distillate Only scenario is estimated to provide the greatest health and economic benefits, minimizing emissions of SO_x, PM, and BC and avoiding nearly 4,500 premature deaths each year, generating $11 billion in monetized benefits annually. Meanwhile, the Scrubber Max scenario yields the lowest health benefits and highest pollutant emissions among the compliance pathways. There are other benefits that have not been quantified in this study that may also accrue, including avoided morbidity, work-loss hours, and enhanced environmental justice.

Future work could assess additional health impacts such as morbidity (non-fatal health effects) and consider the long-term potential of using sulfur limits to complement GHG reduction policies. A cost-benefit analysis that considers the direct economic cost of fuel switching and the monetized health and social benefits of avoided emissions could also reveal the longer-term socioeconomic impacts of each compliance scenario.

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