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Fuel standards to align international shipping with the Paris Agreement

HAE JEONG CHO, GABRIEL ALVAREZ, BRYAN COMER

ACKNOWLEDGMENTS

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International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

EXECUTIVE SUMMARY

In 2023, the International Maritime Organization (IMO) adopted a revised strategy that aims to reduce greenhouse gas (GHG) emissions from international shipping to net-zero by or around 2050. The strategy includes indicative checkpoints targeting a 20% reduction in GHG emissions by 2030 (striving for 30%) and a 70% reduction by 2040 (striving for 80%), both measured against 2008 levels. While these targets align with a well-below 2 °C pathway, defined as 1.7 °C by the ICCT, they fall short of limiting warming to 1.5 °C. Ultimately, it is the cumulative emissions until net-zero is achieved that will determine shipping's contribution to future global warming.

The IMO has already implemented short-term technical and operational measures to improve the GHG intensity of ships, and is now developing mid-term measures, including a global fuel standard (GFS) and an economic measure such as a GHG levy to close the price gap between fossil and renewable fuels. Together, these measures can result in additional operational efficiency improvements that make it easier to achieve the 2030 and 2040 targets. These mid-term measures are expected to be finalized by April 2025 and could enter into force in 2027.

This report is a gap analysis, detailing the reduction in the global average GHG fuel intensity (GFI) and the operational efficiency improvements that would be necessary for the IMO to achieve its climate goals. We model three decarbonization scenarios:

- **IMO Minimum:** The GHG emissions from international shipping decline by 20% by 2030 and 70% by 2040 compared with 2008 emission levels, and the sector achieves net-zero emissions by 2050.
- **IMO Striving:** The GHG emissions from international shipping decline by 30% by 2030 and 80% by 2040 compared with 2008 emission levels, and the sector achieves net-zero emissions by 2050.
- **1.5 °C:** Cumulative GHG emissions from international shipping are below the shipping sector's proportional share of the carbon budget that aligns with a 67% chance of limiting warming to 1.5 °C.

The analysis estimates cumulative emissions from 2020 to 2050 and compares them with shipping's proportional share of global carbon budgets for 1.5 °C, 1.7 °C, and 2 °C warming scenarios. Emission reductions are achieved by either reducing the global average GFI of marine fuels alone, or by combining the GFI reduction with operational efficiency improvements.

We find that the global shipping sector is on a trajectory to exhaust its proportional 1.5 °C carbon budget by 2030, its 1.7 °C budget by 2037, and its 2 °C budget by 2047. Mid-term measures aligned with the targets in the IMO Minimum or IMO Striving scenarios could achieve cumulative emissions that are consistent with limiting warming to 1.7 °C. As illustrated in Figure ES1, projected operational efficiency improvements resulting from the IMO mid-term measures could reduce cumulative emissions by about 10% between 2020 and 2050. The remaining 90% will require replacing fossil fuels with net-zero GHG fuels or energy on a life-cycle basis, which can only be achieved by advanced technologies that have not yet been fully commercialized.

Figure ES1

Cumulative well-to-wake greenhouse gas emissions avoided by scenario and measure, 2020–2050

Note: This figure is adapted from Figure 8 to highlight the emission reductions needed to achieve the GHG reduction goals of the IMO's 2023 GHG Strategy and a 1.5 °C warming target.

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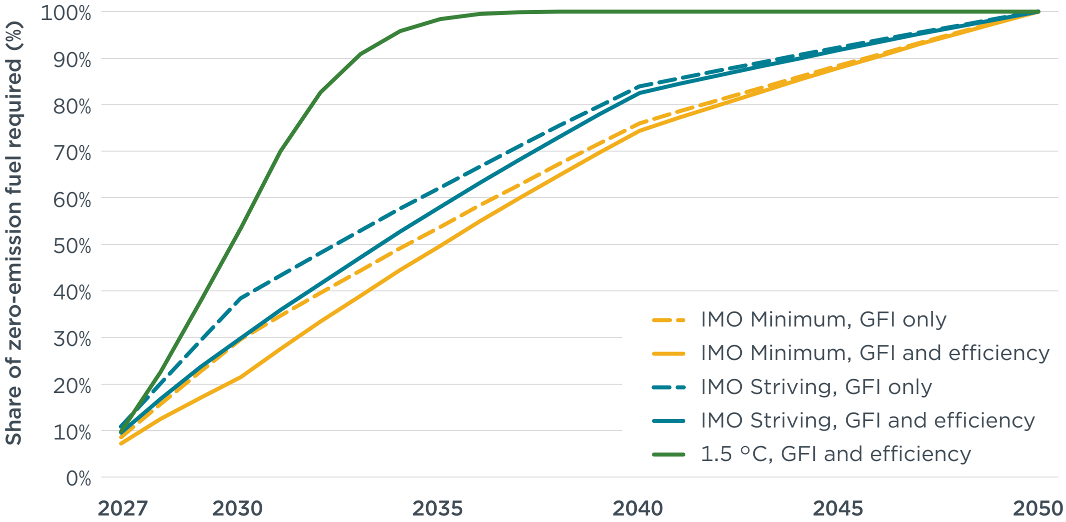
Achieving the GHG targets in the IMO Minimum or Striving scenarios will require immediate, deep, and sustained real-world reductions in shipping's global average GFI. Specifically, it would entail at least a 22% reduction in GFI compared with the 2019 level by 2030 to align with the IMO Minimum scenario targets, or at least a 30% reduction to align with IMO Striving scenario targets. This assumes that IMO mid-term measures also result in operational efficiency improvements. The 1.5 °C scenario requires even steeper reductions in emissions, including a more than 50% reduction from 2019 levels by 2030 and the achievement of net-zero by 2038.

The GFI reduction requirements can be translated to the share of net-zero-emission fuel required to achieve each target, as shown in Figure ES2. Even in the IMO Minimum scenario, and assuming operational efficiency improvements, the share of net-zero-emission fuel would have to reach over 20% by 2030. The IMO's ambition in its revised strategy is to increase the uptake of zero-emission energy sources to 5% (striving for 10%) of energy demand from international shipping by 2030, but such ambition would fall short of its overall GHG targets.

Figure ES2

Share of net-zero-emission fuel required to align with IMO Minimum, IMO Striving, and 1.5 °C scenario carbon budgets, 2027–2050



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Reducing the global average GFI using the GFS would require that the regulation, and the guidelines used to implement it, accurately account for the well-to-tank and tank-to-wake GHG emissions of marine fuels and prevent the use of food- and feed-based biofuels. It would also require an unprecedented level of financial investment in the nascent and pre-commercial technologies necessary to produce genuinely zero-carbon fuels.

If the real-world well-to-wake GHG intensity of the fuel mix used to satisfy the GFS requirements is not accurately accounted for, then the life-cycle GHG emissions from shipping will be higher than implied by the policy. To bridge this gap, regional and national governments would need to implement their own policies to regulate the GHG intensity of the fuels ships use on voyages to, from, or between their ports. These policies would need to be considerably more ambitious than current international best practices, as contained in the FuelEU Maritime regulation.

The results indicate that achieving the IMO's GHG emission reduction targets will necessitate unprecedented ambition in GFS requirements and economic measures that ensure an effective carbon price signal. In addition, these mid-term measures should promote the use of scalable zero-emission fuels that can bring meaningful climate benefits: renewable hydrogen-based e-fuels. The findings underscore the urgency of finalizing and implementing these policies to align shipping with global climate goals.

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INTRODUCTION

In 2023, the International Maritime Organization (IMO) adopted a revised strategy that aims to reduce the greenhouse gas (GHG) emissions from international shipping to net-zero by or around 2050 (IMO, 2023). The strategy also establishes indicative checkpoints for GHG emission reductions, targeting a 20% reduction by 2030 (striving for 30%) and a 70% reduction by 2040 (striving for 80%), both measured against 2008 levels. The emissions reduction pathways implied by the 2023 strategy are compatible with shipping doing its part to limit global warming to well-below 2 °C—defined by the ICCT as 1.7 °C—but fall short of a 1.5 °C warming target (Comer & Carvalho, 2023). However, the cumulative emissions accrued until shipping achieves net-zero GHG emissions will ultimately determine its contribution to future global warming.

The IMO has already implemented short-term measures to reduce the technical and operational GHG intensity of ships. Such measures require or encourage the reduction of tank-to-wake (TTW) carbon dioxide (CO_2) emissions per capacity mile over time. The IMO is now developing mid-term technical and economic measures, which are set to be agreed upon in April 2025 and could enter into force in 2027. The technical measure, a global fuel standard (GFS), is designed to progressively reduce the well-to-wake (WTW) GHG intensity of marine fuels. The economic measure would put a price on WTW GHG emissions, helping close the price gap between fossil and renewable fuels and incentivizing operational efficiency improvements that reduce total fuel consumption.

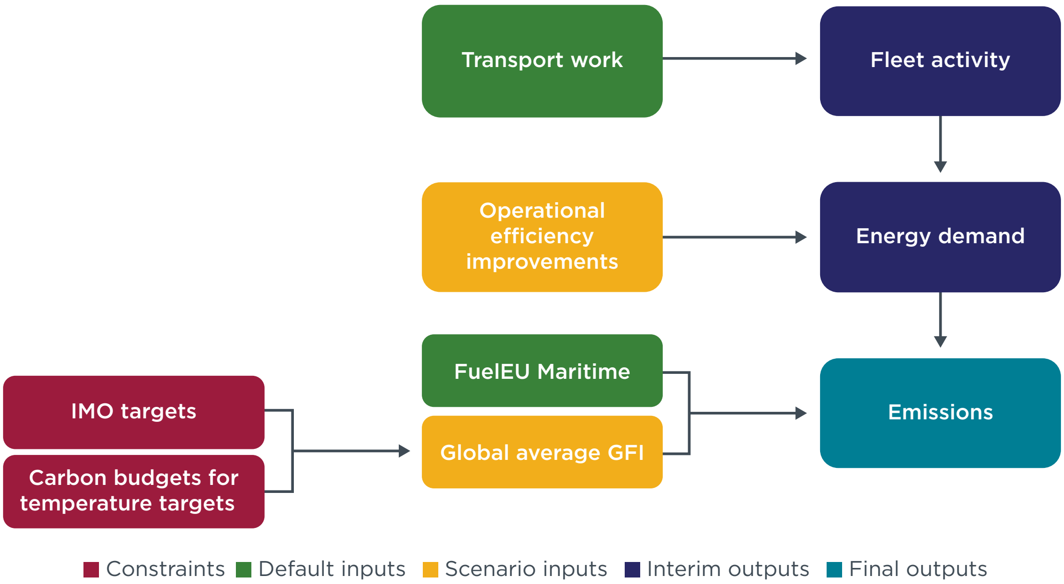
This report is a gap analysis, detailing the reduction in the global average GHG fuel intensity (GFI) and the operational efficiency improvements that would be necessary for the IMO to achieve its climate goals. We model three decarbonization scenarios: IMO Minimum, IMO Striving, and 1.5 °C. For each scenario, we estimate the GHG reductions that need to be achieved using a combination of a reduction in the global average GFI and operational efficiency improvements. Reductions in the global average GFI could potentially be achieved using the IMO GFS if the IMO's life-cycle assessment (LCA) guidelines were amended to accurately account for the real-world life-cycle GHG intensity of marine fuels and limit or prevent the use of food- and feed-based biofuels with indirect land-use change (ILUC) emissions. In the event that the IMO GFS regulation or the guidelines used to implement it fall short, further GFI reductions could be achieved by relatively stronger regional policies modeled after the European Union's FuelEU Maritime regulation. Either route would require an unprecedented level of ambition and sustainability safeguards far in advance of current policy.

We then compare the cumulative emissions from 2020 to 2050 with carbon budgets for 1.5 °C, 1.7 °C, and 2 °C future warming. We describe the absolute emissions, the GHG intensity trajectories of marine fuels, and the required supply of zero-emission fuels associated with each scenario. We end by discussing the policy implications of this work and areas for future research. Detailed data supporting the results are included in the appendix.

METHODS

The methodology of this study is illustrated in Figure 1. Our modeling tool, Polaris, first projects the energy demand from international shipping for a given transport work demand, taking operational efficiency improvements into account when applicable. The IMO and 1.5 °C emission targets are then used to establish GFI requirements for each scenario. The following subsections describe Polaris, carbon budget estimates for international shipping, and our scenarios.

Figure 1
Study methodology



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POLARIS MODEL

The GHG emissions under different scenarios were calculated using version 1.3 of the ICCT's Polaris model. A more detailed description of the model can be found in the model documentation (Alvarez et al., 2025). This section outlines the model's scope and assumptions relevant to this paper's analysis.

Polaris uses the activity-based, bottom-up 2019 inventory of ships from the ICCT's Systematic Assessment of Vessel Emissions (SAVE) model (Mao et al., 2025) and projects its evolution. Polaris uses SAVE 2019 emissions estimates for Type 1 and Type 2 vessels as defined in the Fourth IMO GHG Study (Faber et al., 2020); that is, vessels that are observed in the Automatic Identification System data and can be identified by either their IMO number (Type 1) or Maritime Mobile Service Identity number (Type 2). These ships emitted 757 million tonnes (Mt) of CO_2 in 2019, which is a good approximation of international shipping emissions.[1]

Polaris estimates TTW and WTW GHG emissions, which include CO_2, methane (CH_4), and nitrous oxide (N_2O). Emissions are reported as carbon dioxide equivalents (CO_2e) based on the global warming potentials (GWPs) for both 20-year (GWP20) and 100-year (GWP100) time horizons. This paper used the GWP100 values from the Intergovernmental Panel on Climate Change's (IPCC's) *Sixth Assessment Report* (IPCC, 2021), shown in Table 1.

1 Emissions from Type 1 and 2 vessels and those from international (vessel-based) shipping have considerable overlap and are comparable, at 757 and 746 million tonnes of CO_2 in 2019, respectively (Mao et al., forthcoming). Therefore, in this paper, we refer to activities and emissions from Type 1 and 2 vessels as those from international shipping.

Table 1
Global warming potentials used in this analysis

Pollutant	GWP100
CO_2	1
CH_4	29.8
N_2O	273

Source: Intergovernmental Panel on Climate Change (2021)

CARBON BUDGETS FOR TEMPERATURE TARGETS

We estimated the carbon budgets for international shipping to limit global warming to 1.5 °C, 1.7 °C, and 2 °C based on the sector's historical share of anthropogenic CO_2 emissions. We then adjusted the TTW CO_2 budget to account for upstream (well-to-tank) and non-CO_2 GHG emissions. The cumulative emissions under each scenario can be compared against these budgets.

We used global carbon budgets from 2020 onward from the IPCC *Sixth Assessment Report* (IPCC, 2021) with a 67% likelihood of success to limit global warming to 1.5 °C, 1.7 °C, or 2 °C, with no overshoot. These budgets refer to CO_2 emissions, although they account for the warming effect of non-CO_2 emissions. The Polaris model estimated that TTW CO_2 emissions accounted for 2.05% of global anthropogenic CO_2 emissions on average during the 5-year period from 2019 to 2023. Over the same period, Polaris estimated the WTW GHG emissions (in CO_2e) to be 1.2 times the TTW CO_2 emissions. To estimate international shipping's carbon budgets for each temperature limit, we first multiplied the IPCC global CO_2 budget by 2.05%, which yielded international shipping's proportional TTW CO_2 budget; we then multiplied by 1.2 to arrive at international shipping's proportional WTW CO_2e carbon budget. The resulting budgets, listed in Table 2, were 9.8 Gt CO_2e for 1.5 °C, 17.2 Gt CO_2e for 1.7 °C, and 28.3 Gt CO_2e for 2 °C.

Table 2
Carbon budgets for shipping activity covered by Polaris

Global warming limit	Estimated remaining global anthropogenic CO_2 budgets from the beginning of 2020 (Gt CO_2)[a]	TTW CO_2 budgets for international shipping (Gt CO_2)	WTW CO_2e budgets for international shipping (Gt CO_2e)
1.5 °C	400	8.2	9.8
1.7 °C	700	14.3	17.2
2 °C	1,150	23.5	28.3

[a] Sourced from Intergovernmental Panel on Climate Change (2021)

SCENARIOS

This section describes the five scenarios modeled in this report, which include three decarbonization scenarios. The subsections below provide more detail on the parameters shared across scenarios and those unique to each scenario.

- **Counterfactual:** This scenario excludes the projected emission reductions resulting from FuelEU Maritime. The IMO's existing short-term measures—the Energy Efficiency Design Index, Energy Efficiency Existing Ship Index, and Carbon Intensity Indicator (CII)—are included but are never strengthened, and no new regulations are implemented by the IMO. This scenario is evaluated to calculate the impacts of FuelEU Maritime.
- **Baseline:** This scenario is identical to the Counterfactual scenario except that it includes modeled emission reductions expected from FuelEU Maritime, which entered into force on January 1, 2025. This scenario is treated as the baseline from which new or updated regulations affect future emissions.
- **IMO Minimum:** In this scenario, GHG emissions from international shipping decline by 20% by 2030 and 70% by 2040 compared with 2008 emission levels. The sector achieves net-zero by 2050.
- **IMO Striving:** In this scenario, GHG emissions from international shipping decline by 30% by 2030 and 80% by 2040 compared with 2008 emission levels. The sector achieves net-zero by 2050.
- **1.5 °C:** In this scenario, cumulative GHG emissions from international shipping are below the shipping sector's proportional share of the carbon budget that aligns with a 67% chance of limiting warming to 1.5 °C.

For the IMO Minimum and IMO Striving scenarios, we show two compliance pathways:

- **GFI only:** The scenario goal is met solely by progressively reducing the global average GFI.
- **GFI and efficiency:** All ships improve their operational efficiency and reduce fuel consumption, and the remaining reductions are met by reducing the global average GFI.

For the 1.5 °C scenario, we show only one compliance pathway (GFI and efficiency) because, as shown in the following section, meeting the carbon budget for 1.5 °C requires such rapid and deep emission reductions that the implied GFI requirement without operational efficiency improvements would be prohibitively high.

FuelEU Maritime regulation

We modeled GHG emission reductions from the FuelEU Maritime regulation to establish the Baseline scenario. FuelEU Maritime introduces a GHG intensity reduction requirement, which is implemented from 2025 and gradually strengthened through 2050 (Table 3). As a regional regulation, it covers all the energy consumed in an EU port or used on voyages between continental EU ports, and half of the energy used on voyages between two EU ports if one is in an outermost region or between an EU port and a third country (Baldino, 2023).[2]

2 EU outermost regions refer to nine designated regions that are part of EU Member States but are geographically distant from continental Europe.

Table 3
FuelEU Maritime greenhouse gas intensity requirements by year

Year	2020 (Reference year)	2025–2029	2030–2034	2035–2039	2040–2044	2045–2049	2050-
GHG intensity ($g\ CO_2e100/MJ$)	91.16	89.34	85.69	77.94	62.90	34.64	18.23
Reduction against reference value		2%	6%	14.5%	31%	62%	80%

Note: FuelEU Maritime uses the GWPs from the IPCC's (2007) *Fourth Assessment Report*: 25 for CH_4 and 298 for N_2O (Directive [EU] 2018/2001, 2024). The European Union may revise the FuelEU Maritime GWPs to align with IPCC's (2013) *Fifth Assessment Report* in the future: 28 for CH_4 and 265 for N_2O (Commission Delegated Regulation [EU] 2020/1044, 2021). We did not adjust for the differences in GWPs in this analysis.

According to the EU Monitoring, Reporting, and Verification system, emissions from half of inbound and outbound voyages and from all voyages between two EU ports totaled 82 Mt CO_2 in 2022 (Comer et al., 2024b), which represented 9.3% of global shipping CO_2 emissions that year (Mao et al., forthcoming). We assumed that the share would remain constant from 2025 to 2050 and applied the GHG intensities required by the EU Maritime regulation to the 9.3% of annual global energy consumption estimated by Polaris.

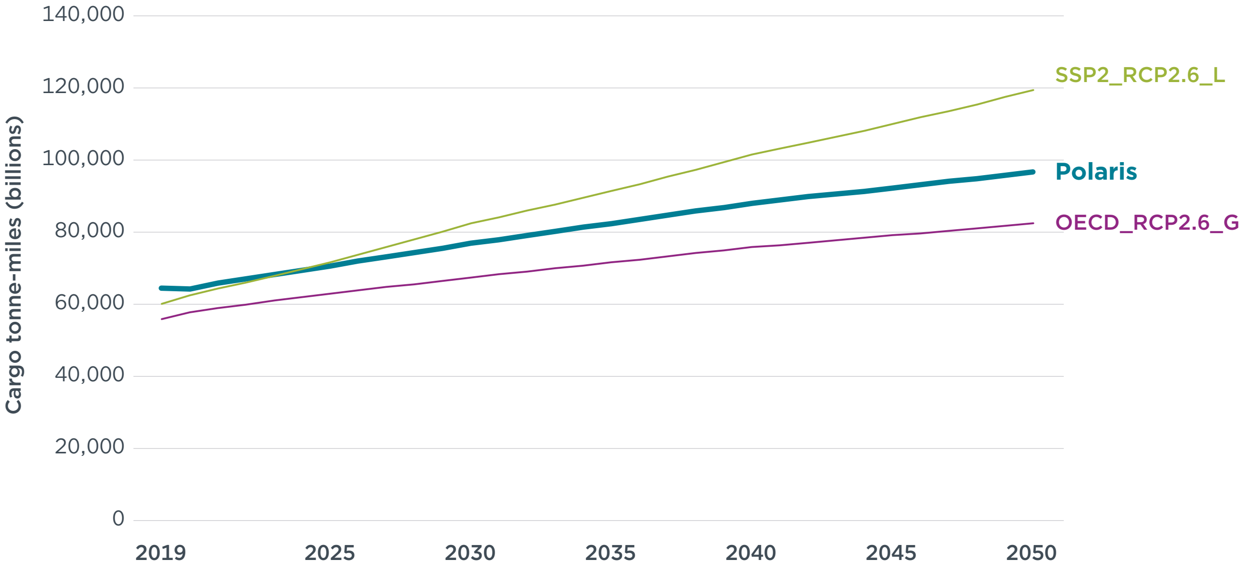
Transport work forecasts

All five scenarios used the baseline transport work projections from Polaris. For most ship classes, Polaris uses linear projections based on historical transport work data from United Nations Trade and Development (2021). However, for oil tankers, it uses projections based on the SSP2_RCP2.6_L scenario in the Fourth IMO GHG Study (Faber et al., 2020) because historical growth patterns are unlikely to continue due to anticipated energy transitions. The SSP2_RCP2.6_L scenario assumes socioeconomic development follows moderate historical patterns (Riahi et al., 2017) and global mean temperature increase is limited to 2 °C (van Vuuren et al., 2011). This results in a 29% decline in oil transport demand from 2019 by 2050.

The resulting total transport work projections in Polaris fall between those of the Fourth IMO GHG Study's OECD_RCP2.6_G scenario, which represents the lowest economic growth and transport work demand, and those of the SSP2_RCP2.6_L scenario, as shown in Figure 2.

Figure 2

Total cargo transport work projections, 2019–2050



Note: The projections include demand from bulk carriers, oil tankers, chemical tankers, gas tankers, container ships, and other unitized cargo ships.

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Well-to-wake GHG emission trajectories for scenarios

The 2023 IMO GHG Strategy's absolute emission targets aim to reduce emissions below a 2008 baseline. Polaris, on the other hand, uses a 2019 baseline. In this analysis, we assumed that achieving the IMO Minimum and IMO Striving scenarios GHG reduction targets from the 2019 Polaris baseline is equivalent to achieving those reductions from a 2008 baseline based on the similarity in TTW emissions between 2008 and 2019.

Specifically, in the Third IMO GHG Study, TTW emissions from international shipping were estimated to be 921 Mt of CO_2 in 2008 (Smith et al., 2014). In the Fourth IMO GHG Study, TTW emissions were about 919 Mt of CO_2 in 2018, nearly identical to 2008 levels (Faber et al., 2020). Mao et al. (forthcoming), using a different methodology, found that 2018 and 2019 TTW CO_2 emissions from international shipping were similar, at 750 Mt and 746 Mt, respectively, a difference of less than 1%.[3] Because the fuel mix in each of these years was similar, with the majority of fuel consumption from heavy fuel oil, we expect the WTW emissions to also be similar.[4] For these reasons, we concluded that it was defensible to use 2019 international shipping emission estimates as a proxy for 2008 emissions when assessing whether a scenario's WTW emissions reduction trajectory is compatible with the emissions reduction targets in the IMO Minimum or IMO Striving scenarios.

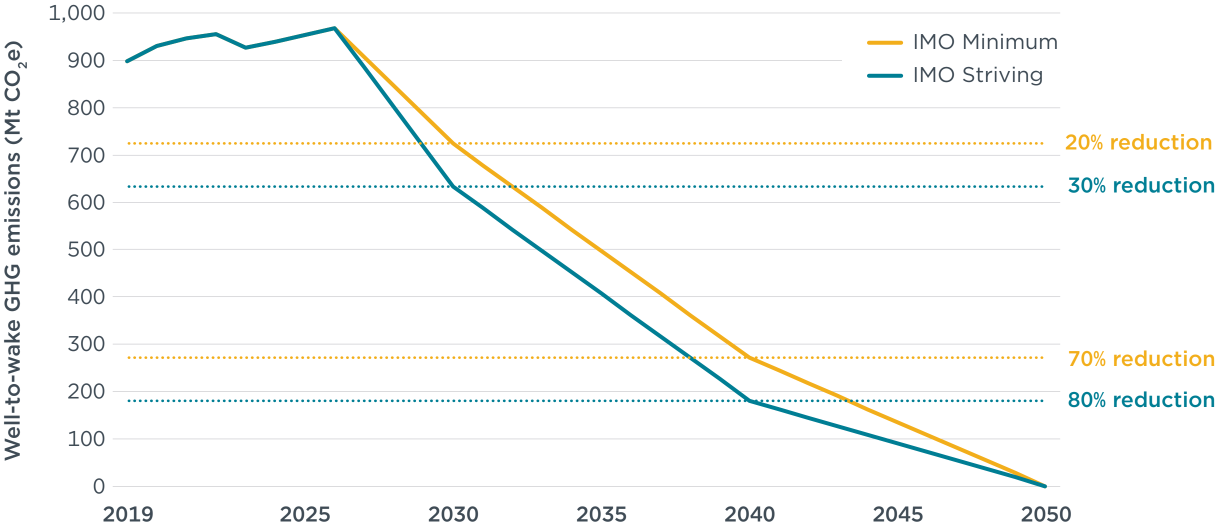
For all trajectories, we used the Baseline emission estimates up to 2026. This is because we do not expect any significant changes in IMO measures, either short-term or mid-term, before 2027. We then calculated the emissions in 2030, 2040, and 2050 required under IMO targets and linearly interpolated for the years in between. The resulting WTW GHG emission trajectories for the IMO Minimum and IMO Striving scenarios are shown in Figure 3.

3 There are methodological differences that result in lower estimates of international shipping emissions in Mao et al. (forthcoming) as compared with Faber et al. (2020), as described in Mao et al. (forthcoming).

4 The IMO's global fuel sulfur limit, which required a switch from high-sulfur heavy fuel oil to very low sulfur fuel oil (<0.50% sulfur) or marine gas oil (<0.10% sulfur) except for ships that have an exhaust gas cleaning system (also known as a scrubber), came into force in 2020 (Osipova et al., 2021).

Figure 3

Well-to-wake greenhouse gas emission trajectories for the IMO Minimum and IMO Striving scenarios



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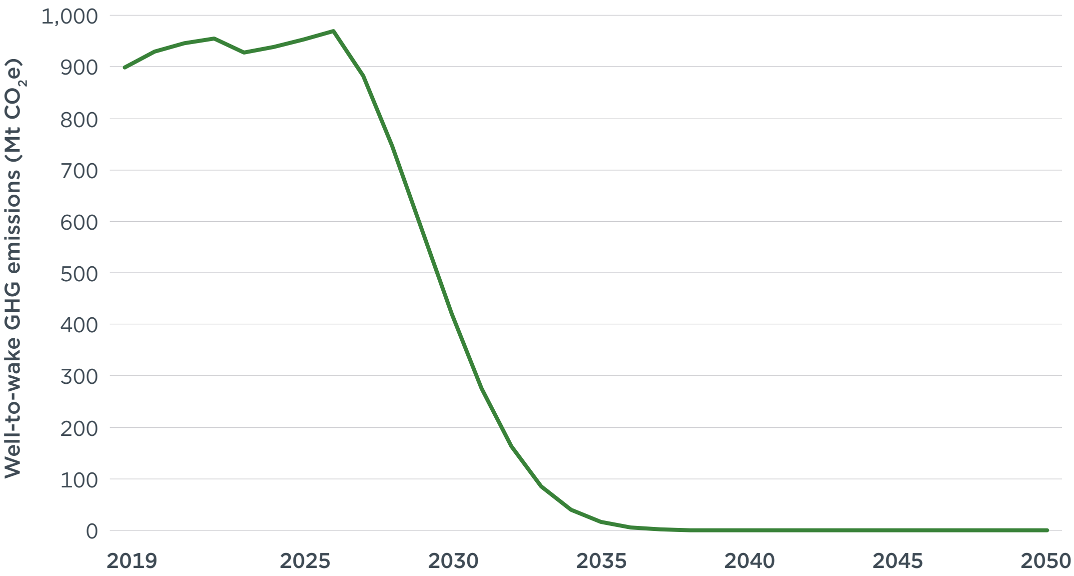
For the 1.5 °C scenario, shown in Figure 4, we assumed that the emissions would need to decrease very rapidly from 2027 to meet the WTW GHG budget of 9.8 Gt CO_2e as emissions from 2020 to 2026 (6.6 Gt) would already have consumed two-thirds of the 1.5 °C-aligned budget. Specifically, emissions would need to decrease by more than 50% by 2030 compared with the 2019 level and reach zero by 2038.

Figure 4

Well-to-wake greenhouse gas emissions trajectory for the 1.5 °C scenario



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Operational efficiency improvements

The IMO's mid-term measures will likely incentivize further improvements in operational efficiency to reduce fuel consumption. Carbon pricing would increase fuel costs and therefore encourage shipowners to reduce energy consumption per transport work. Similarly, achieving GFI reductions under a GFS will require the use of new fuels that are more expensive than conventional fossil fuels, which can also encourage actions to reduce fuel consumption to save on fuel costs. DNV's (2024) comprehensive impact assessment estimated that introducing mid-term measures (GFS and carbon pricing) aligned with either the IMO Minimum or IMO Striving scenario targets would reduce average ship speeds over the period 2023–2050 by 9%–13% and total energy use by 15%–21% relative to a business-as-usual scenario.

One of the IMO's short-term measures, the CII, which entered into force in 2023, could also be amended to require ships to improve their operational efficiency. A ship's CII grade is calculated by dividing its CO_2 emissions by the product of its capacity and distance traveled in a given calendar year. The ship is then given a rating from A to E based on a comparison with the CII reference line and reduction factor for that year. While it is mandatory for covered ships to calculate and report their CII grade to the IMO, there are currently no penalties for ships with failing grades of D or E, except to write a plan of corrective actions if the ship receives a grade of D for three consecutive years or an E in any one year. It also currently does not consider upstream or non-CO_2 emissions.

In this analysis, we modeled improvements in operational efficiency through speed reduction, which can immediately reduce fuel consumption. This is based on the assumption that a ship's main engine power demand and resulting fuel consumption is proportional to the cube of the ship's speed (Faber et al., 2020; Olmer et al., 2017). Under this assumption, reducing speed by 10% reduces hourly main engine fuel consumption by 27%. The total reduction in voyage energy consumption modeled is smaller than this, however, because it is partially offset by an increase in operating hours.

Polaris models the impacts of speed reduction by adjusting the model input for engine power limitation (EPL), which limits the main engine's maximum installed power by a certain percentage and changes its load factor distribution. Hours spent above the maximum defined EPL are shifted to lower engine loads, where the ship is also operating at a slower speed. This reduces hourly and total fuel consumption for that ship. Polaris compensates for any loss of transport work by increasing operating hours or building new ships, if necessary. The detailed methodology can be found in the model documentation (Alvarez et al., 2025).

Table 4 describes the EPL (as a percentage of maximum engine power) used to achieve speed reductions for each scenario. Based on DNV (2024), for compliance pathways that account for operational efficiency improvements, we assumed that the IMO Minimum scenario would achieve about a 10% speed reduction and the IMO Striving and 1.5 °C scenarios about a 12% speed reduction by 2030 compared with the Baseline scenario for that year. The speed was calculated at the fleet level by dividing the total distance traveled by the total cruising hours in each year. We assumed speed reductions begin in 2027, when the IMO mid-term measures are scheduled to enter into force, and gradually ramp up over four years, achieving full effect in 2030.

Table 4
Engine power limitation and speed reduction assumptions

Year	IMO Minimum scenario			IMO Striving / 1.5 °C scenarios		
	EPL	Speed compared with Baseline scenario in that year	Speed compared with 2019	EPL	Speed compared with Baseline scenario in that year	Speed compared with 2019
2027	10.8%	99.2%	96.0%	11.5%	99.1%	95.9%
2028	21.5%	97.5%	94.1%	23.0%	97.2%	93.8%
2029	32.3%	93.8%	90.2%	34.5%	93.0%	89.4%
2030+	43.0%	89.8%	86.1%	46.0%	87.5%	83.9%

Notes: The model estimates that the average speed would be lower even in the Baseline compared with the speed in 2019 due to Energy Efficiency Existing Ship Index requirements, which came into effect in 2023. According to United Nations Trade and Development (2024), there was indeed a drop in sailing speed in 2023.

While we modeled the impact of operational efficiency improvements through speed reduction in this analysis, other operational strategies such as route optimization, better payload utilization, or reducing port waiting times or technical efficiency improvements such as energy efficiency retrofits, hull air lubrication, and other technologies that reduce operational GHG intensity may be able to contribute to the emission reductions we have assigned to this category.

Global average GHG fuel intensity

The global average GFI will need to fall to achieve the IMO's GHG reduction targets. One measure to achieve this will be the GFS, which is the technical element of the IMO's mid-term measures. The standard will regulate the WTW GHG emissions of marine fuels, and be expressed in g CO_2e/MJ, according to the IMO's LCA guidelines (IMO, 2024).[5] Annual GFI values under the GFS are still being negotiated. As previously mentioned, if the IMO's GFS falls short of delivering the real-world GFI reductions required to achieve its climate goals, relatively stronger regional policies similar to, but more stringent than, FuelEU Maritime would be needed to achieve the required global average GFI reductions.

To determine the GFI trajectory required for each scenario, we first calculated the annual WTW GHG emission trajectories aligned with the targets of the IMO scenarios and the 1.5 °C scenario target, as detailed in the prior section. Polaris results were then used to estimate the total energy consumption each year, considering operational efficiency improvements if applicable for the compliance pathway. Lastly, we calculated the required global average GFI for each year by dividing the annual GHG emission target by that year's projected energy consumption.

5 The IMO's current LCA guidelines use GWPs from the IPCC (2013) *Fifth Assessment Report*: 28 for CH_4 and 265 for N_2O. The IMO may update these values to align with the *Sixth Assessment Report*.

RESULTS AND DISCUSSION

EMISSION ESTIMATES

Figure 5 depicts the cumulative emissions from 2020 to 2050 in different scenarios, along with the carbon budgets for the 1.5 °C, 1.7 °C, and 2 °C pathways. Emissions in the Baseline scenario are 2.1% (0.7 Gt CO_2e) lower than in the Counterfactual scenario because of the inclusion of FuelEU Maritime. In the Baseline scenario, the cumulative emissions from 2020 would exceed the 1.5 °C carbon budget in 2030, the 1.7 °C carbon budget in 2037, and the 2 °C carbon budget in 2047, reaching 32.4 Gt CO_2e by 2050. This also means that, without additional IMO regulations, international shipping would consume 3.9% of the global 1.7 °C budget and 6.7% of the 1.5 °C budget through 2050, roughly double or triple its current 2.05% share of global anthropogenic emissions.

Both the IMO Minimum and IMO Striving scenarios are aligned with the 1.7 °C pathway but not with the 1.5 °C pathway. The IMO Striving scenario targets result in an additional reduction of 1.5 Gt CO_2e in cumulative emissions compared with emissions in the IMO Minimum scenario.

Figure 5

Cumulative well-to-wake greenhouse gas emissions by scenario, 2020–2050

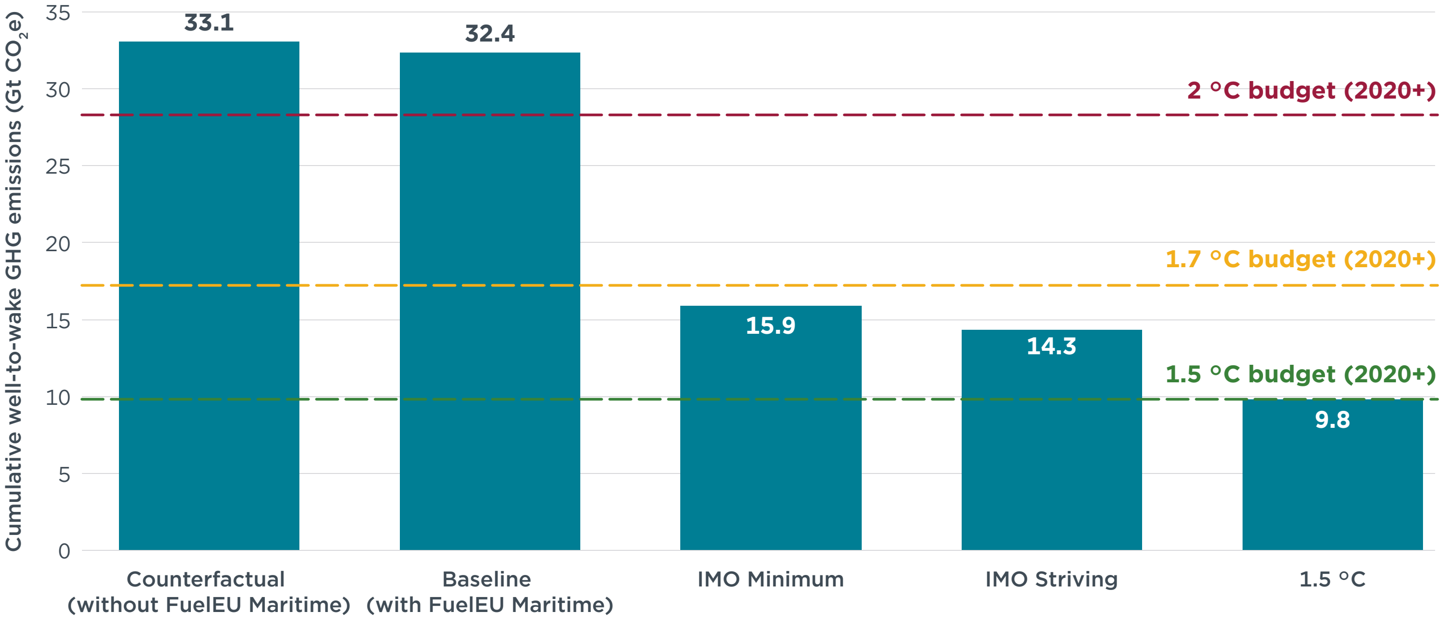

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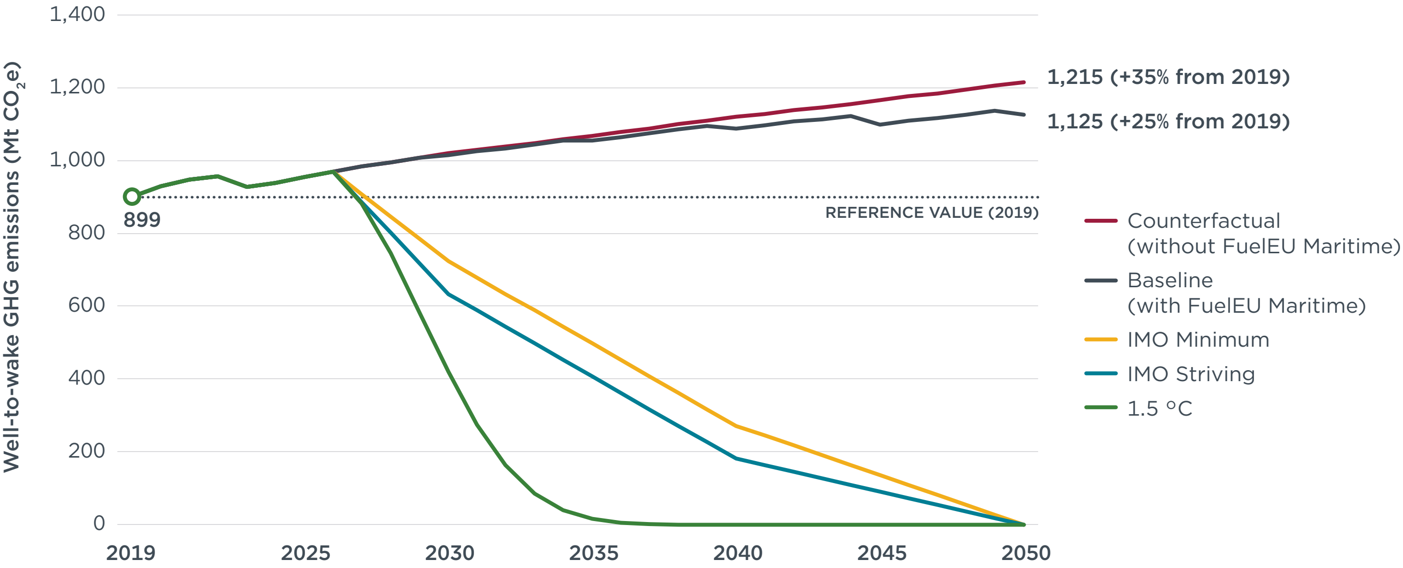
Figure 6 shows the annual emissions from 2019 to 2050 in different scenarios. Due to the growth in transport work demand, emissions in the Counterfactual and Baseline scenarios in 2050 are 35% and 25% higher, respectively, than the emissions in 2019. For the three goal-based scenarios—IMO Minimum, IMO Striving, and 1.5 °C—annual emissions are identical to the trajectories we modeled in the scenarios section.

Figure 6

Annual well-to-wake greenhouse gas emissions by scenario, 2019–2050



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We used Polaris estimates instead of historical data for 2019–2024 emissions. When compared with the ICCT SAVE model's estimates, which were based on actual ship activity data, Polaris overestimated emissions during the COVID-19 pandemic in 2020 and underestimated emissions in 2023. Nonetheless, the cumulative Polaris emission estimates from 2019 to 2023 (3,876 Mt CO_2 on a TTW basis) were comparable to the SAVE model estimates for the same period (3,852 Mt CO_2; Mao et al., forthcoming). Therefore, we do not expect differences in historical emissions to affect the overall projected cumulative emissions or GFI values. Historical emissions data for 2024 were not available when conducting the analysis for this study.

GREENHOUSE GAS FUEL INTENSITY TRAJECTORY

Figure 7 summarizes GFI trajectories under the different scenarios and compliance pathways. The right-hand axis shows GFI values relative to the GHG intensity in 2019 (91 g CO_2e/MJ). As operational efficiency improvements reduce the total energy consumption, the GFI and efficiency pathway results in less need for fuel switching (i.e., less stringent GFI levels) than the GFI-only pathway for a given scenario. For example, in the IMO Minimum scenario, the 2030 GFI would be 71 g CO_2e/MJ with efficiency improvements and 64 g CO_2e/MJ without. In the IMO Striving scenario, these values would be 64 g CO_2e/MJ with improvements and 56 g CO_2e/MJ without. In the 1.5 °C scenario, the emissions would have to achieve net-zero by 2038, so the required GFI is zero from 2038 onward. In all scenarios and compliance pathways, the required GFI is more stringent than those contained in FuelEU Maritime (represented by the dotted line). The annual GFI values and the percentage reductions from the 2019 baseline (91 g CO_2e/MJ) are detailed in Table 5.

Figure 7

Greenhouse gas fuel intensity trajectory by scenario and compliance pathway, 2019–2050

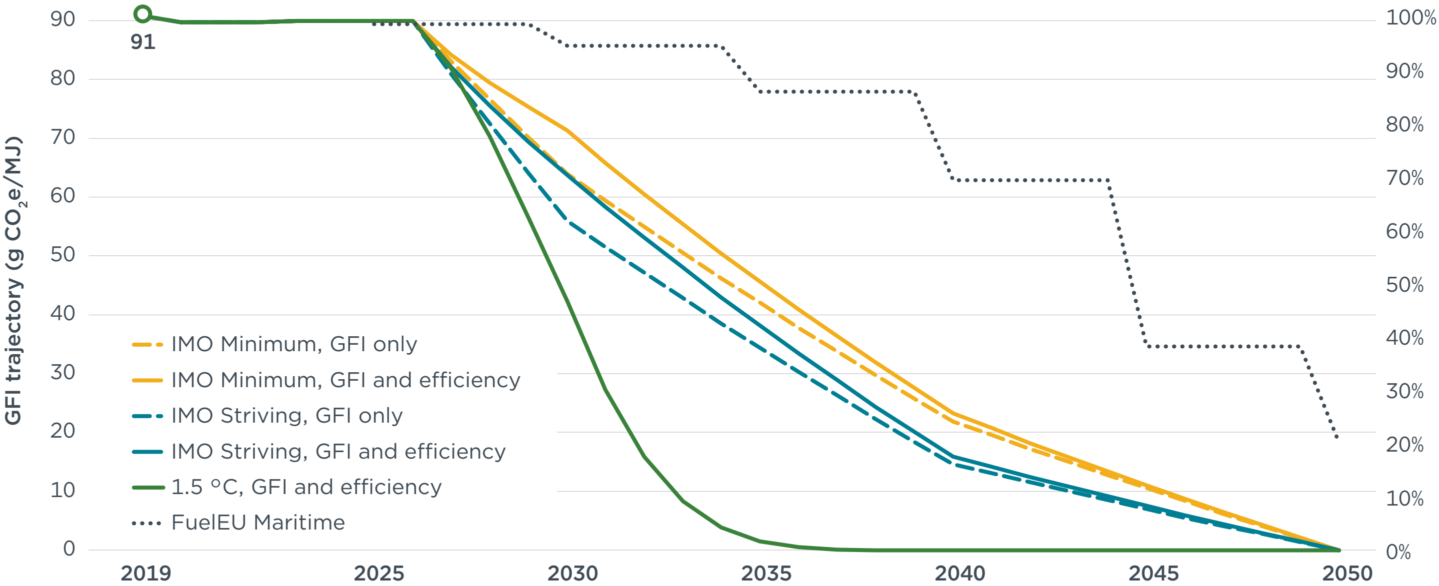

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Table 5

Greenhouse gas fuel intensity values and percentage reduction from 2019 baseline, 2027–2050

Year	IMO Minimum, GFI only		IMO Minimum, GFI and efficiency		IMO Striving, GFI only		IMO Striving, GFI and efficiency		1.5 °C, GFI and efficiency	
	GFI (g CO_2e/MJ)	Reduction from 2019 value (%)	GFI (g CO_2e/MJ)	Reduction from 2019 value (%)	GFI (g CO_2e/MJ)	Reduction from 2019 value (%)	GFI (g CO_2e/MJ)	Reduction from 2019 value (%)	GFI (g CO_2e/MJ)	Reduction from 2019 value (%)
2019	90.84		90.84		90.84		90.84		90.84	
2027	83.07	8.5%	84.23	7.3%	80.97	10.9%	82.16	9.6%	81.88	9.9%
2028	76.56	15.7%	79.42	12.6%	72.49	20.2%	75.5	16.9%	70.31	22.6%
2029	70.15	22.8%	75.3	17.1%	64.08	29.5%	69.34	23.7%	56.47	37.8%
2030	63.94	29.6%	71.25	21.6%	55.9	38.5%	63.69	29.9%	42.26	53.5%
2031	59.4	34.6%	65.82	27.5%	51.44	43.4%	58.27	35.9%	27.25	70.0%
2032	54.91	39.6%	60.52	33.4%	47.1	48.1%	53.07	41.6%	15.83	82.6%
2033	50.55	44.4%	55.41	39.0%	42.81	52.9%	47.97	47.2%	8.28	90.9%
2034	46.19	49.1%	50.44	44.5%	38.45	57.7%	42.94	52.7%	3.8	95.8%
2035	42.03	53.7%	45.67	49.7%	34.35	62.2%	38.16	58.0%	1.5	98.3%
2036	37.79	58.4%	40.88	55.0%	30.26	66.7%	33.45	63.2%	0.46	99.5%
2037	33.72	62.9%	36.31	60.0%	26.26	71.1%	28.89	68.2%	0.09	99.9%
2038	29.68	67.3%	31.85	64.9%	22.22	75.5%	24.36	73.2%	0	100.0%
2039	25.77	71.6%	27.56	69.7%	18.37	79.8%	20.08	77.9%	0	100.0%
2040	21.82	76.0%	23.24	74.4%	14.58	84.0%	15.87	82.5%	0	100.0%
2041	19.5	78.5%	20.69	77.2%	13.02	85.7%	14.12	84.5%	0	100.0%
2042	17.18	81.1%	18.19	80.0%	11.48	87.4%	12.43	86.3%	0	100.0%
2043	14.96	83.5%	15.77	82.6%	10	89.0%	10.78	88.1%	0	100.0%
2044	12.73	86.0%	13.38	85.3%	8.51	90.6%	9.14	89.9%	0	100.0%
2045	10.52	88.4%	11.03	87.9%	7.04	92.2%	7.55	91.7%	0	100.0%
2046	8.36	90.8%	8.75	90.4%	5.52	93.9%	5.91	93.5%	0	100.0%
2047	6.17	93.2%	6.44	92.9%	4.11	95.5%	4.39	95.2%	0	100.0%
2048	4.08	95.5%	4.25	95.3%	2.72	97.0%	2.90	96.8%	0	100.0%
2049	2.02	97.8%	2.1	97.7%	1.35	98.5%	1.44	98.4%	0	100.0%
2050	0	100.0%	0	100.0%	0	100.0%	0	100.0%	0	100.0%

These GFI trajectories can reach their emissions reduction targets only if the IMO LCA guidelines or other guidelines developed to implement the GFS accurately account for the life-cycle GHG emissions of marine fuels. Some default methane emission factors for fossil fuels, biofuels, and e-LNG made using renewable electricity are underestimated (Comer, et al., 2024a). Nitrous oxide emission factors for ammonia-fueled engines have yet to be established and are currently subject to high uncertainties, given the lack of large, commercially available ammonia marine engines (Marine Environment Protection Committee, 2025). In addition, the IMO's sustainability guidelines are not nearly robust enough to prevent the use of food- or feed-based biofuels with high ILUC emissions that erode, and in some cases eliminate, potential life-cycle GHG savings compared with fossil fuels (Sandford & Malins, 2025).

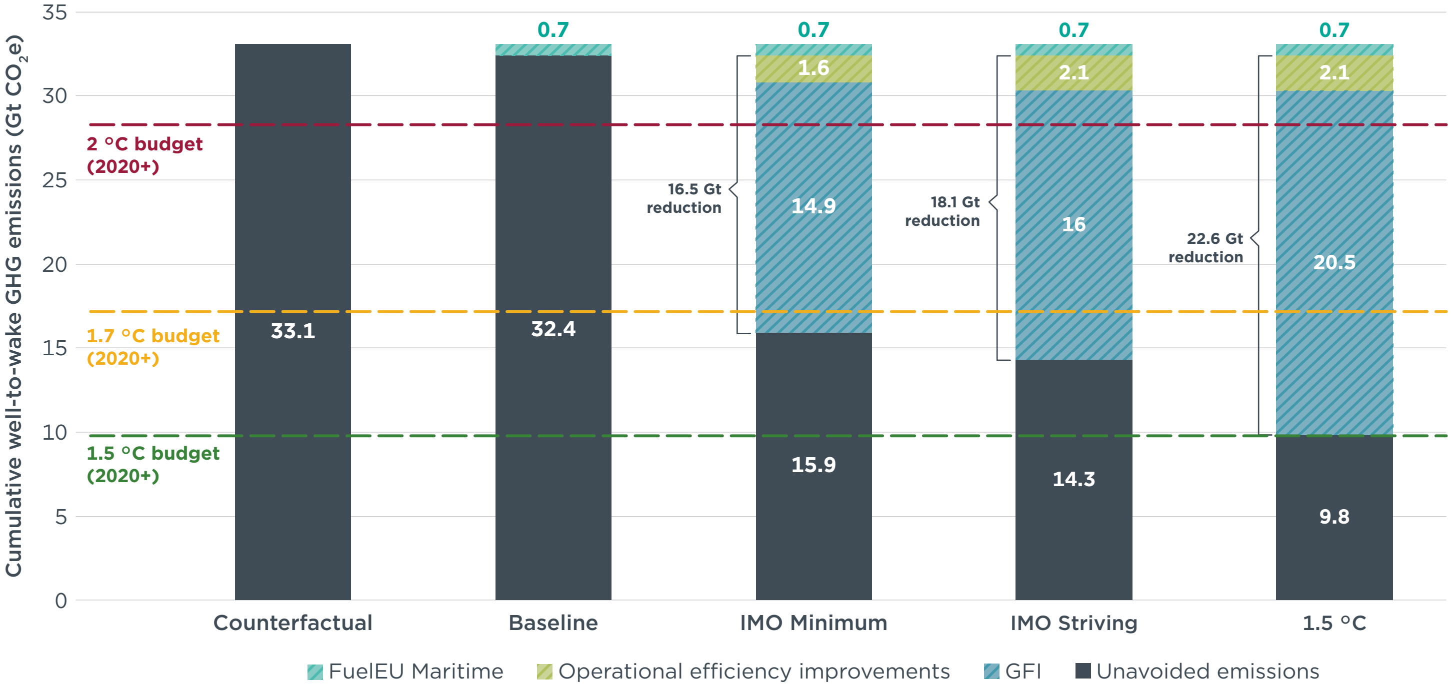
Indirect land-use change occurs when the new demand for biofuels leads to increased demand for feedstock crops and results in cropland expansions (Carvalho et al., 2023). When the cropland expansion occurs on high carbon-stock lands such as forests, wetlands, and peatlands, the WTW GHG intensity of biofuels including ILUC emissions can be even higher than that of fossil fuels (Sandford & Malins, 2025). For this reason, FuelEU Maritime excludes food- and feed-based biofuels from qualifying for compliance. However, the IMO's LCA guidelines currently do not assign ILUC emissions to biofuels nor limit their contribution to the standard, which could incentivize the use of low-cost biofuels that do not bring real climate benefits to comply with the GFS.

CONTRIBUTION OF EACH MEASURE TO EMISSIONS REDUCTION

Figure 8 summarizes the contributions of each measure to cumulative emission reductions. FuelEU Maritime accounts for a 0.7 Gt CO_2e decrease in emissions, representing 3%–4% of the cumulative reduction depending on the scenario. Operational efficiency improvements (which result in 1.6–2.1 Gt CO_2e emissions savings) account for 9.3% of the emissions reduction in the IMO Minimum scenario, 11.2% in the IMO Striving scenario, and 9.0% in the 1.5 °C scenario. The emissions reduction from decreased speed is partially offset by an increase in fleet size and operating hours to meet the transport work demand. Reducing global average GFI is projected to be responsible for the vast majority of emission reductions in each scenario.

Figure 8

Cumulative well-to-wake greenhouse gas emissions avoided by scenario and measure, 2020–2050



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Of the three measures plotted above, FuelEU Maritime is the only existing and legally binding measure. If the IMO's mid-term measures end up being less stringent and fail to deliver the emission reductions modeled in this analysis, more regional and national policies similar to, but more stringent than, FuelEU Maritime would be needed to fill the gap.

ZERO-EMISSION FUEL REQUIREMENTS

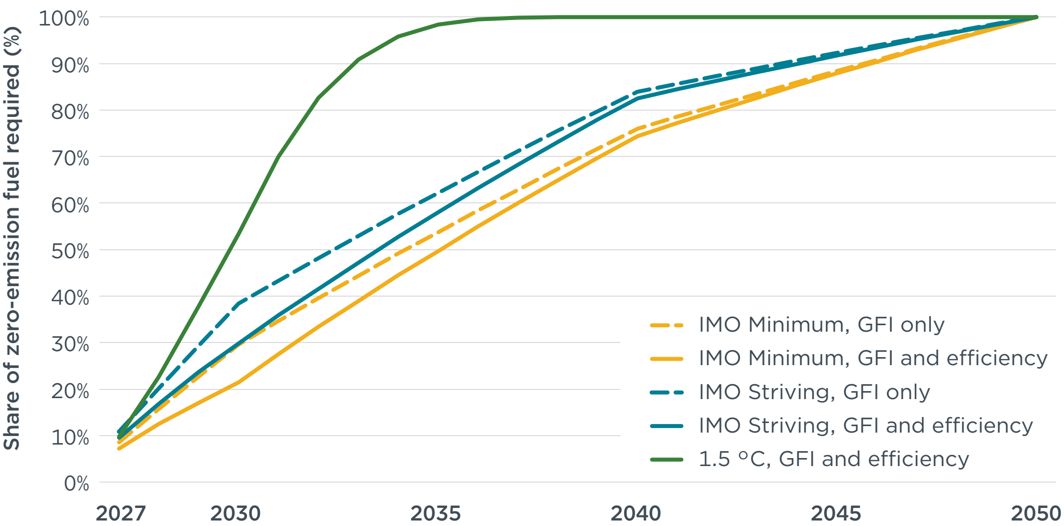
As shown above, about 90% of the emission reductions would need to come from zero or near-zero GHG emission energy sources that meet the GFI requirements. Examples would include ammonia produced using 100% renewable electricity that is additional (i.e., not diverted from existing uses) via electrolysis with strictly controlled N_2O emissions, or methanol produced either using captured carbon and 100% additional renewable electricity via electrolysis or using biogas made from wastes and residues (U.S. Department of Transportation, Maritime Administration, 2024). As mentioned above, biofuels with high ILUC emissions, such as those made from food and feed feedstocks, might have lower direct GHG intensities but higher life-cycle GHG intensities than the fossil fuels currently being used in the shipping sector because of those land-use change emissions.

Figure 9, inverted from Figure 7, illustrates the scale of zero-emission fuel required to achieve the targets in each scenario. In the IMO Minimum scenario, the GFI-only pathway needs to achieve a 30% reduction in the GFI by 2030 compared with the 2019 level to achieve a 20% reduction in total GHG emissions by 2030. This also implies that zero-emission fuel would need to account for 30% of total energy consumption by 2030. With efficiency improvements, the required share of zero-emission fuel by 2030 would fall to 22%. In the IMO Striving scenario, the required share of zero-emission fuel would be 39% without efficiency improvements and 30% with efficiency improvements. Finally, to align with 1.5 °C, the share would need to be 54% in 2030 and 100% from 2038 onward.

One of the ambitions in the 2023 IMO GHG Strategy is to increase the uptake of zero or near-zero GHG emission technologies, fuels, and energy sources to at least 5% (striving for 10%) of the energy used by international shipping by 2030 (IMO, 2023). Our results, however, imply that even the 10% target would not be enough to meet the 2030 emissions target from the IMO Minimum scenario.

Figure 9

Share of zero-emission fuel required, 2027–2050



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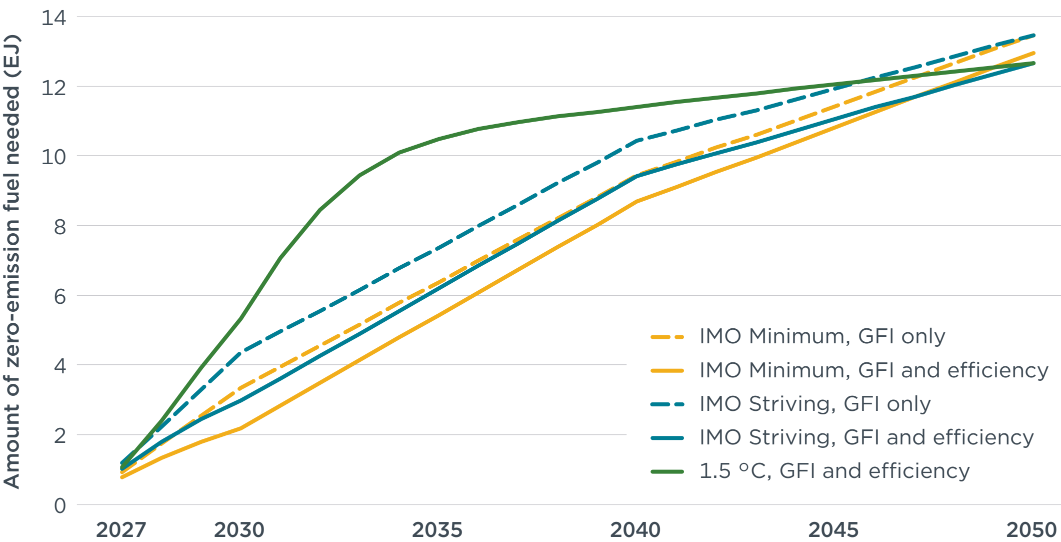
While GFI reduction requirements under the two compliance pathways converge over time, as shown above, efficiency improvements reduce the total energy consumption of international shipping and the amount of zero-emission fuels needed each year through 2050 (Figure 10). These improvements allow international shipping to achieve the IMO Striving scenario target with less zero-emission fuel (shown by the solid blue line) than is required to achieve the IMO Minimum scenario target with only GFI (shown by the dashed yellow line).

Figure 10

Amount of zero-emission fuel needed, 2027–2050



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CONCLUSIONS

This report is a gap analysis, detailing the reduction in the global average GFI and the operational efficiency improvements that would be necessary for the IMO to achieve the absolute GHG emissions reduction goals of the 2023 IMO GHG Strategy, including achieving net-zero GHG emissions by 2050. We assessed three decarbonization scenarios: IMO Minimum (20% GHG reductions by 2030; 70% by 2040), IMO Striving (30% GHG reductions by 2040; 80% by 2040), and 1.5 °C.

We found that the sector is currently on a trajectory to exceed its proportional 1.5 °C carbon budget by 2030, its 1.7 °C budget by 2037, and its 2 °C budget by 2047. The IMO mid-term measures aligned with the targets in the IMO scenarios could achieve cumulative emissions that are consistent with limiting warming to 1.7 °C. Doing so would require rapid, deep, and sustained reductions in the GHG intensity of marine fuels, as well as the adoption of measures that result in operational efficiency improvements.

Operational efficiency improvements can ease the time and financial pressure associated with the switch to zero life-cycle emission fuels, especially in the near term. For example, to achieve the IMO Striving scenario goal of a 30% reduction in total GHG emissions by 2030 would require a 39% reduction in GFI compared with 2019 without efficiency improvements, but a 30% reduction with efficiency improvements. While IMO mid-term measures will likely drive operational efficiency improvements, existing measures like the CII could also be amended to encourage additional advancements. Even with this lever, 90% of the cumulative emissions reduction would require a switch from fossil fuels to net-zero GHG fuels or energy.

We also found that the IMO's ambition of increasing the uptake of zero-emission energy sources to 5% (striving for 10%) of energy demand by 2030 would fall short of its GHG targets. Even in the IMO Minimum scenario, and assuming operational efficiency improvements, the share of zero-emission fuel would have to reach over 20% by 2030 for international shipping to meet the GFI requirement.

Stringent GFI requirements should be accompanied by a robust methodology that accounts for direct and indirect emissions from different fuel pathways. The IMO LCA guidelines underestimate methane emissions from some fuels and engines and lack N_2O emission factors for ammonia-fueled engines. They also fail to adequately address the ILUC emissions of biofuels, which might allow biofuels with low direct emissions but high indirect emissions to comply with the GFS, especially in earlier years, unless the GFS regulation itself disqualifies these fuels. The IMO's mid-term measures should promote the use of scalable zero-emission fuels that can bring meaningful climate benefits, such as e-fuels made from renewable hydrogen produced via electrolysis of water using additional renewable energy. The IMO could follow the European Union's approach by excluding food- and feed-based biofuels, as in FuelEU Maritime, or adopting a cap on the share of food- and feed-based biofuels, as in Renewable Energy Directive, in addition to providing extra rewards for e-fuel use, as in both regulations. In the event that the IMO GFS regulation or the guidelines used to implement it fall short, further GFI reductions could be achieved by relatively stronger regional policies modeled after FuelEU Maritime. However, either route would require an unprecedented level of both ambition and sustainability safeguards far in advance of current policy.

As shown in this study, achieving the IMO's absolute emissions reduction goals will be challenging. Even more challenging will be to align the sector's emissions with a 1.5 °C pathway: the GFI would have to reduce by more than 50% by 2030 compared with the 2019 level, and the sector would need to achieve net-zero GHG emissions by 2038.

Achieving the IMO's revised targets will necessitate stringent GFS requirements and economic measures that ensure an effective carbon price signal that enable a business case to invest in the fuels and infrastructure needed to support shipping's energy transition. The findings of this paper underscore the urgency of finalizing and implementing these policies to align shipping with global climate goals.

FUTURE WORK

As the Polaris model uses 2019 historical data as a baseline, it currently does not capture the changes in fleet or shipping activity since that time, such as a decrease in activity due to the COVID-19 pandemic, or the rapid rise of liquefied natural gas- and methanol-fueled ships. Updating the model baseline would enhance the accuracy of the projections derived from the model. Emission factors for alternative fuels such as ammonia, hydrogen, and methanol, and especially for N_2O emissions from ammonia engines, require additional research and should be revisited as more real-world data become available. Given the importance of operational efficiency measures to reduce the volume of zero-emission fuels needed going forward, future work could also focus on ways to improve and revise the existing CII to deliver meaningful reductions in energy consumption.

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APPENDIX

Supplemental data for this report can be found at https://theicct.org/publication/vision-2050-fuel-standards-to-align-international-shipping-with-the-paris-agreement-mar25. This spreadsheet has numerical data for the following parameters:

» Emission factors: Emission factors of engine and fuel combinations used in analysis

» Activity: Transport work demand projections by cargo type from 2019 to 2050

» Emission trajectories: WTW GHG emission trajectories by scenario

» Annual projections: Annual energy consumption, WTW GHG emissions, and GFI requirements by scenario and compliance pathway from 2019 to 2050

www.theicct.org

communications@theicct.org

@theicct.org

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