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Greenhouse gas emissions and air pollution from global shipping, 2016–2023

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EXECUTIVE SUMMARY

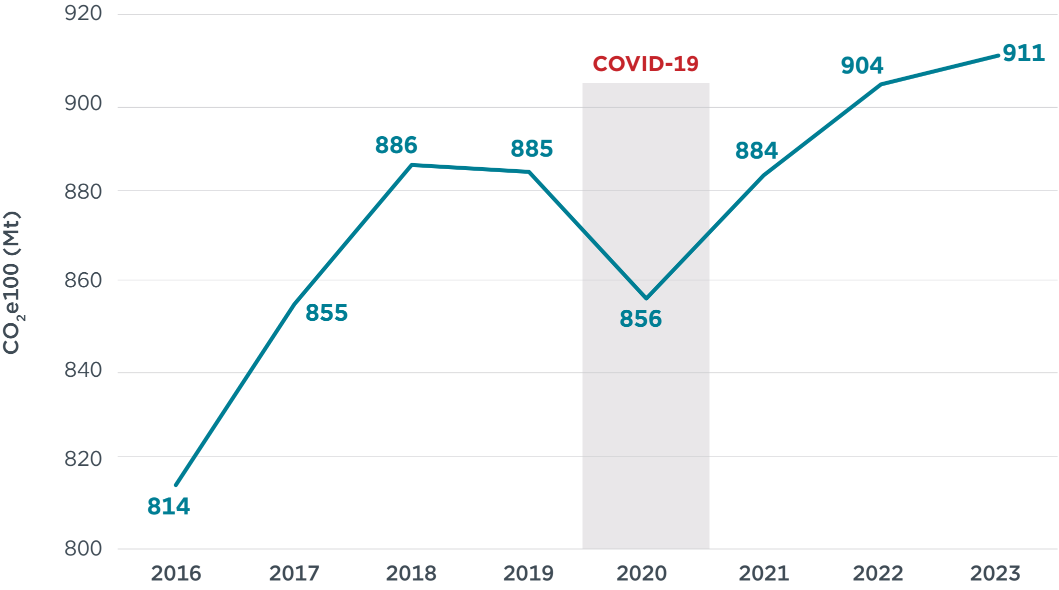
The International Maritime Organization (IMO) aims to achieve net-zero greenhouse gas (GHG) emissions from international shipping by or around 2050 and to cut GHG emissions by 20%–30% below 2008 levels by 2030 and by 70%–80% by 2040. For the IMO to monitor progress and revise the GHG reduction strategy if required, periodic global emissions inventory reports are needed. In 2017, the International Council on Clean Transportation (ICCT) published a report on global ship emissions from 2013 to 2015. Building on that analysis, this report assesses emissions over 2016–2023 using updated, state-of-the-science methods, providing new insights into the maritime shipping sector's climate and environmental performance.

In 2023, global shipping emitted 911 million tonnes (Mt) of tank-to-wake (TTW) carbon dioxide equivalent emissions using 100-year global warming potentials (CO_2e100), or 925 Mt using 20-year global warming potentials (CO_2e20). About 86% of CO_2e100 emissions were from international shipping, with another 10% from domestic shipping and 4% from fishing activities. Between 2016 and 2023, global shipping's share of anthropogenic CO_2e100 emissions remained stable at 1.7%. In terms of CO_2, between 2017 and 2023, shipping accounted for an estimated 2.3% of anthropogenic CO_2 emissions each year, up from 2.2% in 2016. If black carbon (BC) is included, total shipping TTW CO_2e100 emissions increase to 989 Mt, with BC accounting for 8%. Considering 20-year GWPs, total shipping emissions increase to 1,205 Mt CO_2e20, with BC representing 23%.

From 2016 to 2023, global CO_2e100 emissions from shipping grew by 12%, or a compound annual growth rate (CAGR) of approximately 1.4% (Figure ES1). The start of the COVID-19 pandemic temporarily interrupted a steady increase in emissions from the sector: The year-on-year growth rate of global CO_2e100 emissions was -3.2% between 2019 and 2020 and rebounded to +3.2% between 2020 and 2021. Among all GHGs analyzed, methane (CH_4) emissions increased the most because of rapid growth in the use of liquefied natural gas (LNG) as a marine fuel. Methane emissions from LNG-fueled ships were more than 2.5 times higher in 2023 than in 2016, as the number of LNG-fueled ships more than doubled and the use of LNG as a marine fuel grew by more than 80%. The higher growth rate of methane emissions compared with LNG use reflects a shift away from using LNG in steam turbines towards using LNG in dual-fuel internal combustion engines that emit more unburned methane in the form of methane slip.

Figure ES1

Total CO_2e100 emissions from global shipping from 2016 to 2023



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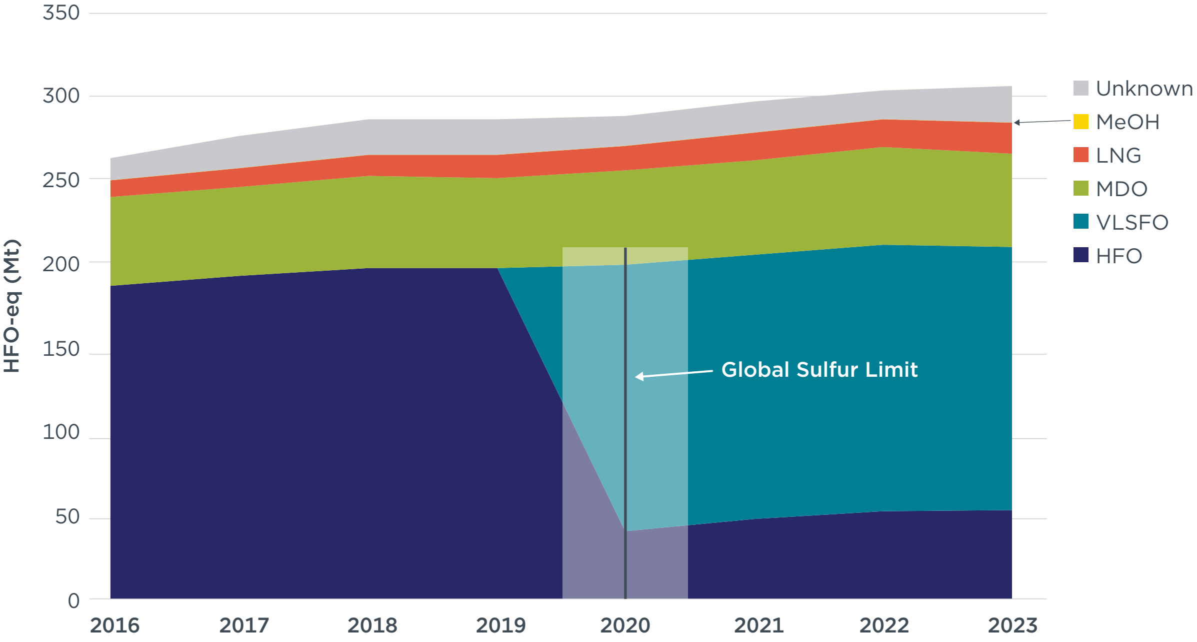
As shown in Figure ES2, between 2016 and 2019, heavy fuel oil (HFO) accounted for more than 70% of fuel consumed by the global shipping fleet; however, following the implementation of the IMO's global sulfur limit in 2020, HFO consumption was largely replaced with very low sulfur fuel oil (VLSFO). Between 2016 and 2023, the use of LNG grew from 10 Mt to 18 Mt in HFO-equivalent (HFO-eq). Marine diesel oil (MDO) consumption grew about 8% from 52 Mt in 2016 to 56 Mt in 2023. The use of methanol (MeOH) nearly quadrupled from 44 thousand tonnes (kt) in 2016 to 160 kt HFO-eq in 2023, as container ships have started using it as a fuel.

Figure ES2

HFO-equivalent fuel consumption by the global shipping fleet by fuel type from 2016 to 2023



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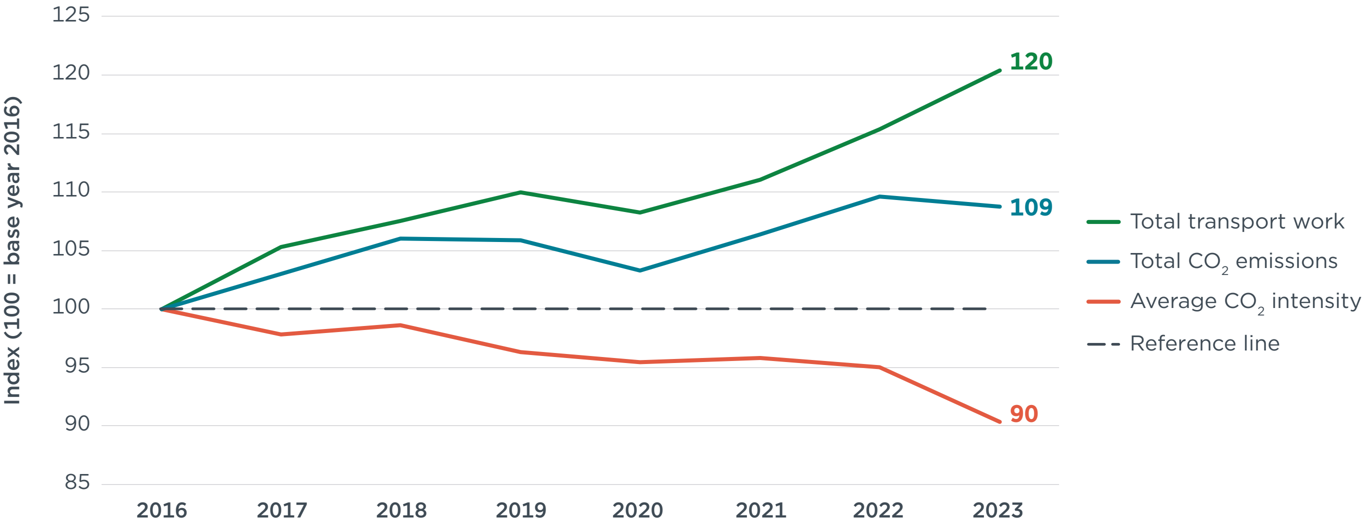
Between 2016 and 2023, the total transport work of the fleet—comprising identified ships, which emitted about 93%–97% of total CO_2 emissions accounted for in this study—grew by 20%, or a CAGR of 2.3%.[1] COVID-19 reduced global shipping transport work by 1.6% between 2019 and 2020, but the sector rebounded quickly, growing 2.6% between 2020 and 2021. The growth of transport work was higher than that of CO_2 emissions (CAGR of 1.1%), indicating that the carbon intensity of shipping improved over the same period. Fleet-wide average carbon intensity changed by about -10.3% from 6.8 g CO_2/dwt-nm in 2016 to 6.1 g CO_2/dwt-nm in 2023, or about -1.3% per year (Figure ES3). Between 2016 and 2023, container ships and liquefied gas tankers made the biggest improvements in CO_2 intensity, while general cargo ships and chemical tankers showed little discernible improvement.

Figure ES3

Transport work, CO_2 emissions, and average carbon intensity from 2016 to 2023



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[1] Transport work is defined as deadweight tonne-nautical miles (dwt-nm) or gross tonnage-nautical miles (GT-nm) depending on ship class. Most transport work is in units of dwt-nm, except for passenger ferries, ro-pax ferries, roll-on/roll-off ships, and cruise ships, for which GT-nm is used.

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INTRODUCTION

In 2023, the International Maritime Organization (IMO) celebrated the 50th anniversary of its adoption of the International Convention for the Prevention of Pollution from Ships (MARPOL), the primary global treaty that regulates ships' environmental impact. Although the IMO only began addressing greenhouse gas (GHG) emissions from ships under the MARPOL framework in 2013, it has made significant improvements in ambition in the past decade. In 2018, IMO Member States agreed to an initial GHG strategy to peak emissions as soon as possible and reduce the total annual GHG emissions by at least 50% by 2050 compared with 2008. In 2023, the body adopted a revised IMO GHG Strategy that sets a net-zero GHG target "by or around" 2050, in addition to interim targets to reduce absolute GHG emissions by at least 20% by 2030 and at least 70% by 2040, both compared with 2008 levels (International Maritime Organization, n.d.-a).

To help IMO delegates make evidence-based policy decisions, the IMO regularly commissions outside experts to conduct emissions inventories. The most recent inventory, the *Fourth IMO GHG Study* (Faber et al., 2020), covered the years 2012 to 2018 and projected emissions out to 2050. The study identified a growing trend of historical global shipping carbon dioxide (CO_2) emissions even as the overall carbon intensity went down over the same period. Such analyses of historical and future emissions must be repeated periodically to assess whether the shipping industry is on track to reach the net-zero target by 2050.

In 2017, the ICCT published global ship emissions inventories for 2013–2015, which followed similar methodologies as used in the *Third IMO GHG Study* (Olmer et al., 2017; Smith et al., 2014). Our 2017 report detailed our methodology for estimating global shipping emissions, which was later summarized as the Systematic Assessment of Vessel Emissions (SAVE) model (Mao et al., 2025). As a co-author of the *Fourth IMO GHG Study*, the ICCT updated the SAVE model to be consistent with the IMO methodology regarding key assumptions and inputs.

In this report, we examine trends in global ship activity and emissions between 2016 and 2023 using methods that are generally aligned with the *Fourth IMO GHG Study*, with some minor modifications. We first provide historical context on ship emissions that relate to recent trends in emissions and emissions intensity. We then outline the methods and input assumptions of the SAVE model, with a focus on updates we have made to the model since Olmer et al. (2017) and changes from the *Fourth IMO GHG Study*. We next proceed to our results, presenting summaries of key metrics of recent trends in ship activity, fuel consumption, GHG and air pollutant emissions, and carbon intensity. An ensuing model validation section compares our model results against self-reported fuel consumption data collected by the IMO and carbon intensity data collected by the European Union's Monitoring, Reporting, and Verification (EU MRV) system. Finally, we draw conclusions and provide suggestions for future work.

BACKGROUND

GREENHOUSE GAS EMISSIONS FROM SHIPS

The *Fourth IMO GHG Study*, released in 2020, provided an updated estimate of ship emissions between 2012 and 2018 as well as a recalibration of baseline emissions in 2008 (Faber et al., 2020). Consistent with the *Third IMO GHG Study*, the study found that ship emissions had increased and were expected to continue to rise, both in absolute terms and in shipping's share of global CO_2 and GHG emissions (Faber et al., 2020; Smith et al., 2014). The *Fourth IMO GHG Study* found that the CO_2e emissions from global shipping grew nearly 10% between 2012 and 2018. More striking were the estimated increases in short-lived climate pollutants, including a 12% increase in black carbon (BC) emissions as well as a 150% increase in methane (CH_4) emissions, largely due to a surge in the number of ships fueled by liquefied natural gas (LNG). Many of the ships fueled by LNG have engines that allow unburned CH_4 to escape into the atmosphere through a process known as methane slip. Moreover, despite an overall improvement in carbon intensity compared with 2008, the study found that more than half of the improvement was achieved before 2012 and improvements had stagnated to 1% to 2% annually since 2015.

REVISED IMO GREENHOUSE GAS STRATEGY

Considering the challenges laid out in the *Fourth IMO GHG Study*, Member States adopted a revised IMO GHG Strategy in 2023 with significantly more ambitious emissions reduction targets (Carvalho & Comer, 2024). As noted above, the revised strategy sets a net-zero goal "by or around" 2050, with interim targets to reduce the carbon intensity of international shipping by 40% by 2030 compared with 2008 levels; it also aims to increase the uptake of zero or near-zero GHG emission technologies, fuels, and energy sources to represent at least 5% (striving for 10%) of the energy used by international shipping by 2030. Additionally, the 2023 strategy added "indicative checkpoints" to reduce total annual GHG emissions from international shipping by at least 20% (striving for 30%) by 2030 and 70% (striving for 80%) by 2040, all relative to 2008 levels. The 2023 strategy therefore represents a substantial increase in ambition compared with the 2018 Initial IMO GHG Strategy, which only aimed to reduce total GHG emissions by 50% below 2008 levels by 2050 and contained no absolute emissions reduction targets for the intervening years.

The Initial IMO GHG Strategy was not compatible with the Paris Agreement's aim to limit global warming to well-below 2 °C (Comer & Rutherford, 2018). ICCT researchers have estimated that international shipping will exceed its current share of the world's 1.5 °C carbon budget by approximately 2032 but will not exceed a well below 2 °C carbon budget (interpreted as below 1.7° C) if it follows the emissions reduction pathway implied by this revised strategy (Carvalho & Comer, 2023).

SHIP OPERATIONAL DATA REPORTING

To support implementation of emerging GHG regulations pertaining to ships, regulators have started to require ship operators to report ship operational data, including fuel consumption, distance traveled, and GHG emissions. Since 2019, the IMO has implemented a mandatory fuel data collection system (DCS), which aggregates data on fuel consumption, distance traveled, and hours underway for individual ships of 5,000 gross tonnage (GT) and above, among other factors. Shipping companies must have the relevant data verified by the flag administration or any duly authorized organization before submission (DNV, n.d.-a). Similarly, in 2018, the European Union introduced the EU MRV system, which mandates shipping companies to report fuel consumption and CO_2 emissions data on an annual basis for ships above 5,000 GT on voyages from and to EU ports, including intra-EU voyages. The EU MRV will extend to general cargo ships between 400 and 5,000 GT and offshore ships of 400 GT and above in 2025 (DNV, n.d.-b). In China, starting in December 2022, all ships calling Chinese ports that are 400 GT and above must report energy consumption data of the previous voyage to the China Maritime Safety Agency (Standard Club, 2023).

These data, once verified and made publicly available, can be used to validate emission estimates from global and regional ship emissions inventories. To date, only the EU MRV data are publicly available in a disaggregated, non-anonymized format (European Maritime Safety Agency, 2025).

COVID-19 IMPACTS ON SHIPPING DEMAND

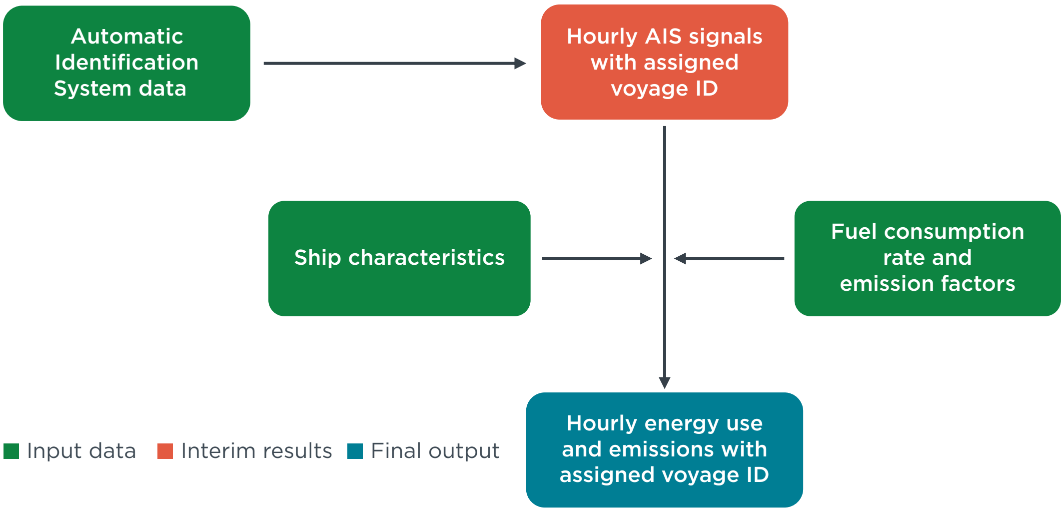
The COVID-19 pandemic has impacted global shipping activity and emissions. According to the UN Trade and Development (UNCTAD) annual report on global maritime transport for 2022, international maritime trade contracted by 3.8% in 2020 but bounced back in 2021 by about 3.2% (UNCTAD, 2022). The report noted some lingering impacts of COVID-19, as port calls were lower in 2021 compared with 2019 due to port congestion and a reduced labor force, especially for dry bulk products. UNCTAD also published its own estimate of total CO_2 emissions of the global merchant fleet annualized monthly between 2012 and 2022. The CO_2 emissions of global shipping recovered to pre-pandemic (November 2019) levels around September 2020, but carbon intensity improvement of shipping seemed to be stalled (UNCTAD, 2022).

METHODS

The SAVE model uses methods consistent with the *Fourth IMO GHG Study* (Faber et al., 2020), with a few exceptions, described here and in the online SAVE model documentation (Mao et al., 2025). The model is summarized in Figure 1 below.

Figure 1

Systematic Assessment of Vessel Emissions (SAVE) model



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We use Automatic Identification System (AIS) data that are commercially available from Spire Ltd. (formerly exactEarth).[2] Ship characteristics come from two main sources: a commercially available database from S&P Global (formerly IHS Markit), and a nonpublic database from Global Fishing Watch that was shared with the ICCT upon request.[3]

Compared with the 2017 study (Olmer et al., 2017), we made a few updates to SAVE to align with the *Fourth IMO GHG Study* and to reflect recent policy developments, as detailed below.

CHANGES TO DATA INPUTS

Ship categorization

Ship sizes have been changing. To accommodate these changes, we expanded or revised ship size categorizations based on deadweight tonnage (dwt), twenty-foot equivalent unit (TEU), cubic meter (CBM), and GT. The new ship size categorization is aligned with the *Fourth IMO GHG study* (Faber et al., 2020).

For the 2017 study, we identified five types of marine fuel: heavy fuel oil (HFO, also known as residual fuel), distillate fuel (MDO), LNG, coal, and nuclear. In this study, we also consider very low sulfur fuel oil (VLSFO) and methanol (MeOH). Heavy fuel oil has largely been replaced by VLSFO since 2020 due to the implementation of the IMO's global sulfur limit, which established a more stringent cap on sulfur content in marine fuels. MeOH, which has been adopted in recent years, albeit slowly, is another new fuel type analyzed in this study to align with the *Fourth IMO GHG study*.

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[2] Spire Ltd. acquired exactEarth Ltd. in 2021.

[3] This brief includes content supplied by S&P Global; Copyright © S&P Global, 2023. All rights reserved. S&P Global acquired IHS Markit in 2022.

Marine engine technologies have also advanced during this period. More specifically, our understanding of engines that can burn LNG as fuel has improved greatly (Comer et al., 2024; Pavlenko et al., 2020). Compared with the 2017 ICCT study, this study classified LNG-fueled ships into more granular engine categories, namely high-pressure dual-fuel 2-stroke (HPDF 2-stroke) engines, low-pressure dual-fuel 4-stroke (LPDF 4-stroke) and 2-stroke (LPDF 2-stroke) engines, lean-burn spark ignition (LBSI) engines, gas turbines (GT), and steam turbines (ST). These categories are aligned with the *Fourth IMO GHG study*.

Ship speed

While conducting the *Fourth IMO GHG study*, we identified a mis-categorization of the speed fields in the IHS Markit (now S&P Global) ship characteristics database that could lead to overestimating engine loads and fuel consumption. In the IHS Markit dataset, the "speed" field was defined as the maximum speed; however, most often, the value was the service speed, which is slower than the maximum speed. The *Fourth IMO GHG study* corrected this overestimate by applying an adjustment factor for the most impacted ship classes, which was derived by comparing reported fuel consumption with modeled fuel consumption (Faber et al., 2020). Since then, S&P Global has provided a separate field for maximum speed and service speed, which allowed us to confirm that the maximum speed was greater than the service speed for the ships covered by this inventory. We use the maximum speed field in this study, precluding the need to apply the adjustment factors from the *Fourth IMO GHG Study*. As ICCT's 2017 study (Olmer et al., 2017) used the now-outdated speed field, our 2013–2015 estimates cannot be directly compared with the 2016–2023 estimates in this study.

Fuel consumption

In the 2017 ICCT report, fuel consumption was estimated on a ship-by-ship basis based on the amount of CO_2 emissions that a ship emitted and its main fuel type (Olmer et al., 2017). In this study, we updated that method by using the load-dependent hourly fuel consumption rate, which is aligned with the *Fourth IMO GHG study* (Faber et al., 2020).

Emission factors

Ships with scrubbers

This report includes updates on sulfur oxide (SO_x) emission factors for ships that use exhaust gas cleaning systems (EGCS, commonly known as scrubbers) in combination with HFO (ECGS + HFO) to comply with the global sulfur limit and regulations within IMO-designated emission control areas (ECAs) intended to reduce SO_x emissions. This update was not considered in the *Fourth IMO GHG study*. The updated SO_x emission factors for ships using EGCS + HFO can be found in Table 1.

We assumed EGCS are optimized for minimal compliance with the global sulfur limit and ECA SO_x regulations. This differs from the ICCT's recommended SO_x emission factor published in a 2020 consulting report conducted for Environment and Climate Change Canada (Comer et al. 2020). In the 2020 consulting report, the ICCT expected that ships with scrubbers would achieve very low SO_x emissions, based on the available literature. Since then, the ICCT has updated its assumptions such that ships with scrubbers seek to reduce SO_x emissions only to the extent required. This assumption is consistent with Canada's approach in the analysis submitted to the IMO's 12th Pollution Prevention and Response Subcommittee (Canada, 2024). We did not account for national or subnational EGCS restrictions in this report, as we expect the impact would be limited on the global scale. This could be addressed in future updates to SAVE.

Table 1

Sulfur oxide emission factors (g/kWh) for ships using heavy fuel oil with exhaust gas cleaning systems

Engine type	Engine age	SO_x (0.5% sulfur-equivalent)	SO_x (0.1% sulfur-equivalent)
Slow-speed diesel	< 1984	2.00	0.40
	1984-2000	1.81	0.36
	2001+	1.71	0.34
Medium-speed diesel	< 1984	2.10	0.42
	1984-2000	1.91	0.38
	2001+	1.81	0.36

Methane slip from LNG-fueled engines

Corresponding to the change in engine categorization for LNG-fueled ships, we updated the methane slip emission factors for these engines from the *Fourth IMO GHG Study*, first developed by the ICCT in Pavlenko et al. (2020). The ICCT recently published findings of real-world CH_4 emissions from LNG-fueled ships as part of the Fugitive and Unburned Methane Emissions from Ships (FUMES) project, which found that real-world measurements of methane slip from LPDF 4-stroke engines (based on 22 plumes from 18 unique vessels) averaged 6.4% with a median of 6.05% (Comer et al., 2024). This is higher than the 3.5% methane slip assumed in the *Fourth IMO GHG study*. Comer et al. (2024) recommended that policymakers assume at least 6% methane slip for these engines when calculating well-to-wake GHG emissions (Table 2). In this study, we reported methane emissions using the *Fourth IMO GHG Study* assumptions and then calculated the impact of updating the LPDF 4-stroke emission factors to reflect 6% methane slip.

Table 2

Methane emission factors recommended in Comer et al. (2024) converted to g/kWh, with equivalent percent methane slip in parentheses

Engine type	Main engine	Auxiliary engine[b]	Boiler
LPDF 4-stroke	9.36 (6.0%)[a]	9.36 (6.0%)	0.04
LPDF 2-stroke	2.5 (1.7%)	9.36 (6.0%)	0.04
HPDF 2-stroke	0.2 (0.15%)	9.36 (6.0%)	0.04
LBSI	4.1 (2.6%)	4.1 (2.6%)	0.04

[a] Faber et al. (2020) assumed 5.5 g CH_4/kWh (3.5%).

[b] Faber et al. (2020) assumed that auxiliary engine power was provided by main engine power takeoff, whereas Comer et al. (2024) found that ships with 2-stroke main engines tended to use LPDF 4-stroke auxiliary engines.

Methanol

We added emission factors for methanol that are consistent with the *Fourth IMO GHG study* (Faber et al., 2020). Since the release of that study, the ICCT has published new information on typical specific fuel consumption and pilot fuel consumption rates for MeOH-fueled engines (Comer & Sathiamoorthy, 2022); however, SAVE has not yet been updated to reflect this improved understanding. Nevertheless, the fleet of MeOH-fueled ships is small (31 vessels) and the difference in specific fuel consumption and pilot fuel consumption rates are negligible on the global scale.

Carbon dioxide equivalents and global warming potentials

To calculate CO_2e100 and CO_2e20 emissions, we updated the global warming potential of GHGs according to the Intergovernmental Panel on Climate Change's *Sixth Assessment Report* (Jäger-Waldau, et al., 2022) and GWPs of black carbon developed by Bond et al. (2013) and used by Comer et al. (2017), as shown in Table 3.

Table 3
Global warming potential assumptions for greenhouse gases

GWPs	GWP 100	GWP 20	Source
CO_2	1	1	Reference level
CH_4	29.8	82.5	IPPC (2022), Table 7.15
N_2O	273	273	IPCC (2022), Table 7.15
BC	900	3200	Bond et al. (2013) and Comer et al. (2017)

Other updated inputs

Auxiliary and boiler power demand

To align with the *Fourth IMO GHG Study* (Faber et al., 2020), we used updated assumptions for ships' default auxiliary engine and boiler power output values at each operating phase.

Air pollution policies

This report accounted for major air pollution policy developments that took place between 2016 and 2023 (Table 4).

Table 4
Major air pollution policy updates included in this report

Policy name	Applicable region(s)	Date entered into force	Regulations	Source
Global sulfur limit	Global	January 1, 2020	Sulfur content of marine fuel < 0.5% by mass	International Maritime Organization (2021)
Tier III NO_x limit	North America ECA	January 1, 2016	Engines on ships built after 2016 need to comply with Tier III NO_x limit	International Maritime Organization (n.d.-b)
	Baltic Sea ECA	January 1, 2021	Engines on ships built after 2021 need to comply with Tier III NO_x limit	
	North Sea ECA	January 1, 2021	Engines on ships built after 2021 need to comply with Tier III NO_x limit	
Domestic emission control area	China territorial sea of 12 nm	January 1, 2019	Sulfur content of marine fuel < 0.5% by mass	Ministry of Transport of the People's Republic of China (2018)

VALIDATION

We compared our inventory results with self-reported data on ships' fuel consumption and CO_2 emissions in the IMO DCS and EU MRV systems for validation. The IMO DCS data cover ships of 5,000 GT and above and have been publicly available since 2019; we thus compared applicable ships' total fuel consumption data with IMO DCS reporting for the 2019–2023 inventories. The EU MRV data, which have been available since 2018, cover EU-related voyages of ships of 5,000 GT and above and comprise self-reported information on annual total fuel consumption, CO_2 emissions, CO_2 intensity measured in different metrics, and distance traveled, among others. Because our inventory results are at the global scale, we cannot compare total fuel consumption, CO_2 emissions, or distance traveled. Instead, we compared ships' CO_2 intensity data in terms of g CO_2/dwt-nm or g CO_2/GT-nm with EU MRV reporting for the 2018–2023 inventories. It is our assumption that for the same ship, the CO_2 intensity value would not be statistically different on EU-related voyages compared with global voyages.

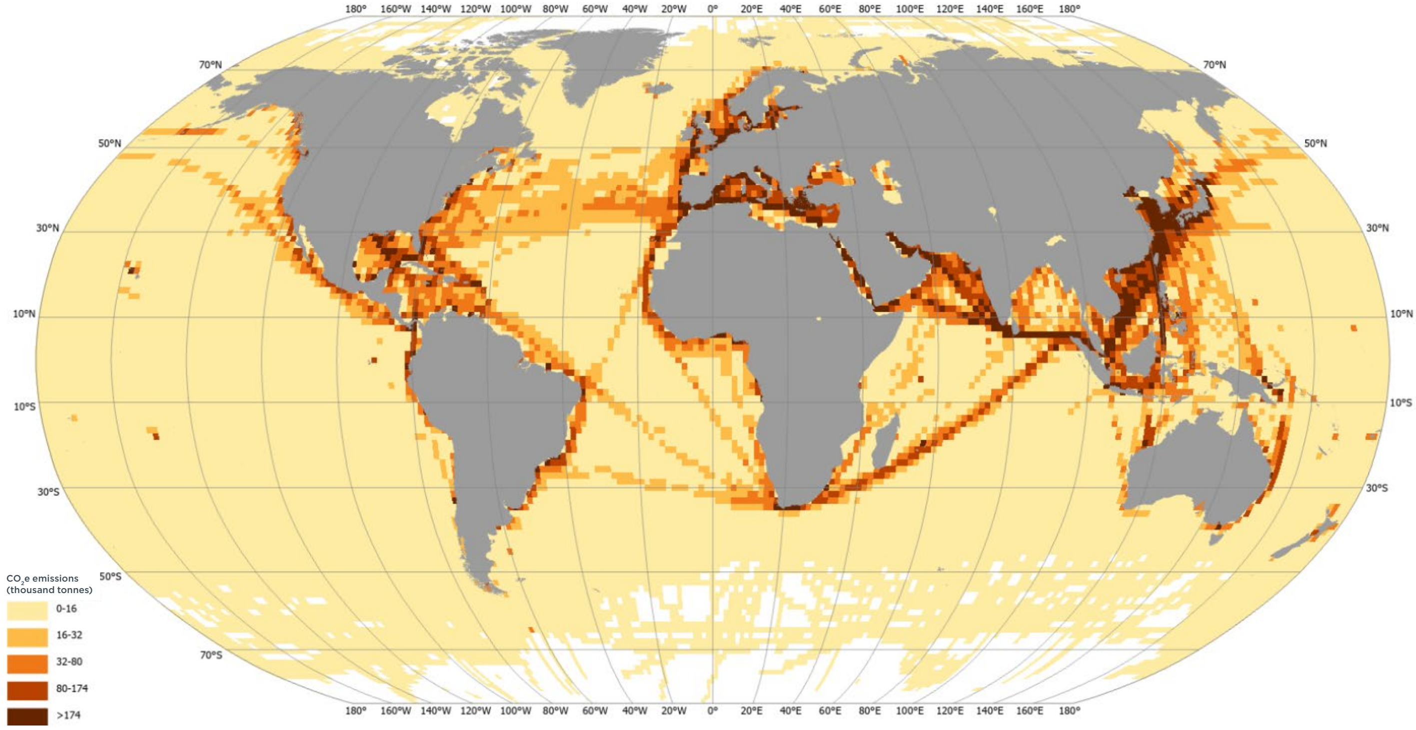
RESULTS

TRENDS IN GREENHOUSE GAS EMISSIONS

In 2023, global shipping emitted 911 Mt of tank-to-wake (TTW) CO_2e100 emissions, which were concentrated on major global shipping routes (Figure 2). Collectively, if counted as a country, global shipping would have ranked as the 9th largest CO_2e100-emitting country in the world in 2023, with a share of approximately 1.7% (Crippa et al., 2024). In terms of CO_2, shipping accounted for an estimated 2.3% of anthropogenic CO_2 emissions in 2023.[4]

Figure 2

Spatial distribution of global ship CO_2e100 emissions in 2023



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From 2016 to 2023, global CO_2e100 emissions grew by 12%, or a compound annual growth rate (CAGR) of approximately 1.4% (Figure 3). This growing trend was temporarily interrupted in 2020 when the COVID-19 pandemic began. The year-on-year growth rate of global CO_2e100 emissions was -3.2% between 2019 and 2020, before jumping to +3.2% between 2020 and 2021. International shipping remained the biggest contributor of global shipping CO_2e100 emissions (around 86%), followed by domestic shipping (9%–10%) and fishing (4%). However, domestic shipping and fishing grew faster (CAGR of 2.0% and 2.9%, respectively) than international shipping (CAGR of 1.3%). Since total global anthropogenic CO_2e100 emissions grew at a similar pace over the same period (CAGR of approximately 1.0%), shipping's share remained relatively stable, at about 1.7% (see Table 4). The COVID-19 impact, a temporary dent in 2020, was seen in all emission sub-categories except for fishing (Table 5).

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[4] This is less than the 2.9% share of 2018 CO_2 emissions reported in the *Fourth IMO GHG Study* (Faber et al., 2020), primarily because of the updated maximum ship speed data in the S&P Global ship characteristics database, which tended to increase the maximum speed assumption for most ships, thereby reducing estimated engine loads, fuel consumption, and emissions. With this updated speed input, the fuel consumption results presented in this study closely align with self-reported fuel consumption aggregated by the IMO DCS, as shown in the Model Validation section.

Figure 3

Global shipping CO_2e100 emissions between 2016 and 2023

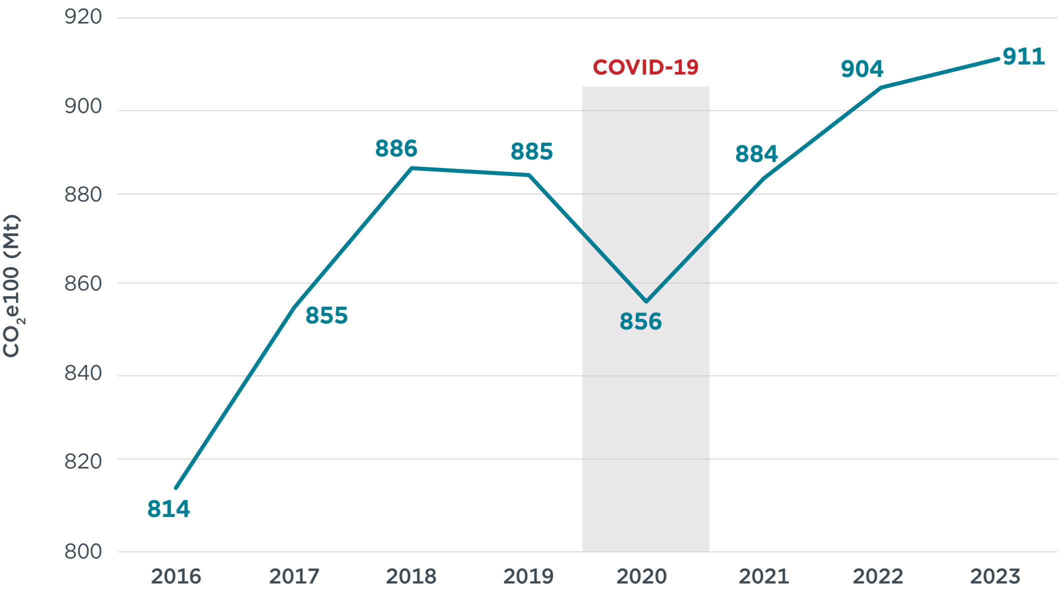

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Table 5

Absolute amount and share of global anthropogenic greenhouse gas emissions from global shipping from 2016 to 2023

	2016	2017	2018	2019	2020	2021	2022	2023
	Metric: CO_2e100 emissions (Mt)							
Global anthropogenic emissions[a]	49,059	49,879	51,027	51,279	49,328	51,568	51,969	52,963
International shipping	709	740	765	762	737	762	782	785
Domestic shipping	74	81	86	87	81	84	84	87
Fishing	31	34	35	36	38	38	38	39
Total shipping	814	855	886	885	856	884	904	911
% of global total	**1.7%**	**1.7%**	**1.7%**	**1.7%**	**1.7%**	**1.7%**	**1.7%**	**1.7%**
	Metric: CO_2 emissions (Mt)							
Global anthropogenic emissions	36,424	37,047	37,975	38,066	36,154	38,121	38,247	39,024
International shipping	696	726	750	746	731	755	775	776
Domestic shipping	73	80	84	85	80	82	82	86
Fishing	30	33	35	35	38	38	38	39
Total shipping	799	839	869	866	849	875	895	900
% of global total	**2.2%**	**2.3%**	**2.3%**	**2.3%**	**2.3%**	**2.3%**	**2.3%**	**2.3%**

[a] Source: Crippa et al. (2024). The data include CO_2, CH_4, N_2O and fluorinated gases. Large scale biomass burning with savannah burning, forest fires, and sources and sinks from land-use, land-use change, and forestry are excluded.

Among all ship classes analyzed in this report, the top 7 emitting classes remained the same across all eight years, collectively contributing nearly three quarters of total CO_2e100 emissions (Figure 4). Liquefied gas tankers saw the largest relative change (+48%), with a CAGR of 5.0% between 2016 and 2023, followed by cruise ships (+32%), with a CAGR of 3.5%. At the same time, a few ship classes[5] showed CO_2e100 emissions reductions; these include general cargo ships (-6%), which were surpassed in terms of overall emissions by cruise ships beginning in 2022 (Figure 4).

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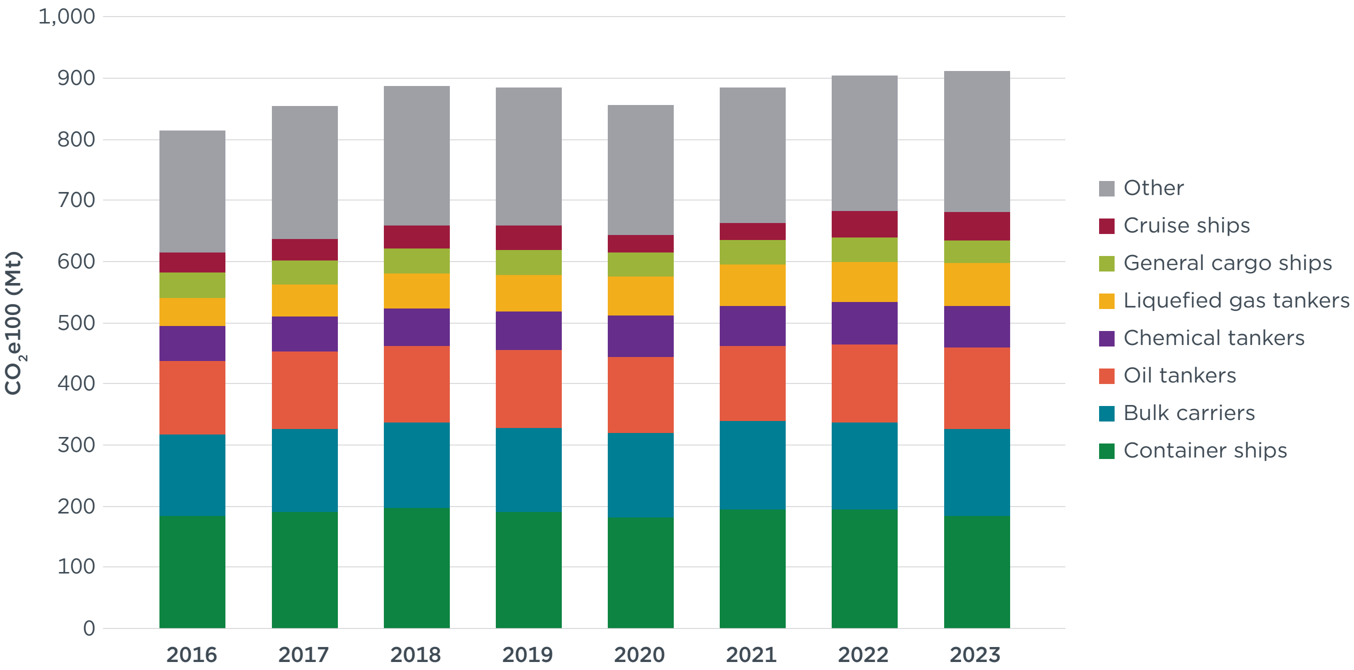
[5] Those are: passenger ferries (-8%), general cargo ships (-6%), refrigerated bulk carriers (-22%), tug boats (-7%), and vehicle carriers (-6%).

Figure 4

CO_2e100 emissions by ship class from 2016 to 2023



* Other ship classes include passenger ferries, ro-pax ferries, roll-on/roll-off ships, tugboats, fishing vessels, offshore vessels, refrigerated cargo ships, vehicle carriers, yachts, and other service vessels.

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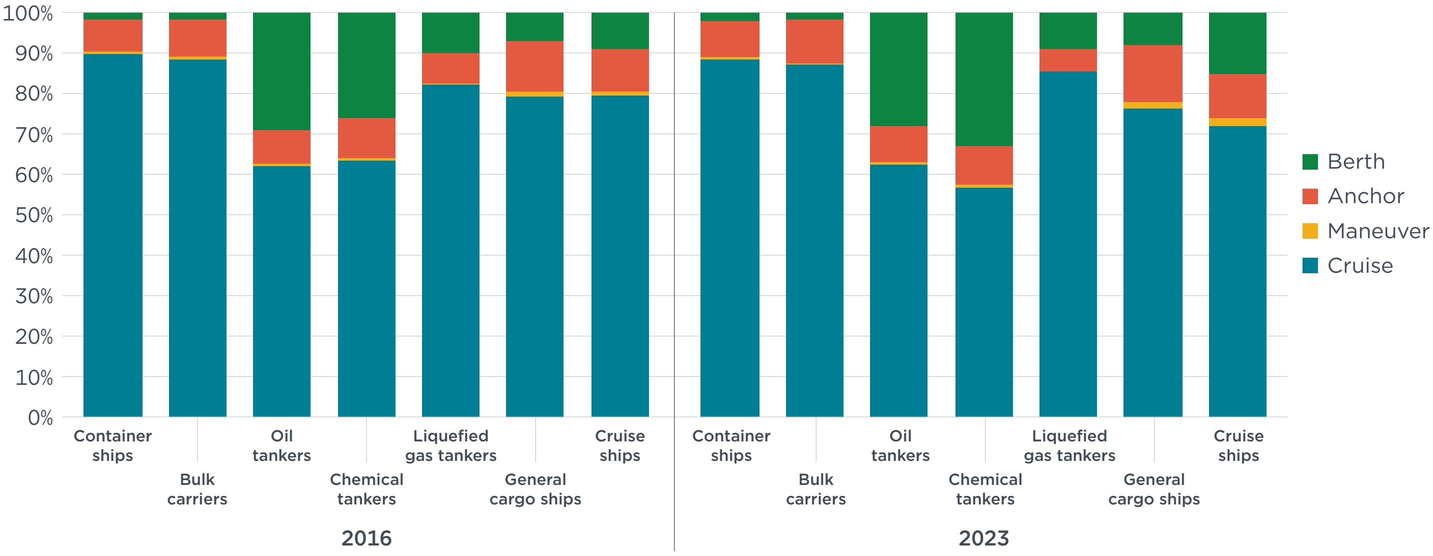
Between 2016 and 2023, most CO_2e100 emissions took place while ships were at sea. Oil tankers and chemical tankers emitted a much larger share of emissions while at berth and at anchor compared with other cargo carriers due to high energy demand to support cargo handling (Figure 5). On average, ships emitted a greater share of emissions while at berth and at anchor in 2023 (11%) compared with 2016 (9.5%).

Figure 5

Share of CO_2e100 emissions by phase for top seven emitting ship classes



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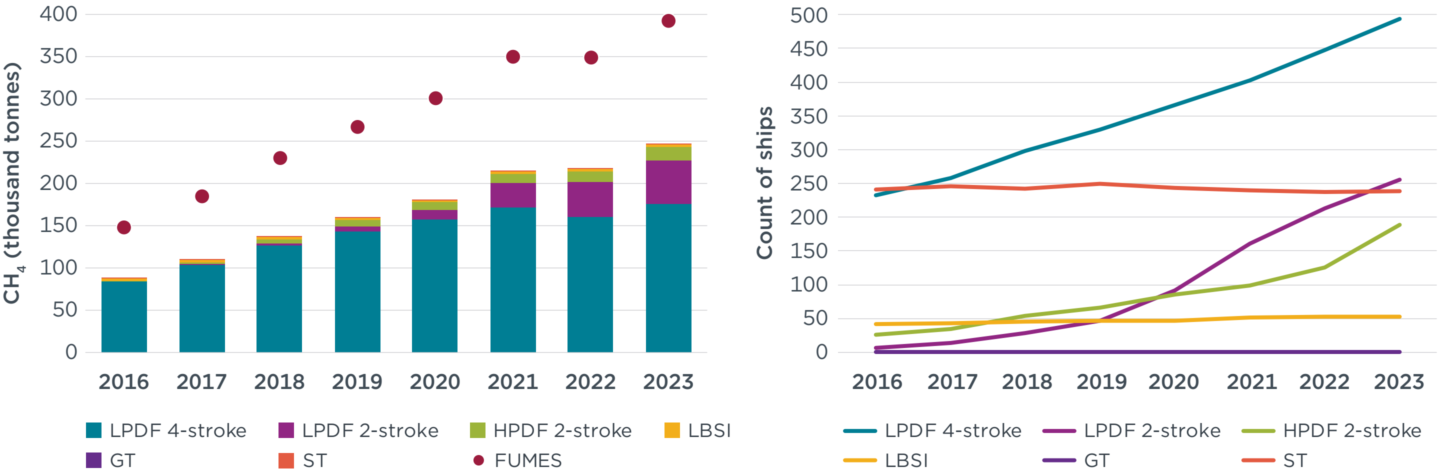
Among GHGs, CH_4 emissions saw the fastest growth, of nearly 180%: from 88,000 tonnes in 2016 to 247,000 tonnes in 2023, using methane slip assumptions from the *Fourth IMO GHG Study*. The large majority (over 90%) of CH_4 emissions came from the LNG-powered fleet, which expanded markedly over the period, growing by over 120% in number. This increase featured strong growth in the number of ships that use LPDF 4-stroke engines, although orders for ships powered by LPDF 2-stroke and HPDF 2-stroke main engines have increased rapidly since 2020 (see Figure 6). Unlike other pollutants analyzed in this study, there was not any visible impact of COVID-19 on CH_4 emissions.

Figure 6

Methane emissions from the LNG-powered fleet by main engine technology from 2016 to 2023



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In the bars presented in Figure 6, methane slip for LPDF 4-stroke engines was assumed to be 3.5%, consistent with the *Fourth IMO GHG Study* (Faber et al., 2020). However, as noted above, real-world measurements as part of the FUMES project found that median methane slip from such engines was approximately 6% (Comer et al., 2024). The circle points in Figure 6 illustrate total methane emissions from the LNG-fueled fleet using the FUMES-recommended 6% methane slip for LPDF 4-stroke main and auxiliary engines instead of the *Fourth IMO GHG Study*'s 3.5%; LPDF 2-stroke main engines are assumed to have 1.7% methane slip, HPDF 2-stroke main engines 0.15% methane slip, and steam turbines negligible methane slip. Under these assumptions, compared with the bars, total CH_4 emissions rose by 67% in 2016, when most LNG-fueled engines were either steam turbines or LPDF 4-stroke engines, and 59% by 2023, which had a higher share of lower-methane-slip LPDF 2-stroke engines and HPDF 2-stroke engines. Overall, if the FUMES methane slip assumptions are used, methane emissions from the LNG-fueled fleet grew more than 165% between 2016 and 2023.

This analysis has reported CO_2e100 emissions excluding BC, a strong but short-lived climate forcer. When BC is included, it contributes a substantial share of CO_2e emissions. Table 6 presents BC emissions with a 100-year GWP of 900 and a 20-year GWP of 3,200. Emissions of BC peaked in 2019, dropped by 9% in 2020 due to COVID-19, and returned to 2018 levels as of 2023 (Table 6). Overall, BC emissions grew nearly 9% between 2016 and 2023. As shown in Figure 7, BC represented 8% of CO_2e100 and 23% of CO_2e20 emissions in 2023.

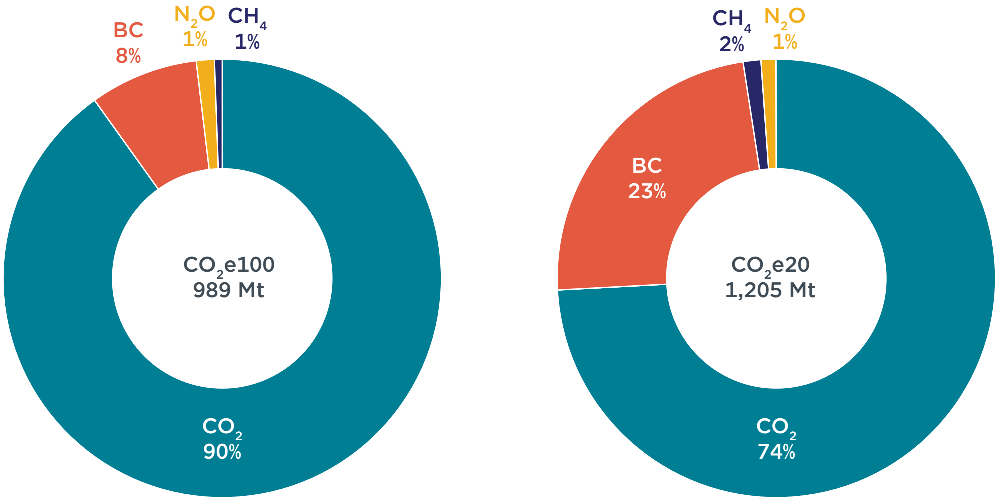
Table 6

Black carbon emissions in thousand tonnes (mass and CO_2 equivalent) from 2016 to 2023

Year	Mass	CO_2e100	CO_2e20
2016	81	73,000	258,000
2017	85	76,000	272,000
2018	88	79,000	282,000
2019	89	80,000	285,000
2020	81	73,000	260,000
2021	83	74,000	264,000
2022	86	77,000	274,000
2023	88	79,000	280,000

Figure 7

Share of CO_2 equivalent emissions by pollutant type in 2023, when black carbon is included



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TRENDS IN FUEL CONSUMPTION

Between 2016 and 2023, HFO-equivalent (HFO-eq) fuel consumption grew approximately 16%, from nearly 261Mt to 304Mt, a CAGR of approximately 1.9% (Figure 8). Over this period, global shipping consumed predominately HFO (over 70%); however, following implementation of the global sulfur limit in 2020, HFO consumption was largely replaced with VLSFO. The remaining HFO-fueled fleet has since used EGCS to comply with the more stringent sulfur limits.

The share of HFO use in total HFO-eq fuel consumption grew from 14% in 2020 to 17% in 2023 due to the expansion of fleet built or retrofitted with EGCS. The share of MDO remained stable at 19%. Meanwhile, use of LNG nearly doubled, from 10Mt in 2020 to 18Mt in 2023, or from 4% to 6% in terms of LNG's share in total HFO-eq fuel consumption.[6] Use of MeOH is included but not easily visible in Figure 8; it more than tripled between 2016 and 2023, although its share in total HFO-eq fuel consumption

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[6] The actual mass of LNG consumed was 8 Mt in 2016 and 15 Mt in 2023.

remained small, at just 0.05% in 2023.[7] The top three users of fuel were container ships, bulk carriers and oil tankers, together consuming more than half of total HFO-eq fuel consumption. Liquefied gas tankers, the types of ships that transport LNG, surpassed chemical tankers in 2018 to become the fourth largest fuel user of global shipping (Figure 9).

Figure 8

HFO-equivalent fuel consumption of global shipping between 2016 and 2023

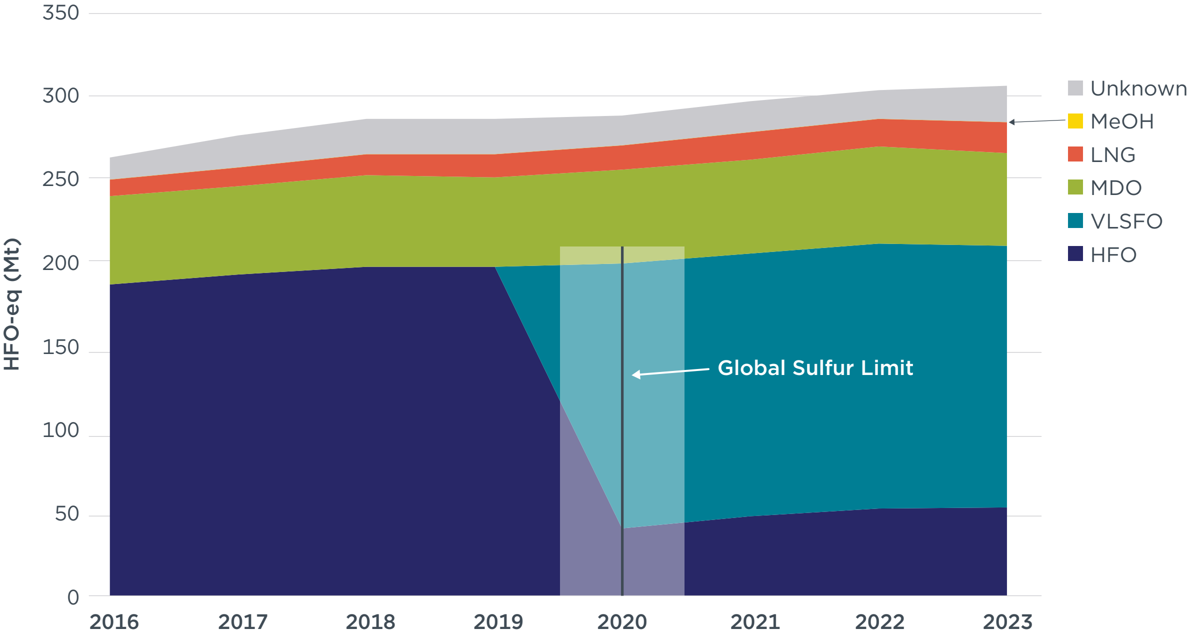

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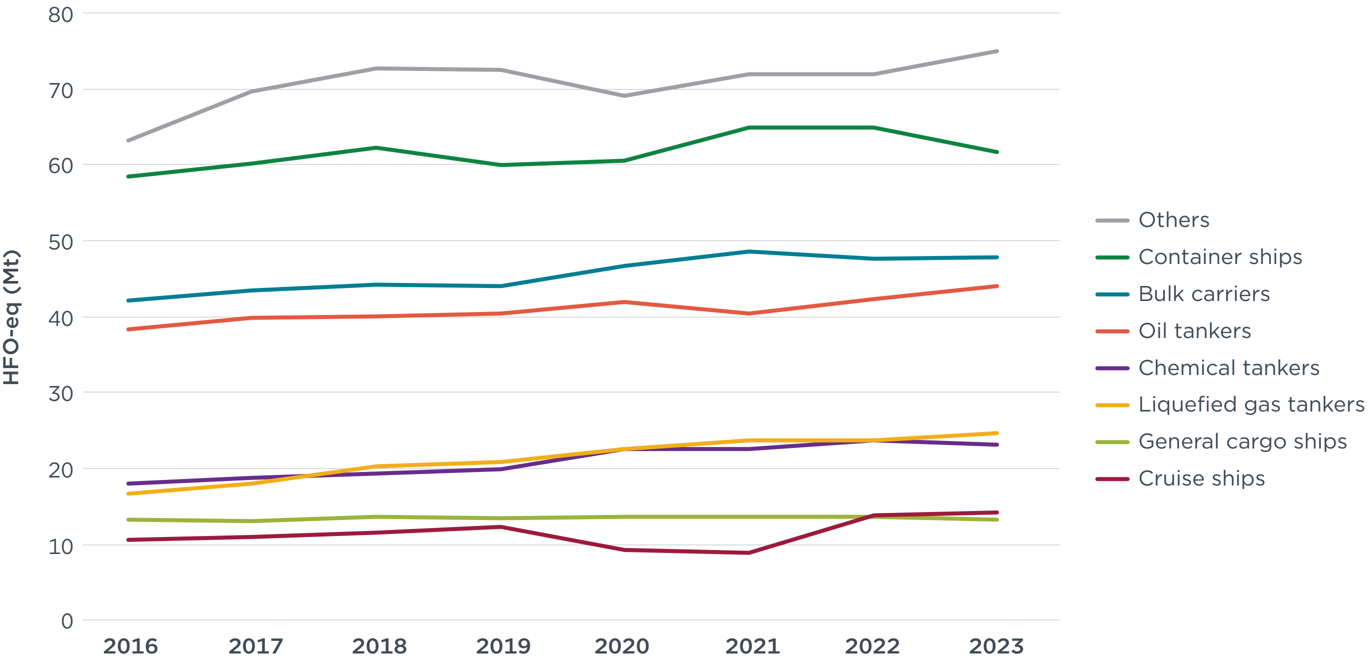
Figure 9

HFO-equivalent fuel consumption by ship class from 2016 to 2023



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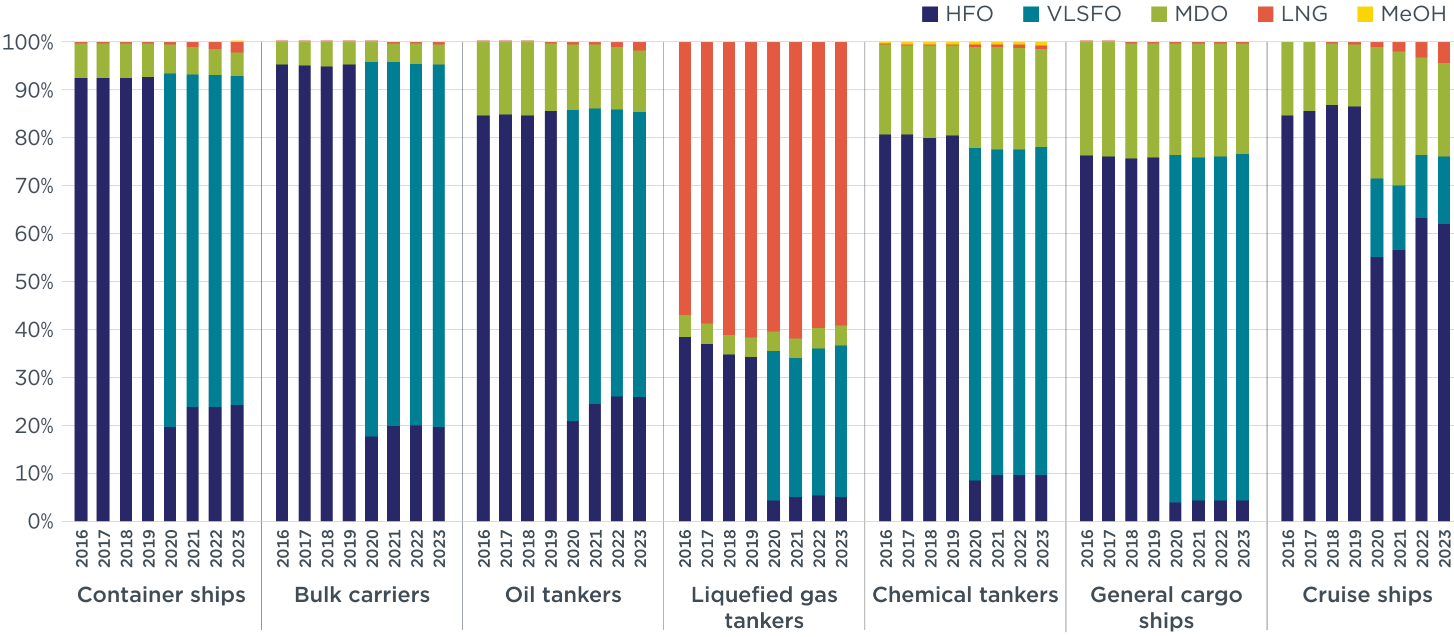
[7] The actual mass of MeOH consumed was 89 kt in 2016 and 326 kt in 2023.

As shown in Figure 10, most ship types mainly used HFO before 2020 and then VLSFO afterward. One notable exception is cruise ships. While the share of HFO used by these vessels did decline between 2019 and 2020, HFO continued to constitute more than half of fuel consumption because a large proportion of the cruise ship segment had invested in EGCS. The share of VLSFO grew over the same period to around 14%, far below other high-emitting ship types. Meanwhile, the share of MDO used by cruise ships nearly doubled. The use of LNG also grew rapidly: Between 2018 and 2023, the use of LNG by cruise ships grew more than 60-fold by mass, resulting in LNG's share of cruise ship fuel consumption growing from 0.1% of HFO-eq in 2019 to 4.3% in 2023.

These trends may partly be in response to sulfur regulations, but also because the use of LNG allows ships to comply with IMO NO_x regulations without exhaust gas aftertreatment systems such as selective catalytic reduction, and because using LNG makes it easier to comply with the IMO's Energy Efficiency Design Index regulation, as explained by Comer and Sathiamoorthy (2022).

Figure 10

Share of HFO-equivalent fuel consumption by fuel type from the seven highest-emitting ship classes from 2016 to 2023



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CHANGES IN SHIP ACTIVITY AND CARBON INTENSITY

Between 2016 and 2023, total transport work increased by 20%, or a CAGR of approximately 2.3% (Figure 11). COVID-19 resulted in a 1.5% decrease in global shipping transport work between 2019 and 2020, which was followed by a 2.6% increase from 2020 to 2021.[8] Overall, transport work grew faster than CO_2e100 emissions, indicating that the carbon intensity of shipping improved over the same period. The fleet-wide average carbon intensity (gCO_2/dwt-nm or gCO_2/GT-nm depending on the ship class) of shipping improved by 10.3% over the period, from 6.8 in 2016 to 6.1 in 2023 (Table 6), a reduction of about 1.3% per year.[9]

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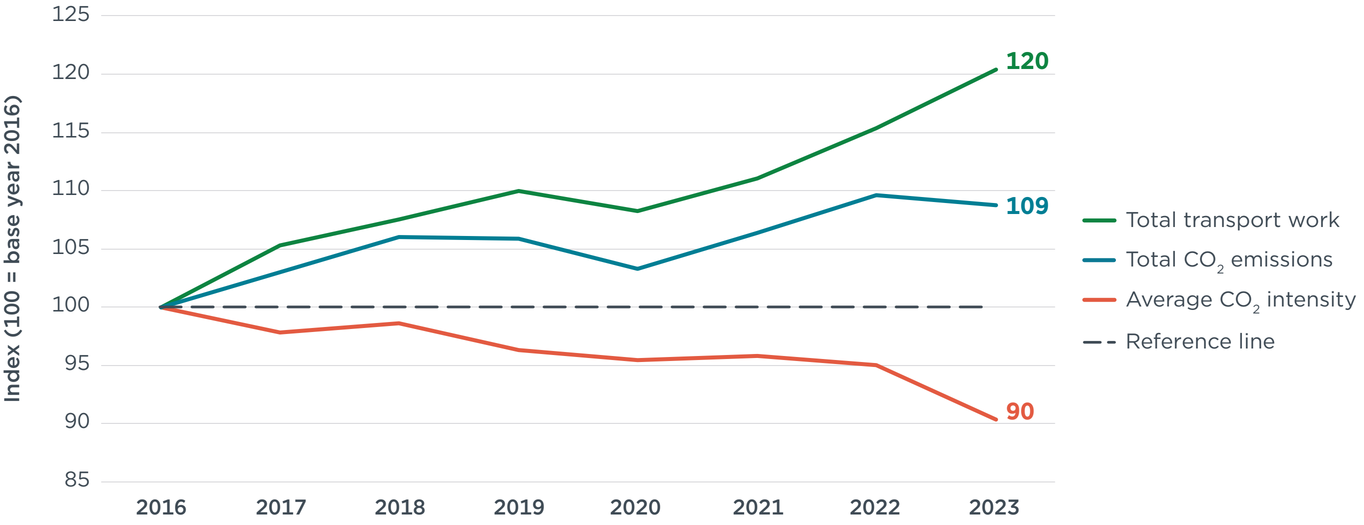
[8] Total transport work is the sum of dwt-nm or GT-nm depending on the ship class. Passenger ferries, ro-pax ferries, roll-on/roll-off ships, and cruise ships use GT-nm while all other ships use dwt-nm.

[9] As indicated in the Note of Figure 11, the fleet here excludes ships with "unknown" ship class.

Figure 11

Transport work, CO_2 emissions, and average carbon intensity from 2016 to 2023



Note: Data excludes ships with unknown ship class, which emitted about 5%–7% of the total CO_2e100 emissions emissions inventory depending on the year.

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Container ships and liquefied gas tankers improved their fleet-wide carbon intensity the most between 2016 and 2023, by 15% and 18%, respectively. Chemical tankers and general cargo ships, on the other hand, have shown little if any improvement in fleet-wide carbon intensity (Table 7). The impact of COVID-19 on carbon intensity was not clear for the seven highest-emitting ship classes, except for cruise ships, which saw a spike in carbon intensity in 2020–2021 but appeared to have mostly recovered to its pre-COVID carbon intensity by 2023.

Table 7

Fleet-wide carbon intensity of the seven highest-emitting ship classes from 2016 to 2023

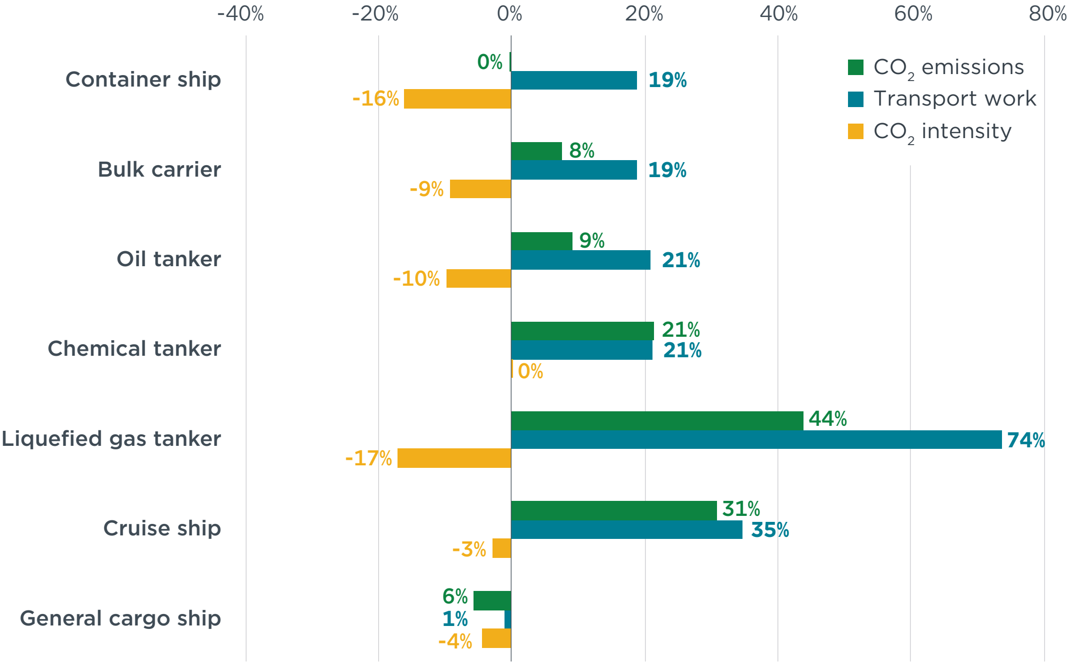
	CO_2 intensity (gCO_2/dwt-nm or GT-nm)							
Year	Fleet	Container ships	Bulk carriers	Oil tankers	Chemical tankers	General cargo ships	Liquefied gas tanker	Cruise ships
2016	6.8	8.4	2.9	4.5	10.7	11.8	10.1	19.4
2017	6.6	8.3	2.8	4.4	10.8	11.7	9.8	18.8
2018	6.7	8.2	2.9	4.3	10.8	12.3	9.8	21.8
2019	6.5	7.8	2.8	4.3	11.1	11.7	9.3	18.5
2020	6.5	7.8	2.7	4.3	10.7	11.6	9.2	34.8
2021	6.5	8.1	2.8	4.2	10.8	11.6	8.6	33.7
2022	6.4	7.8	2.7	4.2	10.6	11.6	8.6	20.9
2023	6.1	7.1	2.6	4.1	10.7	11.3	8.3	18.8

Note: Passenger ferries, ro-pax ferries, roll-on/roll-off ships, and cruise ships use GT-nm while all other ships use dwt-nm.

Among the seven highest-emitting ship classes, transport work for liquefied gas tankers grew the fastest due to rising demand for LNG as a cargo (Zaretskaya, 2024), resulting in a 74% increase between 2016 and 2023. The only ship class that experienced a contraction over this period was general cargo ships, with transport work falling 1.2% between 2016 and 2023 (Figure 12). Also reflected in Figure 12 is that despite improvements in fleet-wide carbon intensity (yellow bars), CO_2e100 emissions (green bars) continued to grow for most ships—with the exception of general cargo ships, which experienced a reduction in transport work—and the change in fleet-wide carbon intensity intensified the change in CO_2 emissions.

Figure 12

Change in transport work, fleet-wide carbon intensity, and total CO_2 emissions in 2023 compared with 2016 for the seven highest-emitting ship classes



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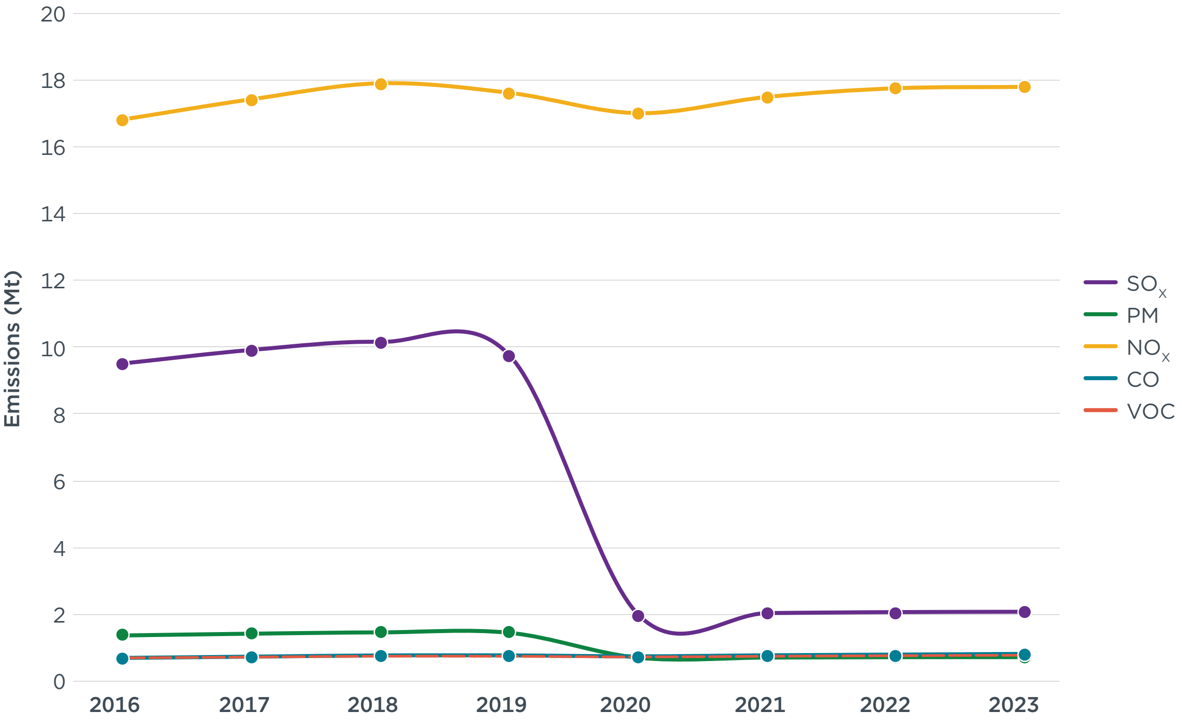
TRENDS IN NON-GREENHOUSE GAS EMISSIONS

Figure 13 charts criteria air pollutant emissions from 2016 to 2023. Carbon monoxide (CO), volatile organic compounds (VOC), and NO_x emissions increased slightly over this timespan, with a temporary dip in 2020. SO_x and PM emissions increased steadily between 2016 and 2019 but decreased significantly starting in 2020. The drastic decrease in SO_x and PM was primarily due to the global sulfur limit, which resulted in an approximately 80% reduction in SO_x emissions and more than 50% reduction in PM in the first year after its implementation. Although the IMO NO_x Technical Code was enacted in 2008, NO_x emissions remained generally stable between 2016 and 2023. This is because the most stringent Tier III NO_x limit, which could reduce NO_x emissions by more than 75% (Mao et al., 2019), applies only to ships built after a NO_x emission control area is enacted and only whilst traveling in it. As of 2023, there were two enacted NO_x emission control areas in the world, and only 1% of global fuel consumption was used by ships that needed to comply with the Tier III NO_x limit.

Figure 13

Emissions of criteria air pollutants from global shipping from 2016 to 2023



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MODEL VALIDATION

COMPARISON WITH IMO DCS TOTAL FUEL CONSUMPTION

Figure 14 compares the ICCT's modeled results against self-reported data in the IMO DCS. We compared this study's estimated fuel consumption with that in the IMO DCS for ships 5,000 GT and above. Total fuel consumption estimates generally agree, with annual deviation of less than 5%.[10] In 4 out of the 5 years compared, our modeled results are slightly higher. We also have more ships than the IMO DCS reported number considering the same scope (Figure 15), which is expected considering observed underreporting by vessels under the IMO DCS (Secretariat of Marine Environment Protection Committee, 2024).

Figure 14

Quantity-based fuel consumption, ICCT estimates compared with IMO DCS data from 2019 to 2023

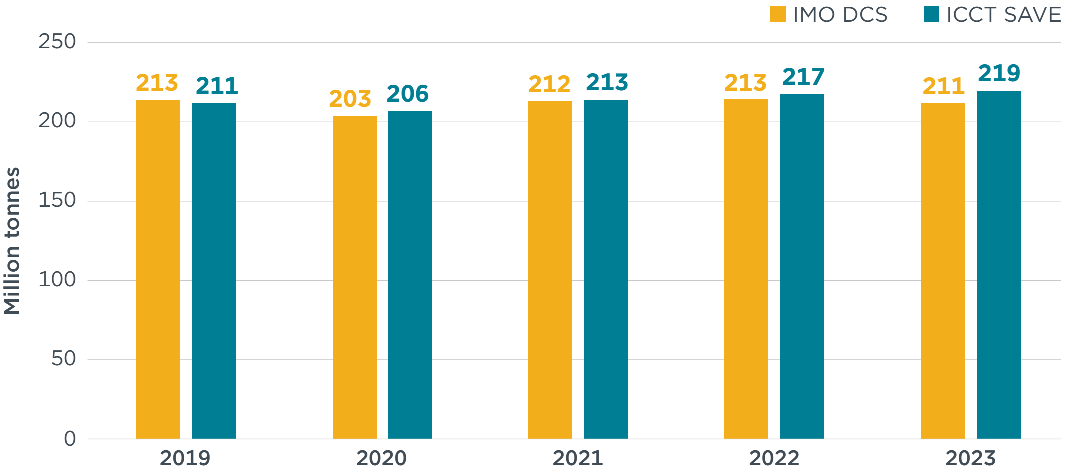

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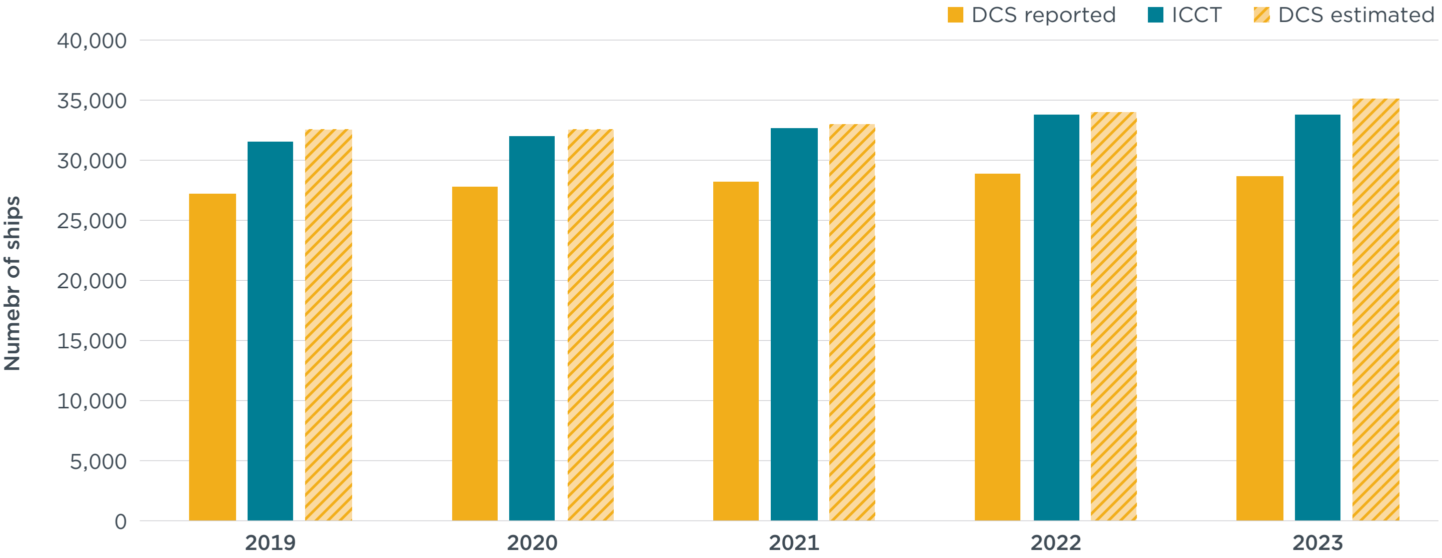
Figure 15

Number of ships reported by IMO DCS, DCS estimated, and number of ships included in SAVE model with the same scope from 2019 to 2023



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[10] Deviation is calculated as the difference between the ICCT modeled result and the IMO DCS report number, divided by the IMO DCS reported number.

COMPARISON WITH EU MRV CARBON INTENSITY

Figure 16 compares the ICCT's modeled results in 2022 for ships' CO_2 intensity in terms of g CO_2/dwt-nm or g CO_2/GT-nm[11] with EU MRV self-reported values in the same reporting year. We present the comparisons for 2022 data; comparison results for 2018–2021 are similar (EU MRV data for 2023 were not available when this analysis was conducted). The figures compare carbon intensity values for the same set of ships reported in EU MRV and modeled by the ICCT. Agreement is strong for the six highest-emitting ship classes except for bulk carriers, for which our modeled results seem to be lower than reported values. There is also strong alignment for other ship classes, except for cruise ships and offshore vessels; if the EU MRV data are correct, our model overestimates the carbon intensity of cruise ships and underestimates the carbon intensity of offshore vessels. However, considering that the overall contribution of these ships to global ship emissions is small (~5%), the deviation has only a small potential impact on our estimates of total global shipping emissions. Overall, we estimated an average fleet-wide carbon intensity of 6.89 (g CO_2/dwt-nm or g CO_2/GT-nm) whereas the EU MRV reported a value of 7.2.[12]

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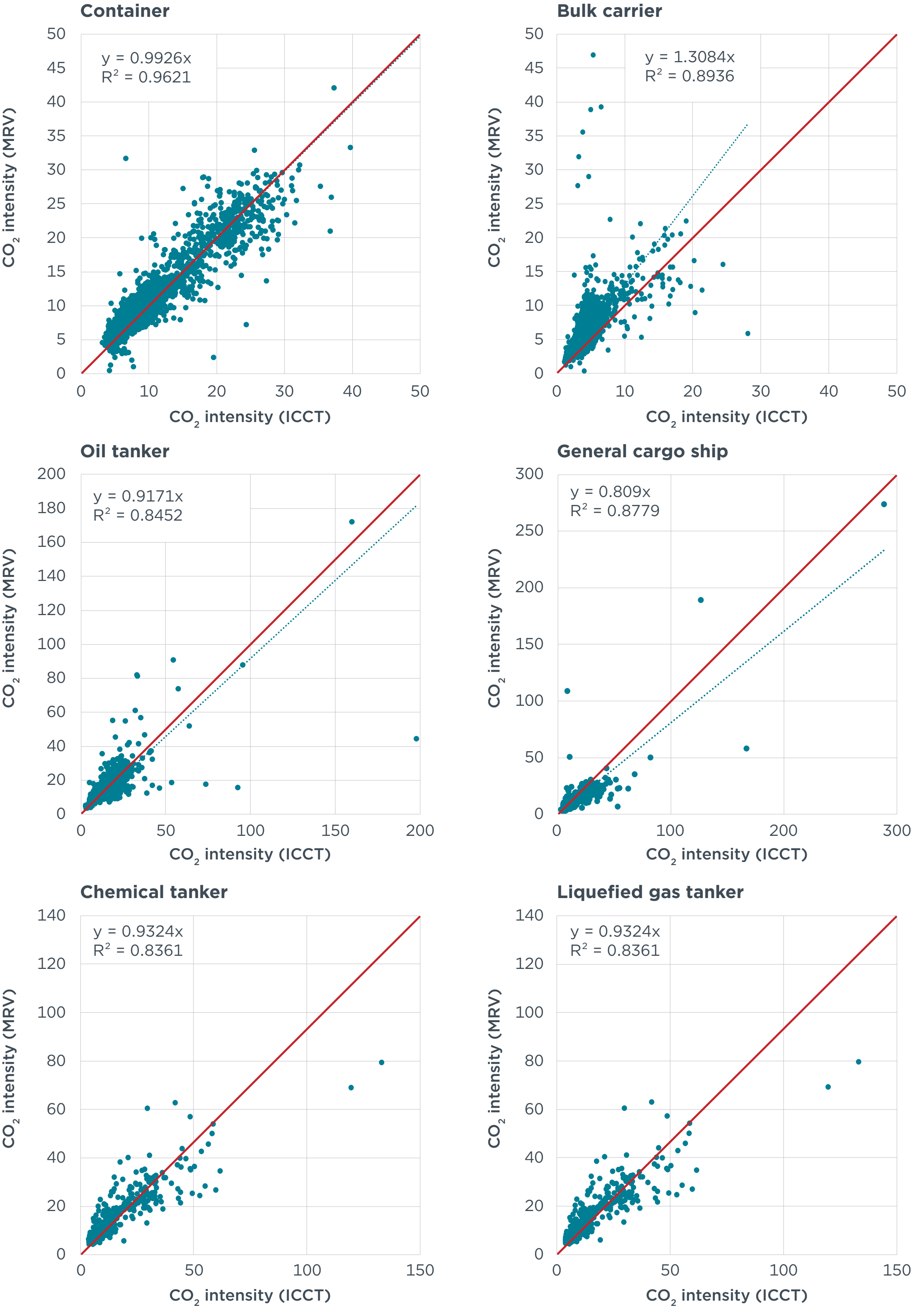
[11] The metric g of CO_2/GT-nm was calculated for passenger ferries, ro-pax ferries, roll-on/roll-off ships, and cruise ships.

[12] "Fleet" refers to the same set of ships reported in EU MRV and modeled by ICCT.

Figure 16

Paired comparison between ICCT modeled results and EU MRV data reported in 2022 for six major ship classes



Note: The red line is the reference line indicating perfect alignment of X and Y values.

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CONCLUSIONS

This report provides a comprehensive assessment of global shipping emissions from 2016 to 2023, highlighting both progress and ongoing challenges in the sector's efforts to decarbonize. While shipping's share of global anthropogenic CO_2e100 emissions has remained stable at approximately 1.7% (or 2.3% of global anthropogenic CO_2), total tank-to-wake GHG emissions have continued to grow, increasing by 12% over the study period with a CAGR of 1.4%.

Despite improvements in fleet-wide carbon intensity, which declined by about 10.3% from 2016 to 2023, absolute emissions have continued to rise. This divergence reflects the rapid growth in global shipping transport work, which expanded by 21% over the same period. While efficiency gains have helped curb emissions growth, they have not been sufficient to achieve absolute reductions in emissions.

The fuel mix in shipping has undergone significant shifts, particularly following the 2020 implementation of the IMO's global sulfur limit. Consumption of HFO has largely been replaced by VLSFO, while the use of LNG nearly doubled between 2016 and 2023. However, this shift has also resulted in a substantial increase in methane emissions. For example, methane emissions from LNG-fueled ships grew by more than 2.5 times between 2016 and 2023 due to the prevalence of dual-fuel internal combustion engines with high methane slip. Methanol use, though still relatively small, nearly quadrupled from 2016 to 2023.

In addition to GHG emissions, BC remains a significant concern, particularly due to its high short-term climate impact. When accounting for BC emissions, total TTW CO_2e100 emissions increase to 989 Mt, with BC representing 8% of the total. Over a 20-year timeframe, the impact of BC is even more pronounced, raising total shipping emissions to 1,204 Mt CO_2e20, with BC accounting for 23% of these emissions. The IMO's effort to cut criteria air pollution from shipping has had mixed impacts. The global sulfur limit has resulted in a significant reduction in SO_X and PM emissions, yet the NO_x Technical Code has not delivered similar results.

The data presented in this report highlight the urgency of accelerating the adoption of zero-emission fuels and technologies to align the shipping sector with global climate goals. Although improvements in fuel efficiency and operational measures have contributed to emissions intensity reductions, the absolute increase in emissions underscores the need for more transformative changes. Policymakers, industry stakeholders, and research organizations can work together to develop and implement policies that incentivize the use of zero- or near-zero life-cycle GHG fuels, improve energy efficiency, and ensure that regulatory measures drive meaningful emissions reductions.

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