MARINE ENVIRONMENT PROTECTION COMMITTEE
75th session
Agenda item 7

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REDUCTION OF GHG EMISSIONS FROM SHIPS

Fourth IMO GHG Study 2020 – Final report

Note by the Secretariat

SUMMARY

Executive summary:	This document provides in the annex the Final report of the Fourth IMO GHG Study 2020, as well as the "Highlights" of the Study and the Executive Summary
Strategic direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 7
Related documents:	Resolution MEPC.304(72); MEPC 73/19/Add.1; MEPC 74/18, MEPC 74/WP.6; MEPC 75/7/3, MEPC 75/7/3/Add.1 and MEPC 75/7/3/Add.2

Background

1 In accordance with the *Initial IMO Strategy on reduction of GHG emissions from ships* (resolution MEPC.304(72)) and its programme of follow-up actions up to 2023 (MEPC 73/19/Add.1, annex 9), MEPC 74 agreed on the terms of reference of the Fourth IMO GHG Study and requested the Secretariat to initiate the Study with a view to consider its Final report during MEPC 76 initially planned for Autumn 2020.

2 Despite the COVID-19 pandemic and regardless of the postponement of MEPC 75, the Fourth IMO GHG Study has been progressed and finalized in line with the steps and timeline approved by MEPC 74 (document MEPC 74/WP.6, annex 2).

3 Documents MEPC 75/7/3, MEPC 75/7/3/Add.1 and MEPC 75/7/3/Add.2 provide detailed information on the steps of the development of the Study, including in particular its supervision by a Steering Committee of Member States.

4 The "Highlights" and the "Executive Summary" of the Fourth IMO GHG Study 2020 are provided in annex 1 to this document, with a view to be also translated into French and Spanish. The full Study and its annexes are provided in annex 2 to this document, in English only.

5 The underlying datasets supporting the findings contained in the Study will be published separately on the IMO website.

Budget and status of contributions

6 The Steering Committee noted that approximately $489,356 has been received from the Governments of Australia, Canada, Denmark, France, Japan, the Netherlands, Norway, the Republic of Korea, the United Arab Emirates and the United Kingdom towards the Fourth IMO GHG Study 2020. The Steering Committee thanked all the donors for their kind and valuable contribution.

Action requested of the Committee

7 The Committee, in conjunction with document MEPC 75/7/3/Add.2, is invited to consider and approve the Fourth IMO GHG Study 2020 as provided in annexes 1 and 2 to this document.

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ANNEX 1

HIGHLIGHTS AND EXECUTIVE SUMMARY OF THE FOURTH IMO GHG STUDY 2020

Highlights

Emissions inventory

- The greenhouse gas (GHG) emissions – including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), expressed in CO_2e – of total shipping (international, domestic and fishing) have increased from 977 million tonnes in 2012 to 1,076 million tonnes in 2018 (9.6% increase). In 2012, 962 million tonnes were CO_2 emissions, while in 2018 this amount grew 9.3% to 1,056 million tonnes of CO_2 emissions.

- The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018.

- Under a new voyage-based allocation of international shipping, CO_2 emissions have also increased over this same period from 701 million tonnes in 2012 to 740 million tonnes in 2018 (5.6% increase), but to a lower growth rate than total shipping emissions, and represent an approximately constant share of global CO_2 emissions over this period (approximately 2%), as shown in table 1. Using the vessel-based allocation of international shipping taken from the Third IMO GHG Study, CO_2 emissions have increased over the period from 848 million tonnes in 2012 to 919 million tonnes in 2018 (8.4% increase).

- Due to developments in data and inventory methods, this Study is the first IMO GHG Study able to produce greenhouse gas inventories that distinguish domestic shipping from international emissions on a voyage basis in a way which, according to the consortium, is exactly consistent with the IPCC guidelines and definitions.[1]

- Projecting the same method to 2008 emissions, this Study estimates that 2008 international shipping GHG emissions (in CO_2e) were 794 million tonnes (employing the method used in the Third IMO GHG Study, the emissions were 940 million tonnes CO_2e).

[1] The choice of the method to distinguish domestic shipping emissions from international shipping emissions does not interpret existing IMO instruments, nor prejudge any future policy developments at IMO and would not constitute IMO's views on the interpretation of the 2006 IPCC Guidelines on national greenhouse gas inventories.

Table 1 – Total shipping and voyage-based and vessel-based international shipping CO_2 emissions 2012-2018 (million tonnes)

Year	Global anthropogenic CO_2 emissions	Total shipping CO_2	Total shipping as a percentage of global	Voyage-based International shipping CO_2	Voyage-based International shipping as a percentage of global	Vessel-based International shipping CO_2	Vessel-based International shipping as a percentage of global
2012	34,793	962	2.76%	701	2.01%	848	2.44%
2013	34,959	957	2.74%	684	1.96%	837	2.39%
2014	35,225	964	2.74%	681	1.93%	846	2.37%
2015	35,239	991	2.81%	700	1.99%	859	2.44%
2016	35,380	1,026	2.90%	727	2.05%	894	2.53%
2017	35,810	1,064	2.97%	746	2.08%	929	2.59%
2018	36,573	1,056	2.89%	740	2.02%	919	2.51%

Carbon intensity 2008, 2012-2018
Table 2 – Estimates on carbon intensity of international shipping and percentage changes compared to 2008 values

Year	EEOI ($gCO_2/t/nm$)				AER ($gCO_2/dwt/nm$)				DIST ($kgCO_2/nm$)				TIME (tCO_2/hr)			
	Vessel-based		Voyage-based		Vessel-based		Voyage-based		Vessel-based		Voyage-based		Vessel-based		Voyage-based	
	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change
2008	**17.10**	—	**15.16**	—	**8.08**	—	**7.40**	—	306.46	—	350.36	—	**3.64**	—	**4.38**	—
2012	**13.16**	**-23.1%**	**12.19**	**-19.6%**	**7.06**	**-12.7%**	**6.61**	**-10.7%**	362.65	**18.3%**	387.01	**10.5%**	**4.32**	**18.6%**	**4.74**	**8.1%**
2013	**12.87**	**-24.7%**	**11.83**	**-22.0%**	**6.89**	**-14.8%**	**6.40**	**-13.5%**	357.73	**16.7%**	380.68	**8.7%**	**4.18**	**14.6%**	**4.57**	**4.1%**
2014	**12.34**	**-27.9%**	**11.29**	**-25.6%**	**6.71**	**-16.9%**	**6.20**	**-16.1%**	360.44	**17.6%**	382.09	**9.1%**	**4.17**	**14.4%**	**4.54**	**3.5%**
2015	**12.33**	**-27.9%**	**11.30**	**-25.5%**	**6.64**	**-17.8%**	**6.15**	**-16.9%**	366.56	**19.6%**	388.62	**10.9%**	**4.25**	**16.6%**	**4.64**	**5.7%**
2016	**12.22**	**-28.6%**	**11.21**	**-26.1%**	**6.58**	**-18.6%**	**6.09**	**-17.7%**	373.46	**21.9%**	397.05	**13.3%**	**4.35**	**19.3%**	**4.77**	**8.7%**
2017	**11.87**	**-30.6%**	**10.88**	**-28.2%**	**6.43**	**-20.4%**	**5.96**	**-19.5%**	370.97	**21.0%**	399.38	**14.0%**	**4.31**	**18.2%**	**4.79**	**9.2%**
2018	**11.67**	**-31.8%**	**10.70**	**-29.4%**	**6.31**	**-22.0%**	**5.84**	**-21.0%**	376.81	**23.0%**	401.91	**14.7%**	**4.34**	**19.1%**	**4.79**	**9.2%**

- Carbon intensity has improved between 2012 and 2018 for international shipping as a whole, as well as for most ship types. The overall carbon intensity, as an average across international shipping, was 21 and 29% better than in 2008, measured in AER and EEOI, respectively, in the voyage-based allocation; while it was 22 and 32% better, respectively, in the vessel-based allocation (Table 2). Improvements in carbon intensity of international shipping have not followed a linear pathway and more than half have been achieved before 2012. The pace of carbon intensity reduction has slowed since 2015, with average annual percentage changes ranging from 1 to 2%.

- Annual carbon intensity performance of individual ships fluctuated over years. The upper and lower quartiles of fluctuation rates in EEOI of oil tankers, bulk carriers and container ships were around ±20%, ±15% and ±10%, respectively. Quartiles of fluctuation rates in other metrics were relatively modest, yet still generally reaching beyond ±5%. Due to certain static assumptions on weather and hull fouling conditions, as well as the non-timely updated AIS entries on draught, factual fluctuations were possibly more scattered than estimated, especially for container ships.

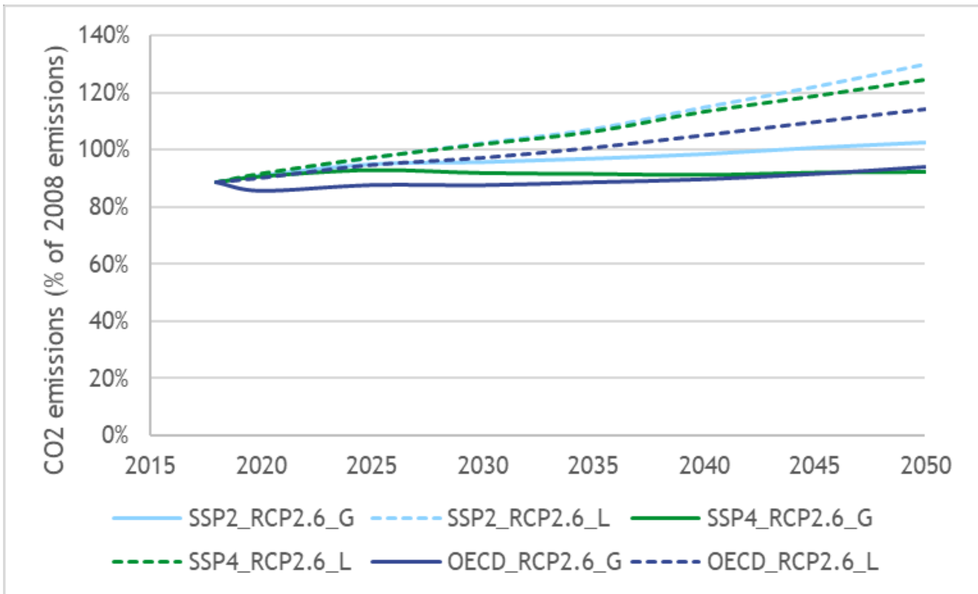
Emission projections 2018-2050

- Emissions are projected to increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios (Figure 1).

- Emissions could be higher (lower) than projected when economic growth rates are higher (lower) than assumed here or when the reduction in GHG emissions from land-based sectors is less (more) than would be required to limit the global temperature increase to well below 2 degrees centigrade.

- Although it is too early to assess the impact of COVID-19 on emission projections quantitatively, it is clear that emissions in 2020 and 2021 will be significantly lower. Depending on the recovery trajectory, emissions over the next decades may be a few percent lower than projected, at most. In all, the impact of COVID-19 is likely to be smaller than the uncertainty range of the presented scenarios.

Figure 1 – Projections of maritime ship emissions as a percentage of 2008 emissions



Executive summary

Inventory of GHG Emissions from International Shipping 2012-2018

Figure 2 – International shipping emissions and trade metrics, indexed in 2008, for the period 1990-2018, according to the voyage-based allocation[2] of international emissions[3]

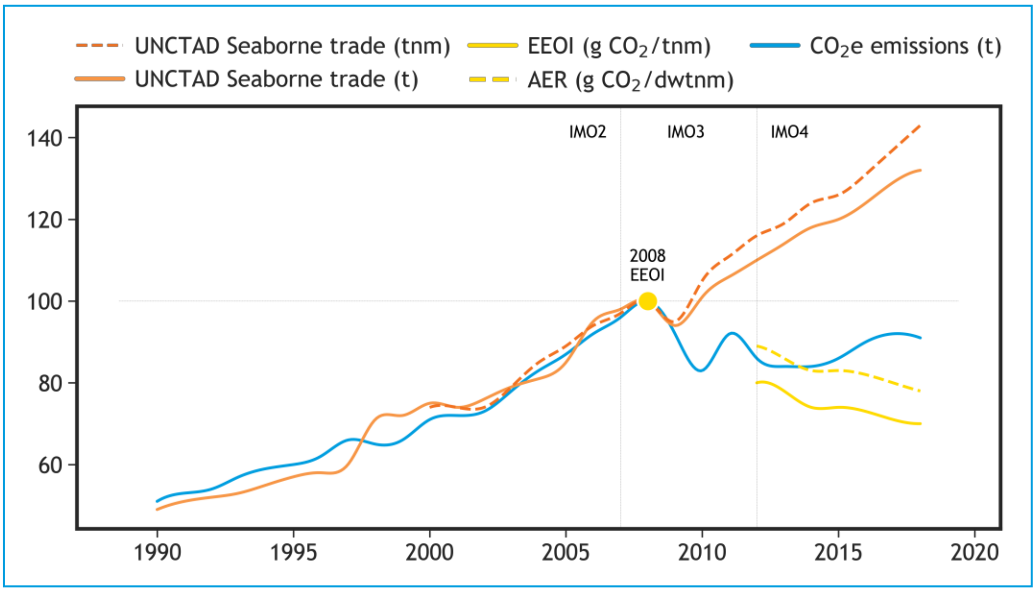


Figure **2** presents emissions, trade and carbon intensity trends as estimated across this Study and the two previous IMO GHG studies. Against a long-run backdrop of steadily increasing demand for shipping (growth in seaborne trade), the three studies approximately align with three discrete periods for international shipping's GHG emissions:

.1 1990 to 2008 – emissions growth (CO_2e) and emissions tightly coupled to growth in seaborne trade (UNCTAD).

.2 2008 to 2014 – emissions reduction (CO_2e) in spite of growth in demand (UNCTAD), and therefore a period of rapid carbon intensity reduction (EEOI and AER) that enabled decoupling of emissions from growth in transport demand.

.3 2014 to 2018 – a period of continued but more moderate improvement in carbon intensity (EEOI and AER), but at a rate slower than the growth in demand (UNCTAD). And therefore, a return to a trend of growth in emissions (CO_2e).

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2 Voyage-based allocation defines international emissions as those which occurred on a voyage between two ports in different countries, whereas the alternative "vessel-based" allocation defines emissions according to ship types, as per the Third GHG Study 2014.

3 Vessel-based allocation of international emissions produces the same trends but different absolute values.

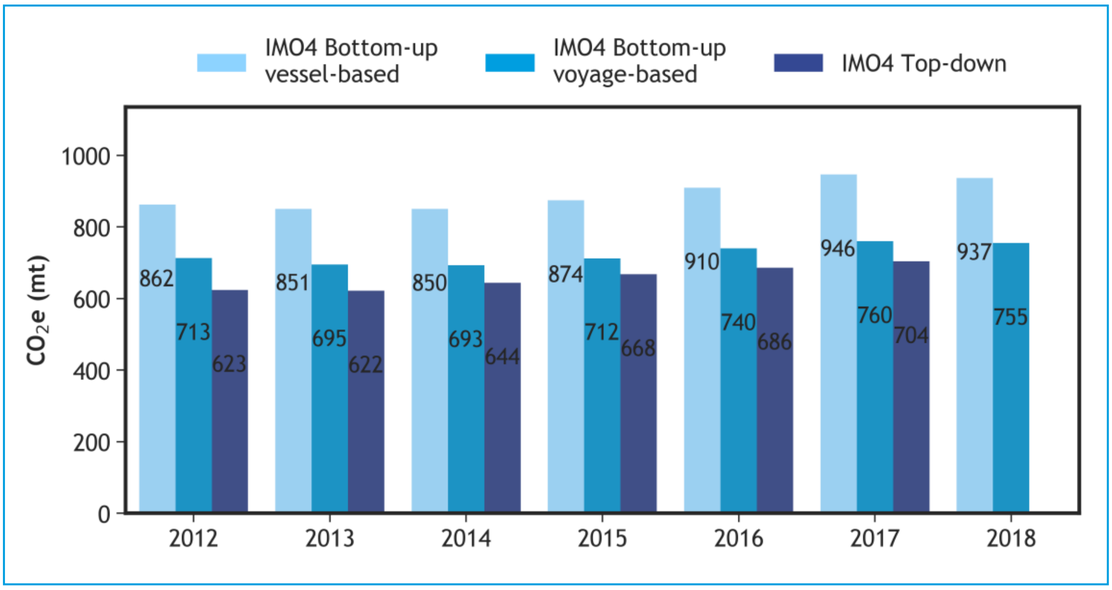
This Study is the first IMO GHG Study able to produce GHG inventories that distinguish domestic shipping from international emissions, following a method that is exactly consistent with the IPCC guidelines and definitions in the view of the consortium. The method is enabled by advances in the use of AIS data to identify port calls which allows allocation of discrete voyages to a definition of either international or domestic shipping. The improved split is reliable and provides a valuable advancement to the accurate assessment of international shipping's emissions, in line with the instruction of the Study's terms of reference:

> "…The Fourth IMO GHG Study should further develop clear and unambiguous definitions and refine methods for differentiation between domestic and international voyages with the aim to exclude domestic voyage from the inventory for 'international shipping'".

The Third IMO GHG Study used a different method for distinguishing the international and domestic GHG inventories, instead using the ship type and size characteristics to group ships which were assumed to be operating either as domestic or international shipping. This method relies on assumptions and uniform behaviour within fleets of similar ship types and size, which this Study's more detailed analysis shows to have shortcomings. However, in order to enable comparison with the Third IMO GHG Study and continued use to understand trends, wherever possible the results from both of these methods are included. The method as used in the Third IMO GHG Study is referred to as vessel-based (Option 1), the new method is referred to as voyage-based (Option 2).

For the avoidance of doubt, where results for international shipping using only one method are presented, this choice is not interpreting existing IMO instruments, does not prejudge any future policy developments at IMO and does not constitute IMO's views on the interpretation of the 2006 IPCC Guidelines on national greenhouse gas inventories.

Figure 3 – Annual greenhouse gas emissions (in CO_2e) for international shipping, according to the vessel-based and voyage-based allocation of international emissions (excluding black carbon (BC) emissions). Both the bottom-up emissions estimates, using ship activity data, as well as the top-down emissions estimates, using fuel sales statistics, are shown.



Source: UMAS.

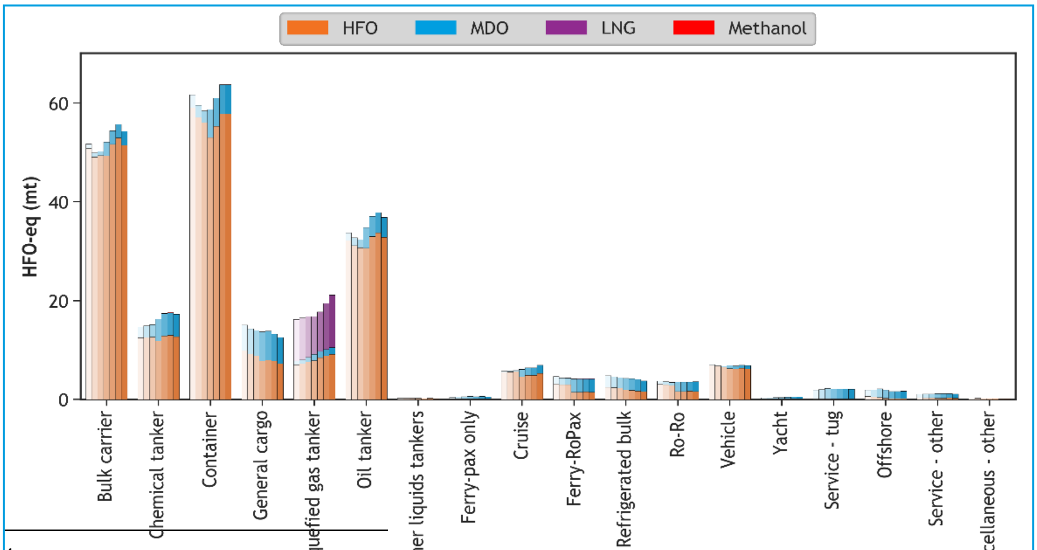
Figure 3 (all GHG emissions in CO_2e, excluding black carbon (BC)) presents the detailed results for the inventory of international shipping emissions for the period of this Study (2012-2018), considering the CO_2e impact of N_2O and CH_4. Over the period, bottom-up international shipping CO_2-equivalent emissions increased by 5.7 and 8.3% by voyage-based and vessel-based allocation, respectively.[4] Including BC, represented with a global warming potential (GWP) of 900, the voyage-based international GHG emissions for shipping in 2018 would be 7% higher, totalling 810 million tonnes CO_2e.

Consistent with the Third IMO GHG Study, CO_2 remains the dominant source of shipping's climate impact when calculated on a GWP-100 year basis, accounting for 98%, or 91% if BC is included, of total international GHG emissions (in CO_2e).

Insights into the composition and drivers for these high-level results and aggregate trends can be formed from the disaggregated data. To simplify presentation, only the voyage-based allocation of international shipping is used here. The vessel-based allocation produces the same insights, albeit with small differences in absolute values. Figure 4 presents the estimated fuel consumption break down across ship types, for each year 2012-2018. Over the period of study, three ship types remain the dominant source of international shipping's GHG emissions: container shipping, bulk carriers and oil tankers. In combination with chemical tankers, general cargo ships and liquefied gas tankers, these ship types constitute 86.5% of international shipping's total emissions when calculated on a voyage-based allocation.

Heavy fuel oil (HFO) remains the dominant fuel in international shipping (79% of total fuel consumption by energy content in 2018, by voyage-based allocation). However, during the period of the study, a significant change in the fuel mix has occurred. The proportion of HFO consumption has reduced by approximately 7% (an absolute reduction of 3%), while the share of marine diesel oil (MDO) and liquid nitrogen gas (LNG) consumption grew by 6 and 0.9% (absolute increases of 51 and 26%, respectively). Methanol's use as a fuel developed during this period and is estimated as the fourth most significant fuel used growing to approximately 130,000 tonnes of consumption in 2018 on voyage-based international routes (160,000 tonnes of total consumption).

Figure 4 – International HFO-equivalent fuel consumption per ship type, according to the voyage-based allocation of international emissions

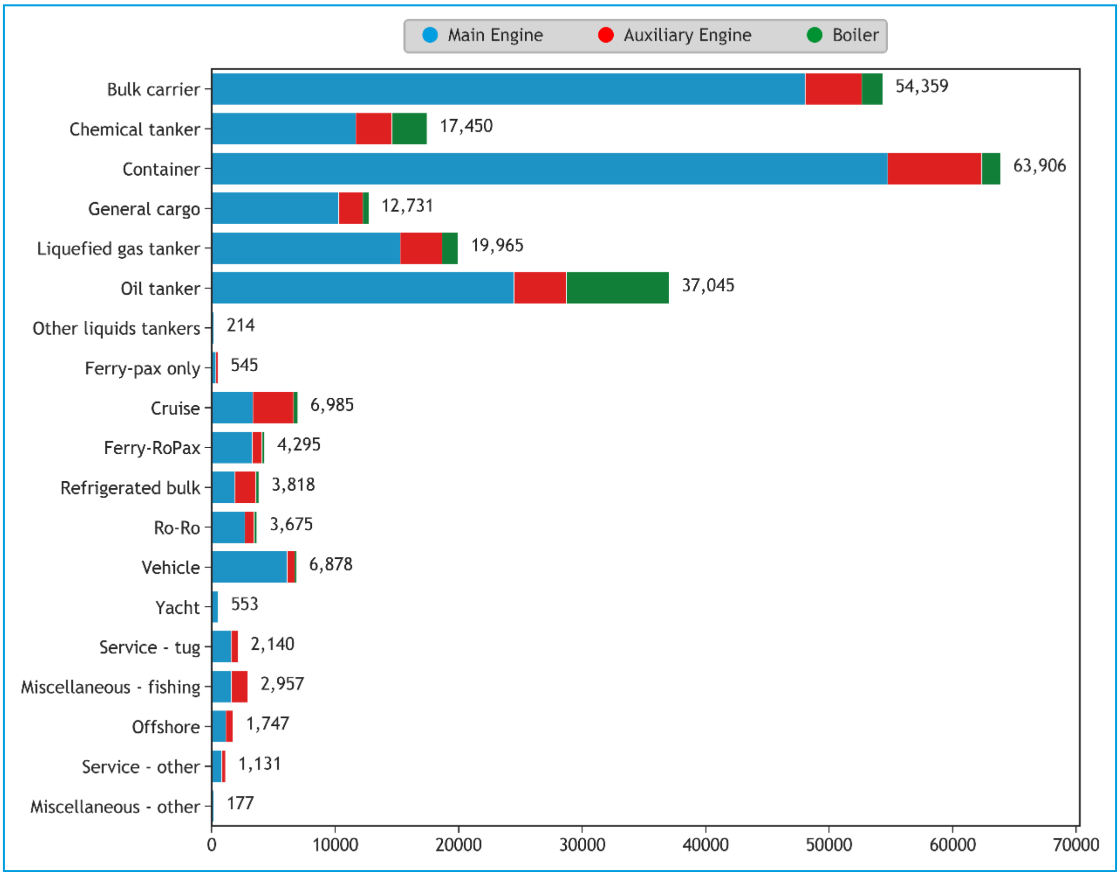


4 Voyage-based allocation defines international emissions as those which occurred on a voyage between two ports in different countries, whereas the alternative "vessel based" allocation defines emissions according to ship types, as per the Third GHG Study 2014.

Figure 5 presents the estimated fuel consumption across onboard machinery with broadly different end uses (main engines – propulsion, auxiliary engines – electrical power and boilers – heat). The results are similar to equivalent estimations in earlier GHG studies.

Consistent with the Third IMO GHG Study, energy use for propulsion remains the primary demand for energy across all ship types, albeit that for some ship types (cruise ships, refrigerated bulk and miscellaneous fishing) total propulsion energy demand is approximately equivalent to total auxiliary and heat energy demand.

Figure 5 – International, voyage-based allocation, HFO-equivalent fuel consumption (thousand tonnes), 2018, split by main engine, auxiliary engine and boiler. Highlighted values are in thousand tonnes.

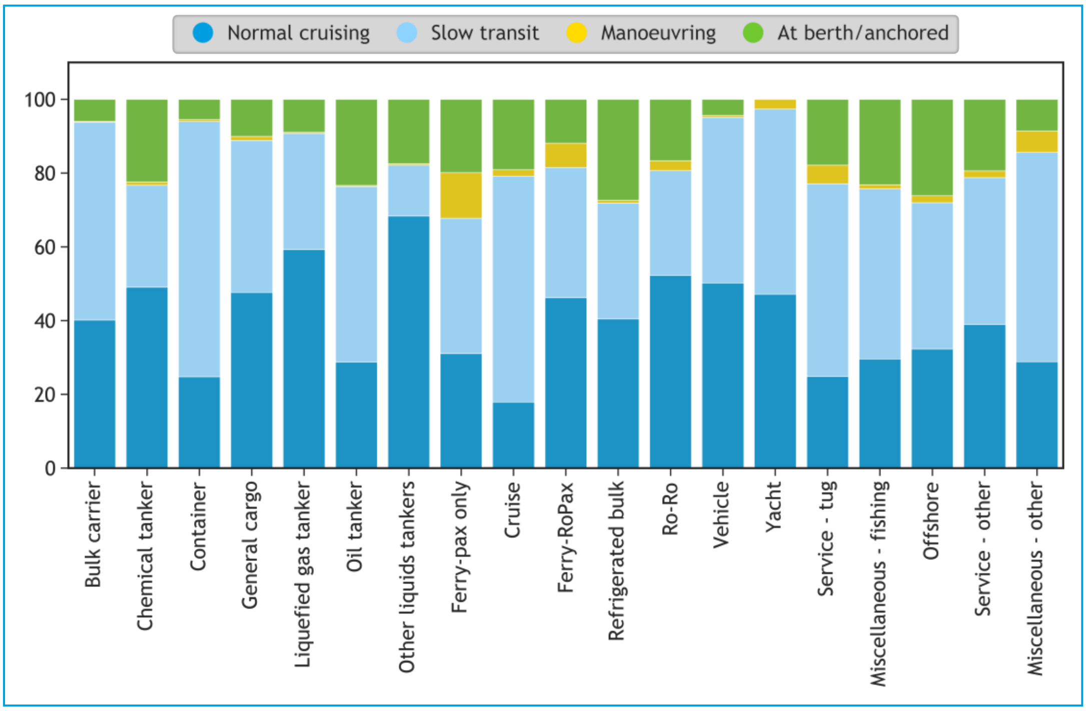


Source: UMAS.

Figure 6 presents the breakdown of GHG emissions across different phases of operation for each ship type. Depending on the ship type, there are differences in the share of emissions that occur at sea on passage, as opposed to during a manoeuvring, anchorage or berthed phase of operation. Of the six ship types most important to the emissions inventories, chemical tankers and oil tankers have on average the largest portion of their total emissions (greater than 20%) associated with phases at or near the port or terminal.

Container ships, cruise ships and oil tankers have the smallest share of their total emissions associated with cruising (definition) due to dominance of time spent slow cruising and/or phases at or near port, with liquefied gas tankers and other liquid tankers showing the largest share of their emissions associated with cruising.

Figure 6 – Proportion of international GHG emissions (in CO_2e) by operational phase in 2018, according to the voyage-based allocation of emissions. Operational phases are assigned based on the vessel's speed over ground, distance from coast/port and main engine load (see Table 16).



Source: UMAS.

Explanations for some of the trends observed over the period can be obtained from the underlying information used to produce the emissions inventories. Figure 7 presents the breakdown of a number of parameters that can further explain the results, and Figure 8 shows trends in average operating speed across the three ship types that dominate the inventory of international shipping emissions (size bins as defined in section 2.2.1).

Trends also observed in the Third IMO GHG Study have continued. Average ship sizes across these three ship types have increased, as has the average installed power. For each of these three ship types, the average ship's fuel consumption has increased over the period, but at a lower rate than the increase in average installed power. This decoupling in the rate of increase in installed power and fuel consumption is the consequence of a general trend of continued reduction in operating speeds (also observed in the Third IMO GHG Study), and continued reductions in the average number of days at sea.

The reduction in operating speeds was not a constant decline for all ship types over the period, with oil tankers and containers seeing increases in average speeds during 2015 and 2016 relative to other years during the period of study. For some of the ship size categories, the increase in speed was temporary and by 2018 average speeds were similar to minimum values over the period. Across the period of the Study, 2015 and 2016 account for the highest rate of total CO_2 emissions growth. This shows that operating speeds remain a key driver of trends in emissions and rate of emissions growth, and are currently susceptible to fluctuating market forces and behaviour trends (e.g. they are not fixed or constrained by the technical or design specifications of the fleet).

This Study's results of continuations of these trends suggest that there has been a further reduction of productivity of the fleet in this period. This in turn means that in 2018, relative to 2012, there is an increased risk of a rapid increase in emissions should the latent emissions in the fleet be realized. This builds further upon a similar finding from the Third IMO GHG Study which noted that the fleet in 2012:

> "…is currently at or near the historic low in terms of productivity (transport work per unit of capacity)…" and that "…these (and many other) sectors of the shipping industry represent latent emissions increases, because the fundamentals (number of ships in service) have seen upwards trends that have been offset as economic pressures act to reduce productivity (which in turn reduces emissions intensity)".

As concluded in the Third IMO GHG Study whether and when the latent emissions increase appears is uncertain and depends on the future market dynamics of the industry. Under certain market conditions, operating speeds could increase again and the associated increases in average fuel consumption and emissions in 2015 and 2016 could return. If their return is sustained, some or all of the reductions in carbon intensity achieved to date can be reversed.

Figure 7 – Trends for average ships for the three most high emitting fleets over the period 2012 to 2018, where fuel consumption represents international activity according to voyage-based allocation

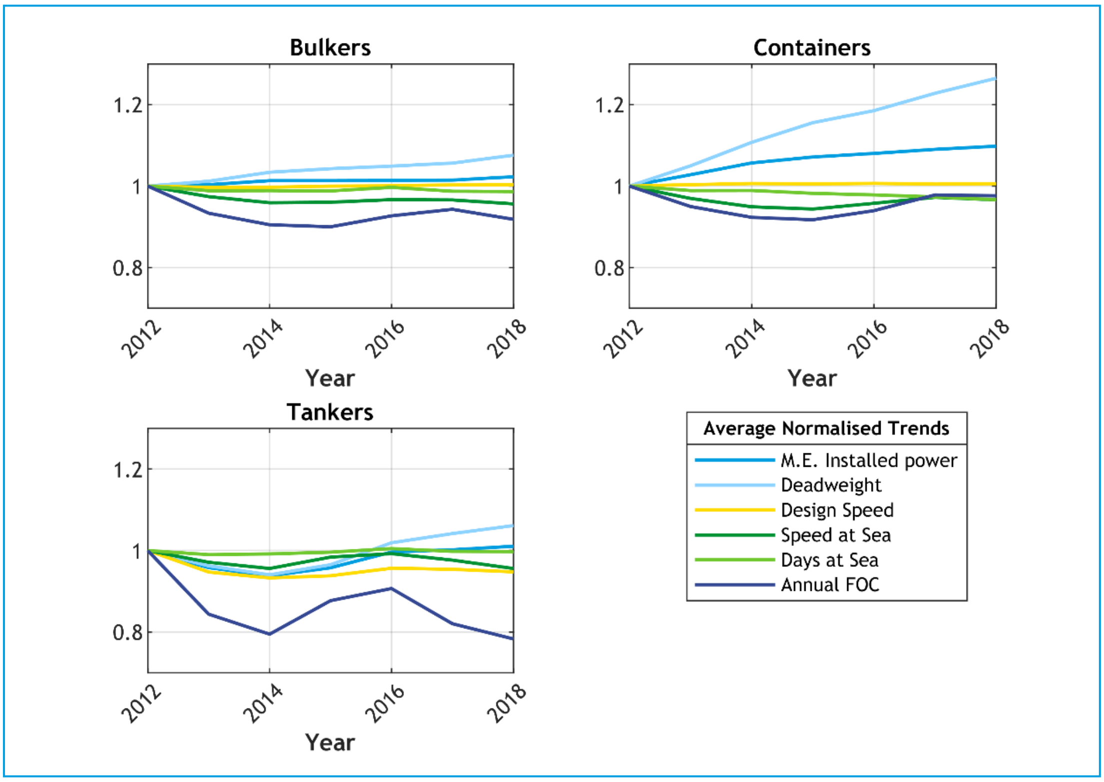


Figure 8 – Speed trends for the three highest emitting fleets aggregated (top left) and broken down for each ship type's size categories, which can be found in Section 2.2.1.

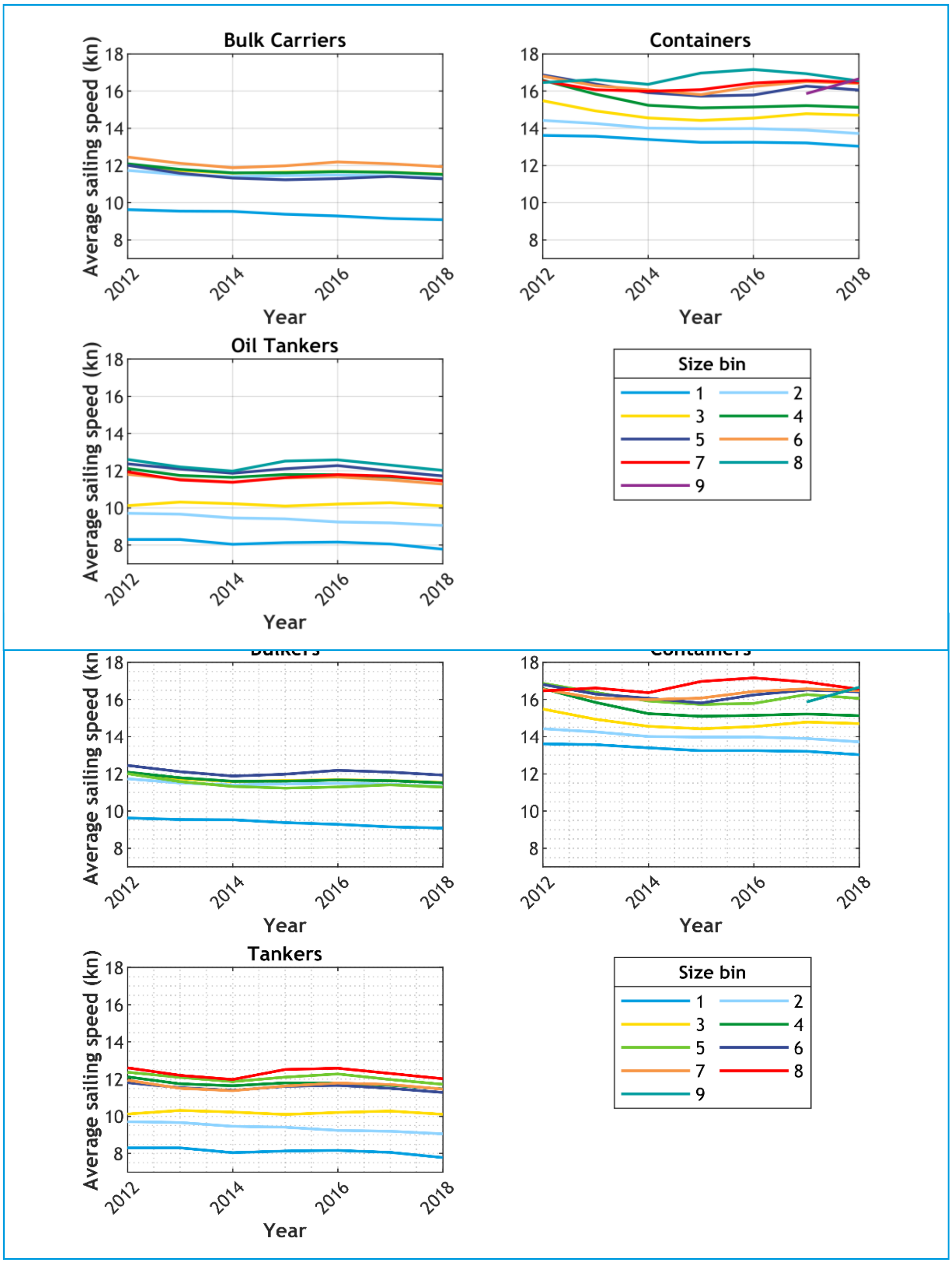


Figure 9 presents the trends in a number of emissions species, both GHG and air pollutants.

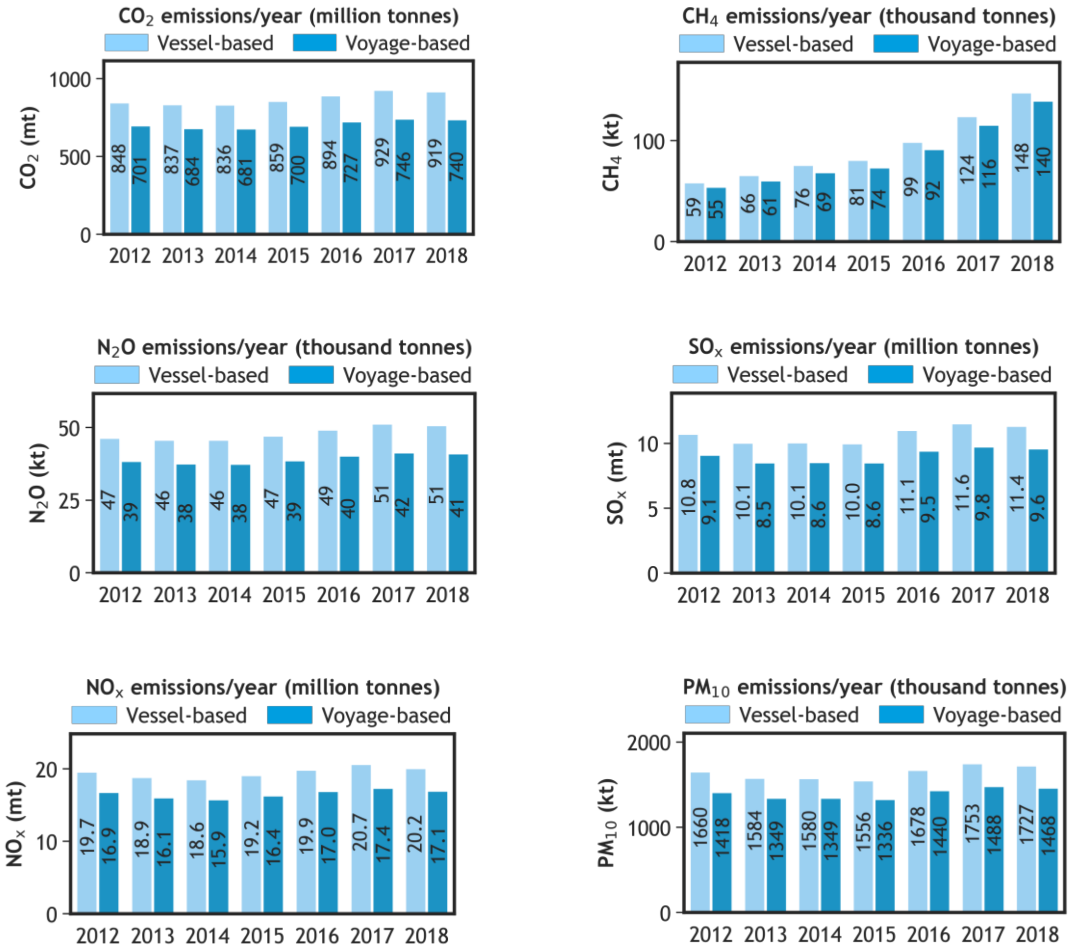
The majority of these trends follow the trend in total fuel consumption over the period. Important details include:

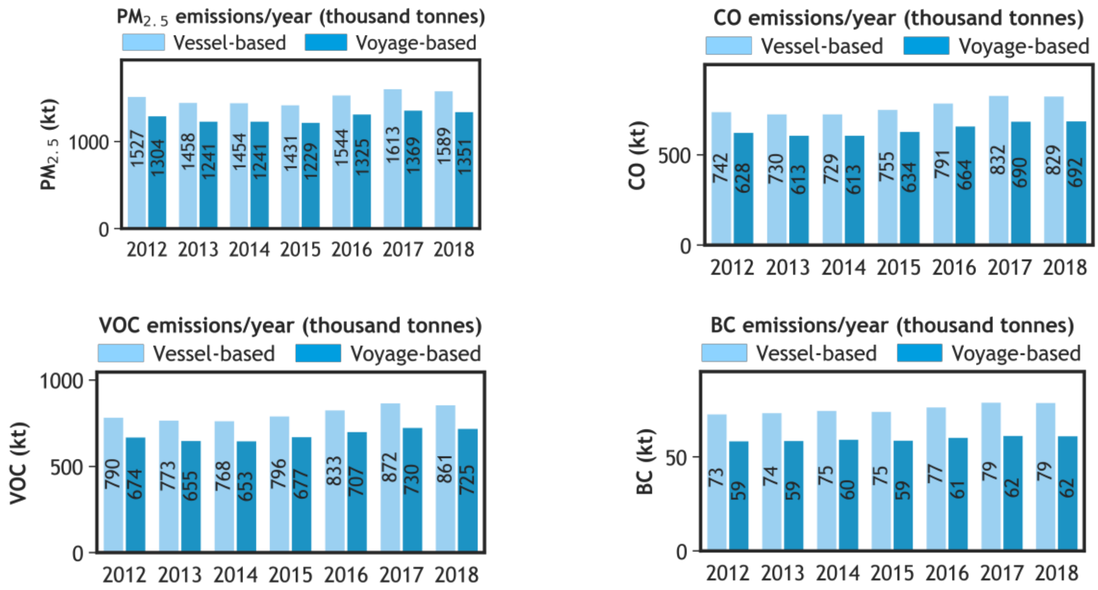
- CH_4 trend saw an 87% increase over the period, which was driven by both an increase in consumption of LNG but the absolute increase is dominated by a change in the machinery mix associated with the use of LNG as a fuel, with a significant increase in the use of dual-fuel machinery that has higher specific exhaust emissions of CH_4.

- SO_X and PM emissions increased over the period in spite of an overall reduction in HFO use and increase in MDO and LNG use (partly driven by the entry into force in 2015 of a number of Emission Control Areas associated with limits on sulfur content of fuels). The explanation is that the average sulfur content increase in HFO over the period exceeds the sulfur content reduction associated with the change in fuel use.

- NO_X emissions saw lower rates of increase over the period than the trend in fuel consumption. This is consistent with the increased number of ships fitted with, and where appropriate operating with, NO_X Tier II and Tier III compliant machinery. In spite of these regulations, the overall trend in NO_X emissions was an increase over the period.

Figure 9 – Emissions species trends, all species 2012-2018, showing both the estimates for voyage-based and vessel-based international shipping emissions





Split between domestic and international shipping

This Study deploys a new method to produce GHG Inventories that distinguish domestic shipping from international emissions on a voyage basis which is in the view of the consortium exactly consistent with the IPCC guidelines and definitions. The method is enabled by advances in the use of AIS data to identify port calls which allows allocation of discrete voyages to a definition of either international or domestic shipping. The improved split is reliable and provides a valuable advancement to the accurate assessment of international shipping's emissions. Figure 10 presents this method graphically.

Figure 10 – Allocation of international and domestic nature of shipping according to voyage-based method

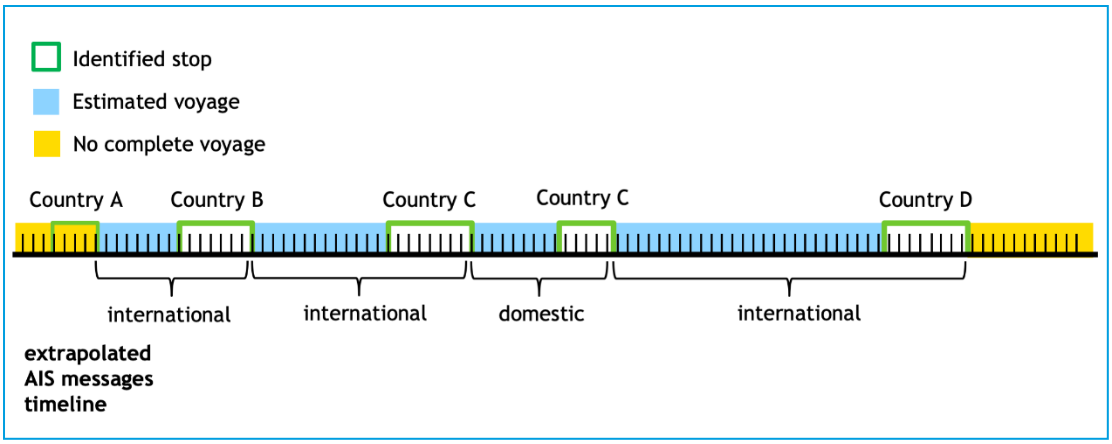
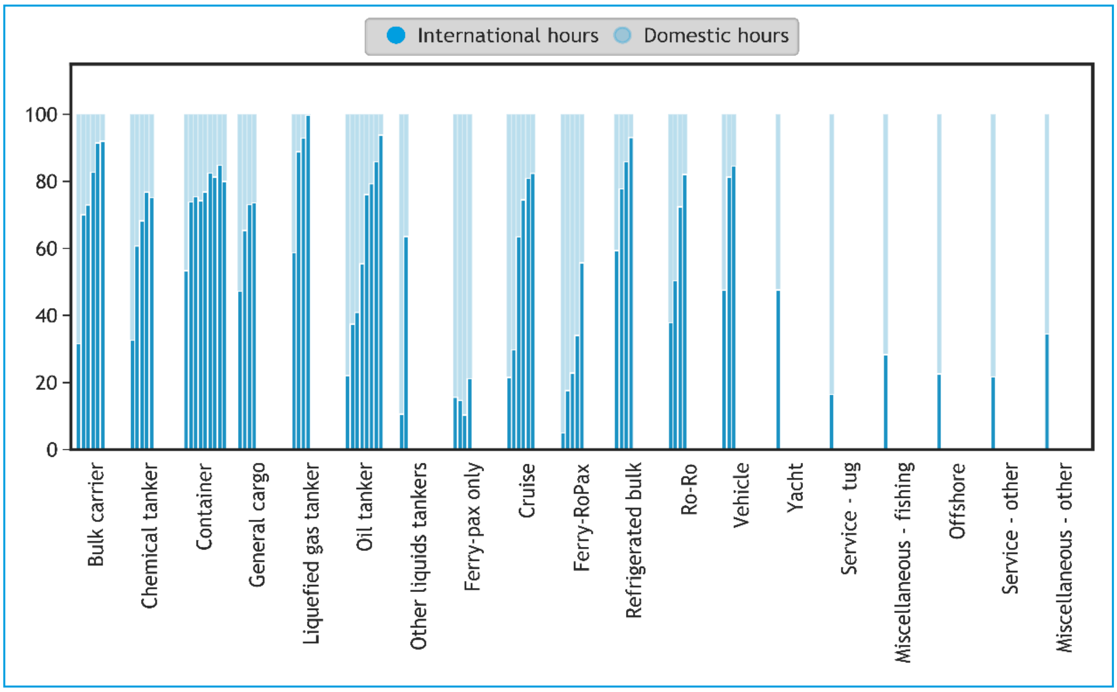


Figure 11 – Proportion of time spent on international and domestic voyages on average by ship type and size in 2018 (%), where ship sizes are order small to large



As presented in Figure 11, this Study finds that every one of the ship type and size categories of ships has some portion of international shipping emissions. For ship types dominant in the inventory of international shipping emissions (oil tankers, bulk carriers and containers), the smallest size categories have 20-40% of their emissions allocated to international shipping. For the largest ship sizes, the allocation to international shipping varies depending on ship type e.g. general cargo ~70%, containers ~80%, oil tankers and bulk carriers ~90% and liquefied gas tankers ~100%.

Quality and uncertainty of the estimates

Extensive quality assurance and control efforts were taken to ensure the highest quality of the inputs, method and results in the bottom-up and top-down inventories. This included validation against:

- Shipowners reported high frequency measurements of fuel consumption and operational parameters.
- Other published studies and inventories.
- Reported results from shipowners in the EU's MRV scheme (EU, 2019).
- The results of the Third IMO GHG Study. The difference in total fuel consumption figures is 3% in the overlapping year 2012, demonstrating both quality and coherency with the preceding study.

Of these validation efforts, the greatest sample size and most comprehensive validation was undertaken by comparing the bottom-up inventory results against reported fuel consumption and other key parameters describing 11,000 ships. This represented a significant step forwards in validation for this GHG Study, and demonstrated high quality in the consensus estimate because:

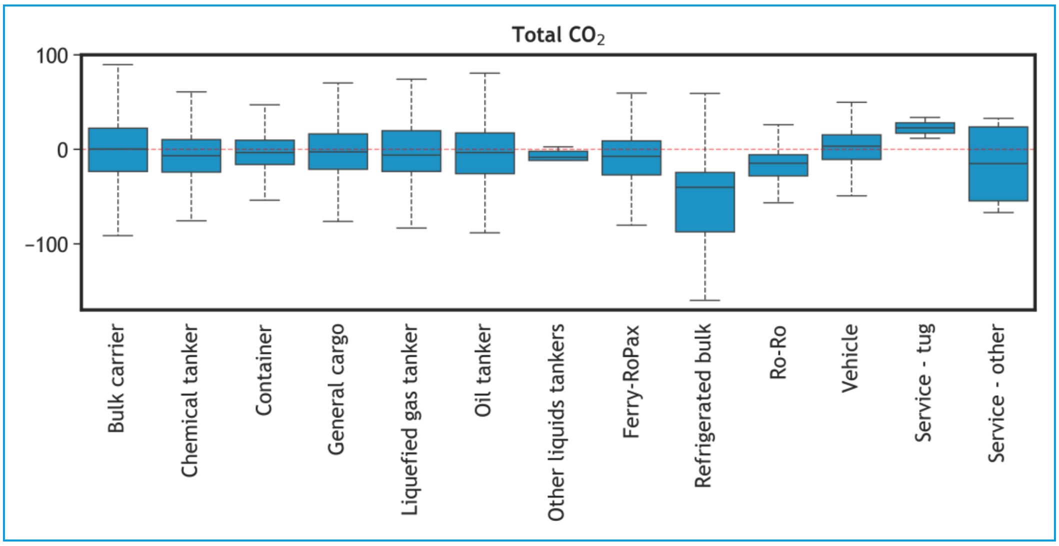
- The CO_2 and distance travelled at sea estimates across the entire fleet covered by MRV are showing only a very small overall deviation – overestimation error of 5.5 and 4.7%, respectively.

- When breaking down the MRV based comparison by vessel type as shown on Figure 12, the CO_2 emissions for three major vessel types are showing only -0.2% error for bulk carriers, 6% for container vessels, and 3% for oil tankers.

- These three vessel types contribute to over 65% of the international CO_2 emissions in 2018 and so represent a dominant share of global international shipping.

- For vessel types, where a poorer agreement is observed, they are shown to be of negligible influence on the inventory's overall accuracy as their overall contribution to the international CO_2 emissions is no more than 3%.

Figure 12 – Agreement between this Study's inventory, with respect to its vessel-specific CO_2 emissions estimates, and entries for 9,739 ships reported in the EU MRV database for 2018, for the duration of shipping activity covered by the EU MRV scheme's reporting requirement



Source: UMAS.

Estimates of carbon intensity of international shipping

This report presents four metrics of carbon intensity, namely Energy Efficiency Operational Indicator (EEOI, g CO_2/t/nm), Annual Efficiency Ratio (AER, g CO_2/dwt/nm), DIST (kg CO_2/nm) and TIME (t CO_2/hr). These metrics can either be calculated with data from the Data Collection System or are included in the SEEMP Guidelines.

These metrics are used in this Study to estimate the carbon intensity performance of international shipping from 2012 to 2018, as well as in 2008. Other variants of AER, including cDIST which uses different capacity units (such as teu, gt and cbm) and Energy Efficiency Performance Indicator (EEPI) which uses laden distance instead of total distance at sea, are also estimated where applicable, for reference purposes. Different carbon intensity metrics have different implications, drivers and reduction potentials, thus yielding different results in indicating the same performance level and percentage changes. Metrics such as EEOI, AER, cDIST and EEPI are potentially applicable to typical cargo and passenger ships, while DIST and TIME as well as their possible variants are more suitable for service, working or fishing vessels.

Table 3 and Table 4 report the carbon intensity levels of world fleet derived from both vessel-based and voyage-based. Seven typical ship types have been chosen as a representative of the world fleet, namely bulk carriers, oil tankers, container ships, chemical tankers, liquefied gas tankers, general cargo ships and refrigerated bulk carriers, which all together accounted for around 88% of CO_2 emissions and 98% of transport work of the world total. The percentage changes in overall and individual based carbon intensity of international shipping are jointly provided in these tables, indexed at 2008 and 2012, respectively. The overall percentage changes are calculated on aggregated data, while the individual based percentage changes are estimated through regression fit.

Table 3 – Carbon intensity levels and percentage changes of international shipping (vessel-based)

Year	EEOI (gCO2/t/nm)					AER(gCO2/DWT/nm)					DIST(kgCO2/nm)					TIME(tCO2/hr)				
	Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012	
		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual
2008	17,10	–	–	–	–	8,08	–	–	–	–	306,46	–	–	–	–	3,64	–	–	–	–
2012	13,16	-23,1%	-16,8%	–	–	7,06	-12,7%	-5,6%	–	–	362,65	18,3%	-5,6%	–	–	4,32	18,6%	-14,7%	–	–
2013	12,87	-24,7%	-18,3%	-2,2%	-2,0%	6,89	-14,8%	-7,1%	-2,4%	-1,7%	357,73	16,7%	-7,1%	-1,4%	-1,7%	4,18	14,6%	-18,1%	-3,3%	-4,2%
2014	12,34	-27,9%	-20,4%	-6,3%	-4,6%	6,71	-16,9%	-7,8%	-4,9%	-2,4%	360,44	17,6%	-7,7%	-0,6%	-2,4%	4,17	14,4%	-19,9%	-3,6%	-6,2%
2015	12,33	-27,9%	-19,0%	-6,3%	-2,8%	6,64	-17,8%	-6,5%	-5,9%	-1,3%	366,56	19,6%	-6,5%	1,1%	-1,3%	4,25	16,6%	-18,5%	-1,6%	-4,9%
2016	12,22	-28,6%	-18,7%	-7,2%	-2,5%	6,58	-18,6%	-6,4%	-6,8%	-1,4%	373,46	21,9%	-6,4%	3,0%	-1,4%	4,35	19,3%	-18,0%	0,6%	-4,4%
2017	11,87	-30,6%	-20,8%	-9,8%	-5,0%	6,43	-20,4%	-8,4%	-8,9%	-3,3%	370,97	21,0%	-8,4%	2,3%	-3,3%	4,31	18,2%	-20,4%	-0,3%	-7,0%
2018	11,67	-31,8%	-21,5%	-11,3%	-6,2%	6,31	-22,0%	-9,3%	-10,6%	-4,2%	376,81	23,0%	-9,3%	3,9%	-4,2%	4,34	19,1%	-22,2%	0,4%	-9,1%

Table 4 – Carbon intensity levels and percentage changes of international shipping (voyage-based)

Year	EEOI (gCO2/t/nm)					AER(gCO2/DWT/nm)					DIST(kgCO2/nm)					TIME(tCO2/hr)				
	Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012	
		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual
2008	15,16	–	–	–	–	7,40	–	–	–	–	350,36	–	–	–	–	4,38	–	–	–	–
2012	12,19	-19,6%	-11,4%	–	–	6,61	-10,7%	-4,6%	–	–	387,01	10,5%	-4,6%	–	–	4,74	8,11%	-13,9%	–	–
2013	11,83	-22,0%	-13,6%	-3,0%	-2,6%	6,40	-13,5%	-6,6%	-3,2%	-2,2%	380,68	8,7%	-6,6%	-1,6%	-2,2%	4,57	4,13%	-17,6%	-3,7%	-4,5%
2014	11,29	-25,6%	-16,2%	-7,4%	-5,5%	6,20	-16,1%	-7,6%	-6,1%	-3,1%	382,09	9,1%	-7,6%	-1,3%	-3,1%	4,54	3,49%	-19,4%	-4,3%	-6,6%
2015	11,30	-25,5%	-14,5%	-7,3%	-3,7%	6,15	-16,9%	-6,2%	-6,9%	-2,0%	388,62	10,9%	-6,2%	0,4%	-2,0%	4,64	5,75%	-18,0%	-2,2%	-5,3%
2016	11,21	-26,1%	-14,0%	-8,1%	-3,2%	6,09	-17,7%	-5,9%	-7,8%	-1,8%	397,05	13,3%	-5,9%	2,6%	-1,8%	4,77	8,68%	-17,4%	0,5%	-4,7%
2017	10,88	-28,2%	-15,9%	-10,8%	-5,4%	5,96	-19,5%	-7,7%	-9,8%	-3,7%	399,38	14,0%	-7,7%	3,2%	-3,7%	4,79	9,21%	-19,7%	1,0%	-7,2%
2018	10,70	-29,4%	-17,2%	-12,3%	-7,0%	5,84	-21,0%	-8,9%	-11,5%	-4,8%	401,91	14,7%	-8,9%	3,8%	-4,9%	4,79	9,17%	-21,5%	1,0%	-9,3%

As illustrated in Figure 13 and Figure 14, values of EEOI and AER have generally kept decreasing between 2012 and 2018, and reached a reduction rate of around 29% and 21% in 2018, respectively, in comparison with 2008. Discrepancies between the two metrics were mainly caused by their opposite reflections on payload utilization. Values of DIST and TIME both showed an increasing trend due to the increasing average ship size, whereas the increasing magnitudes have been diminished to a certain extent by sea speed reduction, especially for values of TIME.

Figure 13 – Percentage changes in overall carbon intensity of international shipping (vessel-based)

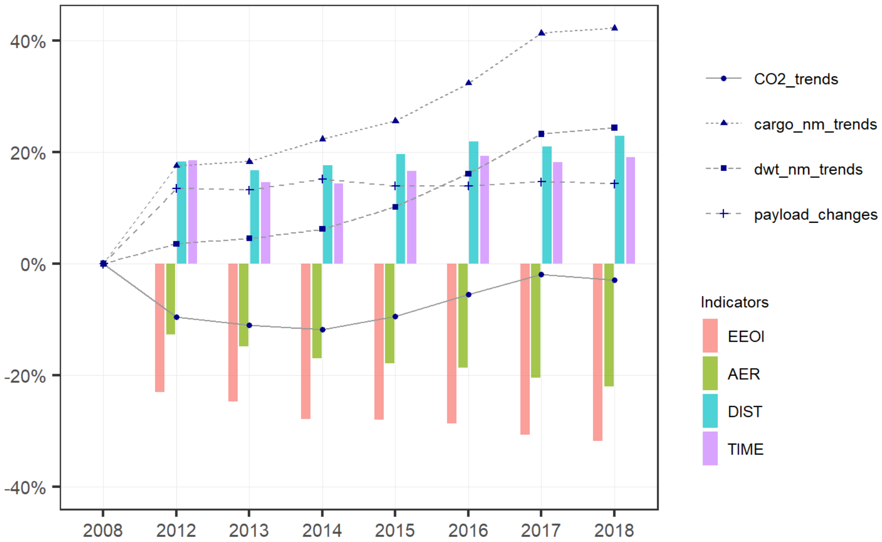
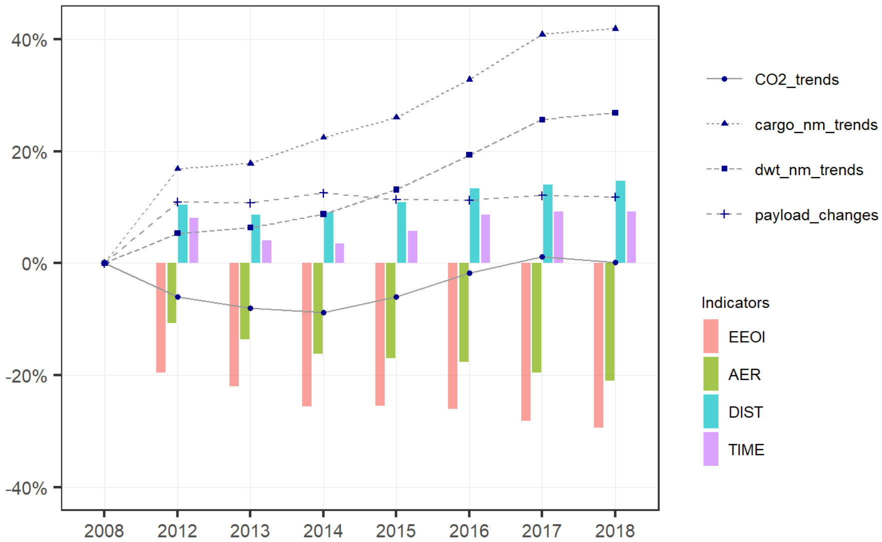


Figure 14 – Percentage changes in overall carbon intensity of international shipping (voyage-based)



As shown in Figure 15 and Figure 16, having not taken the influence of fleet composition shift into account, reduction magnitudes in EEOI and AER both narrowed down significantly. In comparison with 2008, the reductions in EEOI, AER/DIST and TIME in 2018 were around 17%, 9% and 22%, respectively. The relatively smaller improvements in AER/DIST, when compared with in EEOI, were due to their negative response (metric values going up) to the increasing payload utilization, while the relatively larger improvements in TIME were due to their high sensitivity to speed reduction.

Figure 15 – Percentage changes in individual based carbon intensity of international shipping (vessel-based)

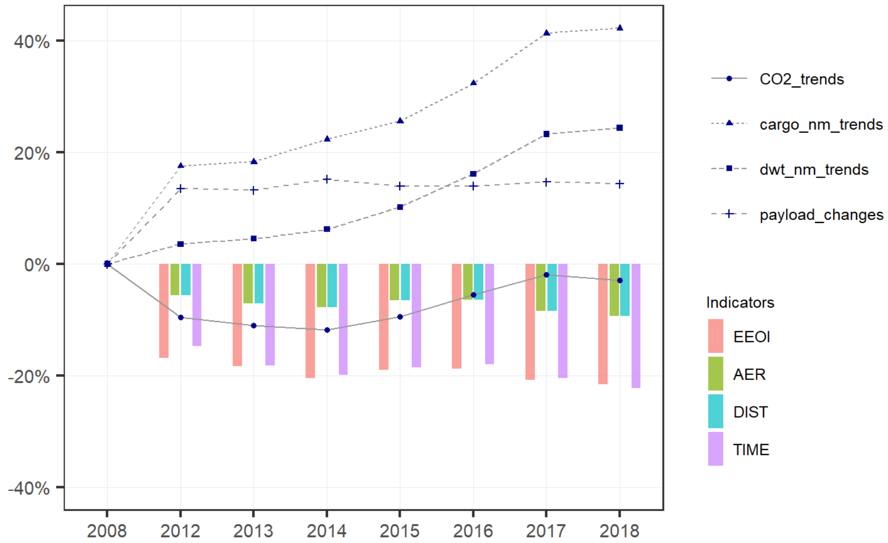
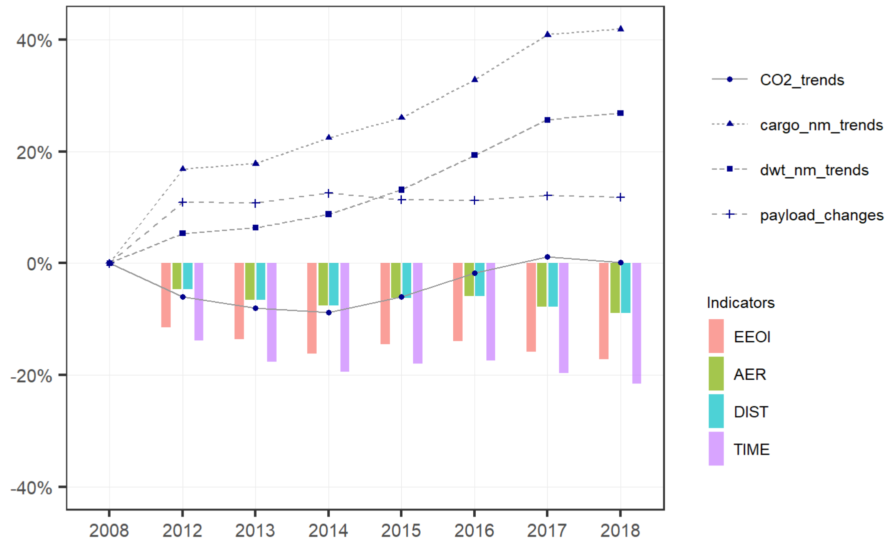


Figure 16 – Percentage changes in individual based carbon intensity of international shipping (voyage-based)



Note that the reduction rates in carbon intensity of international shipping discussed above are all indexed at year 2008, at which time the shipping market was just reaching its peak right before the long-lasting depression. Taking 2012 as the reference instead, the reductions in overall carbon intensity of international shipping narrowed down from 29% (in EEOI) and 21% (in AER) to around 12% (in both EEOI and AER). The individual based percentage changes further shrank to 7% (in EEOI), 5% (in AER/DSIT) and 9% (in TIME). This implies that the improvements in carbon intensity of international shipping has not followed a linear pathway, and more than half have been achieved before 2012. The pace of carbon intensity reduction has been further slowing down since 2015, with average annual percentage changes ranging from 1 to 2%, due to the limit in speed reduction, payload utilization, as well as the technical improvements of existing ships.

Figure 17 and
Figure 18 present the carbon intensity levels of typical cargo ships over years in EEOI and AER, estimated through both vessel-based (Option 1) and voyage-based (Option 2). As

shown in these figures, lowest carbon intensity levels were achieved by bulk carriers and oil tankers, followed by container ships. In the vessel-based option, ships covered by certain types have been undifferentiated categorized as international regardless of their sizes and operational features, including a number of small ships which have been merely or mainly serving domestic transportation. Therefore, carbon intensity levels estimated for the vessel-based option were a little bit higher than (i.e. inferior to) those derived for the voyage-based option. For the sake of brevity, results derived from both vessel- and voyage-based are reported, but discussions on trends and drivers of carbon intensity have mainly focused on voyage-based unless otherwise specified.

Figure 17 – Carbon intensity levels of typical cargo ships over years (in EEOI; left panel: vessel-based; right panel: voyage-based)

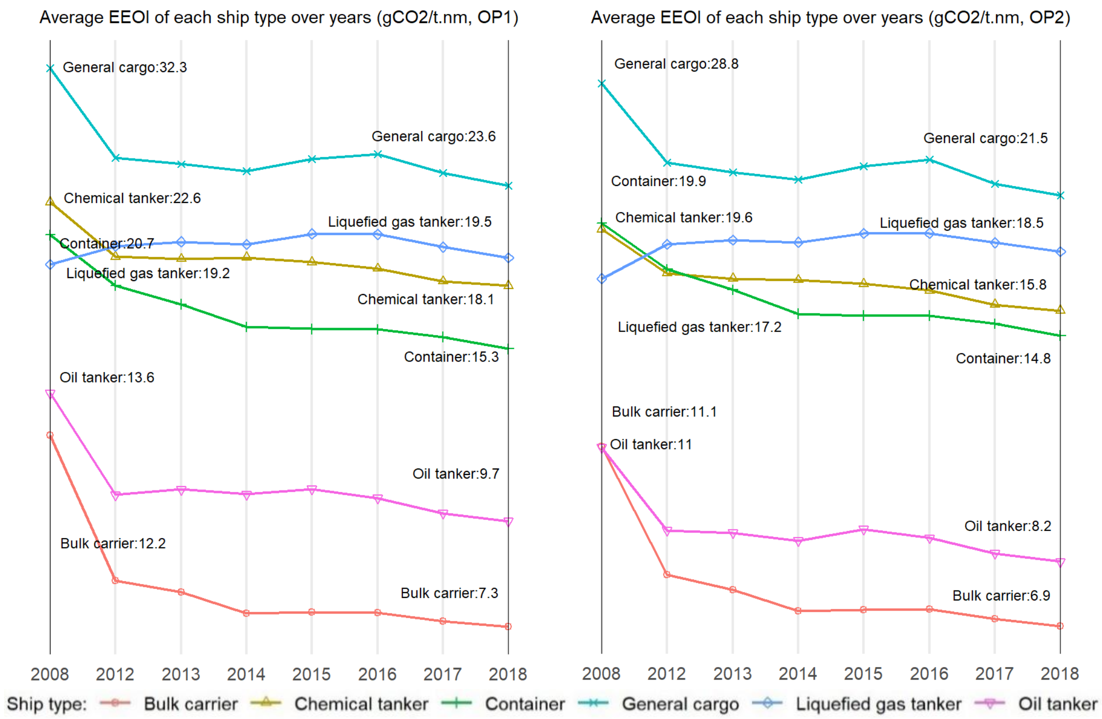
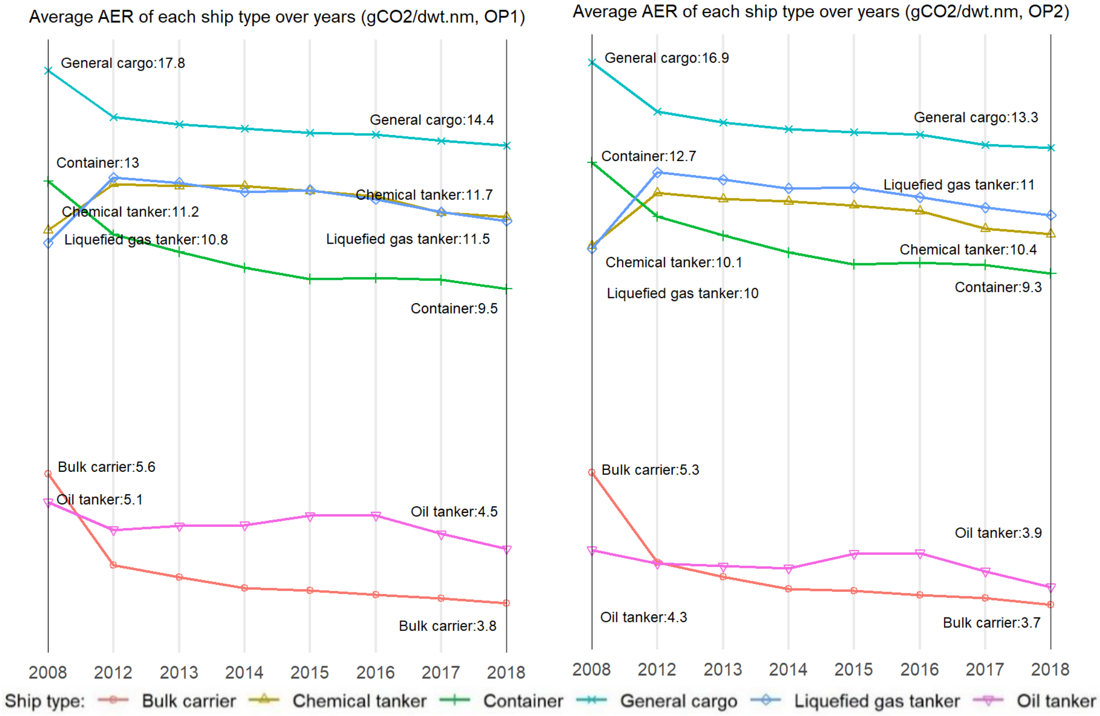


Figure 18 – Carbon intensity levels of typical cargo ships over years (in AER; left panel: vessel-based; right panel: voyage-based)



Carbon intensity performance per ship type varied from each other, but most of which have shared a decreasing trend between 2012 and 2018. Figure 19 and
Figure 20 present of the trends in overall carbon intensity per ship type derived from both vessel-based (Option 1) and voyage-based (Option 2), as well as changes in drivers for carbon intensity reduction. Taking the year 2008 as a reference, the most significant carbon intensity reduction was achieved by bulk carriers, where the overall EEOI and AER in 2018 was around 38% and 31% lower. The trends in overall EEOI of oil tankers, container ships and general cargo ships were roughly identical, all of which decreased by 25-26% in 2018 compared with year 2008.

Figure 19 – Percentage changes in overall carbon intensity per ship type indexed at 2008 (vessel-based)

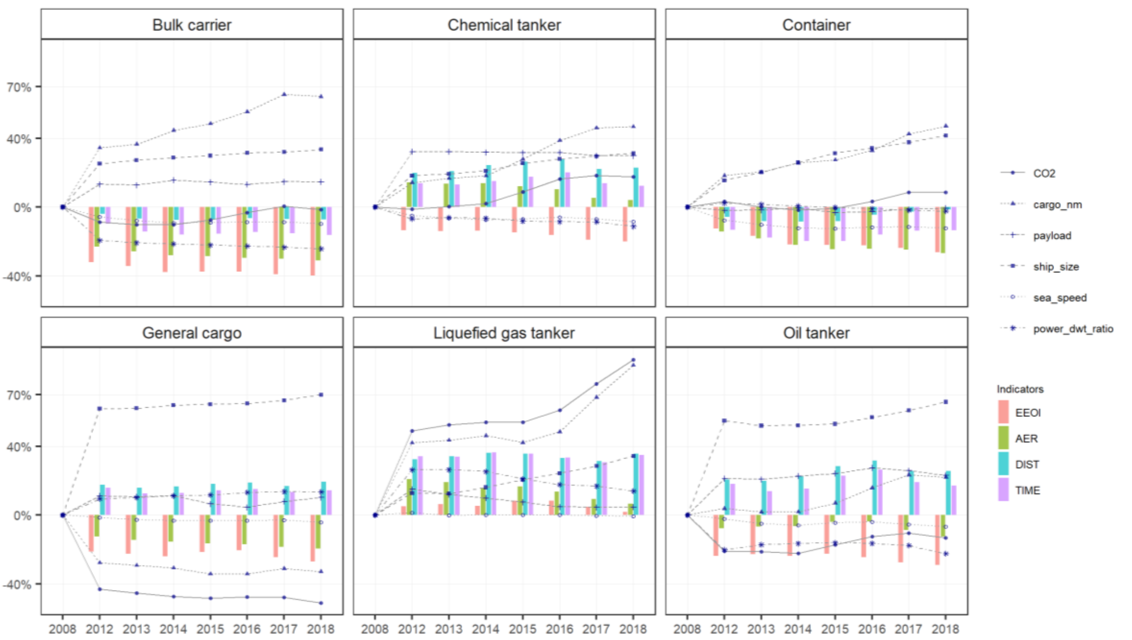
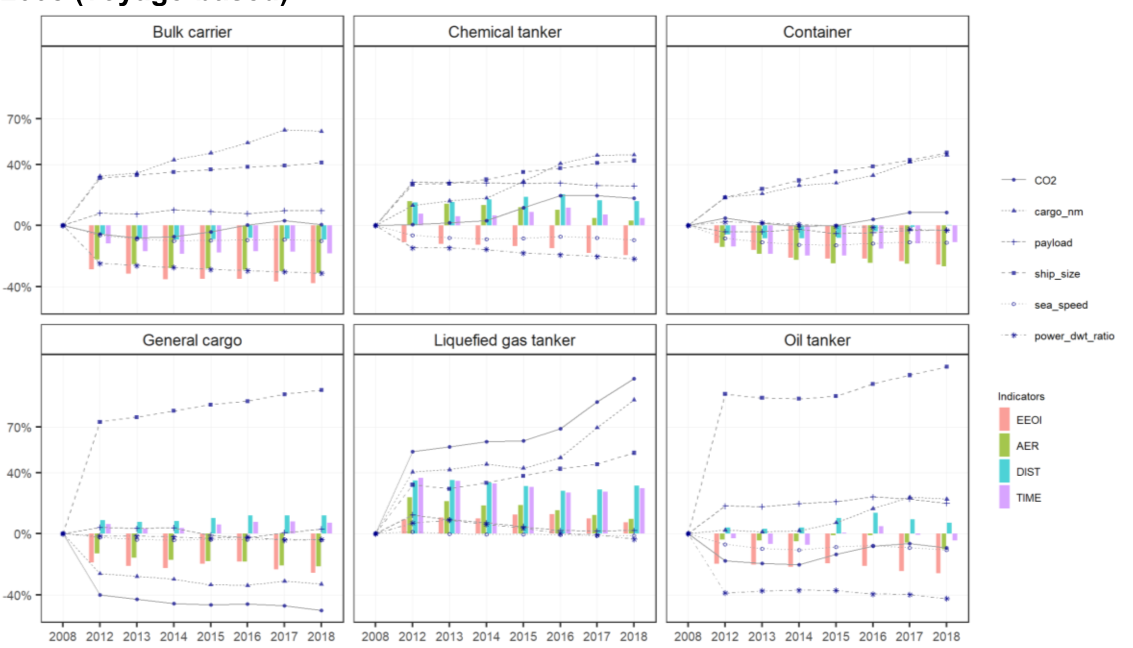


Figure 20 – Percentage changes in overall carbon intensity per ship type indexed at 2008 (voyage-based)



The increasing average ship size had taken a dominant role in carbon intensity reduction in all typical ship types when compared with 2008, yet got less significant when compared with 2012, except for container ships and liquefied gas tankers. In the meanwhile, large improvement in overall design efficiency has been observed in most segments, especially in oil tankers, bulk carriers and chemical tankers. Speed reduction has been another key driver especially for bulk carriers, chemical tankers, container ships and oil tankers since 2008. However, most ship type ceased slowing down further from 2015, due to the improving market situation, decreasing fuel oil price as well as certain technical limitations or concerns. Similarly, payload utilization has been improved more or less for most ship types compared with 2008, but went downwards or fluctuated during 2012-2018. Such volatile trends in speed and payload utilization were largely the lagging consequences of the sluggish recovery from the global financial crisis which started from mid-2008. Another noteworthy finding is that changes in payload utilization showed opposite impacts on the trends in EEOI and AER. This implies that an increase in payload utilization generally leads to a reduction in EEOI, but leads to an increase in AER or compromises its expected reduction magnitude.

Figure 21 and Figure 22 present the trends in individual based carbon intensity per ship type derived from both vessel-based and voyage-based, as well as the changes in drivers for carbon intensity reduction. Such trends are estimated through fitting a series of power law regression curves.

Having not taken the influence of ship size composition shift into account, the individual based carbon intensity reductions in most ship types narrowed down when measured in EEOI or AER. The differences are quite significant in bulk carriers (from 38% to 28%), chemical tankers (from 19% reduction to 4% increase) and oil tankers (from 26% to 8%), yet modest in container ships (from 26% to 20%) and general cargo ships (from 26% to 21%). This implies that the sharp carbon intensity reductions in the former group of ships were largely led by increasing ship size, while in the latter group were mainly achieved by individual design and operational improvement. In this like-to-like comparison, identical trends of AER and DIST can be clearly identified. Having been jointly influenced by increasing ship size and decreasing sea speed, changes in the overall TIME were determined by the one which was dominant, thus showed divergent trends between ship types. Having decoupled from the size factor, however, TIME has showed a decreasing trend in most ship types, with reduction rates even larger than in EEOI. This implies that TIME is much more sensitive to speed reduction than other metrics.

Figure 21 – Percentage changes in individual based carbon intensity per ship type indexed at 2008 (vessel-based)

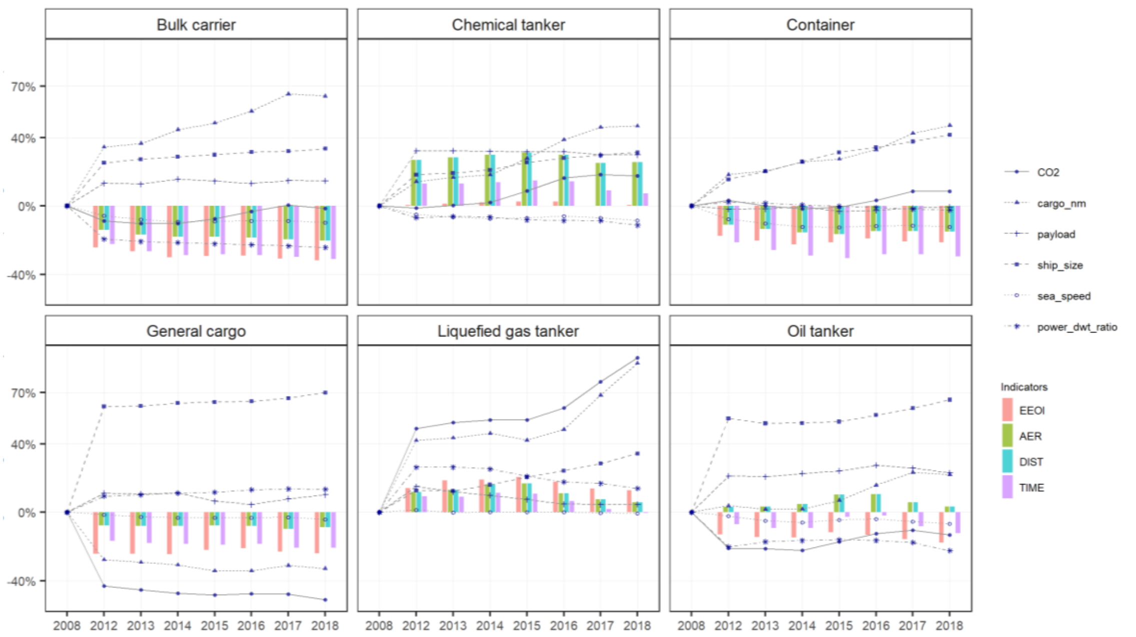
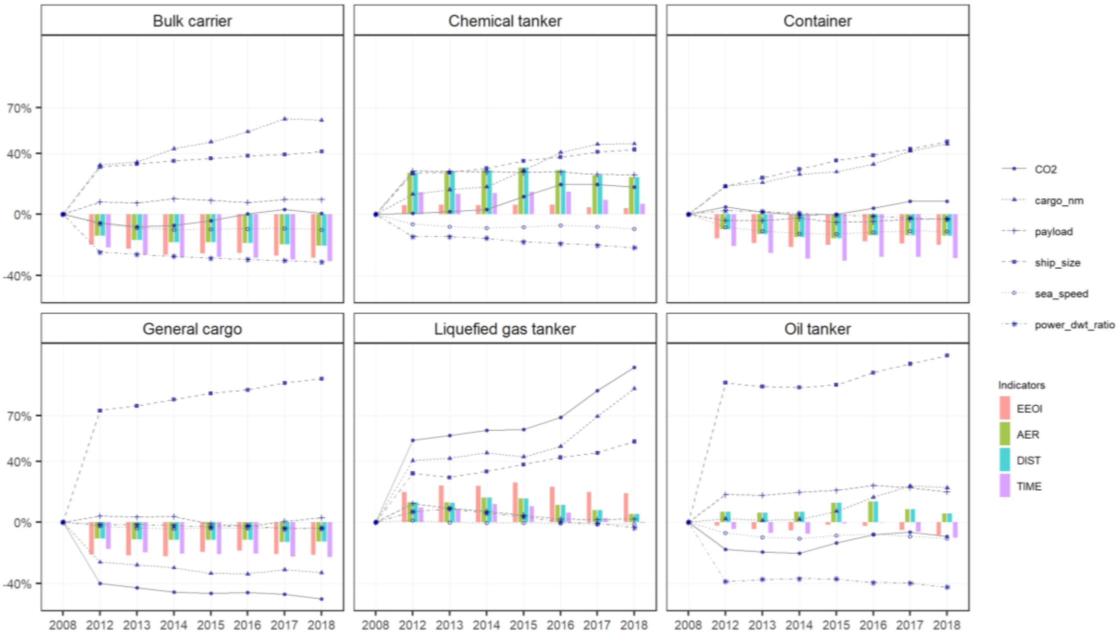


Figure 22 – Percentage changes in individual based carbon intensity per ship type indexed at 2008 (voyage-based)



Large spread scales of metric values have been observed across all ship types and size bins, which are mainly caused by differences in design and operational profiles of individual ships, as well as various external influencing factors. The spread scales in all metrics are generally larger for smaller ships while smaller for larger ships. As per ship types, the largest spread scales of EEOI have been observed in oil tankers, followed by general cargo ships, bulk carriers, liquefied gas tankers and chemical tankers. Spread scales in AER are a little bit smaller than in EEOI due to its immunity to variations in payload utilization. Further to the differences between ship type and size categories, carbon intensity of a specific individual ship also varied over time, due to the various operational and navigational conditions beyond control. The upper and lower quartiles of fluctuation rates in EEOI of oil tankers, bulk carriers and container ships were around ±20%, ±15% and ±10%, respectively. Quartiles of fluctuation rates in other metrics were relatively modest, yet still generally reaching beyond ±5%. Due to certain static assumptions on weather and hull fouling condition, as well as non-timely updated AIS entries on draught, factual fluctuations were possibly more scattered than estimated, especially for container ships.

Uncertainties in carbon intensity estimation partly stem from the inventory estimation and partly from the estimates on transport work. Cross validation with EU MRV data showed that the metric values in EEOI might be underestimated by 10-25% for bulk carriers, container ships, chemical tankers and general cargo ships, while by 50% for liquefied gas tankers.

The discrepancies in oil tankers were less than 5%. Since CO_2 emissions could have been overestimated, the underestimation on EEOI values was likely caused by a larger overestimation on payload utilization. Comparison against the published transport demand in UNCTAD's Review of Maritime Transport (2018) showed that the deviations in estimated cargo ton-miles undertaken by oil tankers, container ships and dry cargo ships (covering bulk, general cargo and refrigerated bulk carriers) were consistently around -2%, 30% and -28% between 2012 and 2018, while the deviations in total cargo ton-miles ranged within ±2%. This was likely caused by the different categorization strategy applied to seaborne trade and to marine transportation. This observation highlights two points: first, the estimates on carbon intensity of international shipping as a whole was more reliable than the results for ship types; second, the estimated trends in carbon intensity performance (in percentage change), which could not be substantially affected by systematically biased estimation in transport work, are more reliable than the absolute metric values. Given the limited data available for validation, subjective rectification such as introducing a series of correction factors to carbon intensity estimates of ship types may incur another uncertainty. Therefore, no corrections have been made to the estimated results. To avoid misleading, however, whenever the estimated carbon intensity levels of ship types are referred to, the possible biasness should be specified jointly.

Scenarios for future shipping emissions

CO_2 emissions of shipping have been projected out to 2050. The method for projecting emissions from shipping in this Study comprises of six steps:

1. Projecting transport work – non-energy products:

   a. Establishing the historical relation between maritime transport work and relevant economic parameters such as world (or country) per capita GDP and population (for transport of non-energy products, such as unitized cargo, chemicals and non-coal dry bulk);

   b. Projecting transport work on the basis of the relations described in (a) and long-term projections of GDP and population (global or by country).

2. Projecting transport work – energy products

   a. Collecting IPCC formal projections of evolution of energy consumption and energy consumption (for transport of energy products like coal, oil and gas).

   b. Projecting transport work using the variation of energy consumption projection when considering seaborne transportation of energy products (coal dry bulk, oil tankers and gas tankers).

3. Making a detailed description of the fleet and its activity in the base year 2018.

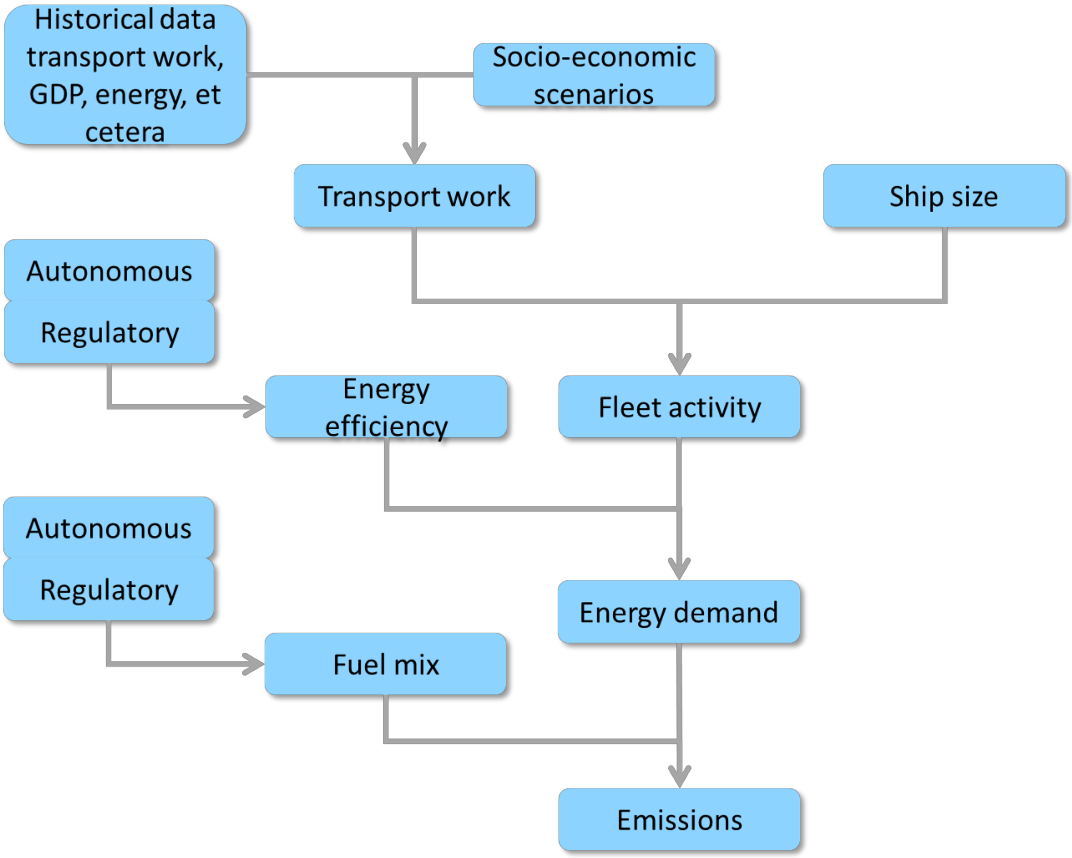
4. Projecting the future fleet composition.

5. Projecting future energy efficiency of the ships, taking into account regulatory developments and market-driven efficiency changes using a marginal abatement cost curve (MACC).

6. Combining the results of steps 4, 5 and 6 above to project shipping emissions.

Figure 23 is a graphical representation of the methodology.

Figure 23 – Graphical representation of methodology to develop emission projections



The transport demand projections depend on three factors:

1 The long-term socio-economic scenario underlying the projection. The higher the projected per capita GDP growth and the population growth, the higher the projected transport work for products that are strongly correlated with economic developments, such as non-coal dry bulk, containerized and other unitized cargoes, and chemicals.

2 The long-term energy scenario. The more fossil fuel is projected to be consumed, the higher transport work of coal dry bulk, oil tankers and gas tankers.

3 The method to establish the relation between transport work and the relevant drivers. This Study has employed two methods for projecting transport work for non-energy products: a logistics analysis which analyses the relation between global transport work and its drivers over the longest period available and projects that relation further using a logistics curve; and a gravitation model analysis, in which bilateral trade flows between countries are analysed to establish the elasticities of trade between those countries and the relevant drivers. We find that typically the logistics approach results in higher transport work projections than the gravitation model approach.

The factors are summarised in Table 5.

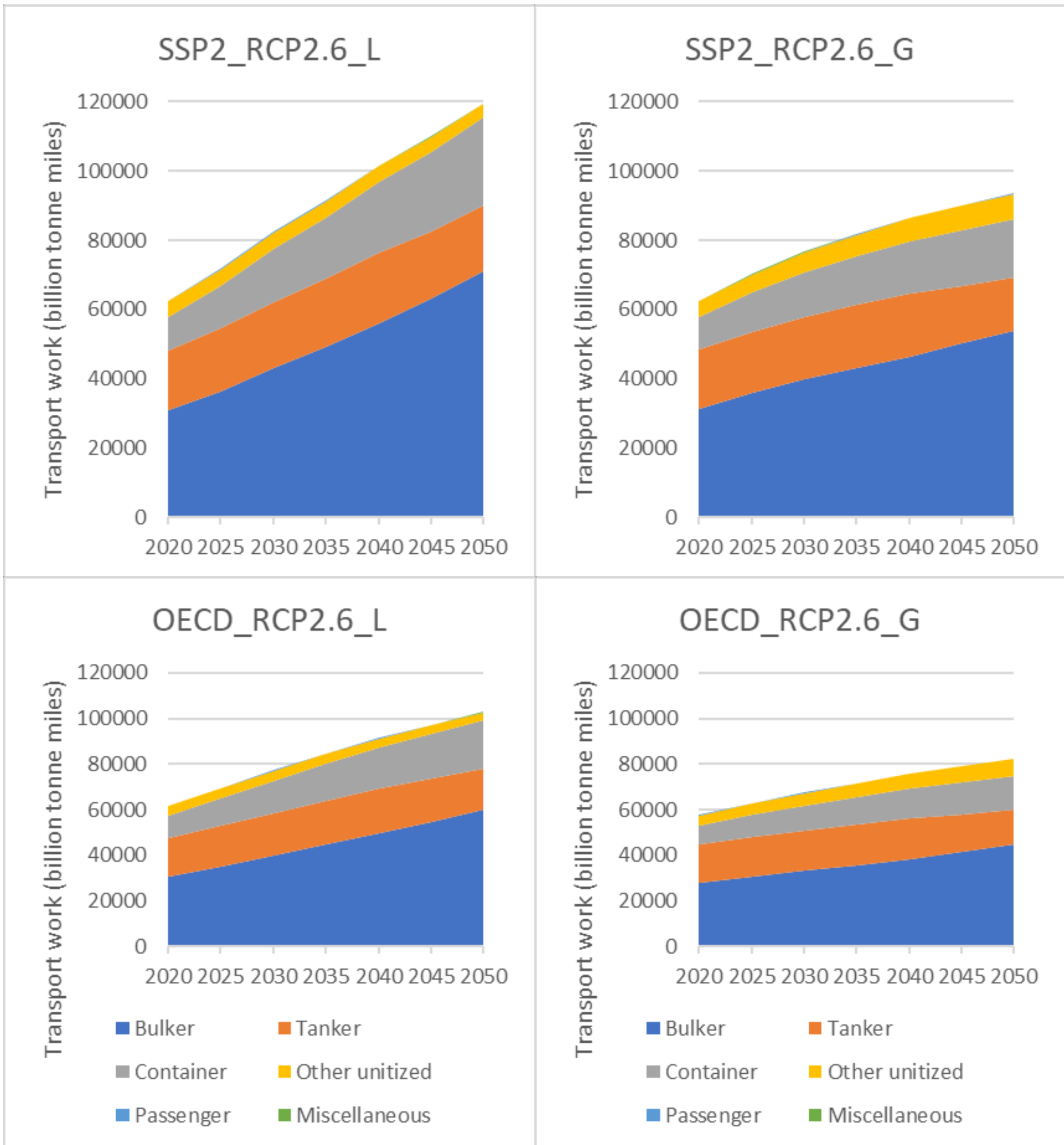
Table 5 – Characteristics of transport work demand projections

Non-coal dry bulk, containers, other unitized cargo, and chemicals (Relation between transport work and relevant drivers: Logistics, denoted by _L; Gravitation model, denoted by _G)	**Coal dry bulk,-oil tankers and gas tankers**
Long-term socio-economic scenarios	**Long-term energy scenarios**
SSP1 (Sustainability – Taking the Green Road)	RCP1.9 (1.5°C) in combination with SSP1, SSP2 and SSP5
SSP2 (Middle of the Road)	RCP2.6 (2°C, very low GHG emissions) in combination with SSP1, SSP2, SSP4 and SSP5
SSP3 (Regional Rivalry – A Rocky Road)	RCP3.4 (extensive carbon removal) in combination with SSP1, SS2, SSP3, SSP4 and SSP5
SSP4 (Inequality – A Road Divided)	RCP4.5 (2.4°C, medium-low mitigation or very low baseline) in combination with SSP1, SS2, SSP3, SSP4 and SSP5
SSP5 (Fossil-fueled Development – Taking the Highway)	RCP6.0 (2.8°Cmedium baseline, high mitigation in combination with SSP1, SS2, SSP3, SSP4 and SSP5
OECD long-term baseline projections	

Source: (Van Vuuren, et al., 2011b), (Riahi, et al., 2017) Making sense of climate change scenarios: Senses Toolkit

In scenarios with an aggregate economic growth in line with SSP 2 and OECD baseline projections and energy demand from land-based sectors that just about limits the global temperature increase to well below 2 degrees centigrade (RCP 2.6), aggregate transport work increases by 40-100%. In general, projections using a logistics analysis exhibit higher growth rates (75-100%) than projections using a gravitation model approach (40-60%). Scenarios that have higher aggregate income and size growth see a larger increase in transport work (see Figure 24).

Figure 24 – Transport work projections (billion tonne miles)



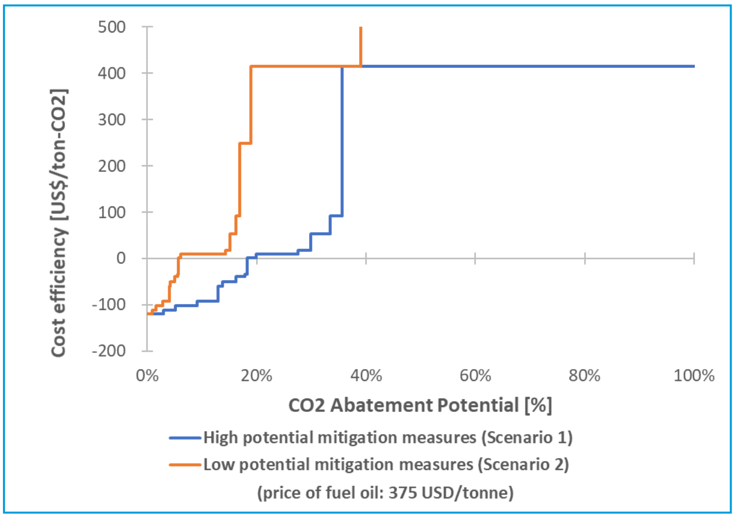
Updated marginal abatement cost curves

There are many ways to improve the energy efficiency or carbon intensity of shipping. This report has assessed the abatement potential and costs of 44 technologies in four groups: energy-saving technologies; use of renewable energy; use of alternative fuels; and speed reduction.

Applying all the potential mitigation measures selected to all newly built ships from 2025, CO_2 emissions reduction in 2050 can achieve both the mid-term and long-term levels of ambition specified in the *Initial IMO Strategy on Reduction of GHG Emissions from Ships*.

In 2050, about 64% of the total amount of CO_2 reduction is contributed to by use of alternative fuels. The marginal abatement cost curve (MACC) depends to a large extent on the projected prices of zero-carbon fuels.

Figure 25 – Marginal abatement cost curve for 2050

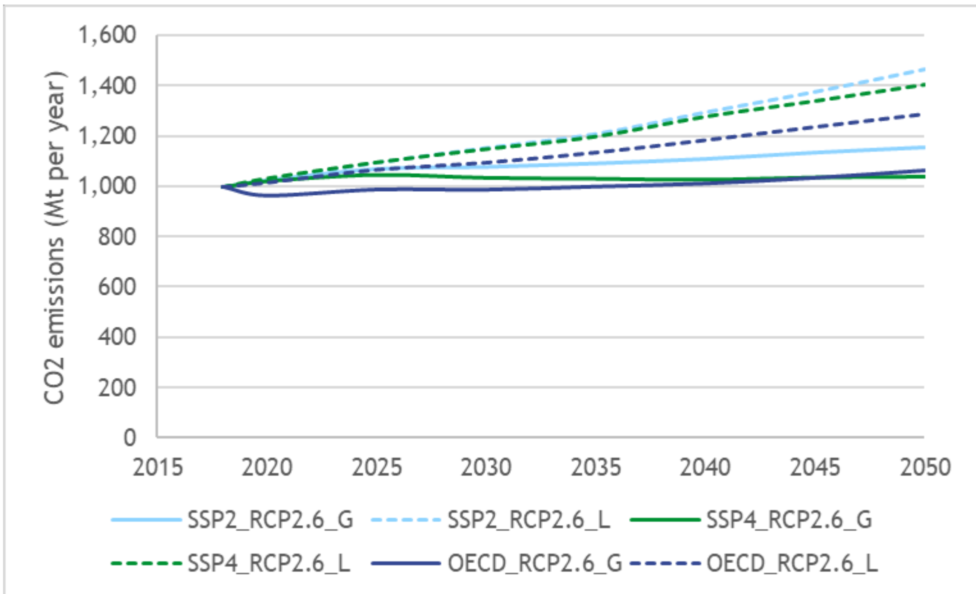


Emission projections

All the projections are so-called business as usual (BAU) projections. In the context of this Study, BAU refers to the shipping sector and is defined as "no adoption of new regulations that have an impact on energy efficiency or carbon intensity". As noted above, the projections are based on long-term socio-economic pathways and representative concentration pathways of the IPCC. Some of these pathways assume that non-shipping sectors undergo transitions that require policies like carbon prices or energy-efficiency regulations. These are still considered to be BAU scenarios in the context of this Study.

Figure 26 shows the BAU scenarios for three long-term scenarios in which the energy mix of land-based sectors would limit the global temperature increase to well below 2 degrees centigrade (Van Vuuren, et al., 2011a) and which have GDP growth projections from the OECD or from the IPCC that are in line with recent projections from the OECD. In these BAU scenarios, the emissions of shipping are projected to increase from 1,000 Mt CO_2 in 2018 to 1,000 to 1,500 Mt CO_2 in 2050. This represents an increase of 0 to 50% over 2018 levels and is equal to 90-130% of 2008 levels.

Figure 26 – BAU scenarios GDP growth in line with recent projections, energy transition in line with 2 degrees target



The differences in the BAU emission projections are caused by differences in transport-work projections which, in turn, are caused by differences in socio-economic projections and different methods to establish the relation between transport work and independent variables like per capita GDP, population and primary energy demand.

The emissions in Figure 26 are for total shipping. It is expected that the share of domestic and international emissions will not change.

Although it is too early to assess the impact of COVID-19 on emission projections quantitatively, it is clear that the emissions in 2020 and 2021 will be significantly lower. Depending on the recovery, the emissions in the next decades may be a few percent lower than projected, at most. In all, the impact of COVID-19 is likely to be smaller than the uncertainty range of the presented scenarios.

***

ANNEX 2

Fourth IMO GHG Study

Final Report

Fourth IMO GHG Study

Final Report

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Abbreviations and definitions

Term	Explanation
AB	Auxiliary Boiler
AE	Auxiliary Engine
AER	Annual Efficiency Ratio in gram CO_2/Dwt/nm)
AFFF	Aqueous Film Forming Foam
AIS	Automatic Identification System
ALB	Available Lower Berth
BAU	Business As Usual
BC	Black Carbon
BOG	Boil Off Gas
BU	Bottom-Up
CAPEX	Capital Expenditures
CBM	Cubic Metre
CCS	Carbon Capture and Storage
cDIST	Cargo-distance, an efficiency metric similar to the AER in which the capacity can be expressed in TEU, cubic metre or other relevant parameters appropriate for certain ship types, in gram CO_2/capacity/nm
CF	Correction Factor
CH4	Methane
CII	Carbon Intensity Indicator
CMD	continuous Monitoring Dataset
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
DIST	CO_2 emissions per distance travelled, in kilogram CO_2/nautical mile
DWT	Deadweight Tonnage
EC	European Commission
ECA	Emission Control Area
EEA	European Environment Agency
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator in gram CO_2/tonne cargo/nm
EEPI	Energy Efficiency Performance Indicator
EFe	Energy-Based Emission Factors
EFf	Fuel-Based Emission Factors
EGR	Exhaust Gas Recirculation
EIV	Estimated Index Value
EU MRV	EU Monitoring, Reporting and Verification of CO_2 emissions
FOC	Fuel Oil Consumption
FSN	Filter Smoke Number
GDP	Gross Domestic Product
GFW	Global Fishing Watch
GHG	Greenhouse Gas
GPS	Global Positioning System
GT	Gross Tonnes
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon

Term	Explanation
HFO	Heavy Fuel Oil
HSD	High-Speed Diesel
ICE	Internal Combustion Engine
IEA	International Energy Agency
IHS	Information Handling Services
IHSF	IHS Fairplay (a data provider)
IMO	International Maritime Organization
IMO DCS	IMO Data collection system
IMO3	Third IMO GHG Study 2014
IMO4	Fourth IMO GHG Study (this study)
IPCC	Intergovernmental Panel on Climate Change
kt	Kilo Tonnes
ktoe	Kilo Tonnes of Oil Equivalent
kW	Kilo Watt
kWh	Kilo Watt-hour
LBSI	Lean Burn Spark-Ignited
LLF	Low Load Factor
LNG	Liquid Natural Gas
LPG	Liquefied Petroleum Gas
LSHFO	Low Sulfur Heavy Fuel Oil
MACC	Marginal Abatement Cost Curve
MAE	Mean Absolute Error
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
ME	Main Engine
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MMSI	Maritime Mobile Service Identity
MS	Medium-Speed
MSD	Medium-Speed Diesel
N2O	Nitrous Oxide
NECA	NOx Emission Control Area
NF3	Nitrogen Trifluoride
NG	Natural Gas
nm	Nautical Mile
NMVOC	Non-Methane Volatile Organic Compounds
NOx	Nitrogen Oxides
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
OPEX	Operational Expenditures
pax	Passengers
PFC	Perfluorocarbon
PM	Particulate matter
QA	Quality Assurance
QC	Quality Control
RCP	Representative Concentration Pathway
ro-pax	Roll-On/Roll-Off/Passengers
Ro-Ro	Roll-On/Roll-Off
RPM	Revolutions Per Minute

Term	Explanation
SCR	Selective Catalytic Reduction
SECA	SOx Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
SF6	Sulfur Hexafluoride
SFC	Specific Fuel Consumption
SOG	Speed Over Ground
SOLAS convention	International Convention for the Safety of Life at Sea
SOx	Sulfur Oxides
SS	Slow-Speed
SSD	Slow-Speed Diesel
SSP	Shared Socio-Economic Pathway
STEAM	Ship Traffic Emission Assessment Model
TEU	Twenty-foot Equivalent Units
TIME	CO_2 emissions per hour underway, in tonne CO_2/hour
UMAS	University Maritime Advisory Services
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
UNSD	United Nations Statistics Division
USD	US Dollar
VBP	Vessel Boarding Program
VLSFO	Very Low Sulphur Fuel Oil
VOC	Volatile Organic Compounds
WERS	Waste Energy Recovery Systems
WHB	Waste Heat Boiler
WTO	World Trade Organization

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Highlights

Emissions inventory

- The greenhouse gas (GHG) emissions — including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), expressed in CO_2e — of total shipping (international, domestic and fishing) have increased from 977 million tonnes in 2012 to 1,076 million tonnes in 2018 (9.6% increase). In 2012, 962 million tonnes were CO_2 emissions, while in 2018 this amount grew 9.3% to 1,056 million tonnes of CO_2 emissions
- The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018.
- Under a new voyage-based allocation of international shipping, CO_2 emissions have also increased over this same period from 701 million tonnes in 2012 to 740 million tonnes in 2018 (5.6% increase), but to a lower growth rate than total shipping emissions, and represent an approximately constant share of global CO_2 emissions over this period (approximately 2%), as shown in Table 1. Using the vessel-based allocation of international shipping taken from the Third IMO GHG Study, CO_2 emissions have increased over the period from 848 million tonnes in 2012 to 919 million tonnes in 2018 (8.4% increase).
- Due to developments in data and inventory methods, this study is the first IMO GHG Study able to produce greenhouse gas inventories that distinguish domestic shipping from international emissions on a voyage basis in a way which, according to the consortium, is exactly consistent with the IPCC guidelines and definitions.[1]
- Projecting the same method to 2008 emissions, this study estimates that 2008 international shipping GHG emissions (in CO_2e) were 794 million tonnes (employing the method used in the Third IMO GHG Study, the emissions were 940 million tonnes CO_2e).

Table 1 - Total shipping and voyage-based and vessel-based international shipping CO_2 emissions 2012-2018 (million tonnes)

Year	Global anthropogenic CO_2 emissions	Total shipping CO_2	Total shipping as a percentage of global	Voyage-based International shipping CO_2	Voyage-based International shipping as a percentage of global	Vessel-based International shipping CO_2	Vessel-based International shipping as a percentage of global
2012	34,793	962	2.76%	701	2.01%	848	2.44%
2013	34,959	957	2.74%	684	1.96%	837	2.39%
2014	35,225	964	2.74%	681	1.93%	846	2.37%
2015	35,239	991	2.81%	700	1.99%	859	2.44%
2016	35,380	1,026	2.90%	727	2.05%	894	2.53%
2017	35,810	1,064	2.97%	746	2.08%	929	2.59%
2018	36,573	1,056	2.89%	740	2.02%	919	2.51%

[1] The choice of the method to distinguish domestic shipping emissions from international shipping emissions does not interpret existing IMO instruments, nor prejudge any future policy developments at IMO and would not constitute IMO's views on the interpretation of the 2006 IPCC Guidelines on national greenhouse gas inventories.

Carbon intensity 2008, 2012 - 2018

Table 2 - Estimates on carbon intensity of international shipping and percentage changes compared to 2008 values

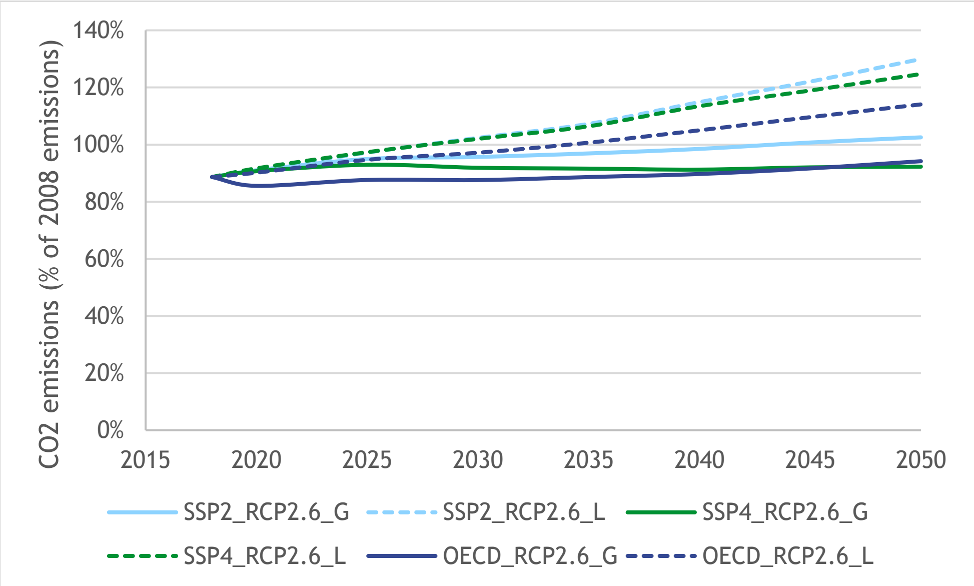
Year	EEOI ($gCO_2/t/nm$)				AER ($gCO_2/dwt/nm$)				DIST ($kgCO_2/nm$)				TIME (tCO_2/hr)			
	Vessel-based		Voyage-based		Vessel-based		Voyage-based		Vessel-based		Voyage-based		Vessel-based		Voyage-based	
	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change	Value	Change
2008	17.10	–	15.16	–	8.08	–	7.40	–	306.46	–	350.36	–	3.64	–	4.38	–
2012	13.16	-23.1%	12.19	-19.6%	7.06	-12.7%	6.61	-10.7%	362.65	18.3%	387.01	10.5%	4.32	18.6%	4.74	8.1%
2013	12.87	-24.7%	11.83	-22.0%	6.89	-14.8%	6.40	-13.5%	357.73	16.7%	380.68	8.7%	4.18	14.6%	4.57	4.1%
2014	12.34	-27.9%	11.29	-25.6%	6.71	-16.9%	6.20	-16.1%	360.44	17.6%	382.09	9.1%	4.17	14.4%	4.54	3.5%
2015	12.33	-27.9%	11.30	-25.5%	6.64	-17.8%	6.15	-16.9%	366.56	19.6%	388.62	10.9%	4.25	16.6%	4.64	5.7%
2016	12.22	-28.6%	11.21	-26.1%	6.58	-18.6%	6.09	-17.7%	373.46	21.9%	397.05	13.3%	4.35	19.3%	4.77	8.7%
2017	11.87	-30.6%	10.88	-28.2%	6.43	-20.4%	5.96	-19.5%	370.97	21.0%	399.38	14.0%	4.31	18.2%	4.79	9.2%
2018	11.67	-31.8%	10.70	-29.4%	6.31	-22.0%	5.84	-21.0%	376.81	23.0%	401.91	14.7%	4.34	19.1%	4.79	9.2%

- Carbon intensity has improved between 2012 and 2018 for international shipping as a whole, as well as for most ship types. The overall carbon intensity, as an average across international shipping, was 21 and 29% better than in 2008, measured in AER and EEOI respectively in the voyage-based allocation; while it was 22 respectively 32% better in the vessel-based allocation (Table 2). Improvements in carbon intensity of international shipping have not followed a linear pathway and more than half have been achieved before 2012. The pace of carbon intensity reduction has slowed since 2015, with average annual percentage changes ranging from 1 to 2%.
- Annual carbon intensity performance of individual ships fluctuated over years. The upper and lower quartiles of fluctuation rates in EEOI of oil tankers, bulk carriers and container ships were around ±20%, ±15% and ±10% respectively. Quartiles of fluctuation rates in other metrics were relatively modest, yet still generally reaching beyond ±5%. Due to certain static assumptions on weather and hull fouling conditions, as well as the non-timely updated AIS entries on draught, factual fluctuations were possibly more scattered than estimated, especially for container ships.

Emission projections 2018 - 2050

- Emissions are projected to increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios (Figure 1).
- Emissions could be higher (lower) than projected when economic growth rates are higher (lower) than assumed here or when the reduction in GHG emissions from land-based sectors is less (more) than would be required to limit the global temperature increase to well below 2 degrees centigrade.
- Although it is too early to assess the impact of Covid-19 on emission projections quantitatively, it is clear that emissions in 2020 and 2021 will be significantly lower. Depending on the recovery trajectory, emissions over the next decades may be a few percent lower than projected, at most. In all, the impact of Covid-19 is likely to be smaller than the uncertainty range of the presented scenarios.

Figure 1 - Projections of maritime ship emissions as a percentage of 2008 emissions



Executive summary

Inventory of GHG Emissions from International Shipping 2012-2018

Figure 2 - international shipping emissions and trade metrics, indexed in 2008, for the period 1990-2018, according to the voyage-based allocation[2] of international emissions[3].

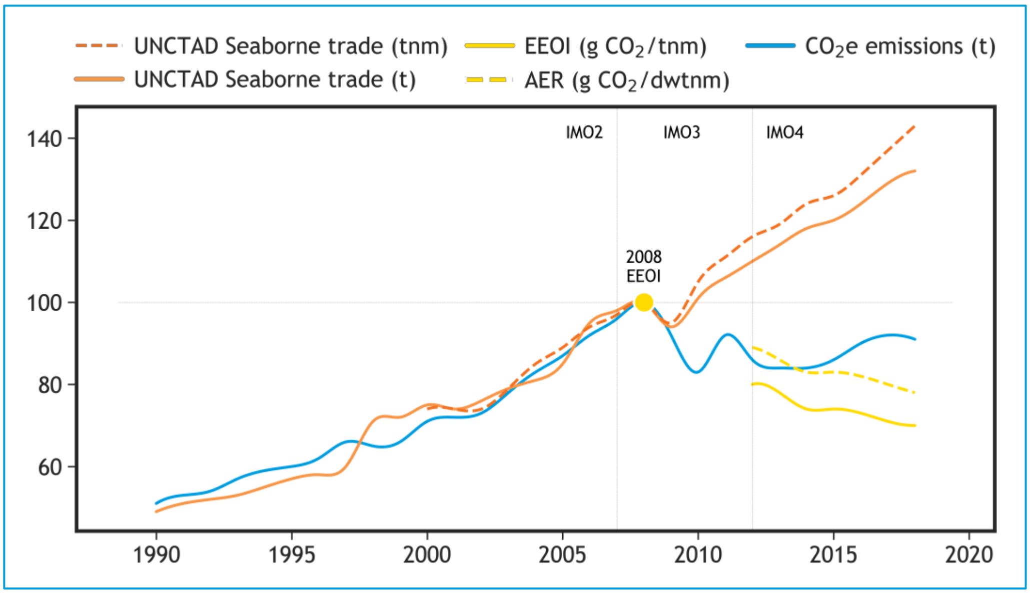


Figure 2 presents emissions, trade and carbon intensity trends as estimated across this study and the two previous IMO GHG studies. Against a long-run backdrop of steadily increasing demand for shipping (growth in seaborne trade), the three studies approximately align with three discrete periods for international shipping's GHG emissions:

1. 1990 to 2008 –emissions growth (CO_2e), and emissions tightly coupled to growth in seaborne trade (UNCTAD).
2. 2008 to 2014 –emissions reduction (CO_2e) in spite of growth in demand (UNCTAD), and therefore a period of rapid carbon intensity reduction (EEOI and AER) that enabled decoupling of emissions from growth in transport demand.
3. 2014 to 2018 — a period of continued but more moderate improvement in carbon intensity (EEOI and AER), but at a rate slower than the growth in demand (UNCTAD). And therefore, a return to a trend of growth in emissions (CO_2e).

This study is the first IMO GHG Study able to produce GHG Inventories that distinguish domestic shipping from international emissions, following a method that is exactly consistent with the IPCC guidelines and definitions in the view of the consortium. The method is enabled by advances in the use of AIS data to identify port calls which allows allocation of discrete voyages to a definition of either international or domestic shipping. The improved split is

2 Voyage-based allocation defines international emissions as those which occurred on a voyage between two ports in different countries, whereas the alternative 'vessel-based' allocation defines emissions according to ship types, as per the Third GHG Study 2014.

3 Vessel-based allocation of international emissions produces the same trends but different absolute values.

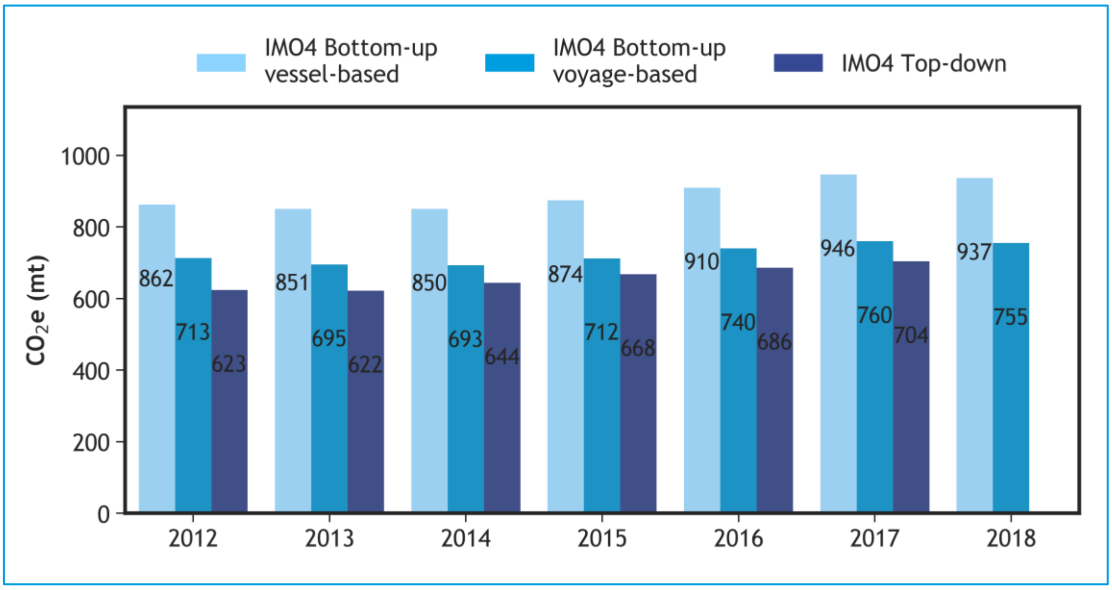
reliable and provides a valuable advancement to the accurate assessment of international shipping's emissions, in line with the instruction of the study's Terms of Reference:

> "…The Fourth IMO GHG Study should further develop clear and unambiguous definitions and refine methods for differentiation between domestic and international voyages with the aim to exclude domestic voyage from the inventory for "international shipping"".

The Third IMO GHG Study used a different method for distinguishing the international and domestic GHG inventories, instead using the ship type and size characteristics to group ships which were assumed to be operating either as domestic or international shipping. This method relies on assumptions and uniform behaviour within fleets of similar ship types and size, which this study's more detailed analysis shows to have shortcomings. However, in order to enable comparison with the Third IMO GHG Study and continued use to understand trends, wherever possible the results from both of these methods are included. The method as used in the Third IMO GHG Study is referred to as vessel-based (Option 1), the new method is referred to as voyage-based (Option 2).

For the avoidance of doubt, where results for international shipping using only one method are presented, this choice is not interpreting existing IMO instruments, does not prejudge any future policy developments at IMO and does not constitute IMO's views on the interpretation of the 2006 IPCC Guidelines on national greenhouse gas inventories.

Figure 3 – Annual greenhouse gas emissions (in CO_2e) for international shipping, according to the vessel-based and voyage-based allocation of international emissions (excluding black carbon (BC) emissions). Both the bottom-up emissions estimates, using ship activity data, as well as the top-down emissions estimates, using fuel sales statistics, are shown.



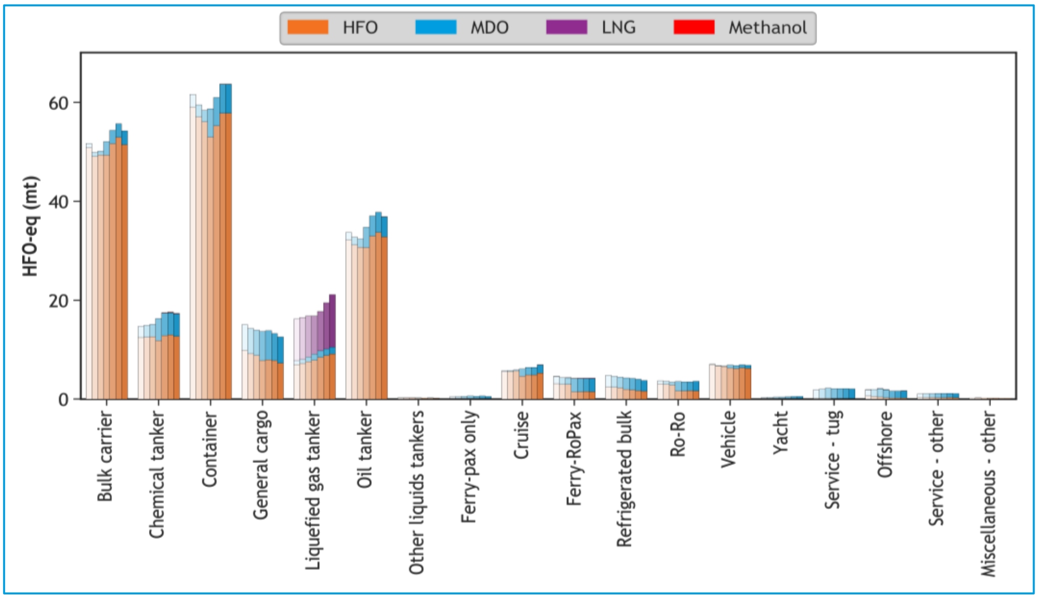
Source: UMAS.

Figure 3 (all GHG emissions in CO_2e, excluding black carbon (BC)) presents the detailed results for the inventory of international shipping emissions for the period of this study (2012-2018), considering the CO_2e impact of N_2O and CH_4. Over the period, bottom-up international shipping CO_2-equivalent emissions increased by 5.7 and 8.3% by voyage-based and vessel-based allocation respectively[4]. Including BC, represented with a global warming potential (GWP) of 900, the voyage-based international GHG emissions for shipping in 2018 would be 7% higher, totalling 810 million tonnes CO_2e.

Consistent with the Third IMO GHG Study, CO_2 remains the dominant source of shipping's climate impact when calculated on a GWP-100 year basis, accounting for 98%, or 91% if BC is included, of total international GHG emissions (in CO_2e).

Insights into the composition and drivers for these high-level results and aggregate trends can be formed from the disaggregated data. To simplify presentation, only the voyage-based allocation of international shipping is used here. The vessel-based allocation produces the same insights, albeit with small differences in absolute values. Figure 4 presents the estimated fuel consumption break down across ship types, for each year 2012-2018. Over the period of study, three ship types remain the dominant source of international shipping's GHG emissions: container shipping, bulk carriers and oil tankers. In combination with chemical tankers, general cargo ships and liquefied gas tankers, these ship types constitute 86.5% of international shipping's total emissions when calculated on a voyage-based allocation.
Heavy fuel oil (HFO) remains the dominant fuel in international shipping (79% of total fuel consumption by energy content in 2018, by voyage-based allocation). However, during the period of the study, a significant change in the fuel mix has occurred. The proportion of HFO consumption has reduced by approximately 7% (an absolute reduction of 3%), whilst the share of marine diesel oil (MDO) and liquid nitrogen gas (LNG) consumption grew by 6 and 0.9% (absolute increases of 51 and 26% respectively). Methanol's use as a fuel developed during this period and is estimated as the fourth most significant fuel used growing to approximately 130,000 tonnes of consumption in 2018 on voyage-based international routes (160,000 tonnes of total consumption).

Figure 4 - International HFO-equivalent fuel consumption per ship type, according to the voyage-based allocation of international emissions

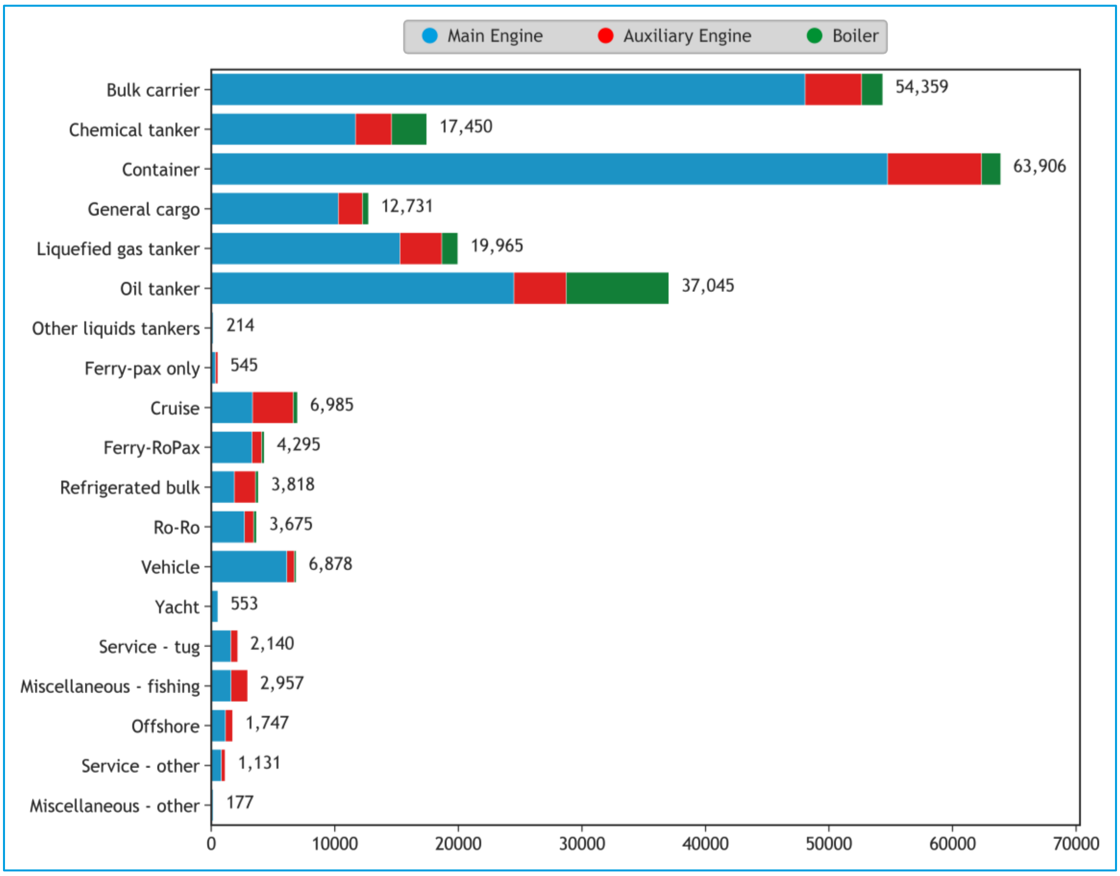


4 Voyage-based allocation defines international emissions as those which occurred on a voyage between two ports in different countries, whereas the alternative 'vessel-based' allocation defines emissions according to ship types, as per the Third GHG Study 2014.

Figure 5 presents the estimated fuel consumption across onboard machinery with broadly different end uses (main engines — propulsion, auxiliary engines — electrical power and boilers — heat). The results are similar to equivalent estimations in earlier GHG studies.

Consistent with the Third IMO GHG Study, energy use for propulsion remains the primary demand for energy across all ship types, albeit that for some ship types (cruise ships, refrigerated bulk and miscellaneous fishing) total propulsion energy demand is approximately equivalent to total auxiliary and heat energy demand.

Figure 5 - International, voyage-based allocation, HFO-equivalent fuel consumption (thousand tonnes), 2018,



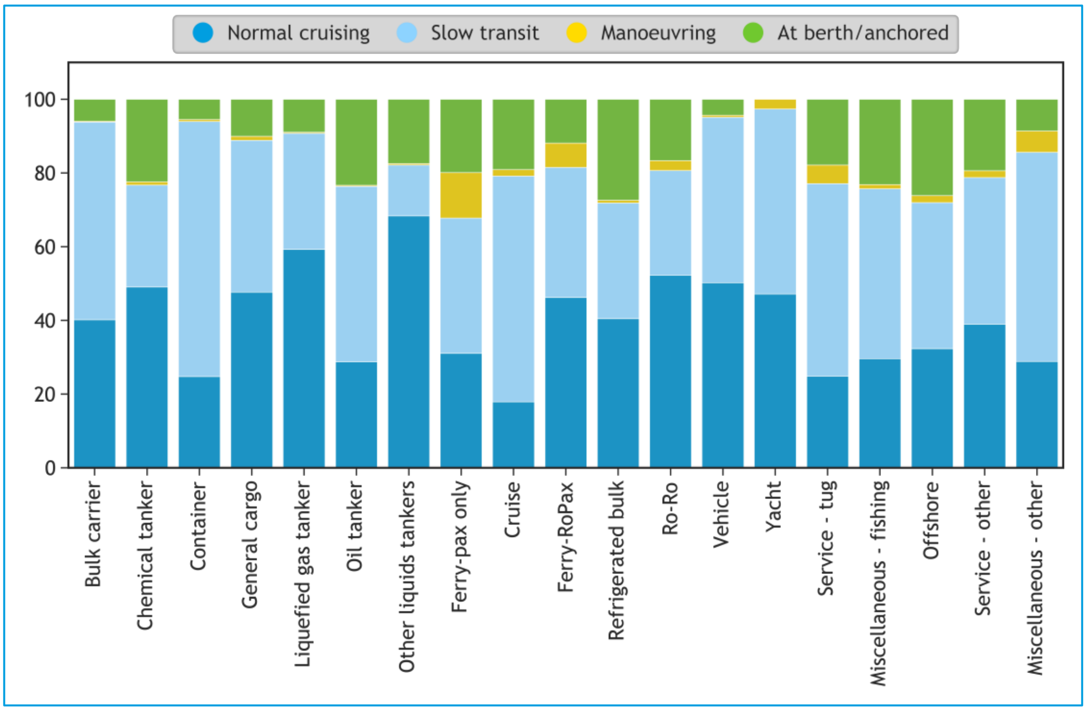
split by main engine, auxiliary engine and boiler. Highlighted values are in thousand tonnes

Source: UMAS.

Figure 6 presents the breakdown of GHG emissions across different phases of operation for each ship type. Depending on the ship type, there are differences in the share of emissions that occur at sea on passage, as opposed to during a manoeuvring, anchorage or berthed phase of operation. Of the six ship types most important to the emissions inventories, chemical tankers and oil tankers have on average the largest portion of their total emissions (greater than 20%) associated with phases at or near the port or terminal.

Container ships, cruise ships and oil tankers have the smallest share of their total emissions associated with cruising (definition) due to dominance of time spent slow cruising and/or phases at or near port, with liquefied gas tankers and other liquids tankers showing the largest share of their emissions associated with cruising.

Figure 6 - Proportion of international GHG emissions (in CO_2e) by operational phase in 2018, according to the voyage-based allocation of emissions. Operational phases are assigned based on the vessel's speed over ground, distance from coast/port and main engine load (see Table 16).



Source: UMAS.

Explanations for some of the trends observed over the period can be obtained from the underlying information used to produce the emissions inventories. Figure 7 presents the breakdown of a number of parameters that can further explain the results, and Figure 8 shows trends in average operating speed across the three ship types that dominate the inventory of international shipping emissions (size bins as defined in Section 2.2.1).

Trends also observed in the Third IMO GHG Study have continued. Average ship sizes across these three ship types have increased, as has the average installed power. For each of these three ship types, the average ship's fuel consumption has increased over the period, but at a lower rate than the increase in average installed power. This decoupling in the rate of increase in installed power and fuel consumption is the consequence of a general trend of continued reduction in operating speeds (also observed in the Third IMO GHG Study), and continued reductions in the average number of days at sea.

The reduction in operating speeds was not a constant decline for all ship types over the period, with oil tankers and containers seeing increases in average speeds during 2015 and 2016 relative to other years during the period of study. For some of the ship size categories, the increase in speed was temporary and by 2018 average speeds were similar to minimum values over the period. Across the period of the study, 2015 and 2016 account for the highest rate of total CO_2 emissions growth. This shows that operating speeds remain a key driver of trends in emissions and rate of emissions growth, and are currently susceptible to fluctuating market forces and behaviour trends (e.g. they are not fixed or constrained by the technical or design specifications of the fleet).

This study's results of continuations of these trends suggest that there has been a further reduction of productivity of the fleet in this period. This in turn means that in 2018, relative to 2012, there is an increased risk of a rapid increase in emissions should the latent emissions in the fleet be realised. This builds further upon a similar finding from the Third IMO GHG Study which noted that the fleet in 2012:

> "…is currently at or near the historic low in terms of productivity (transport work per unit of capacity)…" and that "…these (and many other) sectors of the shipping industry represent latent emissions increases, because the fundamentals (number of ships in service) have seen upwards trends that have been offset as economic pressures act to reduce productivity (which in turn reduces emissions intensity)".

As concluded in the Third IMO GHG Study whether and when the latent emissions increase appears is uncertain and depends on the future market dynamics of the industry. Under certain market conditions, operating speeds could increase again and the associated increases in average fuel consumption and emissions in 2015 and 2016 could return. If their return is sustained, some or all of the reductions in carbon intensity achieved to date can be reversed.

Figure 7 - Trends for average ships for the three most high emitting fleets over the period 2012 to 2018, where fuel consumption represents international activity according to voyage-based allocation

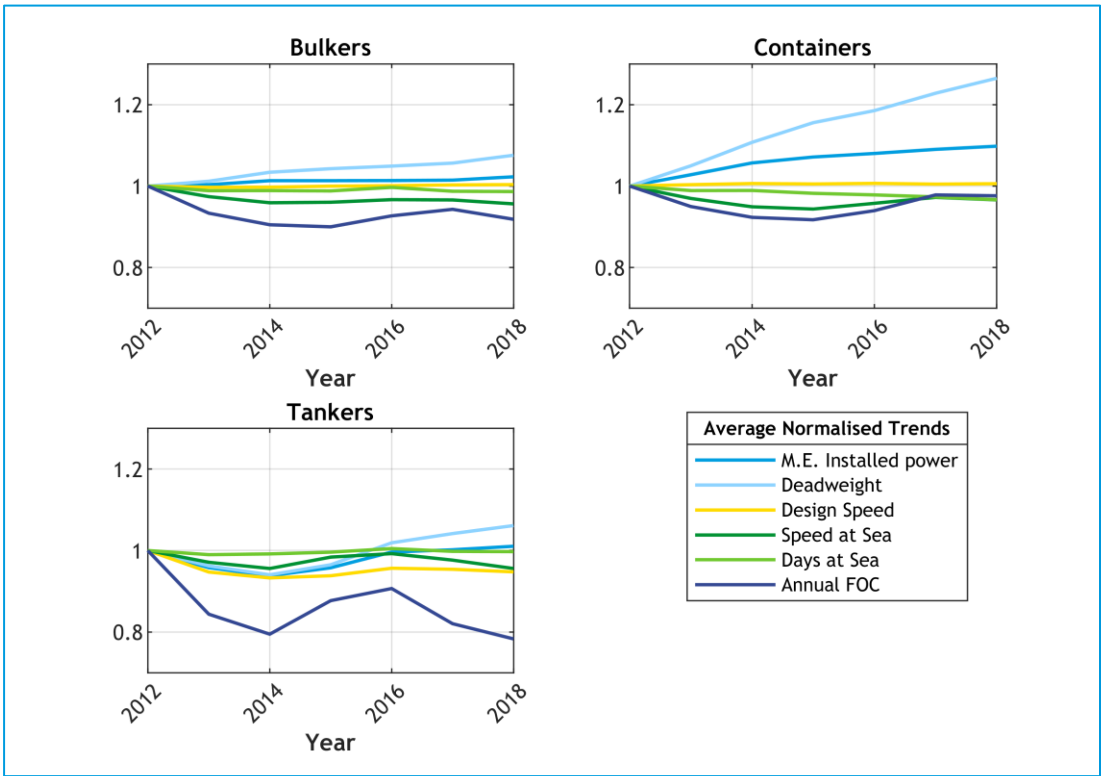
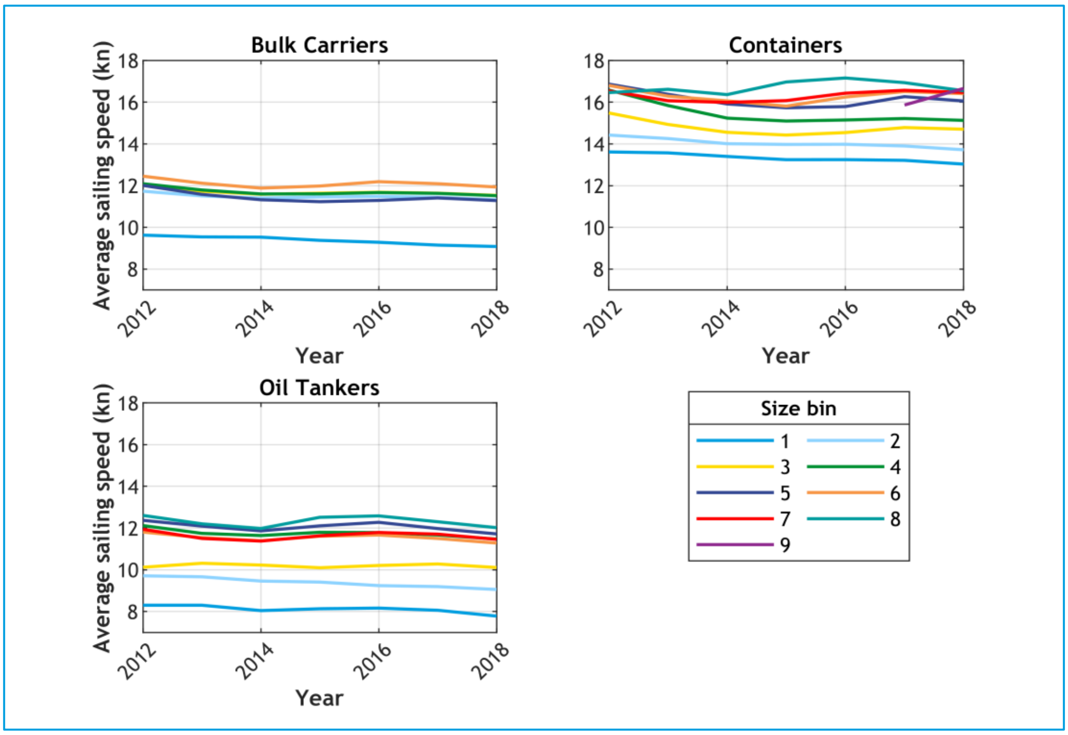


Figure 8 - Speed trends for the three highest emitting fleets aggregated (top left) and broken down for each ship type's size categories, which can be found in Section 2.2.1



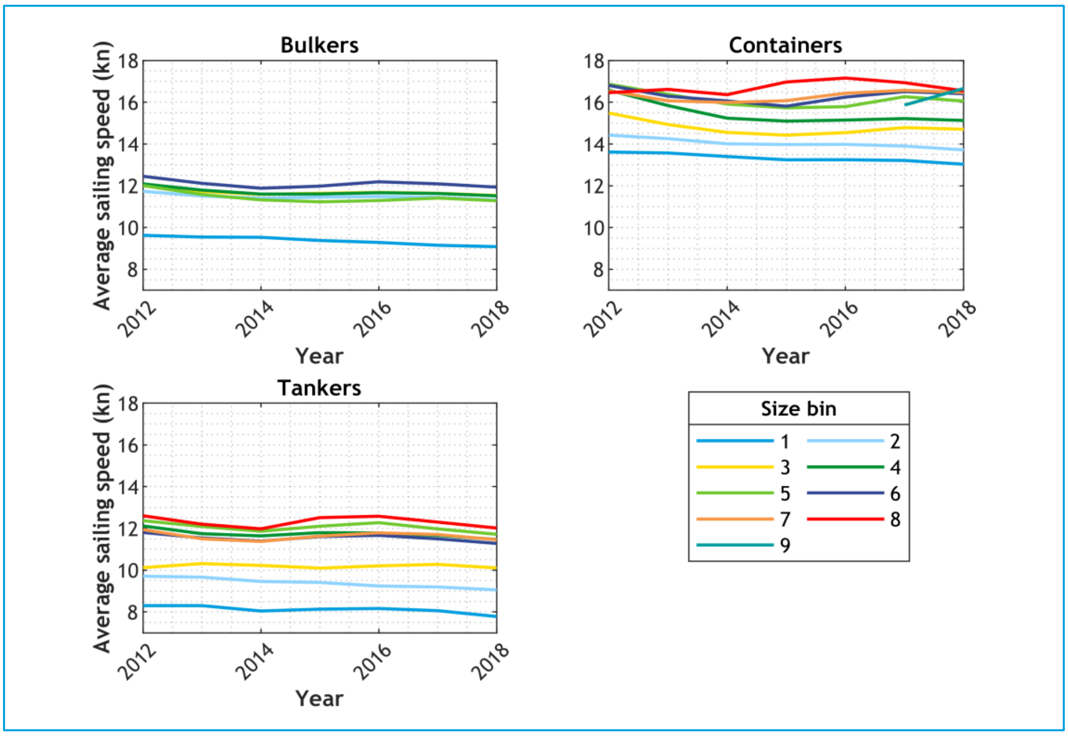
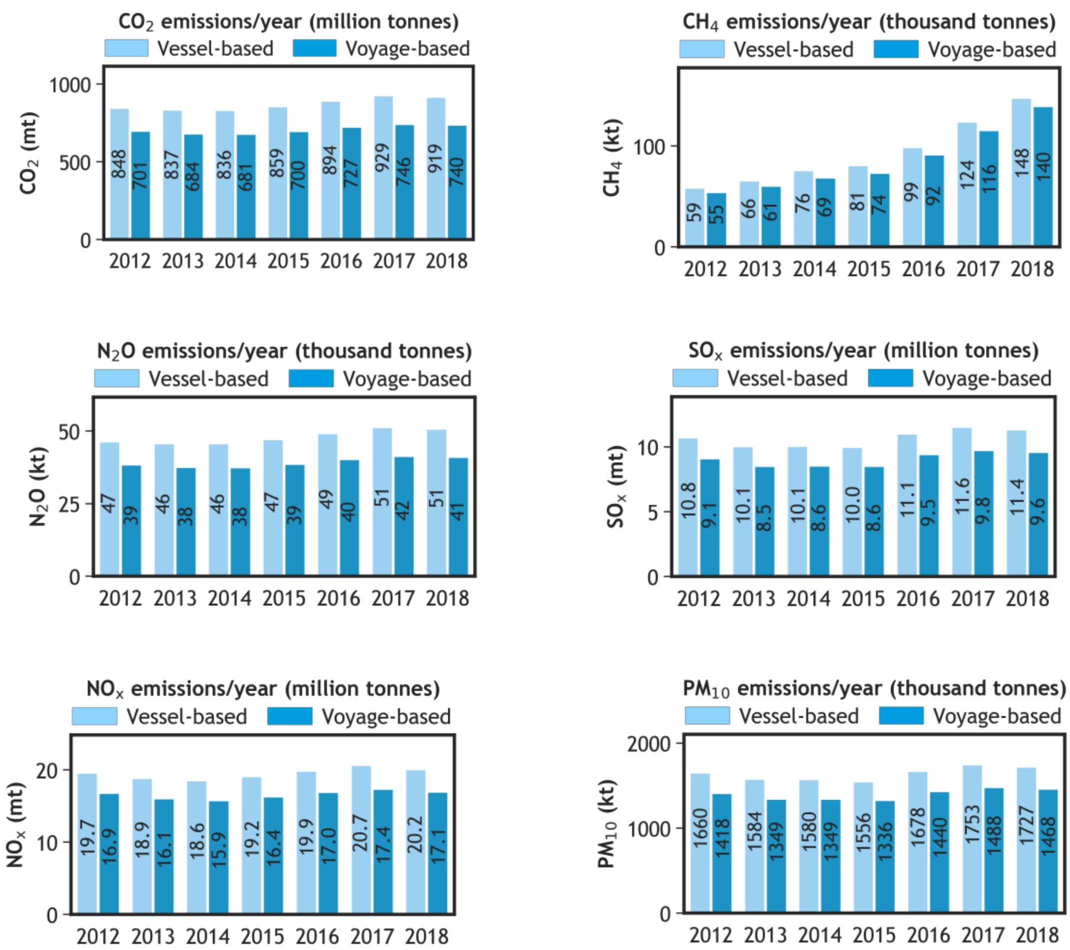


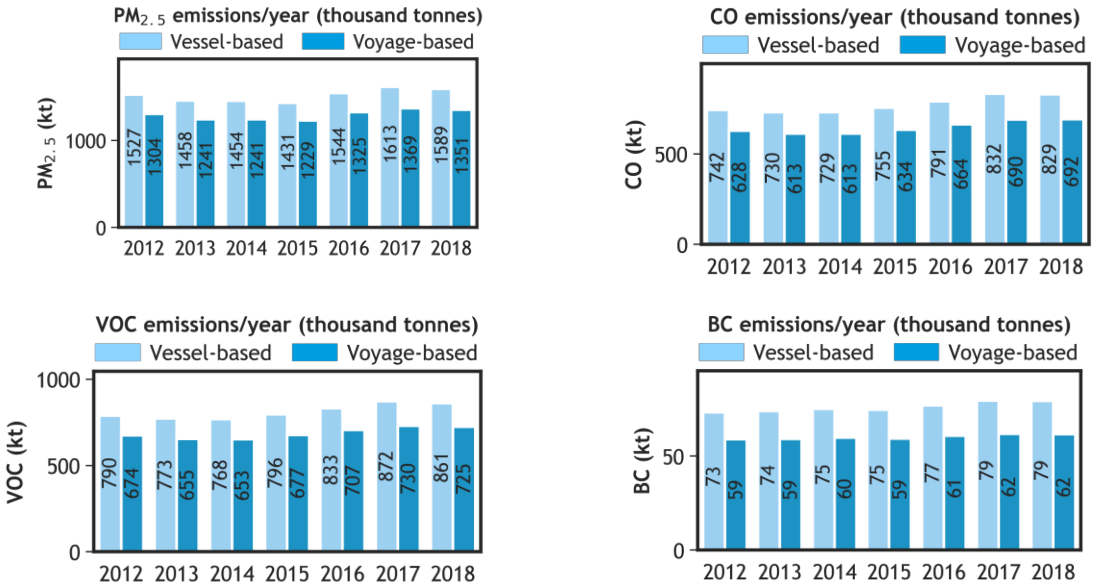
Figure 9 presents the trends in a number of emissions species, both GHG and air pollutants.

The majority of these trends follow the trend in total fuel consumption over the period. Important details include:

- CH_4 trend for international shipping sees a 150% increase over the period, which is driven by both an increase in consumption of LNG but the absolute increase is dominated by a change in the machinery mix associated with the use of LNG as a fuel, with a significant increase in the use of dual-fuel machinery that has higher specific exhaust emissions of CH_4.
- SO_x and PM emissions increase over the period in spite of an overall reduction in HFO use and increase in MDO and LNG use (partly driven by the entry into force in 2015 of a number of Emission Control Areas associated with limits on sulfur content of fuels). The explanation is that the average sulfur content increase in HFO over the period exceeds the sulfur content reduction associated with the change in fuel use.
- NO_x emissions saw lower rates of increase over the period than the trend in fuel consumption. This is consistent with the increased number of ships fitted with, and where appropriate operating with, NO_x Tier II and Tier III compliant machinery. In spite of these regulations, the overall trend in NO_x emissions was an increase over the period.

Figure 9 - Emissions species trends, all species 2012-2018, showing both the estimates for voyage-based and vessel-based international shipping emissions





Split between domestic and international shipping

This study deploys a new method to produce GHG Inventories that distinguish domestic shipping from international emissions on a voyage basis which is in the view of the consortium exactly consistent with the IPCC guidelines and definitions. The method is enabled by advances in the use of AIS data to identify port calls which allows allocation of discrete voyages to a definition of either international or domestic shipping. The improved split is reliable and provides a valuable advancement to the accurate assessment of international shipping's emissions. Figure 10 presents this method graphically.

Figure 10 - Allocation of international and domestic nature of shipping according to voyage-based method

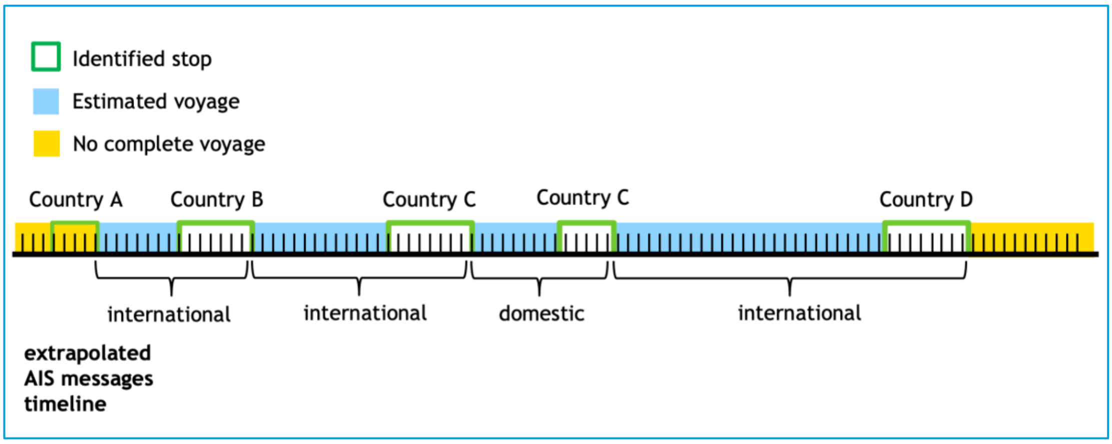
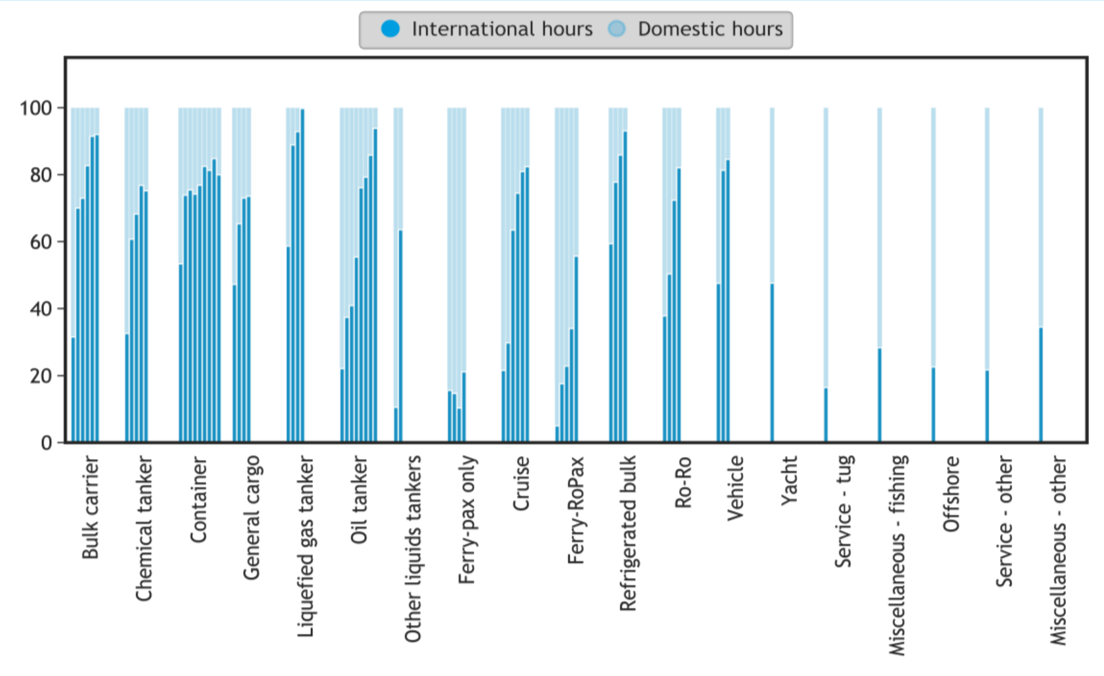


Figure 11 - Proportion of time spent on international and domestic voyages on average by ship type and size in 2018 (%), where ship sizes are order small to large



As presented in Figure 11, this study finds that every one of the ship type and size categories of ships has some portion of international shipping emissions. For ship types dominant in the inventory of international shipping emissions (oil tankers, bulk carriers and containers), the smallest size categories have 20-40% of their emissions allocated to international shipping. For the largest ship sizes, the allocation to international shipping varies depending on ship type e.g. general cargo ~70%, containers ~80%, oil tankers and bulk carriers ~90% and liquefied gas tankers ~100%.

Quality and uncertainty of the estimates

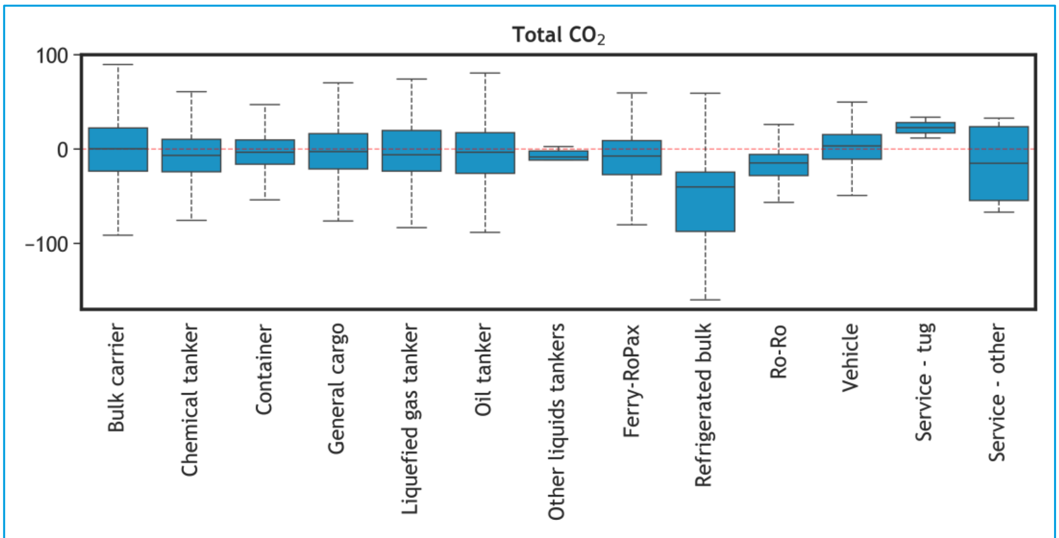
Extensive quality assurance and control efforts were taken to ensure the highest quality of the inputs, method and results in the bottom-up and top-down inventories. This included validation against:

- Shipowner reported high frequency measurements of fuel consumption and operational parameters.
- Other published studies and inventories.
- Reported results from shipowners in the EU's MRV scheme (EU, 2019).
- The results of the Third IMO GHG Study. The difference in total fuel consumption figures is 3% in the overlapping year 2012, demonstrating both quality and coherency with the preceding study.

Of these validation efforts, the greatest sample size and most comprehensive validation was undertaken by comparing the bottom-up inventory results against reported fuel consumption and other key parameters describing 11,000 ships. This represented a significant step forwards in validation for this GHG study, and demonstrated high quality in the consensus estimate because:

- The CO_2 and distance travelled at sea estimates across the entire fleet covered by MRV are showing only a very small overall deviation — overestimation error of 5.5 and 4.7% respectively.
- When breaking down the MRV based comparison by vessel type as shown on Figure 12, the CO_2 emissions for three major vessel types are showing only -0.2% error for bulk carriers, 6% for container vessels, and 3% for oil tankers.
- These three vessel types contribute to over 65% of the international CO_2 emissions in 2018 and so represent a dominant share of global international shipping.
- For vessel types, where a poorer agreement is observed, they are shown to be of negligible influence on the inventory's overall accuracy as their overall contribution to the international CO_2 emissions is no more than 3%.

Figure 12 - Agreement between this study's inventory, with respect to its vessel-specific CO_2 emissions estimates, and entries for 9,739 ships reported in the EU MRV database for 2018, for the duration of shipping activity covered by the EU MRV scheme's reporting requirement



Source: UMAS.

Estimates of Carbon Intensity of International Shipping

This report presents four metrics of carbon intensity, namely Energy Efficiency Operational Indicator (EEOI, g CO_2/t/nm), Annual Efficiency Ratio (AER, g CO_2/dwt/nm), DIST (kg CO_2/nm) and TIME (t CO_2/hr). These metrics can either be calculated with data from the Data Collection System or are included in the SEEMP Guidelines.

These metrics are used in this study to estimate the carbon intensity performance of international shipping from 2012 to 2018, as well as in 2008. Other variants of AER, including cDIST which uses different capacity units (such as teu, gt and cbm) and Energy Efficiency Performance Indicator (EEPI) which uses laden distance instead of total distance at sea, are also estimated where applicable, for reference purposes. Different carbon intensity metrics have different implications, drivers and reduction potentials, thus yielding different results in indicating the same performance level and percentage changes. Metrics such as EEOI, AER, cDIST and EEPI are potentially applicable to typical cargo and passenger ships, while DIST and TIME as well as their possible variants are more suitable for service, working or fishing vessels.

Table 3 and Table 4 report the carbon intensity levels of world fleet derived from both vessel-based and voyage-based. Seven typical ship types have been chosen as a representative of the world fleet, namely bulk carrier, oil tankers, container ships, chemical tankers, liquefied gas tankers, general cargo ships and refrigerated bulk carriers, which all together accounted for around 88% CO_2 emissions and 98% transport work of the world total.
The percentage changes in overall and individual based carbon intensity of international shipping are jointly provided in these tables, indexed at 2008 and 2012 respectively.
The overall percentage changes are calculated on aggregated data, while the individual based percentage changes are estimated through regression fit.

Table 3 - Carbon intensity levels and percentage changes of international shipping（vessel-based）

Year	EEOI (gCO2/t/nm)					AER(gCO2/DWT/nm)					DIST(kgCO2/nm)					TIME(tCO2/hr)				
	Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012	
		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual
2008	17,10	–	–	–	–	8,08	–	–	–	–	306,46	–	–	–	–	3,64	–	–	–	–
2012	13,16	-23,1%	-16,8%	–	–	7,06	-12,7%	-5,6%	–	–	362,65	18,3%	-5,6%	–	–	4,32	18,6%	-14,7%	–	–
2013	12,87	-24,7%	-18,3%	-2,2%	-2,0%	6,89	-14,8%	-7,1%	-2,4%	-1,7%	357,73	16,7%	-7,1%	-1,4%	-1,7%	4,18	14,6%	-18,1%	-3,3%	-4,2%
2014	12,34	-27,9%	-20,4%	-6,3%	-4,6%	6,71	-16,9%	-7,8%	-4,9%	-2,4%	360,44	17,6%	-7,7%	-0,6%	-2,4%	4,17	14,4%	-19,9%	-3,6%	-6,2%
2015	12,33	-27,9%	-19,0%	-6,3%	-2,8%	6,64	-17,8%	-6,5%	-5,9%	-1,3%	366,56	19,6%	-6,5%	1,1%	-1,3%	4,25	16,6%	-18,5%	-1,6%	-4,9%
2016	12,22	-28,6%	-18,7%	-7,2%	-2,5%	6,58	-18,6%	-6,4%	-6,8%	-1,4%	373,46	21,9%	-6,4%	3,0%	-1,4%	4,35	19,3%	-18,0%	0,6%	-4,4%
2017	11,87	-30,6%	-20,8%	-9,8%	-5,0%	6,43	-20,4%	-8,4%	-8,9%	-3,3%	370,97	21,0%	-8,4%	2,3%	-3,3%	4,31	18,2%	-20,4%	-0,3%	-7,0%
2018	11,67	-31,8%	-21,5%	-11,3%	-6,2%	6,31	-22,0%	-9,3%	-10,6%	-4,2%	376,81	23,0%	-9,3%	3,9%	-4,2%	4,34	19,1%	-22,2%	0,4%	-9,1%

Table 4 - Carbon intensity levels and percentage changes of International shipping（voyage-based）

Year	EEOI (gCO2/t/nm)					AER(gCO2/DWT/nm)					DIST(kgCO2/nm)					TIME(tCO2/hr)				
	Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012	
		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual
2008	15,16	–	–	–	–	7,40	–	–	–	–	350,36	–	–	–	–	4,38	–	–	–	–
2012	12,19	-19,6%	-11,4%	–	–	6,61	-10,7%	-4,6%	–	–	387,01	10,5%	-4,6%	–	–	4,74	8,11%	-13,9%	–	–
2013	11,83	-22,0%	-13,6%	-3,0%	-2,6%	6,40	-13,5%	-6,6%	-3,2%	-2,2%	380,68	8,7%	-6,6%	-1,6%	-2,2%	4,57	4,13%	-17,6%	-3,7%	-4,5%
2014	11,29	-25,6%	-16,2%	-7,4%	-5,5%	6,20	-16,1%	-7,6%	-6,1%	-3,1%	382,09	9,1%	-7,6%	-1,3%	-3,1%	4,54	3,49%	-19,4%	-4,3%	-6,6%
2015	11,30	-25,5%	-14,5%	-7,3%	-3,7%	6,15	-16,9%	-6,2%	-6,9%	-2,0%	388,62	10,9%	-6,2%	0,4%	-2,0%	4,64	5,75%	-18,0%	-2,2%	-5,3%
2016	11,21	-26,1%	-14,0%	-8,1%	-3,2%	6,09	-17,7%	-5,9%	-7,8%	-1,8%	397,05	13,3%	-5,9%	2,6%	-1,8%	4,77	8,68%	-17,4%	0,5%	-4,7%
2017	10,88	-28,2%	-15,9%	-10,8%	-5,4%	5,96	-19,5%	-7,7%	-9,8%	-3,7%	399,38	14,0%	-7,7%	3,2%	-3,7%	4,79	9,21%	-19,7%	1,0%	-7,2%
2018	10,70	-29,4%	-17,2%	-12,3%	-7,0%	5,84	-21,0%	-8,9%	-11,5%	-4,8%	401,91	14,7%	-8,9%	3,8%	-4,9%	4,79	9,17%	-21,5%	1,0%	-9,3%

As illustrated in Figure 13 and Figure 14, values of EEOI and AER have generally kept decreasing between 2012 and 2018, and reached a reduction rate around 29% and 21% in 2018 respectively, in comparison with year 2008. Discrepancies between the two metrics were mainly caused by their opposite reflections on payload utilization. Values of DIST and TIME both showed an increasing trend due to the increasing average ship size, whereas the increasing magnitudes have been diminished to a certain extent by sea speed reduction, especially for values of TIME.

Figure 13 - Percentage changes in overall carbon intensity of international shipping (vessel-based)

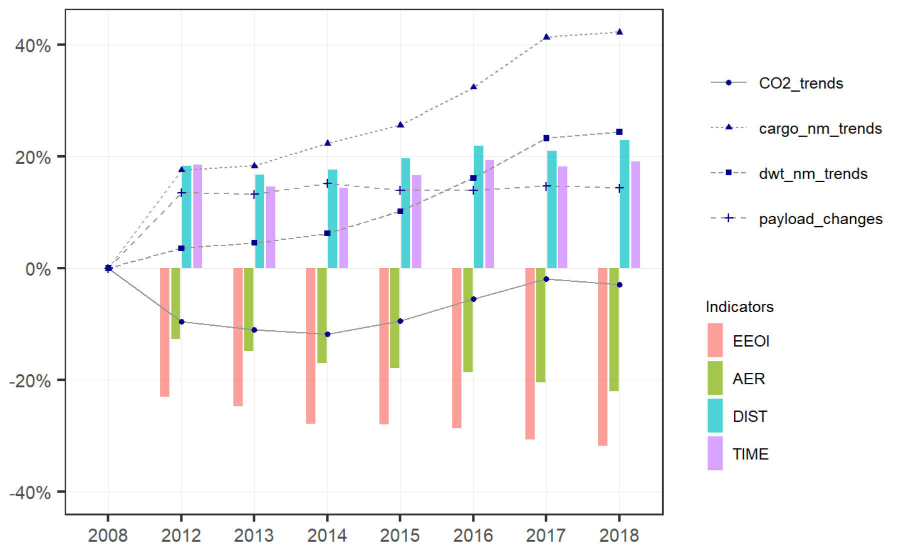
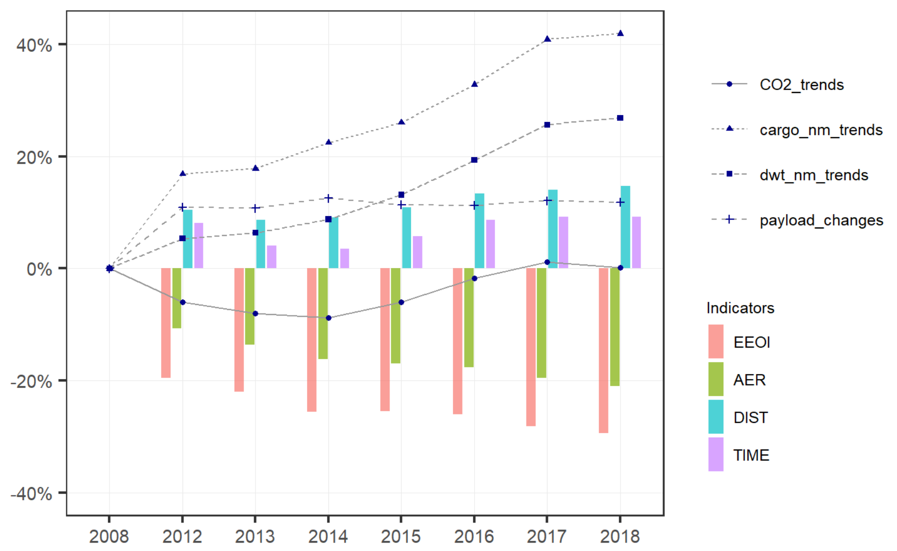


Figure 14 -Percentage changes in overall carbon intensity of international shipping (voyage-based)



As shown in Figure 15 and Figure 16, having not taken the influence of fleet composition shift into account, reduction magnitudes in EEOI and AER both narrowed down significantly. In comparison with 2008, the reductions in EEOI, AER/DIST and TIME in 2018 were around 17%, 9% and 22% respectively. The relatively smaller improvements in AER/DIST, when compare with in EEOI, were due to their negative response (metric values going up) to the increasing payload utilization, while the relatively larger improvements in TIME were due to their high sensitivity to speed reduction.

Figure 15 - Percentage changes in individual based carbon intensity of international shipping (vessel-based)

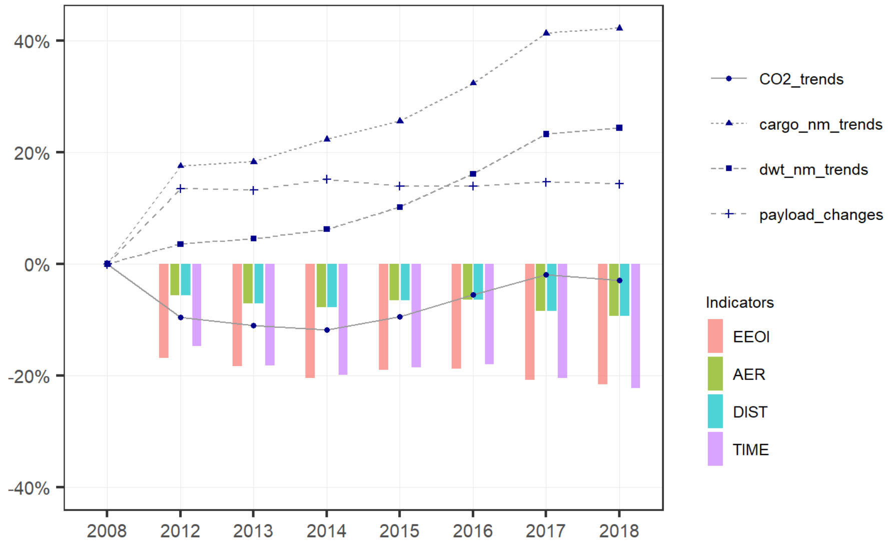
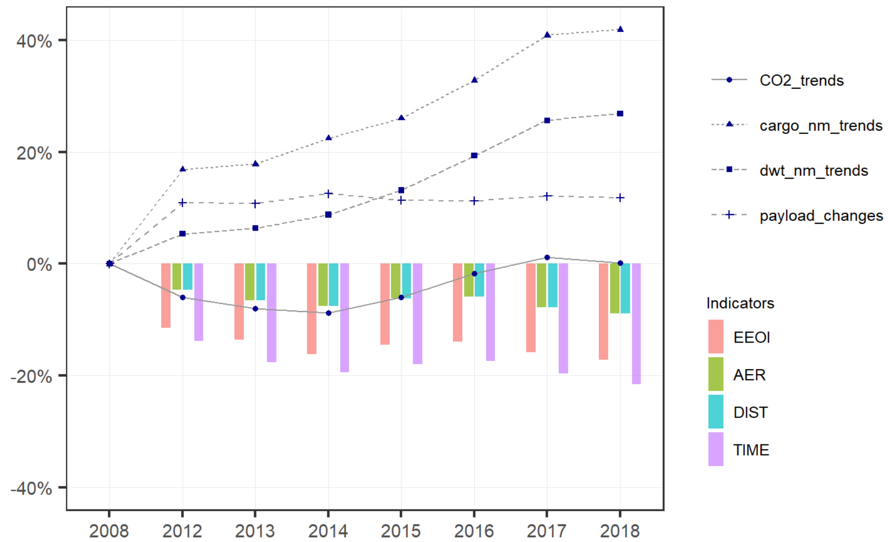


Figure 16 - Percentage changes in individual based carbon intensity of international shipping (voyage-based)



Note that the reduction rates in carbon intensity of international shipping discussed above are all indexed at year 2008, at which time the shipping market was just reaching its peak right before the long-lasting depression. Taking year 2012 as the reference instead, the reductions in overall carbon intensity of international shipping narrowed down from 29% (in EEOI) and 21% (in AER) to around 12% (in both EEOI and AER). The individual based percentage changes further shrank to 7% (in EEOI), 5% (in AER/DSIT) and 9% (in TIME). This implies that the improvements in carbon intensity of international shipping has not followed a linear pathway, and more than half have been achieved before year 2012. The pace of carbon intensity reduction has been further slowing down since 2015, with average annual percentage changes ranging from 1 to 2%, due to the limit in speed reduction, payload utilization as well as the technical improvements of existing ships.

Figure 17 and Figure 18 present the carbon intensity levels of typical cargo ships over years in EEOI and AER, estimated through both vessel-based (Option 1) and voyage-based (Option 2). As shown in these figures, lowest carbon intensity levels were achieved by bulk carriers and oil tankers, followed by container ships. In the vessel-based option, ships covered by certain types have been undifferentiated categorized as international regardless of their sizes and operational features, including a number of small ships which have been merely or mainly serving domestic transportation. Therefore, carbon intensity levels estimated for the vessel-based option were a little bit higher than (i.e. inferior to) those derived for the voyage-based option. For the sake of brevity, results derived from both vessel- and voyage-based are reported, but discussions on trends and drivers of carbon intensity have mainly focused on voyage-based unless otherwise specified.

Figure 17 - Carbon intensity levels of typical cargo ships over years (in EEOI; left panel: vessel-based; right panel: voyage-based)

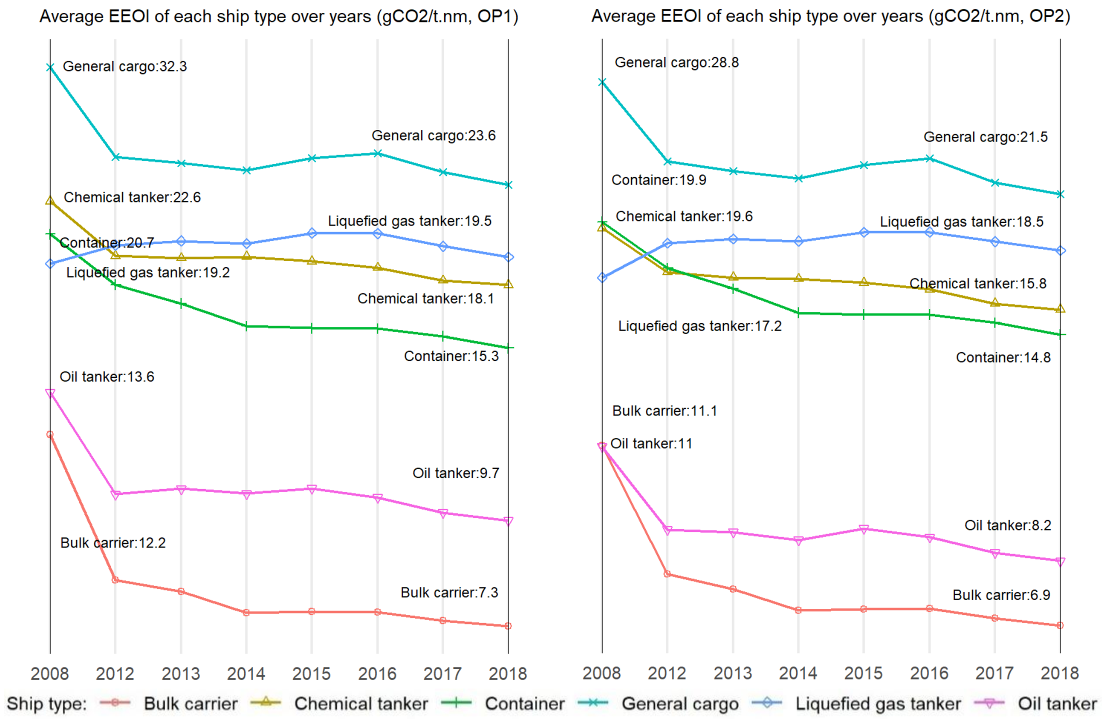
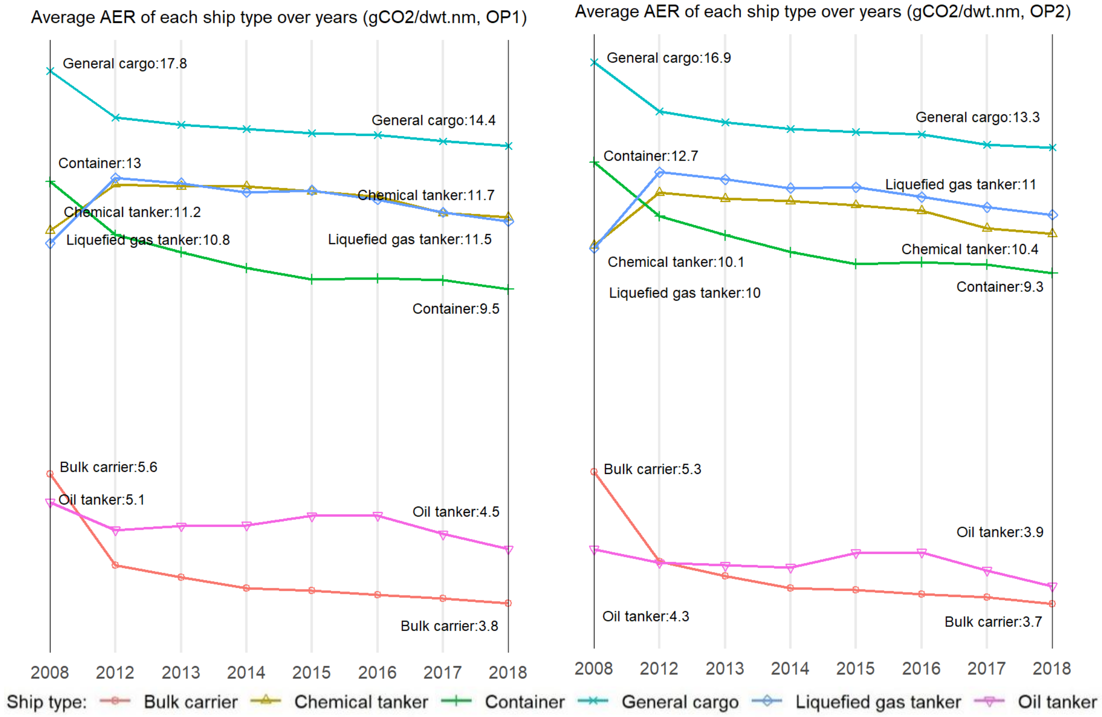


Figure 18 - Carbon intensity levels of typical cargo ships over years (in AER; left panel: vessel-based; right panel: voyage-based))



Carbon intensity performance per ship type varied from each other, but most of which have shared a decreasing trend between 2012 and 2018. Figure 19 and Figure 20 present of the trends in overall carbon intensity per ship type derived from both vessel-based (Option 1) and voyage-based (Option 2), as well as changes in drivers for carbon intensity reduction. Taking the year 2008 as a reference, the most significant carbon intensity reduction was achieved by bulk carriers, where the overall EEOI and AER in 2018 was around 38% and 31% lower. The trends in overall EEOI of oil tankers, container ships and general cargo ships were roughly identical, all of which decreased by 25-26% in 2018 compared with year 2008.

Figure 19 – Percentage changes in overall carbon intensity per ship type indexed at 2008 (vessel-based)

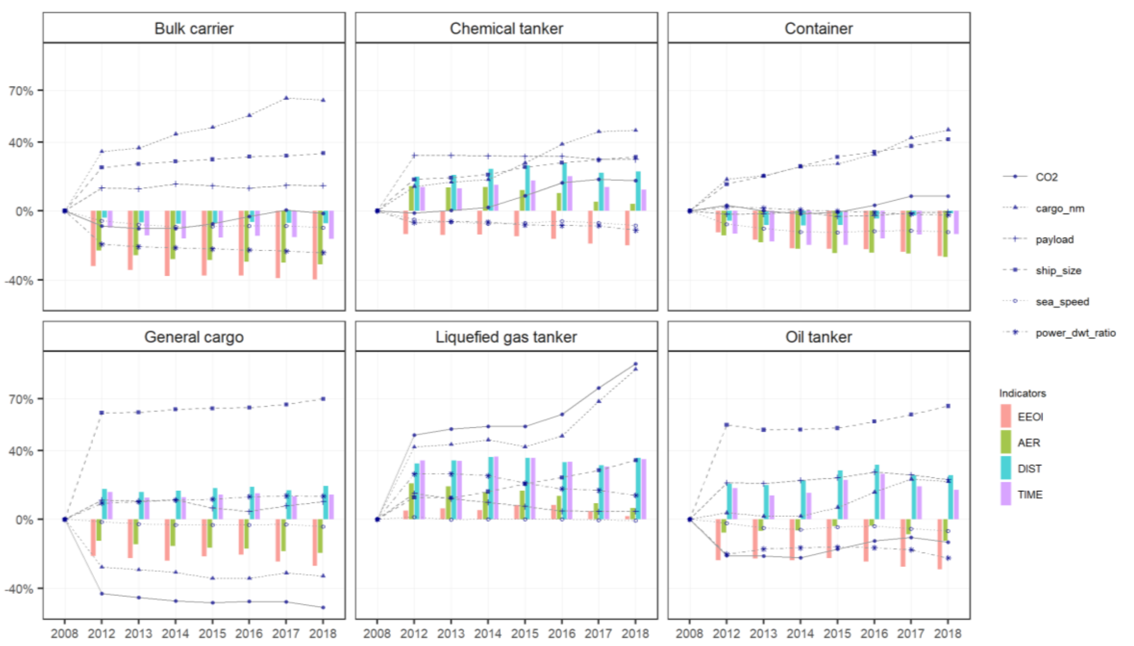
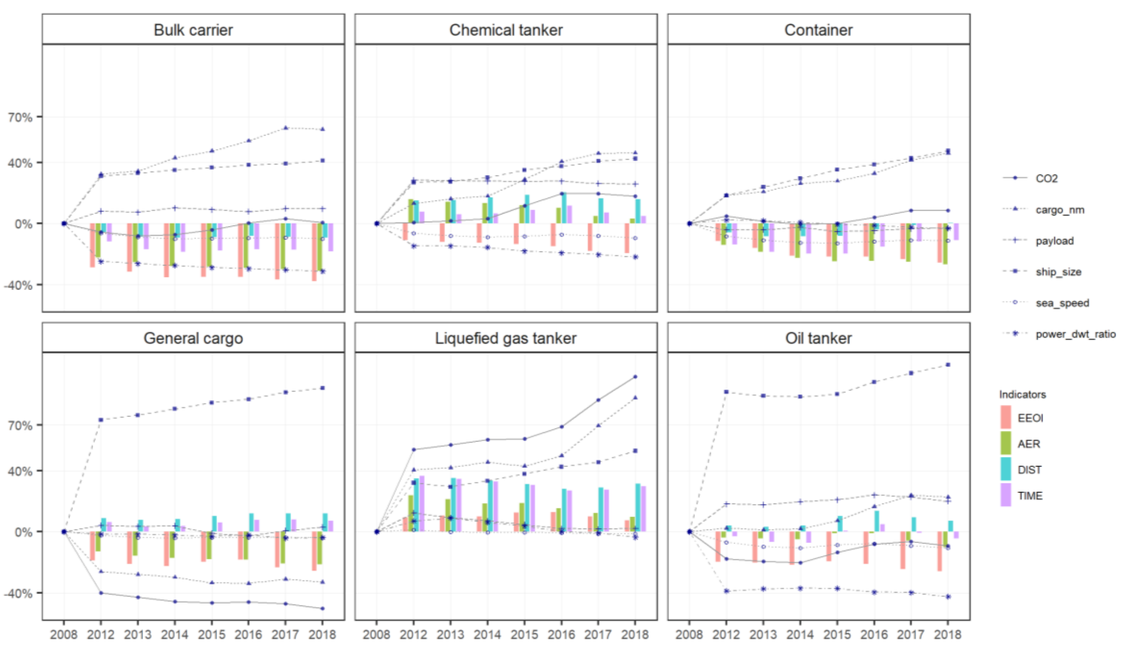


Figure 20 –Percentage changes in overall carbon intensity per ship type indexed at 2008 (voyage-based)



The increasing average ship size had taken a dominant role in carbon intensity reduction in all typical ship types when compared with year 2008, yet got less significant when compared with year 2012, except for container ships and liquefied gas tankers. In the meanwhile, large improvement in overall design efficiency has been observed in most segments, especially in oil tankers, bulk carriers and chemical tankers. Speed reduction has been another key driver especially for bulk carriers, chemical tankers, container ships and oil tankers since 2008. However, most ship type ceased slowing down further from year 2015, due to the improving market situation, decreasing fuel oil price as well as certain technical limitations or concerns. Similarly, payload utilization has been improved more or less for most ship types compared with year 2008, but went downwards or fluctuated during 2012-2018. Such volatile trends in speed and payload utilization were largely the lagging consequences of the sluggish recovery from global financial crisis which started from mid-2008. Another noteworthy finding is that changes in payload utilization showed opposite impacts on the trends in EEOI and AER. This implies that an increase in payload utilization generally leads to a reduction in EEOI, but leads to an increase in AER or compromises its expected reduction magnitude.

Figure 21 and Figure 22 present of the trends in individual based carbon intensity per ship type derived from both vessel-based and voyage-based, as well as the changes in drivers for carbon intensity reduction. Such trends are estimated through fitting a series of power law regression curves.

Having not taken the influence of ship size composition shift into account, the individual based carbon intensity reductions in most ship types narrowed down when measured in EEOI or AER. The differences are quite significant in bulk carriers (from 38% to 28%), chemical tankers (from 19% reduction to 4% increase) and oil tankers (from 26% to 8%), yet modest in container ships (from 26% to 20%) and general cargo ships (from 26% to 21%). This implies that the sharp carbon intensity reductions in the former group of ships were largely led by increasing ship size, while in the latter group were mainly achieved by individual design and operational improvement. In this like-to-like comparison, identical trends of AER and DIST can be clearly identified. Having been jointly influenced by increasing ship size and decreasing sea speed, changes in the overall TIME were determined by the one which dominant, thus showed divergent trends between ship types. Having decoupled from the size factor, however, TIME has showed a decreasing trend in most ship types, with reduction rates even larger than in EEOI. This implies that TIME is much more sensitive to speed reduction than other metrics.

Figure 21 – Percentage changes in individual based carbon intensity per ship type indexed at 2008 (vessel-based)

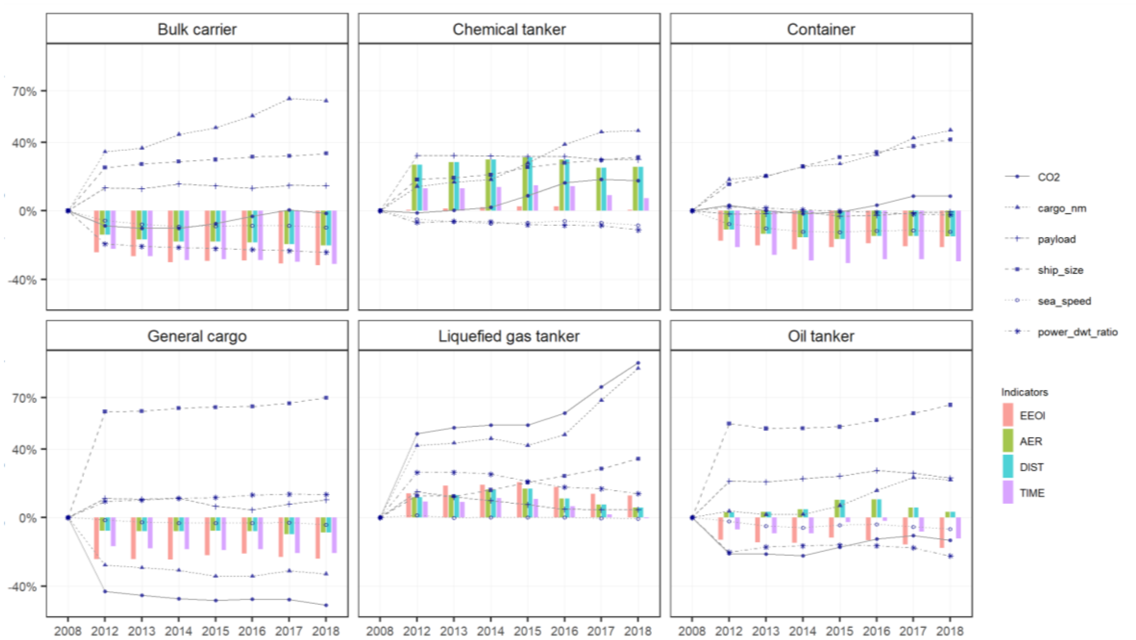
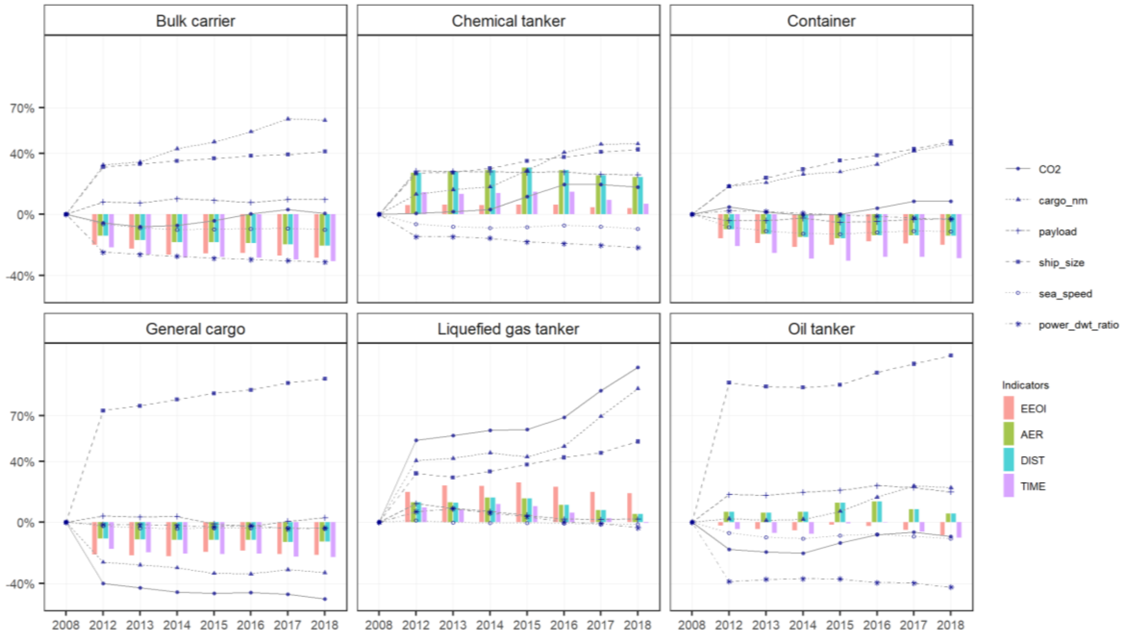


Figure 22 – Percentage changes in individual based carbon intensity per ship type indexed at 2008 (voyage-based)



Large spread scales of metric values have been observed across all ship types and size bins, which are mainly caused by differences in design and operational profiles of individual ships, as well as various external influencing factors. The spread scales in all metrics are generally larger for smaller ships whist smaller for larger ships. As per ship types, the largest spread scales of EEOI have been observed in oil tankers, followed by general cargo ships, bulk carriers, liquefied gas tankers and chemical tankers. Spread scales in AER are a little bit smaller than in EEOI due to its immunity to variations in payload utilization. Further to the differences between ship type and size categories, carbon intensity of a specific individual ship also varied over time, due to the various operational and navigational conditions beyond control. The upper and lower quartiles of fluctuation rates in EEOI of oil tankers, bulk carriers and container ships were around ±20%, ±15% and ±10% respectively. Quartiles of fluctuation rates in other metrics were relatively modest, yet still generally reaching beyond ±5%. Due to certain static assumptions on weather and hull fouling condition, as well as non-timely updated AIS entries on draught, factual fluctuations were possibly more scattered than estimated, especially for container ships.

Uncertainties in carbon intensity estimation partly stem from the inventory estimation and partly from the estimates on transport work. Cross validation with EU MRV data showed that the metric values in EEOI might be underestimated by 10-25% for bulk carriers, container ships, chemical tankers and general cargo ships, whilst by 50% for liquefied gas tankers. The discrepancies in oil tanker were less than 5%. Since CO_2 emissions could have been overestimated, the underestimation on EEOI values was likely caused by a larger overestimation on payload utilization. Comparison against the published transport demand in UNCTAD's Review of Maritime Transport (2018) showed that the deviations in estimated cargo ton-miles undertaken by oil tankers, container ships and dry cargo ships (covering bulk, general cargo and refrigerated bulk carriers) were consistently around -2%, 30% and -28% between 2012 and 2018, while the deviations in total cargo ton-miles ranged within ±2%. This was likely caused by the different categorization strategy applied to seaborne trade and to marine transportation. This observation highlights two points: first, the estimates on carbon intensity of international shipping as a whole was more reliable than the results for ship types; second, the estimated trends in carbon intensity performance (in percentage change), which could not be substantially affected by systematically biased estimation in transport work, are more reliable than the absolute metric values. Given the limited data available for validation, subjective rectification such as introducing a series of correction factors to carbon intensity estimates of ship types may incur another uncertainty. Therefore, no corrections have been made to the estimated results. To avoid misleading, however, whenever the estimated carbon intensity levels of ship types are referred to, the possible biasness should be specified jointly.

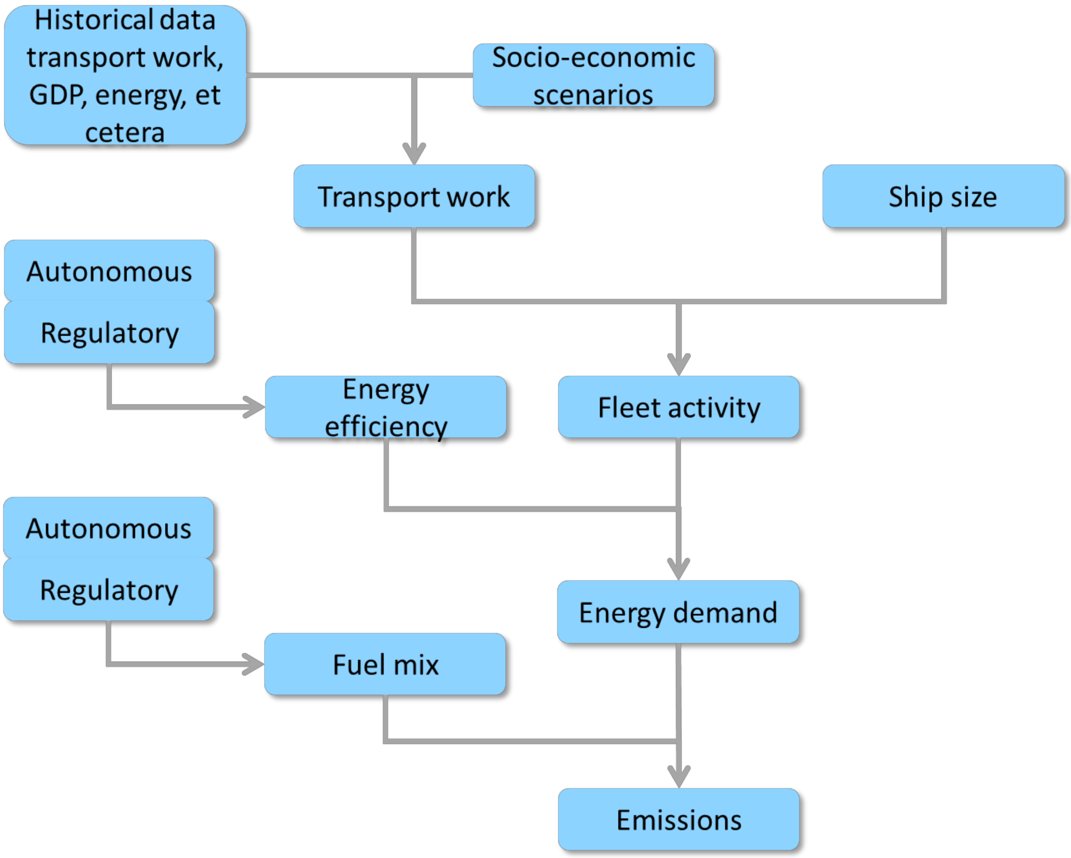
Scenarios for Future Shipping Emissions

CO_2 emissions of shipping have been projected out to 2050. The method for projecting emissions from shipping in this study comprises six steps:

1. Projecting transport work – non-energy products:
   a. Establishing the historical relation between maritime transport work and relevant economic parameters such as world (or country) per capita GDP and population (for transport of non-energy products, such as unitized cargo, chemicals and non-coal dry bulk);
   b. Projecting transport work on the basis of the relations described in (a) and long-term projections of GDP and population (global or by country).
2. Projecting transport work – energy products
   a. Collecting IPCC formal projections of evolution of energy consumption and energy consumption (for transport of energy products like coal, oil and gas).
   b. Projecting transport work using the variation of energy consumption projection when considering seaborne transportation of energy products (coal dry bulk, oil tankers and gas tankers).
3. Making a detailed description of the fleet and its activity in the base year 2018.
4. Projecting the future fleet composition.
5. Projecting future energy efficiency of the ships, taking into account regulatory developments and market-driven efficiency changes using a marginal abatement cost curve (MACC).
6. Combining the results of Steps 4, 5 and 6 above to project shipping emissions.

Figure 23 is a graphical representation of the methodology.

Figure 23 - Graphical representation of methodology to develop emission projections



The transport demand projections depend on three factors:

1. The long-term socio-economic scenario underlying the projection. The higher the projected per capita GDP growth and the population growth, the higher the projected transport work for products that are strongly correlated with economic developments, such as non-coal dry bulk, containerized and other unitized cargoes, and chemicals.
2. The long-term energy scenario. The more fossil fuel is projected to be consumed, the higher transport work of coal dry bulk, oil tankers and gas tankers. And
3. The method to establish the relation between transport work and the relevant drivers. This study has employed two methods for projecting transport work for non-energy products: a logistics analysis which analyses the relation between global transport work and its drivers over the longest period available and projects that relation further using a logistics curve; and a gravitation model analysis, in which bilateral trade flows between countries are analysed to establish the elasticities of trade between those countries and the relevant drivers. We find that typically the logistics approach results in higher transport work projections than the gravitation model approach.

The factors are summarised in Table 5.

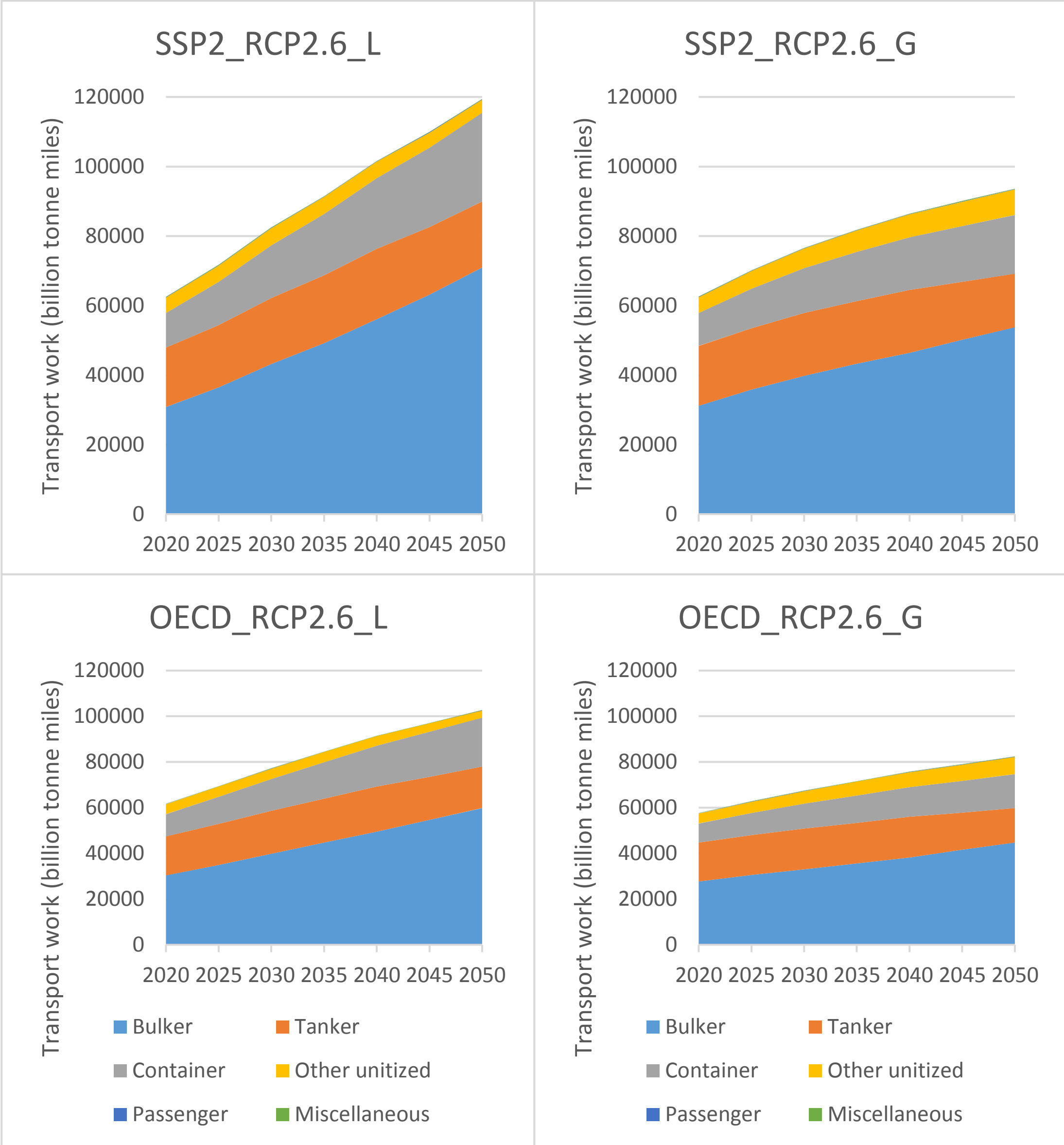
Table 5 - Characteristics of transport work demand projections

Non-coal dry bulk, containers, other unitized cargo, and chemicals (Relation between transport work and relevant drivers: Logistics, denoted by _L; Gravitation model, denoted by _G)	Coal dry bulk,-oil tankers and gas tankers
Long-term socio-economic scenarios	**Long-term energy scenarios**
SSP1 (Sustainability - Taking the Green Road)	RCP1.9 (1.5°C) in combination with SSP1, SSP2 and SSP5
SSP2 (Middle of the Road)	RCP2.6 (2°C, very low GHG emissions) in combination with SSP1, SSP2, SSP4 and SSP5
SSP3 (Regional Rivalry - A Rocky Road)	RCP3.4 (extensive carbon removal) in combination with SSP1, SS2, SSP3, SSP4 and SSP5
SSP4 (Inequality - A Road Divided)	RCP4.5 (2.4°C, medium-low mitigation or very low baseline) in combination with SSP1, SS2, SSP3, SSP4 and SSP5
SSP5 (Fossil-fueled Development - Taking the Highway)	RCP6.0 (2.8°Cmedium baseline, high mitigation in combination with SSP1, SS2, SSP3, SSP4 and SSP5
OECD long-term baseline projections	

Source: (Van Vuuren, et al., 2011b), (Riahi, et al., 2017) Making sense of climate change scenarios: Senses Toolkit

In scenarios with an aggregate economic growth in line with SSP 2 and OECD baseline projections and energy demand from land-based sectors that just about limits the global temperature increase to well below 2 degrees centigrade (RCP 2.6), aggregate transport work increases by 40-100%. In general, projections using a logistics analysis exhibit higher growth rates (75-100%) than projections using a gravitation model approach (40-60%). Scenarios that have higher aggregate income and size growth see a larger increase in transport work (see Figure 24).

Figure 24 - Transport work projections (billion tonne miles)



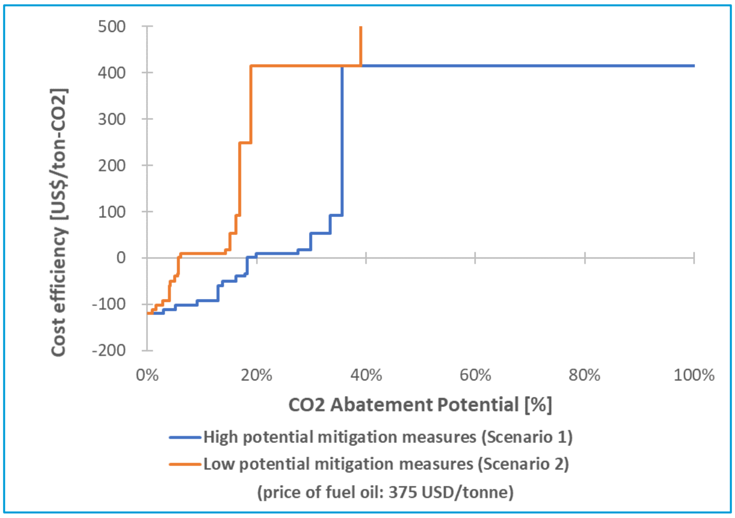
Updated Marginal Abatement Cost Curves

There are many ways to improve the energy efficiency or carbon intensity of shipping. This report has assessed the abatement potential and costs of 44 technologies in four groups: energy-saving technologies; use of renewable energy; use of alternative fuels; and speed reduction.

Applying all the potential mitigation measures selected to all newly built ships from 2025, CO_2 emissions reduction in 2050 can achieve both the mid-term and long-term levels of ambition specified in the Initial IMO Strategy on Reduction of GHG Emissions from Ships.

In 2050, about 64% of the total amount of CO_2 reduction is contributed to by use of alternative fuels. The Marginal Abatement Cost Curve (MACC) depends to a large extent on the projected prices of zero-carbon fuels.

Figure 25 - Marginal abatement cost curve for 2050

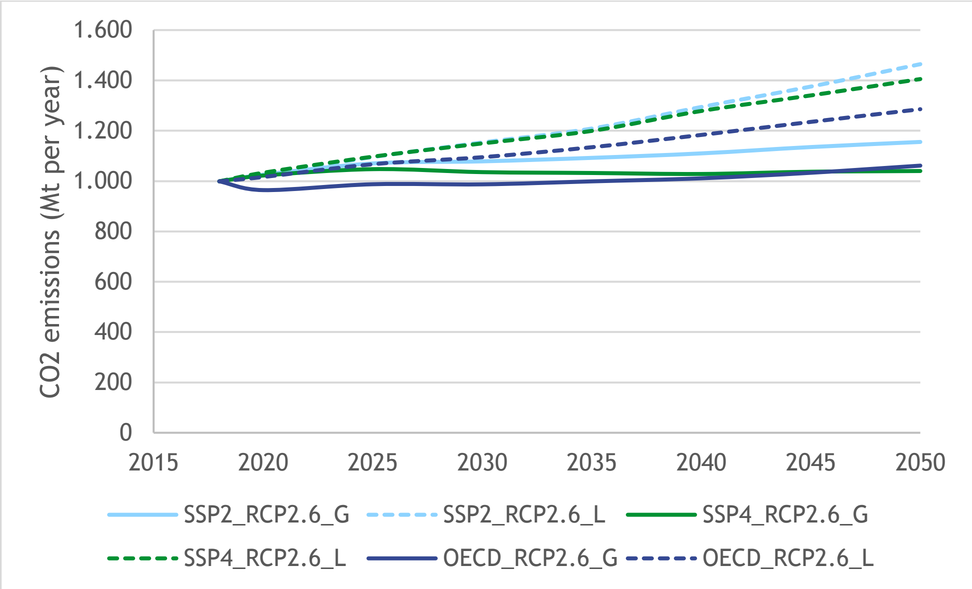


Emission projections

All the projections are so-called business as usual (BAU) projections. In the context of this study, BAU refers to the shipping sector and is defined as 'no adoption of new regulations that have an impact on energy efficiency or carbon intensity'. As noted above, the projections are based on long-term socio-economic pathways and representative concentration pathways of the IPCC. Some of these pathways assume that non-shipping sectors undergo transitions that require policies like carbon prices or energy-efficiency regulations. These are still considered to be BAU scenarios in the context of this study.

Figure 26 shows the BAU scenarios for three long-term scenarios in which the energy mix of land-based sectors would limit the global temperature increase to well below 2 degrees centigrade (Van Vuuren, et al., 2011a) and which have GDP growth projections from the OECD or from the IPCC that are in line with recent projections from the OECD. In these BAU scenarios, the emissions of shipping are projected to increase from 1,000 Mt CO_2 in 2018 to 1,000 to 1,500 Mt CO_2 in 2050. This represents an increase of 0 to 50% over 2018 levels and is equal to 90-130% of 2008 levels.

Figure 26 - BAU scenarios GDP growth in line with recent projections, energy transition in line with 2 degrees target



The differences in the BAU emission projections are caused by differences in transport-work projections which, in turn, are caused by differences in socio-economic projections and different methods to establish the relation between transport work and independent variables like per capita GDP, population and primary energy demand.

The emissions in Figure 26 are for total shipping. It is expected that the share of domestic and international emissions will not change.

Although it is too early to assess the impact of Covid-19 on emission projections quantitatively, it is clear that the emissions in 2020 and 2021 will be significantly lower. Depending on the recovery, the emissions in the next decades may a few percent lower than projected, at most. In all, the impact of Covid-19 is likely to be smaller than the uncertainty range of the presented scenarios.

1 Introduction

1.1 Background

The International Maritime Organization (IMO) has a history in addressing GHG emissions of ships in its Marine Environment Protection Committee (MEPC), starting in 1997 with a resolution on CO_2 emissions from ships (Resolution 8) and continuing to date.

Important milestones have been the adoption of the Energy Efficiency Design Index for new ships and the Ship Energy Efficiency Management Plan in 2011 and the adoption of the Initial IMO Strategy on Reduction of GHG emissions from ships in 2018.

The adoption of the Initial Strategy was a milestone in the Roadmap for developing a comprehensive IMO strategy on reduction of GHG emissions from ships (MEPC 70/18/Add.1) which contains a timetable for, amongst others, the initial and revised strategy, the completion of the so-called Three step approach and the Fourth IMO GHG Study. The Fourth IMO GHG Study has been initiated in line with the Roadmap at MEPC 74 where the Terms of Reference have been adopted.

Earlier IMO GHG Studies have been published in 2000, 2009 and 2014. Each study has fed into the debate at IMO and each study has been recognised as an important contribution to the understanding of emissions by a wide audience. Each study also has improved on the methodologies used to quantify the emissions and to project the future development of emissions.

This Fourth IMO GHG Study provides an inventory of GHG emissions from shipping for the period 2012-2018; presents an analysis of carbon intensity of international shipping for 2008 and 2012–2018; and develops emission projections for the period 2018–2050.

In comparison to the Third IMO GHG Study, this study has made a number of major methodological improvements:
- The methodologies for the emission inventories have been refined, thus reducing the level of uncertainty in the results.
- We have applied a new method to distinguish between domestic and international voyages which is fully in line with the IPCC Guidelines for National Greenhouse Gas Inventories. This method was made possible because better AIS data are available. In order to improve the comparability with the Third IMO GHG Study, the method employed in the Third IMO GHG Study has also been applied.
- We have developed a methodology to estimate the carbon intensity of shipping which is fully integrated in the bottom-up methodology to estimate emissions.
- A new marginal abatement cost curve for the reduction of CO_2 emissions has been developed which also includes low- and zero-carbon fuels.
- Two methods have been employed to project transport work in the future which provide a better view on the range of possible developments.

1.2 Objective

The objective of the study is to develop an accurate estimate of historical emissions of international shipping and state-of-the-art projections of future emissions. To that end, it aims to develop:

1. Inventory of GHG emissions from international shipping 2012-2018; and
2. Scenarios for future international shipping emissions 2018-2050.

1.3 Scope

The inventory includes global emissions of GHGs and relevant substances emitted from ships of 100 GT and above engaged in both domestic and international voyages. The emissions are presented as totals and disaggregated to ship types and –size categories.

The following substances are included in the emission inventory:
1. The six gases initially considered under the UNFCCC process: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6).
2. Other relevant substances: nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), particulate matter (PM) and sulfur oxides (SO_x).
3. black carbon (BC).

The emission estimates include total annual GHG emission for each year from 2012 to 2018. In addition, estimates of carbon intensity for 2008 have been calculated.

The emission projections cover the period up to 2050 and focus on CO_2 emissions only as the main greenhouse gas emitted by shipping.

1.4 Outline of this report

This report has three further chapters and a number of annexes. Chapter 2 presents the Inventory of GHG emissions from international shipping 2012-2018. Chapter 3 focusses on estimates of carbon intensity. Chapter 4 contains the projections of CO_2 emissions of shipping until 2050.

2 Inventory of GHG emissions from international shipping 2012-2018

2.1 Introduction

This chapter focuses on describing global ship activity and emissions for the years 2012 to 2018, as to update the previously estimated shipping emissions inventory studies commissioned by the IMO. It specifically discusses the observed trends in international shipping and highlights some of the key drivers in those observed trends. It focuses on the estimation of fuel consumption and the associated emitting of CO_2 emissions and other greenhouse gases, including black carbon (BC), as well as the most prevalent air pollutants. To put shipping's greenhouse gas emissions inventory in context, this chapter discusses the global fleet in terms of the total time spent at sea, distance travelled, its average operating speed and other important metrics. Following the Third IMO GHG Study 2014, this section estimates fuel consumption and emissions according to a similar 'bottom-up' and 'top-down' method.

As done in previous IMO GHG Studies, the bottom-up method derives estimates of emissions by leveraging AIS-transmitted data, which describes individual vessels' operational activity. These data are used to calculate the fuel consumption and emissions on an hourly, per-vessel basis for each year in the inventory, where individual ships are identified as "in service" using the IHS database. Alongside key improvements to the bottom-up method discussed in this section, this study deploys a new method to allocate emissions to either international or domestic shipping activity. This method is consistent with the IPCC guidelines and definitions. It is enabled by the technical advances made as it uses AIS data to identify port calls, which subsequently allows for the allocation of discrete voyages to distinguish between international and domestic shipping.

In parallel to the bottom-up approach, this study also estimates the fuel consumption and emissions associated with shipping using the top-down approach, as done in both the Second and Third IMO GHG studies. This method leverages World Energy Statistics provided by IEA to estimate global shipping emissions for the period 2012-2017 and applies emissions factors based on the total mass of pollutants divided by the total mass of fuel consumption, estimated using the bottom up approach.

Extensive quality assurance and control efforts are presented and discussed to ensure the highest quality of the inputs, method and results in the bottom-up and top-down inventories. The comparison between the two approaches along with the QA procedures are discussed in dedicated section within this chapter. Consistent with earlier GHG Studies, the consortium has selected a single estimate for presentation of results, being the bottom-up method estimation, calculated using the voyage-based allocation between international and domestic emissions. More details underlying this decision are discussed in Section 2.9.

Over the seven years included in this study's inventory international CO_2-eq. emissions saw an overall increase of 5.9%.

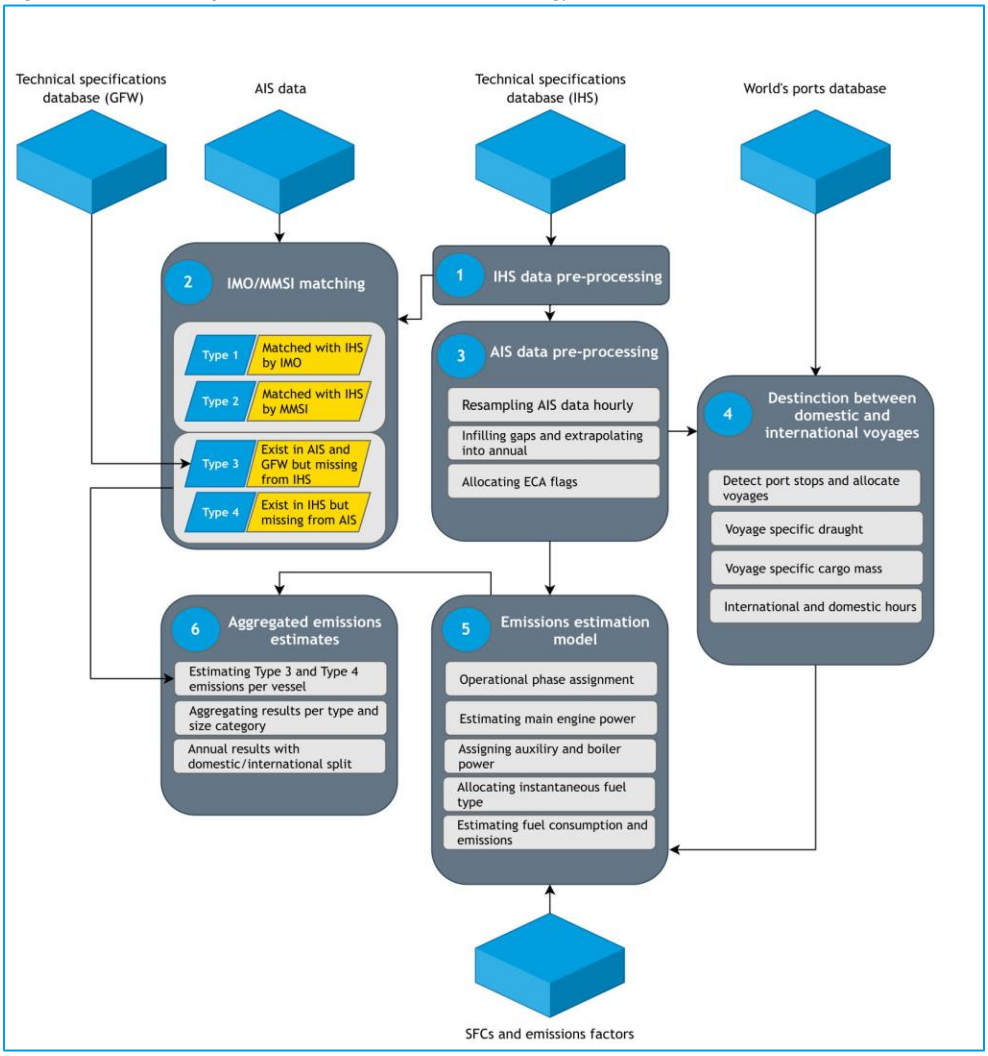
2.2 Bottom-up methodology and data sources

The following data sources have been used in this study's bottom-up approach:

- Terrestrial and satellite Automatic Identification System (AIS) data from exactEarth;
- Ship technical specifications data from the Information Handling Services (IHS) database.
- Ship technical specifications data from Global Fishing Watch (GFW).
- World database of port locations including longitude and latitude coordinates internally collated by UMAS International.
- A set of assumptions including specific fuel oil consumption values, auxiliary engines and boiler machinery power demand, and emissions factors that are partially adopted from the proceeding Third IMO GHG Study 2014 or were updated based on more recent research work or review by maritime industry experts.

The overall bottom-up emissions estimation methodology applied in this study is illustrated in the flowchart below, Figure 27, with each module highlighted further discussed in detail in this section.

Figure 27 - Bottom-up emissions estimation methodology



Source: UMAS.

Module 1 - Pre-processing vessels technical specifications.

This module handles the infilling of most of the missing technical specifications, the allocation of size category bins, and the mapping of the initial assumptions regarding the fuel types used in main engine, auxiliary and boiler machinery. The algorithms used in this module are described in Section 2.2.1

Module 2 - Matching AIS vessels with their technical specifications.

At this stage all unique vessels successfully identified in the AIS dataset for each year are first mapped with the IHS technical specifications database, by either International Maritime Organization (IMO) or Maritime Mobile Service Identity (MMSI) number. Vessels that are matched by IMO number with the IHS database are labelled as Type 1 vessels, while those matched by MMSI number are labelled as Type 2 vessels. All remaining vessels that are found in the AIS datasets are then checked against the GFW database by MMSI number. Only vessels with a capacity greater than 100 Gross Tonnes (GT) are considered to be in scope for this study and were labelled as Type 3 vessels. Finally, all remaining vessels that remain unmatched in the IHS database with an “in service” status during a given year and with a capacity between 100 GT and 300 GT are also considered in scope and marked as Type 4 vessels. The algorithms applied in this module are described in Section 2.2.2.

Module 3 - AIS data cleaning, gap infilling, and resampling.

Module 3 addresses AIS data preparation and processing, covering a set of processes for data cleaning, filtering, and merging as well as resampling and extrapolation into annual hourly observations for each year of interest. This also involves infilling possible gaps in the time series of various metrics required for further modelling. All the principal steps with regards to AIS data preparation are described in Section 2.2.3. Lastly, at this stage, Emission Control Area (ECA) flags and the distances from shore and nearest port are allocated to each of the extrapolated hours in the AIS datasets.

Module 4 – Distinction between domestic and international emissions.

The first stage of this module detects port stops and allocates voyages to each vessel, which is an important addition to the Fourth IMO GHG Study approach. This step allows emissions to be allocated based upon where a vessel has operated (i.e. domestic or international voyages) rather than upon the ship type and/or size. This module is a core approach for splitting emissions domestically vs. internationally under Option 2 and is detailed in Section 2.2.4.

The use of instantaneous AIS draughts corrected on a voyage-specific basis, rather than potentially erroneous instantaneous draught values, is another important refinement to this study. This allows for cargo mass to be estimated at the voyage level as an input into carbon intensity metrics.

Module 5 – Emissions estimation model

This is a core module of the bottom-up methodology. This module is comprised of all the components responsible for fuel consumption and emissions estimation, including operational phase assignment, the estimation of instantaneous main, auxiliary and boiler power demands, the allocation of instantaneous fuel types ensuring compliance with SO_x and NO_x ECA (SECA and NECA respectively) limits, and estimating fuel consumption and all emission species in the scope of this study. All of these components are discussed further in Section 2.2.5.

Module 6 – Aggregated emissions estimates

All processes associated with AIS data usage covered in modules 3–5 are primarily concerned with larger Type 1 and Type 2 vessels that have been matched with the IHS technical specifications database. In this module, the modelled fuel consumption and emissions rates from these vessels were used to estimate Type 3 and Type 4 emissions, as described in Section 2.2.6.

Lastly, all operational transport metrics, fuel consumption, and emissions were aggregated into per-vessel type and size categories with annual statistics and applied domestic and international splits under both approaches to assign emissions to international and domestic inventories respectively, where the method applied in the Third IMO GHG Study is referred to by ‘Option 1’ and a newly introduced voyage-based allocation is referred to by ‘Option 2’ (see Section 2.2.4). The final figures and trends are discussed in the bottom-up results in Section 2.5.

2.2.1 Vessel technical specifications data pre-processing

Similar to the Third IMO GHG Study 2014, a vessel technical specification dataset provided by the IHS is used in this study to obtain the principle vessel characteristics required for the emissions estimation model using the bottom-up approach. Unlike the Third IMO GHG Study 2014, however, where a separate IHS dataset was provided for each year of interest, in the current study a single cumulative dataset was used, containing all data collected and updated to 2018. Because of this, each vessel’s status was checked against a timestamp of the most recent change in status separately to ensure that only “in service” vessels are included in this analysis.

The IHS database contains ship characteristics for 188,220 ships as of mid-2018 and is continuously updated with newly-built ships. The ships range from 100 GT fishing, ferries and service vessels to the largest bulk carriers and cargo ships, covering both ships that engage in international as well as domestic navigation. However, a large proportion of the domestic shipping fleet is not covered in the IHS database. For example, there are more than 165,000 ships flagged to mainland China in 2015, whereas the IHS database reports less than 6,000 (Olmer, et al., 2017b).

The IHS database provides a range of metrics useful for estimating fuel consumption and emissions from ships, as described in the following sections.

Infilling missing technical specifications

Vessels identified in the raw AIS datasets need to first be matched with the IHS technical specification database by one of two identification numbers, their IMO or MMSI number. However, for some vessels the technical information was found to be missing. Therefore, a robust infilling algorithm is required to address the potential uncertainty when infilling these missing technical specifications.

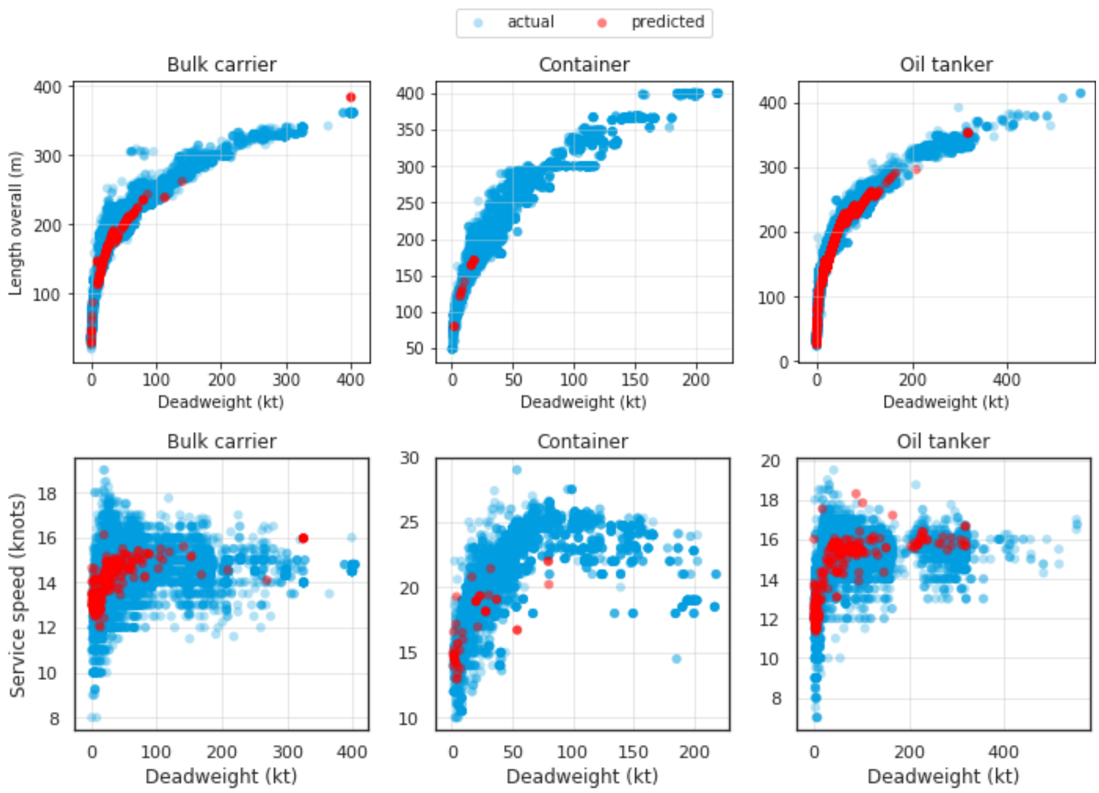
In the Third IMO GHG Study 2014, gap filling was performed using the average value for each ship class, sub-class and capacity bin for each technical attribute. Since the Third IMO GHG Study 2014, the original methodology to infill the fleet’s missing technical specifications has been updated. The current algorithm implemented by UMAS International is based on a multilinear regression created for each ship type, taking into account individual vessel's known design parameters such as beam, draught and capacity. The following regressions were applied:

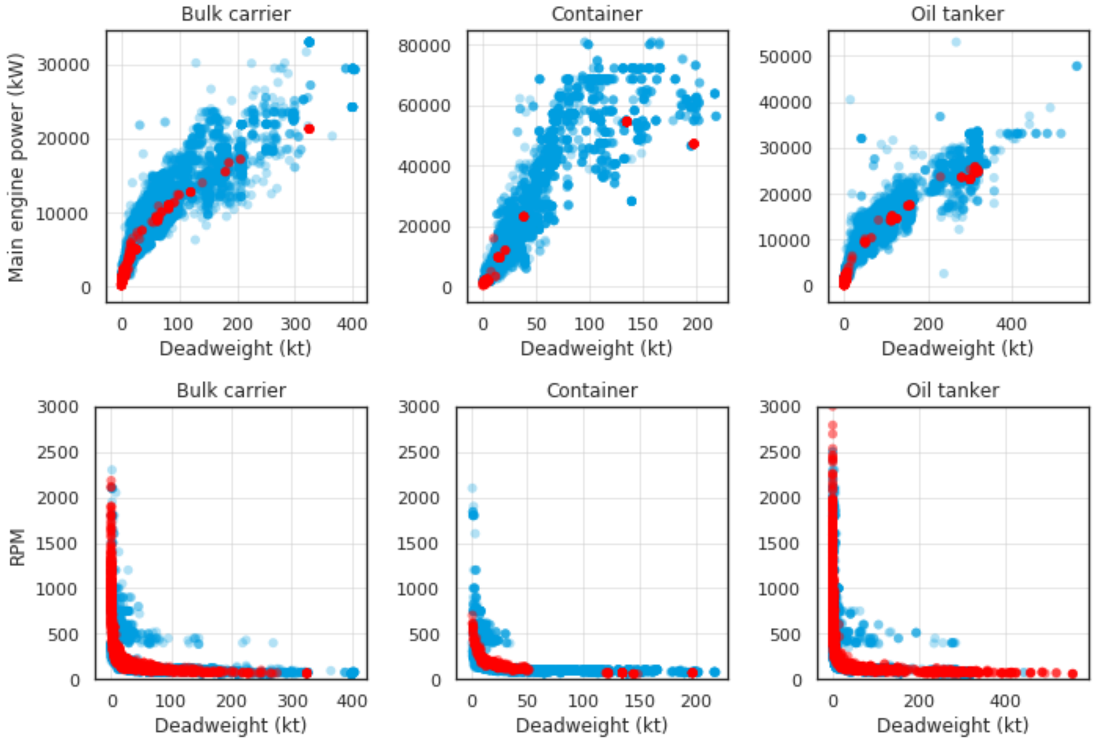
— Length overall (meters):
$$loa = b_1 + b_2 \cdot beam + b_3 \cdot draught + b_4 \cdot deadweight \quad (1)$$
— Capacity depending on vessel type:
$$capacity = b_1 + b_2 \cdot beam + b_3 \cdot draught + b_4 \cdot loa \quad (2)$$
— Design/service speed (knots):
$$speed = b_1 + b_2 \cdot loa + b_3 \cdot power_{ME} + b_4 \cdot deadweight \quad (3)$$
— Main engine installed power (kW)
$$power_{ME} = b_1 + b_2 \cdot loa + b_3 \cdot speed + b_4 \cdot deadweight \quad (4)$$
— Main engine RPM:
$$RPM_{ME} = b_1 + b_2 \cdot speed + b_3 \cdot power_{ME} + b_4 \cdot deadweight \quad (5)$$

Since both beam and draught serve as a base starting point in the estimation of length and capacity metrics, the missing values for these metrics were infilled first, based on median values per type and size category.

Figure 28 below illustrates the above regressions fit to each of the major vessel type categories for infilling missing length overall, design speed, installed main engine power, and rpm. The 'predicted' values are those that have been infilled and 'actual' values are those metrics originally listed in the IHS database. For ships that could not be infilled due to too many missing entries, the median values per type and size were used.

Figure 28 - Example fits when infilling missing technical specification using multilinear regression approach





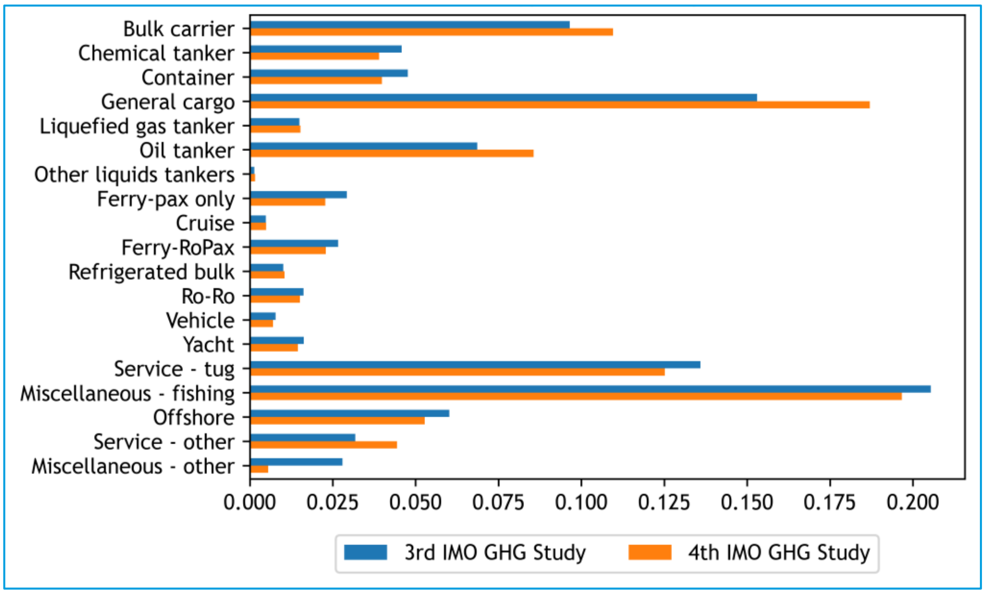
Source: UMAS.

A share of the infilled records varies depending on a metric and a year of interest whereas the number of missing values is increasing with the increasing year because more vessels are being detected overtime from the cumulative IHS database. With regards to the metrics, the relationship is slightly different. For example, length overall and main engine power were originally very well populated in the IHS database. For these metrics the proportion of the infilled points is less than 3%. The population of metrics such as deadweight, speed and rpm are slightly less dense where the proportion of infilled values accounts for up to 15%.

Allocation of ship type categories

The principles used for vessel aggregation apply definitions closely aligned with those used in the Third IMO GHG Study 2014, that in turn originated from classification methodologies for EEDI (IMO, 2013a; 2013b)and have been expanded for ship classes not included in the EEDI methodology. The EEDI methodology ensures that vessel types are consistent with the categorization method defined in the IHS database. Each vessel listed in the IHS database is accompanied by one of 258 unique StatCode5 designations that further disaggregates the fleet by vessel functionality. The mapping from these granular categories to the 19 IMO ship types is aligned as closely as possible with the Third IMO GHG Study 2014, but has been updated to align with the new ship coding system released by IHS Markit in (2017).

Figure 29 - IHS ship type allocation proportions comparison between the 3rd IMO GHG and this study



Source: UMAS.

Figure 29 compares the proportion of ships in each IHS database from the Third IMO GHG Study 2014 and the current study. The differences between the two proportional allocations are caveated by noting that the Third IMO GHG Study 2014 used a discrete IHS database for each year under consideration, whereas the current study employed a cumulative database of all years up to 2018. The most significant changes in mapping between the two studies occurred in the 'Miscellaneous — other', 'Service — other', and 'Other liquids tankers', though as can be seen in Figure 29, these represent a small proportion of the overall fleet size and a very small proportion of the overall fleet emissions profile. The largest proportional differences in 'General cargo', 'Bulk carrier', and 'Oil tanker' are not explained by changes in type allocation as the StateCode5 categories for these types is highly unambiguous.

Table 6 outlines the 19 IMO ship types and the four principal groupings used by the IHS. The majority of international shipping falls in the 'Cargo-carrying transport ships' group and represents the main focus of this study. The other categories principally capture domestic shipping and are key to the comparison of the top-down and bottom-up inventories.

Table 6 - Vessel type groupings

Vessel group	Vessel class
Cargo-carrying transport ships	1 - Bulk carrier
	3 - Chemical tanker
	4 - Container
	5 - General cargo
	6 - Liquified gas tanker
	7 - Oil tanker
	8 - Other liquids tanker
	9 - Ferry - passengers (pax) only
	10 - Cruise
	11 - Ferry - roll-on/passengers (ro-pax)

Vessel group	Vessel class
	12 - Refrigerated cargo
	13 - Roll-on/roll-off (Ro-Ro)
	14 - Vehicle
Non-merchant ships	15 - Yacht
	17 - Miscellaneous - fishing
Work vessels	16 - Service - tug
	18 - Offshore
	19 - Service - other
Non-seagoing merchant ships	20 - Miscellaneous - other

Allocation of ship size categories

Given that the Third IMO GHG Study 2014 was conducted in 2012, a review of vessel size categories is included in this study to assess the adequacy of existing size definitions that accounts for the changes in fleet demographics. Another factor considered is the current trend in shipbuilding to ensure that any updates remain relevant in the near future.

Backwards compatibility with the Third IMO GHG Study 2014 is ensured by only applying additional size categories which subdivide those used in the earlier study, such that the current study's results can be aggregated across the new size categories if required. With these changes, the accuracy of estimates within size bins increases due to reduced variation, making the overall carbon inventory calculation more precise as well as being more useful to operators in particular markets. The importance of this structural change is increasingly relevant due to the importance of carbon intensity-based metrics and policy drawing on this study for benchmarking purposes.

General fleet overview

Table 7 presents an overview of the global fleet as in the IHS vessel database (vessels in service as of mid-2018) with the associated vessel types arranged in descending order based on the proportion of the total Deadweight Tonnage (DWT) that they represent. The top five vessel types account for 90% of tonnage but only 40% of the actual population, with the remaining 15 categories splitting the rest. This implies that changes to the deep-sea fleet will have a large impact on the overall accuracy of emissions estimates.

Table 7 - Global fleet vessel number and deadweight proportion by type

IMO Type	Type	Count	% Count	DWT	% DWT
1	Bulk Carrier	11,672	9.8	8.1E+08	41.5
7	Oil Tanker	8,177	6.8	4.9E+08	25.1
4	Container	5,182	4.3	2.6E+08	13.4
3	Chemical Tanker	5,506	4.6	1.1E+08	5.6
5	General Cargo	14,994	12.5	8.1E+07	4.2
18	Offshore	7,555	6.3	7.4E+07	3.8
6	Liquefied Gas Tanker	1,953	1.6	6.5E+07	3.3
14	Vehicle	828	0.7	1.3E+07	0.7
19	Service - Other	6,180	5.2	1.2E+07	0.6
13	Ro-Ro	2,002	1.7	6.4E+06	0.3
16	Service - Tug	20,251	16.9	5.8E+06	0.3
17	Miscellaneous Fishing	23,911	20.0	4.8E+06	0.2

IMO Type	Type	Count	% Count	DWT	% DWT
12	Refrigerated Bulk	895	0.7	4.4E+06	0.2
11	Ferry - Ro-Pax	3,148	2.6	4.1E+06	0.2
20	Miscellaneous - Other	645	0.5	4.0E+06	0.2
10	Cruise	612	0.5	2.2E+06	0.1
8	Other Liquids Tankers	179	0.1	4.3E+05	0.0
9	Ferry - Pax Only	3,459	2.9	3.1E+05	0.0
15	Yacht	2,477	2.1	2.8E+05	0.0

In light of analysis of vessel types and sizes, an update to vessel size bins is presented in Table 8 in order to ensure the development of the fleet between 2012 and 2018 is captured accurately whilst also considering future fleet development.

Under the following headings, the vessel size categories that have been updated are analysed and justified. Further details regarding all size allocations can be found in Annex G In order to compare the implications of using the established size bins from Third IMO GHG Study 2014 and assess the need for changes, two plots were drawn up for each vessel type. Firstly, histograms for ship types are presented to assess the number of vessels that fall into each size bin, revealing whether any particular tonnages are misrepresented. Secondly, to judge the development of the global fleet over a ten-year period from 2008 to 2018, a time series is drawn for each vessel type with the associated representation in each type bin. This identifies historic and possibly new trends to help assess the efficacy of representation by the current and proposed size bins.

Table 8 - Updated vessel type and size categories

Type bin	IMO4 size bin	Capacity	Unit	IMO3 size bin	Type bin	IMO4 size bin	Capacity	Unit	IMO3 size bin
Bulk carrier	1	0-9,999	DWT	1	Other liquids tankers	1	0-999	DWT	1
	2	10,000-34,999	DWT	2		2	1,000-+	DWT	1
	3	35,000-59,999	DWT	3	Ferry-pax only	1	0-299	GT	1
	4	60,000-99,999	DWT	4		2	300-999	GT	1
	5	100,000-199,999	DWT	5		3	1,000-1,999	GT	1
	6	200,000-+	DWT	6		4	2,000-+	GT	2
Chemical tanker	1	0-4,999	DWT	1	Cruise	1	0-1,999	GT	1
	2	5,000-9,999	DWT	2		2	2,000-9,999	GT	2
	3	10,000-19,999	DWT	3		3	10,000-59,999	GT	3
	4	20,000-39,999	DWT	4		4	60,000-99,999	GT	4
	5	40,000-+	DWT	4		5	100,000-149,999	GT	5
Container	1	0-999	TEU	1		6	150,000-+	GT	5
	2	1,000-1,999	TEU	2	Ferry-RoPax	1	0-1,999	GT	1
	3	2,000-2,999	TEU	3		2	2,000-4,999	GT	2
	4	3,000-4,999	TEU	4		3	5,000-9,999	GT	2
	5	5,000-7,999	TEU	5		4	10,000-19,999	GT	2
	6	8,000-11,999	TEU	6		5	20,000-+	GT	2
	7	12,000-14,499	TEU	7	Refrigerated bulk	1	0-1,999	DWT	1
	8	14,500-19,999	TEU	8		2	2,000-5,999	DWT	1

Type bin	IMO4 size bin	Capacity	Unit	IMO3 size bin
	9	20,000-+	TEU	8
General cargo	1	0-4,999	DWT	1
	2	5,000-9,999	DWT	2
	3	10,000-19,999	DWT	3
	4	20,000-+	DWT	3
Liquefied gas tanker	1	0-49,999	CBM	1
	2	50,000-99,999	CBM	2
	3	100,000-199,999	CBM	2
	4	200,000-+	CBM	3
Oil tanker	1	0-4,999	DWT	1
	2	5,000-9,999	DWT	2
	3	10,000-19,999	DWT	3
	4	20,000-59,999	DWT	4
	5	60,000-79,999	DWT	5
	6	80,000-119,999	DWT	6
	7	120,000-199,999	DWT	7
	8	200,000-+	DWT	8

Type bin	IMO4 size bin	Capacity	Unit	IMO3 size bin
	3	6,000-9,999	DWT	1
	4	10,000-+	DWT	1
Ro-Ro	1	0-4,999	DWT	1
	2	5,000-9,999	DWT	2
	3	10,000-14,999	DWT	2
	4	15,000-+	DWT	2
Vehicle	1	0-29,999	GT	1
	2	30,000-49,999	GT	2
	3	50,000-+	GT	2
Yacht	1	0-+	GT	1
Service - tug	1	0-+	GT	1
Miscellaneous - fishing	1	0-+	GT	1
Offshore	1	0-+	GT	1
Service - other	1	0-+	GT	1
Miscellaneous - other	1	0-+	GT	1

Chemical tankers

A rise in 50,000 DWT chemical tankers from 2012 onwards identified by the spike in Figure 30 and the increase in deadweight in Size 4 seen in Figure 31. This results in the largest size category bin in the Third IMO GHG Study 2014 having vessels with a large variation in operating profile and market segmentation, thus an additional size bin at 40,000 DWT has been introduced to account for this.

Figure 30 - A comparison of size bins for the chemical tanker fleet

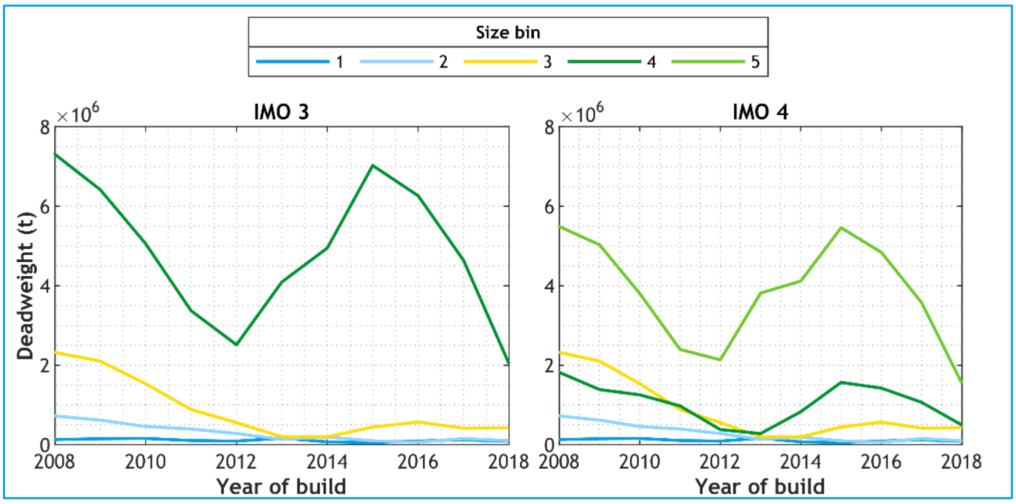
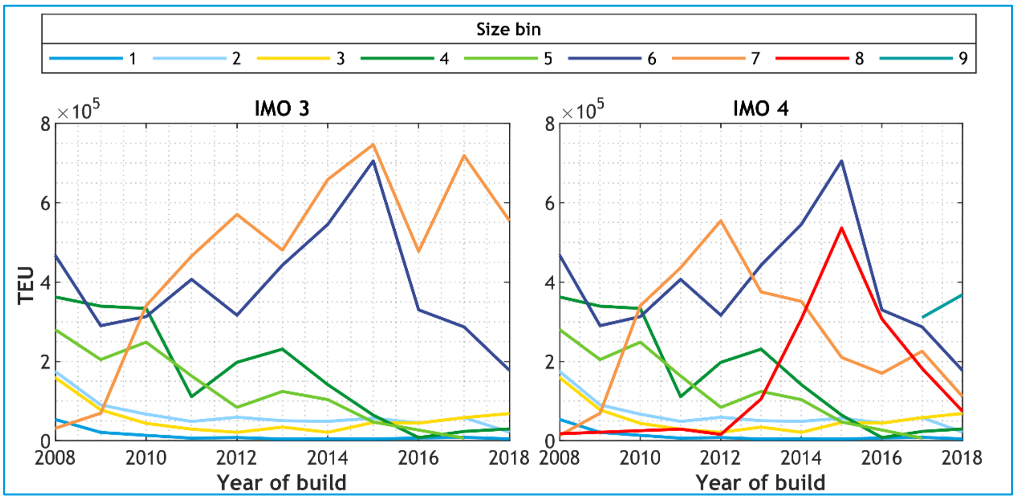


Figure 31 - A time series of size bins for the chemical tanker fleet



Source: UMAS.

Container ships

Throughout the second half of the 2000's and 2010's, the market has seen a rise in popularity of container vessels of increasing capacity going up to over 20,000 Twenty-foot Equivalent Units (TEUs, Figure 32). This took place in two steps, with vessels going up from 15,000 to 20,000 TEU in the first instance and then moving above 20,000 TEU later in the decade (Figure 33). To this end, the largest size category bin has been split to account for this and also accommodate possible future introduction of vessels with higher capacities, considering the projected increase in transport demand of around 4.5% annually (UNCTAD, 2019).

Figure 32 - A time series of size bins for the container fleet

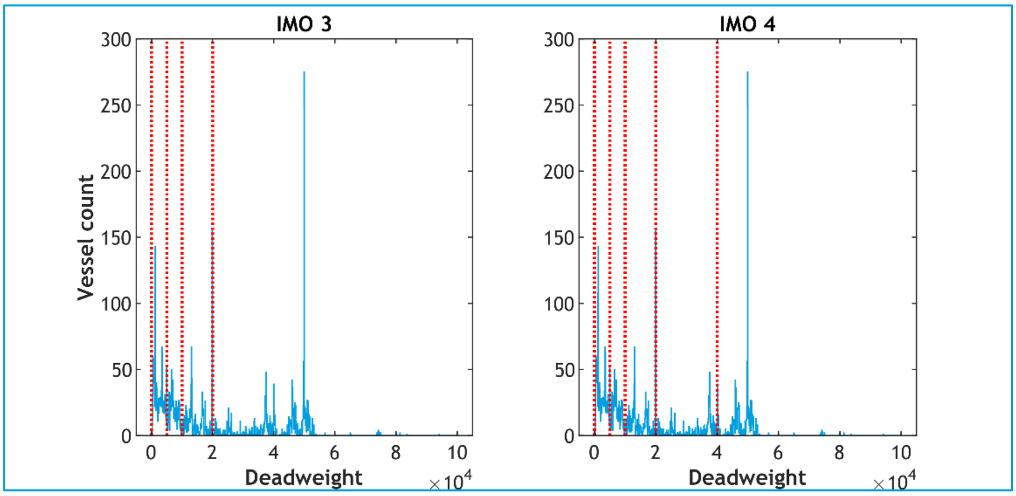
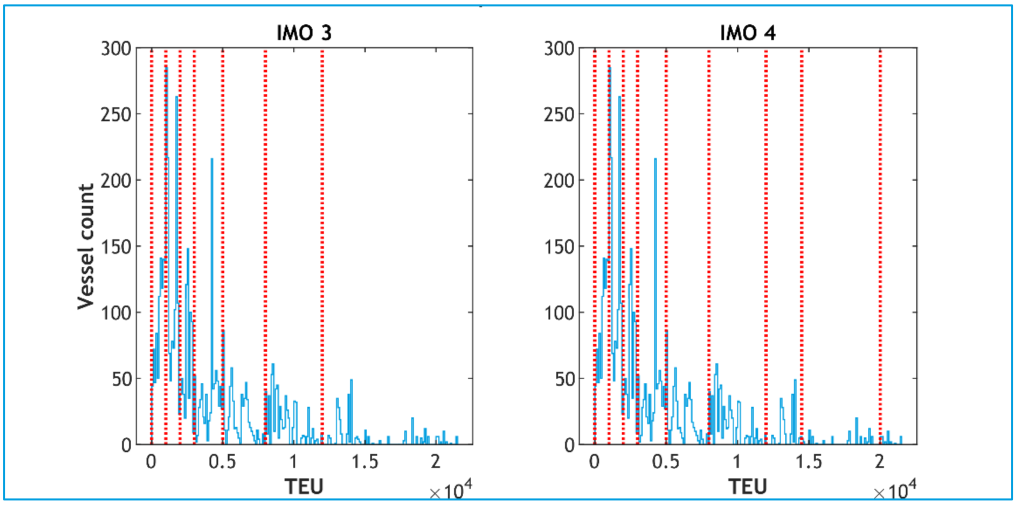


Figure 33 - A comparison of size bins for the container fleet



General cargo

This type category is very diverse in the nature of its vessel characteristics and cargos. Some examples include heavy lift vessels, lumber, livestock, and combination carriers. This factor makes the interpretation of trends difficult; however, a long tail is observed in Figure 34, thus the largest bin has been divided into two to be more representative of the current demographic.

Figure 34 - A comparison of size bins for the general cargo fleet

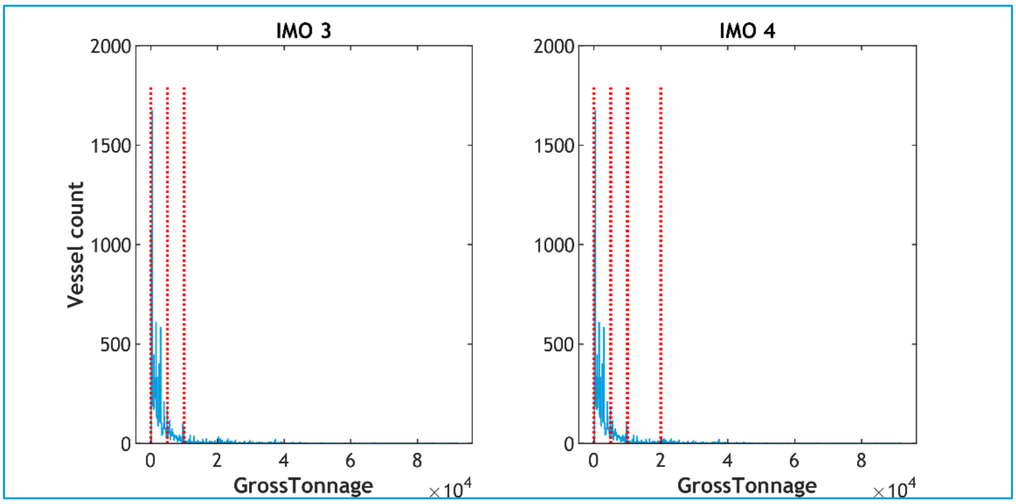
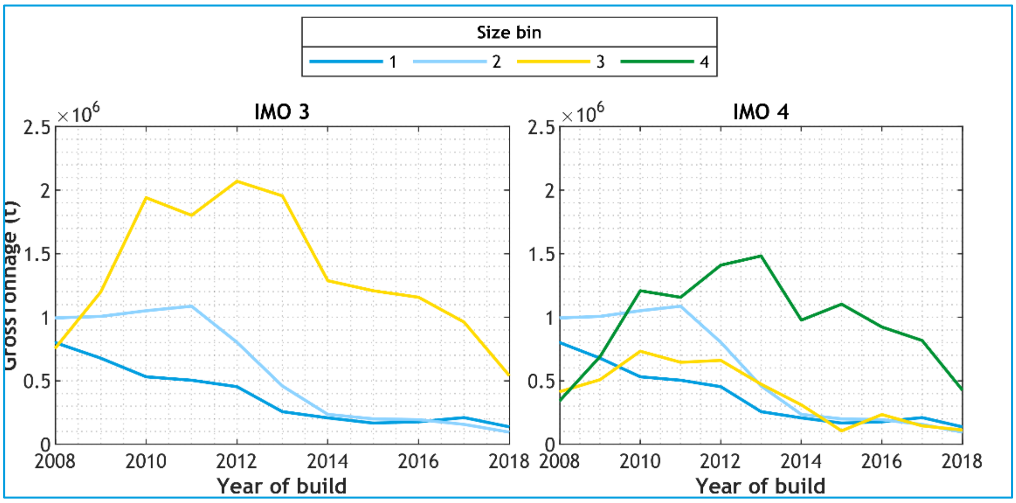


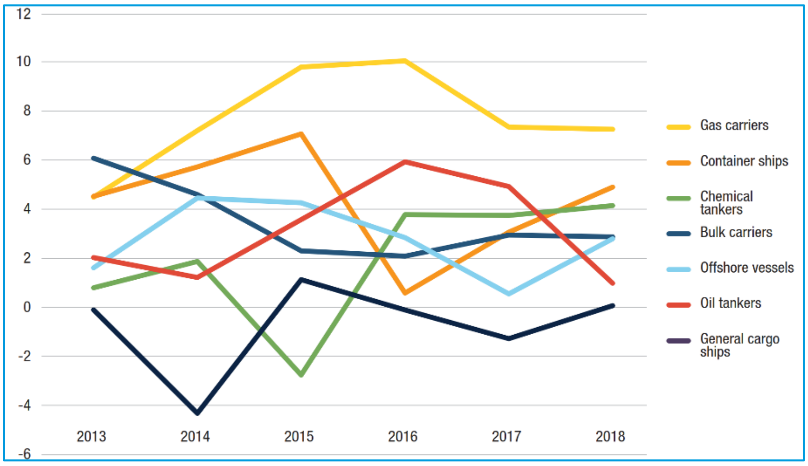
Figure 35 - A time series of size bins for the general cargo fleet



Liquified gas tankers

The market for liquefied gas tankers has developed significantly since 2012, with the Liquified Natural Gas (LNG) market specifically seeing many newbuilds creating new segments in the fleet (Figure 36). Smaller vessels are predominantly used for the transport of Liquified Petroleum Gas (LPG) while larger vessels are used in the LNG sector. Thus, the vessel type has been split further into four size bins, with the first two dominated by LPG vessels and the latter by LNG vessels (Figure 37). Figure 38 shows that the boom in vessel building was mostly in the size 2 bin, which was capturing two families of vessels that have been split in the updated size bins for better segment representation.

Figure 36 - Growth of world fleet (annual percentage change in deadweight tonnage)



Source: (UNCTAD, 2019).

Figure 37 - A comparison of size bins for the liquified gas tanker fleet.

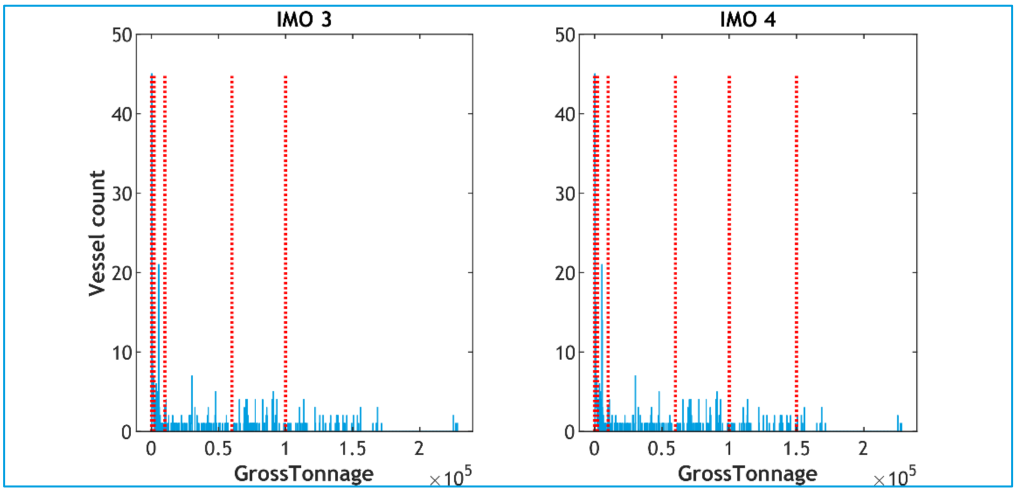
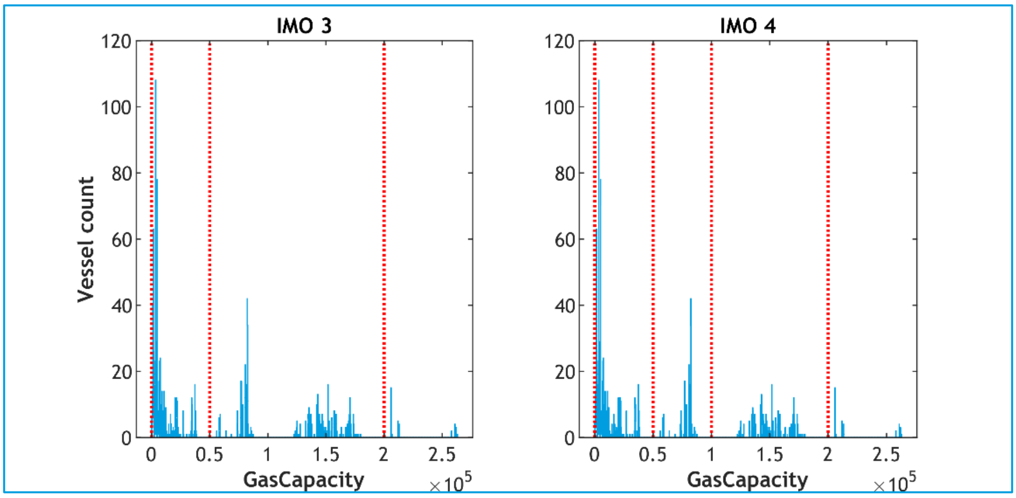


Figure 38 - A time series of size bins for the liquified gas tanker fleet



Source: UMAS.

Cruise

The cruise industry has seen growth in shipbuilding with designs increasing in size over the years from 2012 (Figure 40) and passenger numbers increasing by 10% over the 2008-2018 period (CLIA, 2020). The addition of a size bin at the larger end creates a distinct new category at the higher end of the tonnage scale, while also accommodating further development of the fleet into larger sizes if the market continues to grow as it has in the recent past.

Figure 39 - A comparison of size bins for the cruise fleet

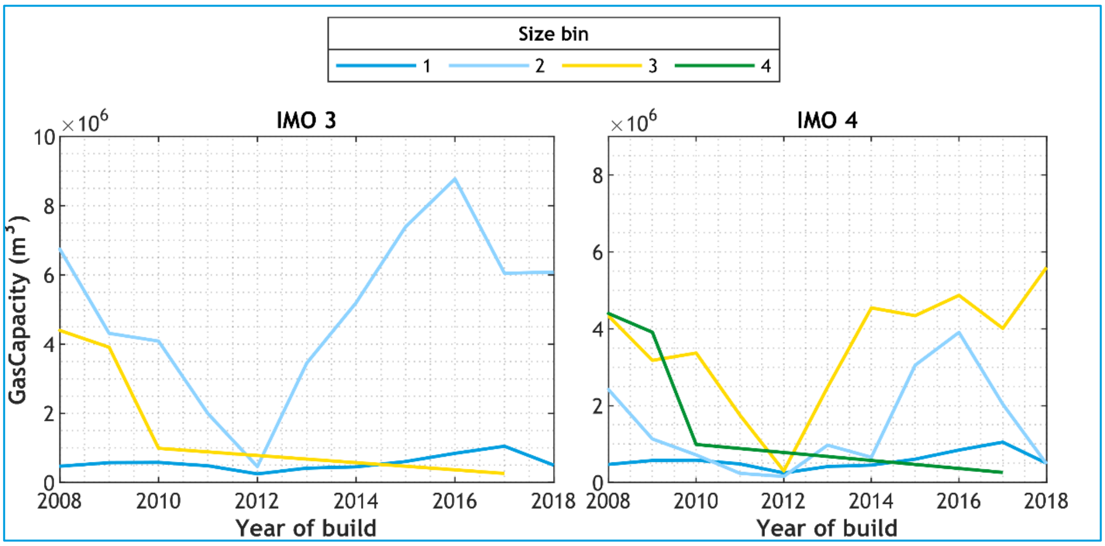
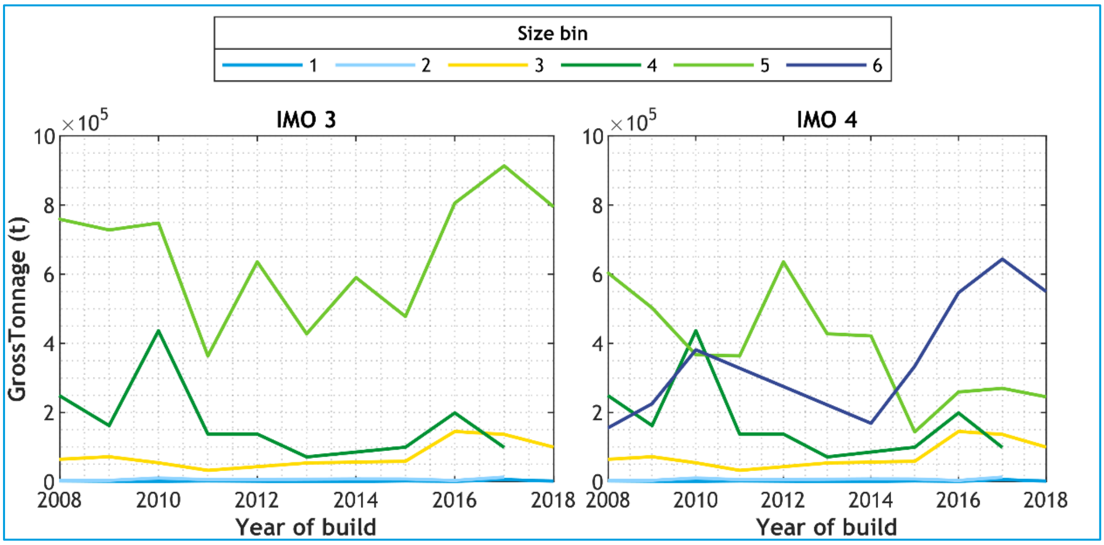


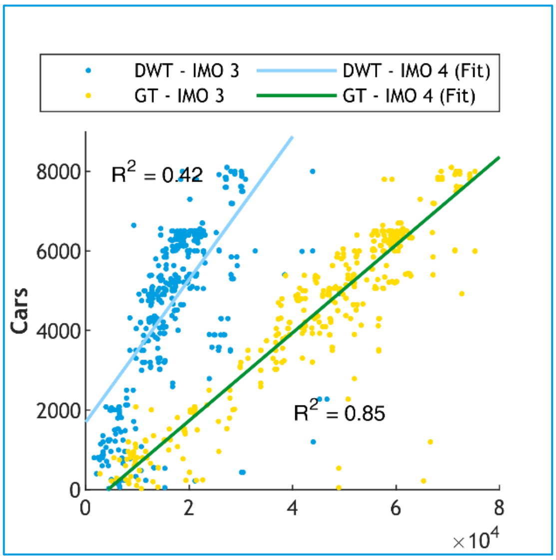
Figure 40 - A time series of size bins for the cruise fleet



Vehicle carriers

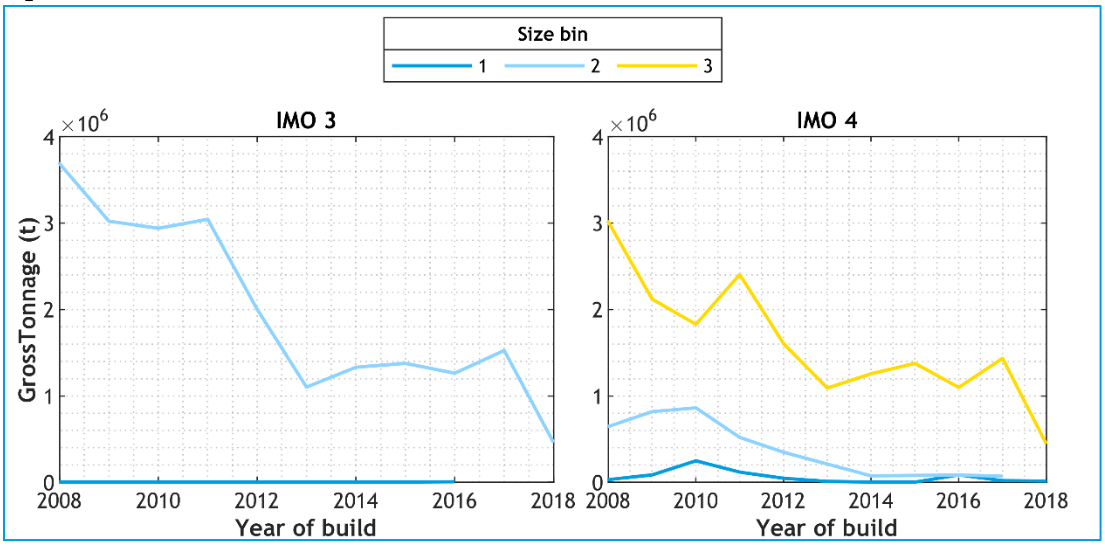
The IHS vessel database used in this study does not define car-carrying capacity for car carriers, therefore a proxy had to be found to define size category bins. A check for the correlation of car capacity with geometric features was carried out using the vessel database from the Third IMO GHG Study 2014. Deadweight and gross tonnage were considered, and gross tonnage was found to be strongly correlated with vessel capacity, thus size bins have been redefined accordingly (Figure 41).

Figure 41 - Vehicle carrier size proxy comparison



Source: UMAS.

Figure 42

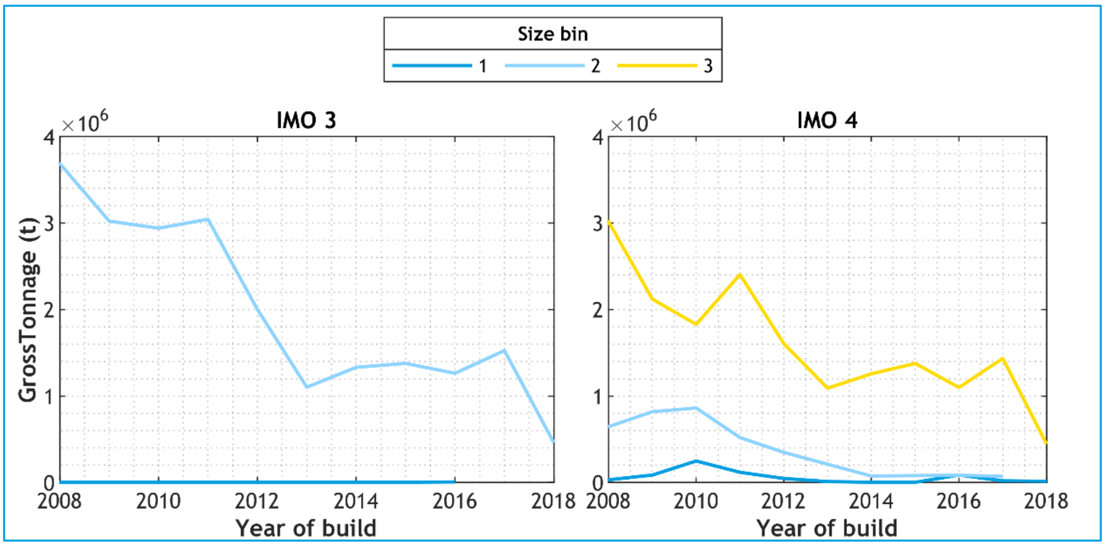


illustrates how the vehicle number-based size bins in the Third IMO GHG Study 2014 translate into gross tonne-based bins. The proposed GT-based size bins account for the peak at the 60,000 GT mark and also the family of smaller vessels below 30,000 GT.

Figure 42 - A comparison of size bins for the vehicle carrier fleet

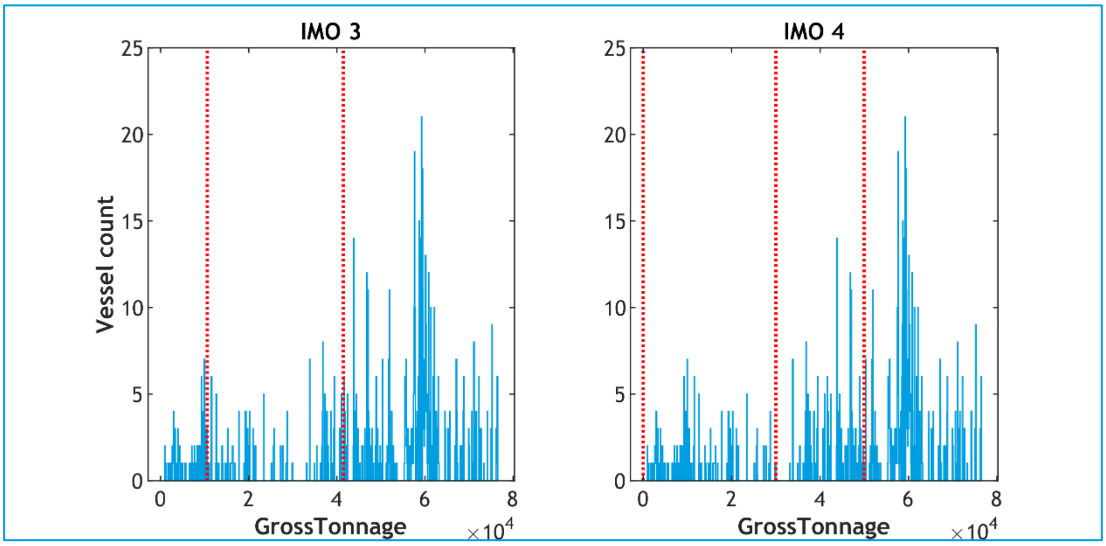
Figure 43 illustrates how size bin 2 is divided to represent the higher and lower edges more evenly.

Figure 43 - A time series of size bins for the vehicle carrier fleet



Ro-Ro, Refrigerated bulker, Ferry-RoPax, Ferry-pax only, other liquid tankers

For these vessel types, long tails were observed which lead to the largest size bin being segmented into smaller bins as large variation was observed which was not accounted for by the size bins in the Third IMO GHG Study 2014.



Fuel type allocation

Fuel type is one of the most important inputs to the model due to its key role in converting energy demand into fuel consumption and in defining empirical emission factors. First, vessels with full or partial information on their fuel type usage are allocated a fuel type as per the process detailed below. Once vessels with available information have been allocated a main fuel, the dataset is grouped by vessel type and size to identify the most common fuel for each group. The results are then used to infill the details of vessel fuel type without reported data in the IHS data set.

Fuel selection process

The IHS database provides a description of the fuel types used by each vessel under two headings: “FuelType1First” describing the lightest fuel and referred to here as ‘Fuel 1’, and “FuelType2Second” describing the densest fuel, referred to here as ‘Fuel 2’. Table 9 outlines the procedure used to select the most representative main fuel of the two for each vessel. The fuel types selected as main fuels for use in the Fourth IMO GHG Study model are listed in the column “Allocated fuel”. The second column explains the conditional logic used to arrive at this allocation, while the third column explains the reasoning behind the selection. An ‘NA’ in the IHS database for either fuel can indicate either “Unknown”, “Not Applicable”, or “Yes, but type not known”.

Table 9 - Allocation algorithm for the main engine fuel type

Allocated fuel	Condition	Reasoning
Heavy Fuel Oil (HFO, Residual fuel)	Fuel 1 or Fuel 2 is “Residual Fuel”	HFO is the most common residual fuel used in marine ships and is less expensive than distillate fuels.
	Exemption: if propulsion type is “Steam Turbine” and vessel type is “liquefied gas tanker” then the allocated fuel type is “LNG”.	
MDO (Distilled fuel)	Fuel 1 and Fuel 2 are “Distilled Fuel”	No other fuel is reported.
	Fuel 1 or Fuel 2 is “Distilled Fuel” and the remaining column is “NA”***	Only Distilled Fuel is reported either as lighter or denser fuel
	Fuel 1 is “Coal” and Fuel 2 is “Distilled Fuel”	Given that coal is not competitive enough in terms of costs and energy density, it is assumed that a ship is likely to operate on Distillate Fuel
	Exemption: Fuel 1 is “Methanol” and Fuel 2 is “Distilled Fuel”	*Exemption: twelve vessels were found to be Methanol propelled. Given the potential of this fuel to become more widespread in the future, these vessels were allocated Methanol rather than Distilled Fuel.*
LNG (Gas boil-off)	Fuel 1 or Fuel 2 is “Residual fuel”, propulsion type is “Steam”, and ship type is “Liquefied gas tanker”	All vessels with a steam turbine and are liquefied tankers are allocated LNG.
	Fuel 1 is “Gas boil-off” and Fuel 2 is “Distilled fuel”	Gas boil-off engines use LNG.
	Fuel 1 is “LNG” and Fuel 2 is “Distilled fuel”	From these two options, LNG is more likely to be used as the main fuel, based on the assumption that the investment required for them to be compatible with LNG can only be recovered with the use of this fuel type.

Allocated fuel	Condition	Reasoning
	Fuel 1 or Fuel 2 is “LNG” and the remaining column is “NA”	Only “LNG” is provided in the data.
	Fuel 2 is “Gas boil-off”	Used by LNG carriers, “Gas boil-off” is the use of excess or evaporated LNG as main engine fuel. This is done to regulate the pressure within the LNG cargo tanks.
Nuclear	Fuel 1 is “Nuclear” and Fuel 2 is “Distilled fuel”	Most vessels in this bracket are icebreakers with high power demand.
	Fuel 1 is “Nuclear” and Fuel 2 is “NA”	Only “Nuclear” is provided in the fuel specifications.
Coal	Fuel 1 is “Coal” and Fuel 2 is “NA”	Only “Coal” is provided in fuel specifications.
Methanol	Fuel 1 is “Methanol”	As with the explanation for MDO, the second fuel is always “Distillate” but Methanol is allocated.

Missing fuel type

Through the procedure outlined above, a main engine fuel type was assigned to approximately 50% of the vessels reported in the IHS database. The remaining vessels could not be allocated a main engine fuel type due to the Fuel 1 and Fuel 2 parameters containing missing or ambiguous entries. For these vessels, the median fuel per type and size category is allocated based on the results of the successfully allocated vessels. The majority of the remaining 50% where the fuel type is missing or ambiguous are spread across the following categories: 29% - “Miscellaneous – fishing”, 18% - “General cargo” and 17% - “Service - tug”. The implications of this selection are rather marginal as most of these vessels are small or are labelled with a “broken up” ship status.

Auxiliary engine and boiler fuel type

The procedure above describes how the main engine fuel allocation is performed. However, for the fuel allocation of auxiliary machinery and boiler there is negligible data from IHS data and assigning the same fuel as the main engine is a highly uncertain approach. Instead, a similar approach to the Third IMO GHG Study 2014 based on statistics from the top-down approach and as reference the fuel allocation done in the Second IMO GHG Study 2009.

Main engine type allocation

The IHS database provides various fields containing information that is suitable for classifying the main engine type of each vessel. This includes the propulsion type, generic engine family, fuel type, revolutions per minute (RPM), engine number of strokes, engine brand, and model. To cover the widest range of possible engine types while still meeting the scope of the bottom-up emissions inventory, the taxonomy of engine types was reduced to 12 as shown in Table 10. This table lists a percentage share of the allocated engine types for each of the years inside the scope of this study. Please note that this table only covers in service vessels that were matched with the IHS database by either IMO (Type 1) or MMSI (Type 2) and had valid AIS data hence all vessels covered by the bottom-up emissions inventory. Vessels accounted for by the IHS dataset but missing the required details associated with engine type were assigned with the median engine type for its specific ship class and size. This is found from those vessels for which the relevant data was available.

Table 10 - Engine types annual percentage share for Type 1 and Type 2 vessels

Engine Type	2012	2013	2014	2015	2016	2017	2018
Percentage (%)							
Slow-Speed Diesel (SSD)	42.3	40.7	39.8	39.2	39.1	38.8	38.6
Medium-Speed Diesel (MSD)	34.7	34.7	34.2	33.9	34.0	39.9	33.6
High-Speed Diesel (HSD)	21.6	23.2	24.5	25.4	25.4	25.7	26.2
Percentage ($1x10^{-2}$ %)							
LNG-Otto Slow-Speed (SS)	0.2	0.6	0.9	0.9	1.6	2.5	3.6
LNG-Otto Medium-Speed (MS)	11.6	14.7	19.8	23.7	27.6	30.6	34.8
LNG-Diesel	0.2	0.2	0.2	0.6	2.4	4.6	7.6
Lean Burn Spark-Ignited (LBSI)	3.8	4.2	5.1	6.0	5.7	6.0	5.7
Methanol (both SS and MS)	-	-	-	0.3	1.3	1.3	1.4
Gas Turbine	11.3	11.0	11.0	10.6	11.2	10.3	9.8
Sail	28.1	27.3	27.6	28.6	29	29.5	30.5
Steam Turbine	54.9	50.3	48.9	46.3	42.5	41.7	42.0
Batteries	0.2	0.2	0.2	0.3	0.3	0.7	2.3
Non-Propelled	24.5	29.9	31.5	30.8	27.5	27.3	31.1

The engine classification method and conditions used to allocate each vessel to one of these main engine types are described below.

Oil Engines

The main classification threshold for oil engines (i.e. that consumes fuel oil) is the "propulsion types category" field in the IHS database. According to this field, the following vessels will have their engines classified as oil engines: *"Oil Engine(s), Electric Drive", "Oil Eng(s) & Gas Turb(s) El.D", "Oil Eng(s), Elec-Dr, Aux Sail", "Oil Engines, Direct & Elec. Dr", "Oil Engines, Elec. & Geared Dr", "Engines, Geared & Elec. Dr", "Eng(s) Direct Dr, Aux Sail", "Engs & Gas Turb(s)", "Geared, Engine(s), Direct Drive", "Engine(s), Geared Drive", "Oil Eng(s), Geared, Aux Sail", "Engines, F&S, Geared Drive", "Oil Engine(s), Drive Unknown"*. All oil engines were assumed to be powered by diesel cycles, with the sub-classification outlined below:

1. **Slow-Speed Diesel (SSD):** All main engines where the main propulsion type description contains "Oil" are assumed to be two-stroke engines with an engine speed lower than or equal to 300 RPM. This engine type was assumed to be the default option for all oil-propelled ships that could not be identified in any other category.
2. **Medium-Speed Diesel (MSD):** All engines where the main propulsion type contains "Oil" with an engine speed ranging from 300 to 900 RPM.
3. **High-Speed Diesel (HSD):** All engines for which the main propulsion type contains "Oil" with an engine speed above 900 RPM or the word "Petrol" was found in this field.

LNG Engines

Expanding on the methodology of the Third IMO GHG Study 2014, this study considers various internal combustion engine types that can be fueled by LNG. The fuel type "LNG" in the IHS fuel headings is the principal characteristic that allows the identification of LNG engines, and is further sub-divided, thus:

1. **LNG-Otto SS**: Two-stroke, slow-speed, dual-fuel engines that operate similar to the Otto cycle. These engines were identified as those with engine model names containing "X"

and "DF". To date, these engines have been sold as WinGD engines built by Wärtsilä. Recently, MAN Energy Solutions announced that they will produce Otto cycle, 2-stroke, dual-fuel engines that will be called "ME-GA", so the selection procedure will need to be updated to reflect this for emissions inventories for the year 2020 and later.

2. **LNG-Otto MS**: Four-stroke, medium-speed, dual-fuel engines that operate on the Otto cycle. These engines were identified as any four-stroke LNG engine with an engine speed above 300 RPM, except those engines identified as LBSI (see below). Also, this category includes LNG engines not otherwise classified under any other LNG category.
3. **LNG-Diesel:** Two-stroke, slow-speed, dual-fuel engines that operate on the Diesel cycle. These engines were identified by selecting those engine model names containing "ME". These engines have so far only been built by MAN Energy Solutions. This procedure will need to be changed in the future because MAN Energy Solutions recently announced that they will produce Otto cycle, 2-stroke, dual-fuel engines that will be called "ME-GA".
4. **LBSI:** Four-stroke, medium-speed, mono-fuel engines that are low-pressure-injection and ignite the gas/air mixture in the cylinder using a spark. These engines are mainly built by Rolls-Royce/Bergen, although there may be other manufacturers. For this study, LNG engines built by Rolls-Royce/Bergen were identified as LBSI. This procedure could be improved for future studies.

Other Engines

The classification of other engine types seen in shipping is dependent on the following conditions:

1. **Methanol:** All vessels that are allocated Methanol as their main fuel type. These were further classified as SS for engine speeds lower than or equal to 300 RPM, and MS if above 300 RPM.
2. **Gas turbine**: Vessels whose propulsion type is specified as "Gas Turbine", or vessels previously classified as Oil Engines (SSD or MSD) but with the fuel type classified as "Gas".
3. **Sail:** Vessels whose propulsion type classification contains "Sail".
4. **Steam Turbine**: Vessels whose propulsion type classification contains "Steam Turbine". This includes ships fueled by oil-based fuels and those powered by LNG or boil-off gas.
5. **Batteries**: Vessels whose propulsion type classification contains "Batteries".
6. **Non-Propelled**: Vessels whose propulsion type classification contains "Non propelled".

Main engine NO_x tier allocation

According to Regulation 13 of MARPOL Annex VI (IMO, 2013b), ships with marine engines rated above 130 kW are subject to maximum NO_x emissions per kilowatt-hour based on their age and rated engine speed. Following this convention, tiers were allocated to each vessel based on the "keel laying year" field specified in the IHS dataset (see Table 11). Vessels built before the 1st of January 2000 were allocated "Tier 0".

Table 11 – Engine tier differentiation per year of manufacturing.

Tier	Construction Date
0	Before 1st of Jan 2000
I	After 1st of Jan 2000
II	After 1st of Jan 2011
III	After 1st of Jan 2016

Tier III NO_x limits apply only to vessels operating in NECA, outside such areas Tier II limits apply.

Engine Generation

There are three different engine generations for the internal combustion engines defined by the ship's construction year as registered in the IHS database. Distinct generations allow the differences in the internal combustion engine's energy efficiency evolution through the changes in Specific Fuel Consumption (SFC) to be captured. This is the same age classification methodology used in the Third IMO GHG Study 2014, and are listed below:
- *Generation 1*: Any engine built before 1984.
- *Generation 2*: Any engine built between 1984 and 2000.
- *Generation 3*: Any engine built after 2000.

2.2.2 Matching AIS vessels with technical specifications

The bottom-up methodology requires both the technical specifications and activity data for each vessel in the global fleet. For the majority of cases in the international fleet, there is a single unambiguous pairing each year between a vessel's technical specifications in the IHS database and the voyage activity in the AIS dataset. However, a methodology is needed to match the significant minority of ships that have no recorded activity in the AIS dataset yet appear as active in the IHS database, or vice versa, in addition to clearly differentiating those with duplicated IMO or MMSI values from either data source.
Each vessel in the IHS database is identified by a unique 7-digit IMO number and, with moderate frequency, an accompanying 9-digit MMSI number identifying the transponder installed on the vessel. Conversely, the AIS dataset contains activity messages that are identified by an MMSI number and infrequently a non-unique IMO number. To segment the vessel matching procedure, we identify four types of vessels predicated on the combination of these factors with which they were identified. Each matching type takes precedence over the next, i.e. if a vessel is matched as Type 1, it will not be subsequently matched as Type 2. These types are described below, and summarized in Table 12.

1) Type 1 —– Vessels that have a matching IMO number in both the IHS and AIS datasets. These are the strongest matches as the IMO number is unique to the vessel and will not change in its lifetime.
2) Type 2 —– Vessels that have a matching MMSI number in both the IHS and AIS datasets but do not have a valid IMO number in the AIS dataset.
3) Type 3 — Vessels that are observed in the AIS dataset, cannot be matched as Type 1 or Type 2 vessels, but have valid MMSI entries in the AIS datasets, at least one period of continuous activity lasting longer than 24 hours, and are heavier than 100 GT. Vessels could appear in this category due to faulty AIS transponders, incomplete records in the IHS database, or operate in a domestic capacity only and hence not requiring registration with the IHS; this distinction is particularly important for those vessels under cabotage. In order to estimate the activity of these Type 3 vessels, their presence in the Global Fishing Watch (GFW) database is checked. The number of vessels successfully matched in this way are also included in a separate column in Table 12.
4) Type 4 — Vessels that appear as 'active' in the IHS dataset but are not observed in the AIS dataset by their IMO or MMSI number, and weigh between 100 and 300 GT. This range is chosen to eliminate vessels less than 100 GT that are excluded from the scope of this study, and vessels greater than 300 GT that are legally required to have an AIS transponder under chapter five of the SOLAS convention, and so would have appeared in the AIS dataset if they were truly active in a given year. For vessels less than 300 GT, AIS transponders are voluntary, and so they may not appear in the AIS dataset despite being active. Passenger ships are obliged to have AIS transponders, regardless of size; however, for this study, a passenger ship identified as Type 4 was processed alongside all other vessel types.

Table 12 - Summary of IHS/AIS matching criteria

Matching type	Identified in AIS dataset	Identified in IHS database	Reason for non-matching	Estimation target
1	Yes, by IMO number	Yes, by IMO number	-	Yes
2	Yes, by MMSI	Yes, by MMSI	Incomplete data	Yes
3	Yes, by MMSI	No	Domestic, not registered with IHSF	Yes
4	No	Yes, by IMO number	Less than 300GT and no AIS transponder	Yes
0	No	Yes, by IMO number	Ship is not active	No

During the development of this methodology, it was discovered that many of the IMO numbers in the AIS dataset had been recorded improperly, the most common error found to be additional digits added to a valid IMO number. To improve matching, an initial check is performed on each IMO number in the AIS dataset, prior to the matching algorithm above. Where an entry is found to have more than the standard seven digits of a valid IMO number, the checksum calculation (Vuori, 2013) is performed on the first seven digits and, if found to be a valid number, replaces the incorrect IMO number in the AIS dataset entry. This additional procedure successfully increased the number of matched vessels per year by 1–3%.

To determine whether a vessel was active for a given year in the IHS dataset, a set of rules are applied based on each vessel's year of construction, the current ship status, and the year that the vessel's ship status was last updated. A vessel is marked as active for a given year if both criteria below are satisfied:

1. The year of construction is less than or equal to the given year;
2. The ship status is in the *active* category, and the year the status changed is less than or equal to the given year, or the ship status is in the *inactive* category, but the year the status changed is greater than the given year.

During the resampling and extrapolation process, vessels are filtered out from those matched using the above process due to an insufficient number of data points or incomplete speed measurements; these are differentiated in Table 13 below in columns four and five. Columns five and six subsequently differentiate between the number of Type 3 vessels identified in the AIS dataset per year, and those that were successfully matched with the Global Fishing Watch (GFW) database using the methodology outlined in Section 2.2.6.

Table 13 - Vessel Matching and Filtering Counts for each Year

Year	Unique AIS IMO Numbers	Unique AIS MMSI Numbers	Type 1 and 2 Matched Vessels	Type 1 and 2 Filtered Vessels	Type 3 Vessels	GFW-Matched Type 3 Vessels	Type 4 Vessels
2012	59,071	395,883	66,079	60,091	174,940	45,679	27,564
2013	97,099	353,811	69,631	63,804	227,277	71,108	27,591
2014	64,713	378,276	72,156	66,295	267,461	85,699	27,790
2015	66,329	390,728	74,839	68,853	274,745	84,685	27,467
2016	68,009	425,472	77,491	70,635	299,809	96,970	26,454
2017	115,921	677,443	79,019	71,888	475,114	130,132	26,114
2018	112,144	708,450	78,410	72,362	489,899	139,053	26,090

2.2.3 AIS data pre-processing

As with the Third IMO GHG Study 2014, the primary source of vessel activity incorporated in this study is AIS data. The AIS data deliver, among other parameters, a ship's identity, position, speed, and draught at a given timestamp. The data are transmitted with a broadcast frequency of one message every six seconds.

Both terrestrial and satellite AIS data are included in this study. However, unlike the Third IMO GHG Study 2014, where the data was collated and merged from three satellite-derived global and four terrestrial coastal providers, in the current study the entire AIS dataset covering all the years of interest was provided by a single provider, exactEarth.

The number of AIS messages transmitted per year is increasing over the span of this study's years of interest. This is evident from Figure 44 which demonstrates the improvement in global AIS coverage between 2012 and 2018. However, in many cases the gaps between the observations exceed the standard transmission frequency due to signal inconsistency.

Generally, the growth observed in AIS coverage is primarily influenced by a) the number of satellites and terrestrial receivers installed over the years, b) the number of new vessels that install AIS receivers, and c) the overall growth of the global fleet. The second point is especially relevant in the case of smaller domestic vessels where AIS receivers are installed on a voluntary basis. However, the AIS coverage can also be influenced by disruptions in AIS dataflow due to maintenance or when switching terrestrial data providers. Due to the latter, in 2012, despite being fully available from April onwards, the terrestrial AIS dataset is not accessible between January and March. To tackle this issue, the approach was to temporally extrapolate from May to December inclusive by applying a random sample from this period onto the first four months where the terrestrial coverage is missing or low.

Figure 44 - Global AIS coverage in 2012 (top) and 2018 (bottom)

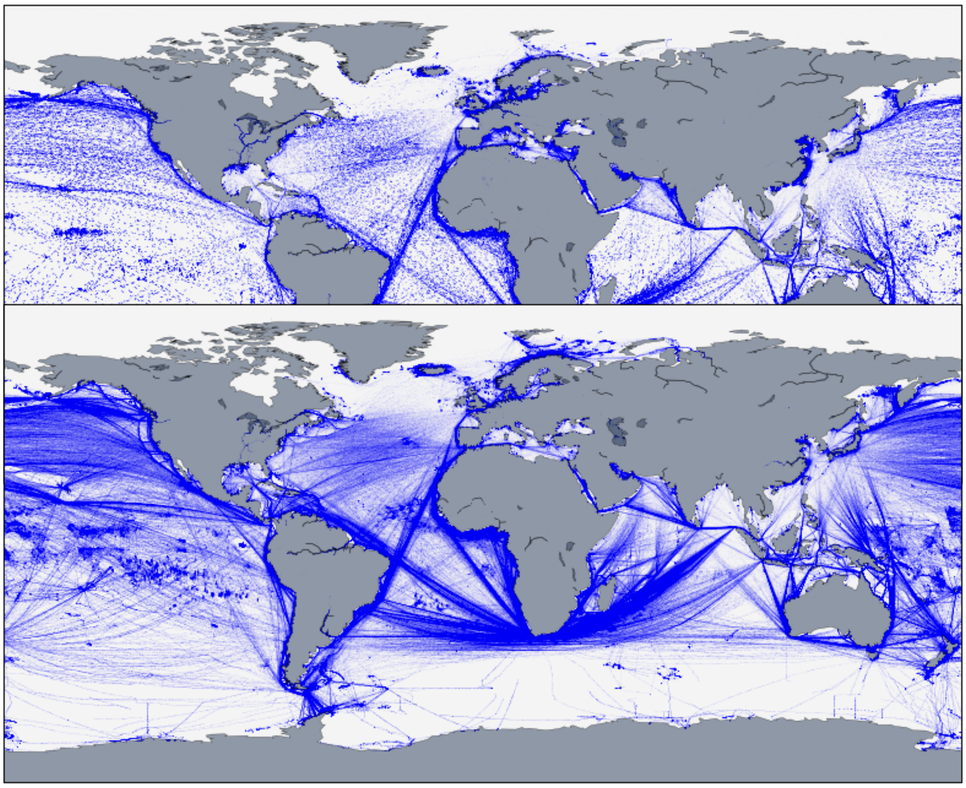
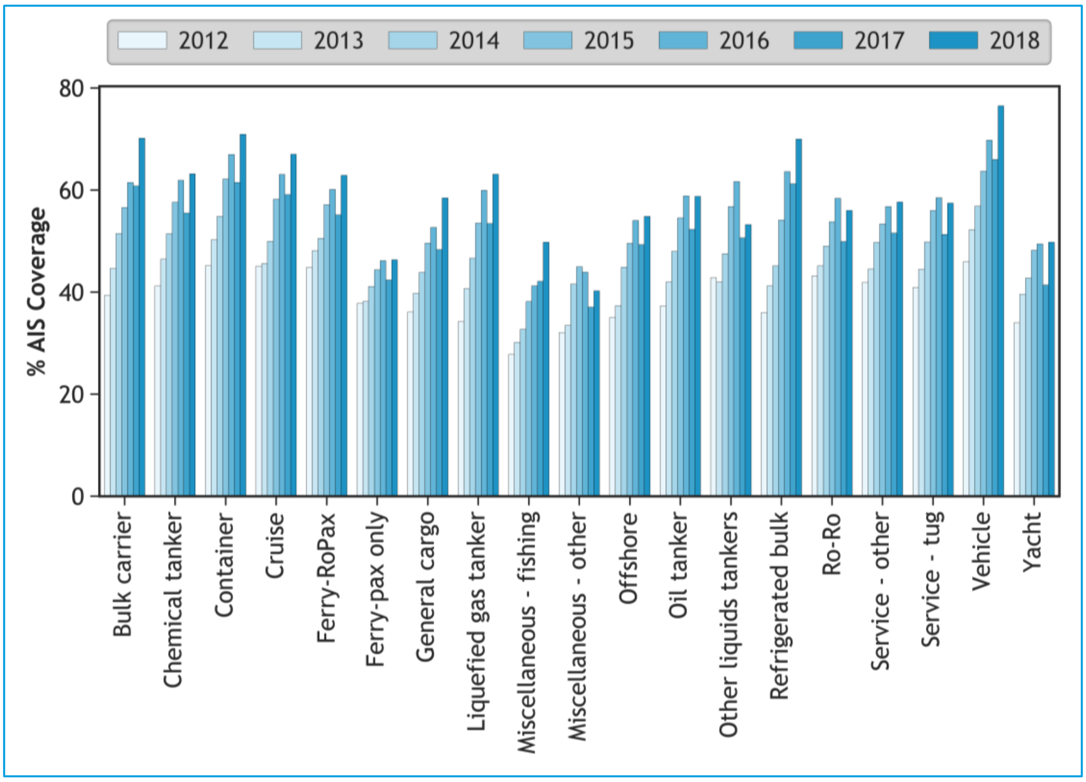


Figure 45 illustrates the overall trend in average annual AIS coverage over the years of interest. The sudden drop in AIS coverage in 2017 can also be explained by a change of terrestrial data provider by exactEarth, resulting in a decrease in the total number of terrestrial AIS messages.

Initially, the AIS data received directly from the provider is in a raw format and requires a range of pre-processing actions to be completed before utilizing it in the bottom-up emissions estimation model. These actions include: a) merging the relevant AIS messages on a per-IMO basis, b) resampling the AIS data into a standard hourly-denominated annual set on a per-IMO basis, c) filtering incomplete or spurious values, and d) infilling the possible gaps in coverage. The detailed methodology required to complete these steps is described further in this section.

Figure 45 - Overall trend in AIS percentage coverage growth over the 2012-2018



AIS data merging, filtering, and re-sampling

The first AIS pre-processing step is to generate a complete annual dataset for each vessel. Since a single vessel may be associated with multiple MMSI numbers within a 12-month period of operation (for example a vessel is assigned with a new MMSI in the case of reflagging), the initial merging process involves combining all vessel-specific messages into a single IMO-grouped dataset. IMO numbers are only reported in the static message (usually message 5), and therefore do not appear in every activity report. Hence, the IMO numbers are mapped to their associated MMSI. The data is then split respectively into ship activity reports, which could potentially have multiple MMSI numbers associated with a single ship in any given year.

MMSI numbers could also be spread across more than one IMO number if the MMSI has been reassigned within a year; in this case, the mapping allocates the MMSI number to the IMO associated with the longest period of consecutive observation for a given year.

The merged annual AIS data is then resampled hourly and extrapolated into a full year for each IMO number resulting in exactly 8,760 (or 8,784 for a leap year) hours for each vessel. This procedure controls the effect of continuously improving AIS coverage on the level of emissions, because an increasing number of AIS messages detected each year would otherwise introduce an artificial growth in detected emissions. Therefore, in order to exclude these unwanted influences and reflect the actual changes in operational profiles and growth of the global fleet, each Type 1 and Type 2 vessel's operational profile was extrapolated and resampled into a year based on the same number of hours.
The basic principle of the resampling methodology is that for each hour in a year the algorithm searches for the temporally closest observed AIS data point, and assigns values aligned with the principal data metrics listed below. Where no observations are found in the hour of interest, there would be a gap which, in turn, is to be interpolated later at the infilling stage discussed below.

The principal metrics associated with each merged AIS observation include:
- **IMO number**: a unique 7-digit identification number associated with each registered vessel.
- **MMSI**: a unique 9-digit identification number associated with each AIS transmitting device.
- **Time**: the timestamp associated with each AIS point, formatted as YYYY-MM-DD HH:MM:SS.
- **Latitude**: latitude associated with each AIS point, in decimal degrees.
- **Longitude**: longitude associated with each AIS point, in decimal degrees.
- **SOG**: speed-Over-Ground associated with each AIS point, in knots.
- **Draught**: instantaneous draught associated with each AIS point, in decimetres.
- **Observed Data:** a flag indicating whether a particular hour was 1 — observed or 0 — infilled.

During the resampling process, the model also applies a range of filters to remove or correct invalid and spurious data points including:
- latitudes outside the usual range of -90 to +90 degrees;
- longitudes outside the range of -180 to +180;
- SOG greater than 1.5 times the design speed are replaced with an interpolated speed by applying the AIS SOG infilling methodology described below.
- draughts greater than the design draught are replaced with the design draught values.

Moreover, the following additional filters are designed to assess the quality of an entire AIS dataset for a particular vessel in order to make the infilling process as accurate and realistic as possible. A vessel is not extrapolated into a full year when a) there are less than 10 AIS observations detected, b) the number of AIS observations with an SOG greater than 3 knots are less than 20, and c) when the entire set of SOG and GPS observations are missing or incorrect. These filtered vessels were most likely inactive during the year or had their AIS receivers switched off. By applying these filters, approximately 8-9% per year of the originally matched Type 1 and Type 2 vessels were excluded.

Infilling the AIS data gaps

For cases where periods of activity were missing from the AIS dataset, the coordinates, instantaneous draughts and SOG of the ship during missing hours were infilled using the methodologies and assumptions described below.

GPS coordinates

To account for missing ship movements, a Type 1 or Type 2 vessel's hourly resampled GPS coordinates are linearly interpolated whilst accounting for spherical curvature. Linear interpolation should result in more accurate emissions estimates because it allows for a more accurate application of location-dependent emission factors, such as those that are unique to Emission Control Areas (ECAs). Moreover, taking into account the curvature of the globe by applying the Haversine formula (6) for distance between each two contiguous points is essential, as gaps may significantly differ in duration across the globe and throughout the years in question. This means that these distances cannot be considered within the 2D Euclidean reference frame as illustrated in Figure 46.

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1)\cdot\cos(\phi_2)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right)$$

$$c = 2\cdot \operatorname{arctan2}(\sqrt{a}, \sqrt{1-a})$$

$$d = R\cdot c \tag{6}$$

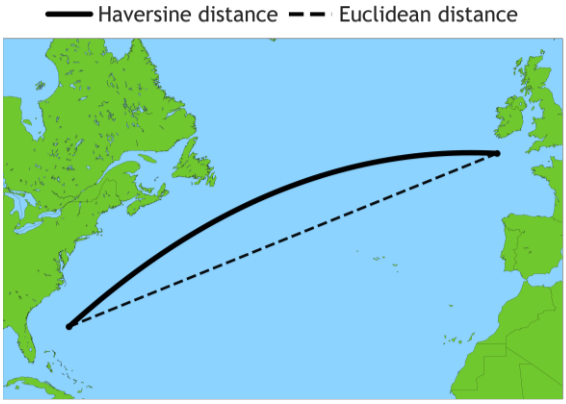
Where:

$\phi = latitude$

$\lambda = longitude$

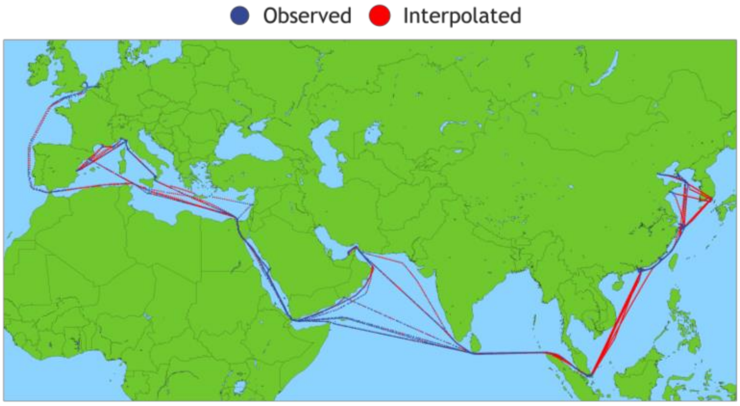
$R = radius\ of\ the\ globe$

Figure 46 - Difference between Haversine and Euclidean distance



The interpolation of GPS coordinates calculates the Haversine distance between two sets of coordinates (World Geodetic System 84) and infills each missing hour in between the two points, equidistance to each other on the great-circle distance between these observed points. Figure 47 illustrates this method by plotting a vessel's annual interpolated activity in 2018, where observed GPS coordinates represent 59% of the entire year. Over the full sample of years, linearly interpolated positions represent 50.8% of total records in the inventory for Type 1 and Type 2 vessels.

Figure 47 - A vessel's annual linearly interpolated ship activity, where 59% is represented by its observed activity and 41% is linearly interpolated



It is known that this method can produce anomalous results with ship tracks crossing land, depending on the coverage quality in given geographies. This is illustrated in Figure 47 by the vessel's positions relative to the Korean peninsular. This behavior is very specific to a vessel's coverage and particular the number of contiguous hours for which no GPS-data is available. With AIS coverage improving, this issue decreases. The two key areas in this study which rely on GPS coordinates, and hence are sensitive to its uncertainties, are the ECA allocation process, i.e. fuel type allocation (see Sections 2.2.3 and 2.2.5) and the stop identification method, i.e. international vs. domestic emissions inventories (see Section 2.2.4).

Speed over ground

The methodology to infill missing SOG measurements in this study is very similar to the approach used in the Third IMO GHG Study 2014, where the full year activity reports were disaggregated into discrete trips comprised of a port phase, a transition phase, and a voyage phase. Each voyage was separately considered, with the infilling of missing speeds drawn from in-phase samples. The algorithm defines the phases as below:

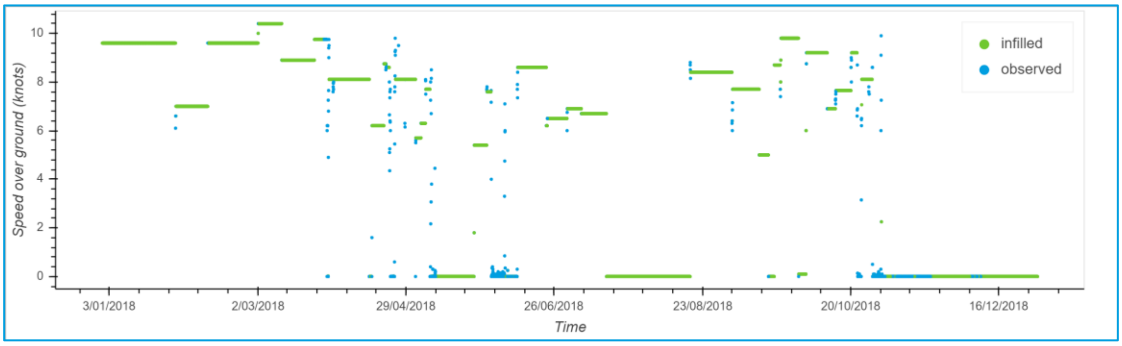
1. **Port phase**: any activity report with a speed of less than 3 knots.
2. **Voyage phase**: represented by an SOG above a calculated threshold and a standard deviation of less than 2 knots within a six-hour rolling window. This threshold is the 90th percentile of speeds reported above 3 knots.
3. **Transition phase**: this phase is defined as the period when a ship is transiting in and out of the port phase. It consists of the remaining activity reports that have not been classified as port or voyage.

The process of SOG infilling follows the steps outlined below:

1. Each hour where an activity report exists is classified as one of the above phases.
2. The activity dataset is split by port activity, resulting in a sequence of individual voyages.
3. An acceptable missing period threshold is calculated as the median port-to-port time bounded by 6 and 72 hours.
4. Where the contiguous missing periods are less than the missing period threshold, the intervening hours are infilled with a mean speed over ground based on the set of reported speeds for that phase.
5. Where the missing periods are greater than the missing period threshold, the whole voyage to which the contiguous missing periods belong is removed and replaced with SOG populated using backward and forward infilling.

Figure 48 shows an example vessel with less than 50% observed AIS data scattered across the year, with infilled intervals obtained by applying this speed interpolation approach.

Figure 48 - A vessel's annual infilled speed over ground activity with observed AIS coverage of < 50%



AIS draughts

The raw AIS data includes instantaneous draught measurements in decimeters that are reported in the static AIS messages, which appear less frequently than those messages containing a vessel's location. A draught measurement is typically only altered at the beginning of a new voyage and therefore does not experience the degrees of uncertainty that SOG, for example, has across the hour. Its uncertainty is instead a result of infrequent and incorrect reporting, due to the static message process occurring manually. In order to lessen the effect of erroneous instantaneous draught values on uncertainty, its resampling and infilling includes two key steps, resulting in two different draught estimates for Type 1 and Type 2 vessels: the AIS-reported draughts, and the voyage-specific estimated draughts.

Firstly, as was described for GPS-coordinates and SOG recordings, the hourly gaps in draught measurements are infilled. Gaps in a vessel's AIS-reported draughts are filled using backward and forward filling, with respect to time. The aggregated mean AIS-reported draughts by ship type and size are subsequently used to infill draughts for those vessels which have no AIS-reported draughts in that particular year. These vessels are flagged to indicate their lack of draught reporting and are subject to a larger level of uncertainty, particularly with respect to carbon intensity estimations. These AIS-derived draughts are subject to further sanity checks: where these draught values are larger than the vessel's design draught as reported in the IHS database, they are replaced with the vessel design draught. Note that the IHS vessel specification database was also subject to an infilling process, as explained in Section 2.2.1, where missing design draughts were infilled with the vessel type and size median design draught.

Secondly, a voyage-specific draught is estimated for each ship in this study, as to be compatible with energy efficiency estimates in a similar fashion to MEPC 68/INF.24. These are derived from a vessel's instantaneous infilled draughts as described above, in conjunction with its identified voyages. For each identified voyage and stop, the voyage-specific draught is calculated as the median AIS-derived draughts during the voyage and stop respectively, as shown in Figure 49. The start and end of the year, where no complete voyages have been identified, are similarly assigned their respective median AIS-derived draughts, as if these segments were complete voyages. If no voyages have been identified for a particular vessel, the median AIS-derived draught of the entire year is assigned as the voyage draught. These voyage-specific operational draughts are then used as an input to the cargo estimation model.

Figure 50 demonstrates the dampening effect of this process, by plotting the AIS-infilled draughts and voyage-specific draughts in relation to the vessel's design draught over time.

Figure 49 - Deriving voyage-specific draughts from AIS-infilled instantaneous draughts for both voyages and stops separately

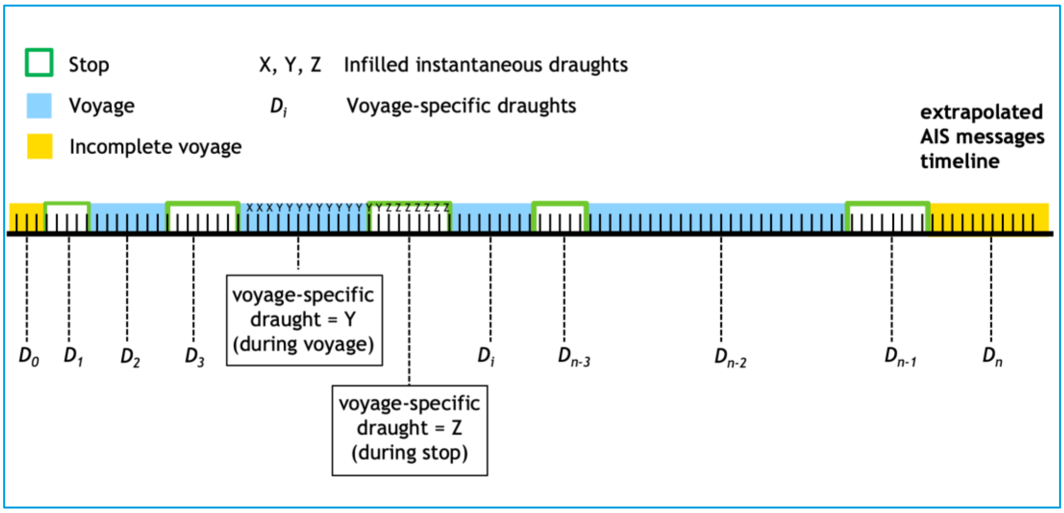
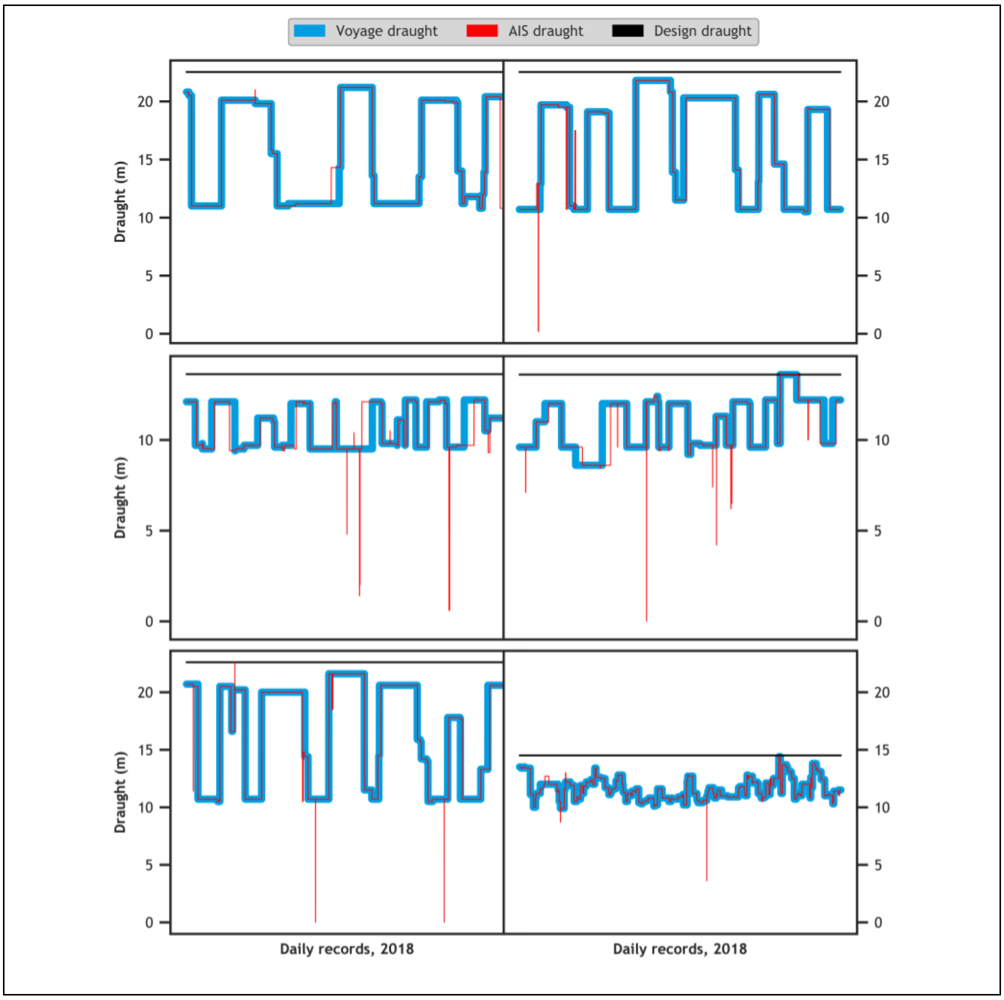


Figure 50 - Timeseries of voyage-specific draught, AIS-infilled draught, and design draught over time for a sample of six vessels



Emission control area zonal allocation

As per the Third IMO GHG Study 2014, this study considers the locations of ECAs and their respective restrictions to capture a vessel's fuel switching activity, in its efforts to comply with the maximum allowed sulfur content, as well as related nitrogen regulations. For each vessel's interpolated hourly activity, two flags are added to indicate whether the vessel is sailing within an active sulfur- and/or nitrogen-regulated ECA respectively. Table 14 highlights the regions, operating periods, and stringencies of the four ECAs considered in this study, as well as the sources of their geographical mapping, while Figure 51 maps locations.

A few amendments have been made to the inputs from the sources listed, to guarantee all activity within each ECA is captured. This includes the buffering of individual shapefiles, to account for vessel activity at port or close to land borders, of which some AIS messages might transmit GPS coordinates which seem to be on land due to inaccuracies caused by satellite signal uncertainty, and therefore would not be captured by an ECA shapefile.

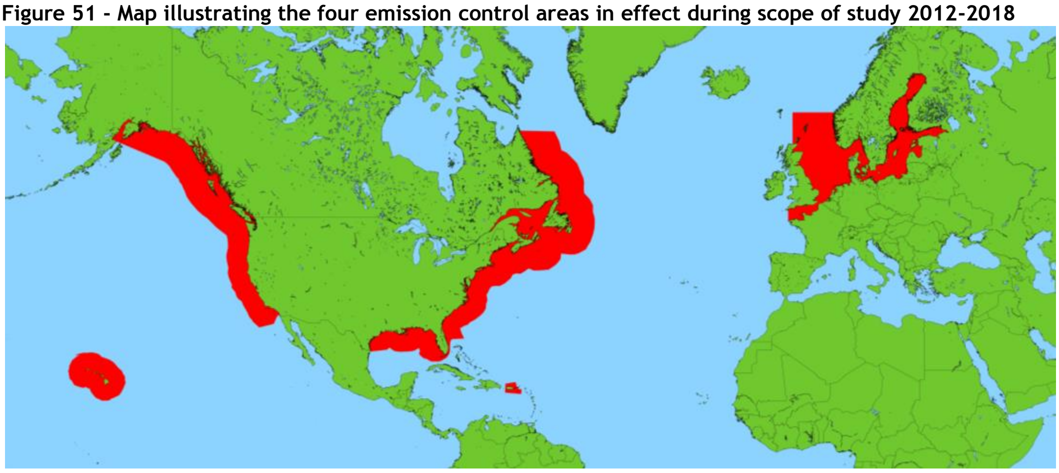
Table 14 - Emission control areas considered in study during period 2012-2018 and their respective stringency and defined geography

Name	In effect (including only years in scope)	Stringency		Source/definition of geographical mapping
		SO_x	NO_x	
Baltic Sea	01.01.2012 – 31.12.2014	1.00% m/m (10,000 ppm)	-	ECA includes the Gulf of Bothnia, the Gulf of Finland and the entrance to the Baltic Sea bounded by the parallel of the Skaw in the Skagerrak at 57°44.8' N.**
	01.01.2015 – 31.12.2018	0.10% m/m (1,000 ppm)	-	
North Sea	01.01.2012 – 31.12.2014	1.00% m/m (10,000 ppm)	-	ECA includes seas within North Sea and is defined by (i) the North Sea southwards of latitude 62°N and eastwards of longitude 4°W; (ii) the Skagerrak, the southern limit of which is determined east of the Skaw by latitude 57°44.8´ N; and (iii) the English Channel and its approaches eastwards of longitude 5°W and northwards of latitude 48°30´N.**
	01.01.2015 – 31.12.2018	0.10% m/m (1,000 ppm)	-	
North America	01.08.2012 – 31.12.2014	1.00% m/m (10,000 ppm)	-	ECA includes the sea area located off the Pacific coasts of the United States and Canada, defined by geodesic lines connecting the coordinates listed by IMO (2020).
	01.01.2015 – 31.12.2015	0.10% m/m (1,000 ppm)	-	
	01.01.2016 – 31.12.2018	0.10% m/m (1,000 ppm)	Y*	
U.S. Caribbean Sea	01.01.2014 – 31.12.2014	1.00% m/m (10,000 ppm)	-	ECA is defined by coordinates listed by IMO (2020).
	01.01.2015 – 31.12.2015	0.10% m/m (1,000 ppm)	-	
	01.01.2016 – 31.12.2018	0.10% m/m (1,000 ppm)	Y*	

* *As of January 2016, engines installed on new and modified vessels are subject to the Annex VI Tier III NO_x standards while those engines are operating in the ECA.*

** *Shapefiles made with publicly available Natural Earth data.*

Figure 51 - Map illustrating the four emission control areas in effect during scope of study 2012-2018



2.2.4 Distinction between national and international emissions

As in the Third IMO GHG Study 2014, bottom-up fuel use was estimated in post-processing based upon vessel type and size, not on a route-basis. This study applied an important new approach for the classification, based on the identification of port stops to estimate discrete voyages, by leveraging the geospatial and temporal content of AIS messages.

The identification of routes allows emissions to be allocated to allocate international and domestic shipping according to IPCC definitions, where international shipping is defined as shipping between ports of different countries (excluding military and fishing vessels). By this definition, the same ship may frequently be engaged in both international and domestic shipping operations (Smith, et al., 2015a).

This study's consortium chose to apply two allocation methods: Option 1 (vessel-based allocation) as used in the Third IMO GHG Study 2014; and Option 2 (voyage-based allocation) according to vessel-specific voyage intelligence. Option 1 allows for comparison and consistency, whereas Option 2 incorporates advances made in using AIS data, further reducing the gap between modelled and observed data by applying the IPCC definition of international shipping and domestic shipping.

Option 1 – Original vessel type-based approach

To allow comparison between bottom-up and top-down allocation of international and domestic navigation, the Third IMO GHG Study 2014 allocated ship activity by assigning fleet sectors to domestic and international services respectively. It found that based on general voyage behaviour, some ship types are likely to engage in international shipping more often than domestic navigation and vice versa. Table 15 describes those vessel types and sizes considered in the international and domestic split in shipping activity, respectively.

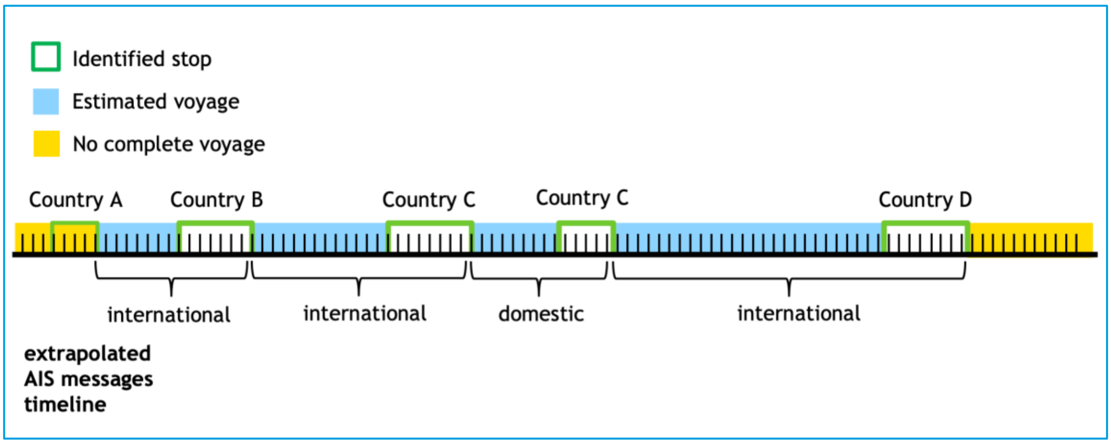
Table 15 - Allocation of vessel types and sizes according to assumed international or domestic shipping activity.

International		Domestic	
Vessel type	**Vessel sizes (unit)**	**Vessel type**	**Vessel sizes (unit)**
Bulk carrier	All sizes	Ferry- pax only	0 - 1,999 (gt)
Chemical tanker	All sizes	Ferry - ro-pax	0 - 1,999 (gt)
Container	All sizes	Yacht	All sizes
General cargo	All sizes	Service - tug	All sizes
Liquified gas tanker	All sizes	Miscellaneous - fishing	All sizes
Oil tanker	All sizes	Offshore	All sizes
Other liquids tankers	All sizes	Service - other	All sizes
Ferry - pax only	2,000 - + (gt)	Miscellaneous - other	All sizes
Ro-ro	All sizes		
Vehicle	All sizes		

Option 2 – Voyage-based allocation

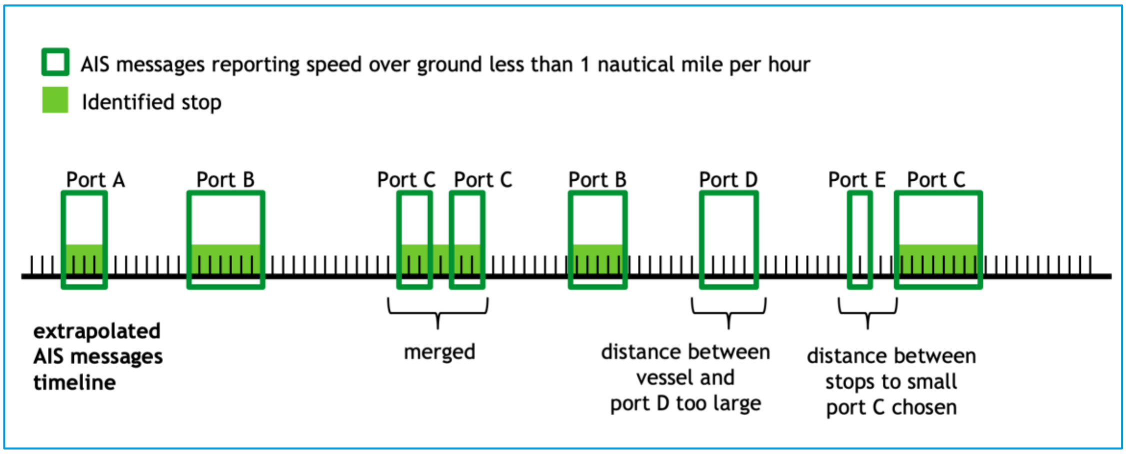
In the voyage-based allocation, this study defines a domestic voyage as a voyage between two ports, where the port of departure and the port of arrival are in the same country, while international voyages are defined as voyages between two ports where the port of departure is in a different country than the port of arrival. Option 2 allocates shipping activity on the basis of sequences of port calls and aggregates fuel consumption and emissions on the basis of the nature of the voyage. As shown in Figure 52, each destination port call is assigned the international or domestic label of the voyage which precedes it. Any unallocated time at the start and end of the year is allocated according to the vessel's international-domestic shipping split.

Figure 52 - Allocation of international and domestic nature of shipping according to voyage-based method (Option 2)



Individual port calls are identified by leveraging the high-frequency information relayed in the fleet's AIS messages. The algorithm primarily considers the Speed Over Ground (SOG) reported and the distance between the vessel and its closest port at any time, using the linearly interpolated and reported GPS-coordinates. Those messages that report a vessel to be travelling at an SOG below one nautical mile per hour are grouped together and treated as a cluster, as shown in Figure 53.

Figure 53 - Sequence of extrapolated AIS messages and potential port calls to highlight merging and filtering process in stop identification method



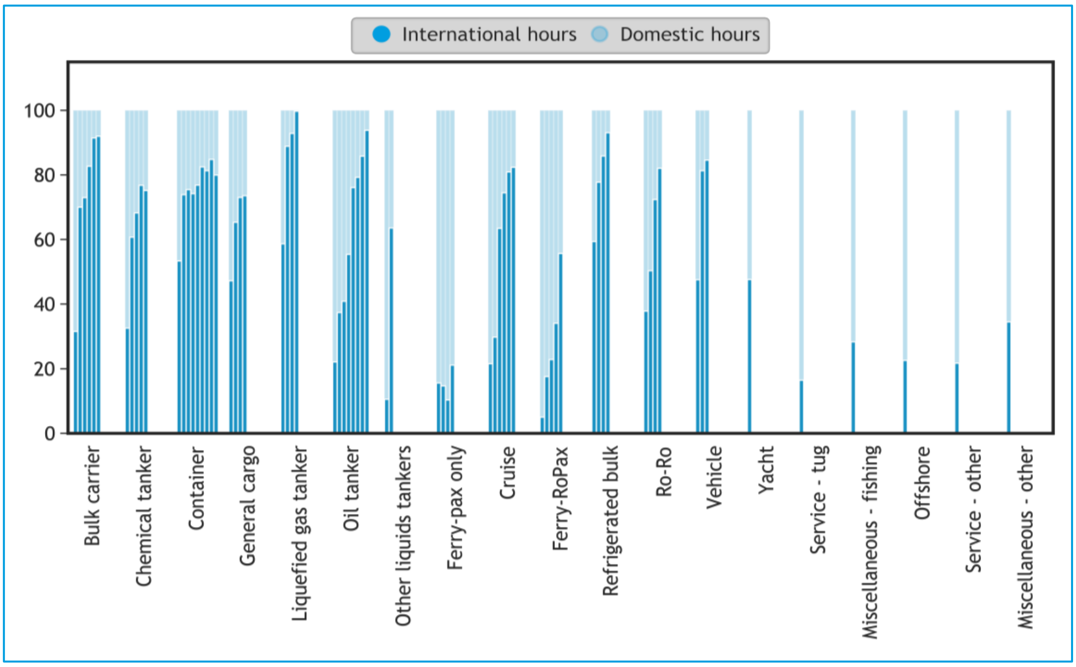
Each cluster is then assigned a closest port, as well as an estimated distance from this port, while consecutive clusters matched to the same port are merged. This method relies on a vast port dataset, containing 13,000 global ports, their unique identifier, GPS coordinates, and country (see Figure 94 in section 2.7.1). A cluster of AIS messages is considered a stop if a) the distance to its nearest port is sufficiently small, ranging from 5 to 30 nautical miles, b) the time at port is sufficiently large, ranging from 6 to 12 hours as a minimum, and c) the distance between the cluster itself and both its neighboring clusters is sufficiently large, ranging from 30 to 60 nautical miles.

These criteria are area-specific, as ports in certain areas may witness different shipping behaviour, as well as dependent on each other, where for example a more stringent time at port might mean that the required distance from that port is slightly relaxed. For example, ship activity in canals and narrow straits, where either congestion may take place or vessels are waiting to pass or enter a port, requires a more stringent time consideration when identifying a port stop. This stringency is specifically applied to the Panama, Suez and Kiel canals, as well as the straits of Gibraltar and Singapore and the Bosporus, all prone to stop over-identification as a result of vessels slowing down and idling close to neighboring ports. To further minimize the over-identification, filters are applied to eliminate wrongly identified stops, including if a vessel arrives too early and is observed stationary close to port E (reference to Figure 53) waiting to go into port C, causing an additional port stop to be identified. Stops like these are removed based on their close proximity to subsequent stops and the most frequent appearing port is chosen as the actual stop location and timestamp. Lastly, due to gaps in AIS coverage and the nature of the method applied to interpolate SOG (described in Section 2.2.3) to infill these gaps, some stops are not detectable by the two key criteria, speed and distance. To minimize the under-identification of stops related to this, clusters can also be identified based on proximity to port alone, if and only if the speed messages specific to this cluster have been interpolated contiguously for a certain period of time, while the distance travelled based on interpolated GPS coordinates is estimated to be relatively low.

Comparison of approaches and way forward

Of the two approaches described to separate international, domestic, and fishing activity, the original approach (Option 1) allows for a coherent and consistent comparison with the results of the Third IMO GHG Study 2014, while the latter approach (Option 2) achieves a closer alignment with the IPCC's definition of international shipping. When looking at the voyage-based split between times spent on international voyages and domestic ones, this study finds that not all of a certain ship type are 100% international or domestic, by a significant margin (see Figure 54). Notably, some of the smaller dry bulk carriers, oil tankers and chemical tankers classified as international ships spend on average 70% of the year sailing on domestic voyages, and the vessel types considered domestic under Option 1 operate between foreign ports roughly 20% of the year on average.

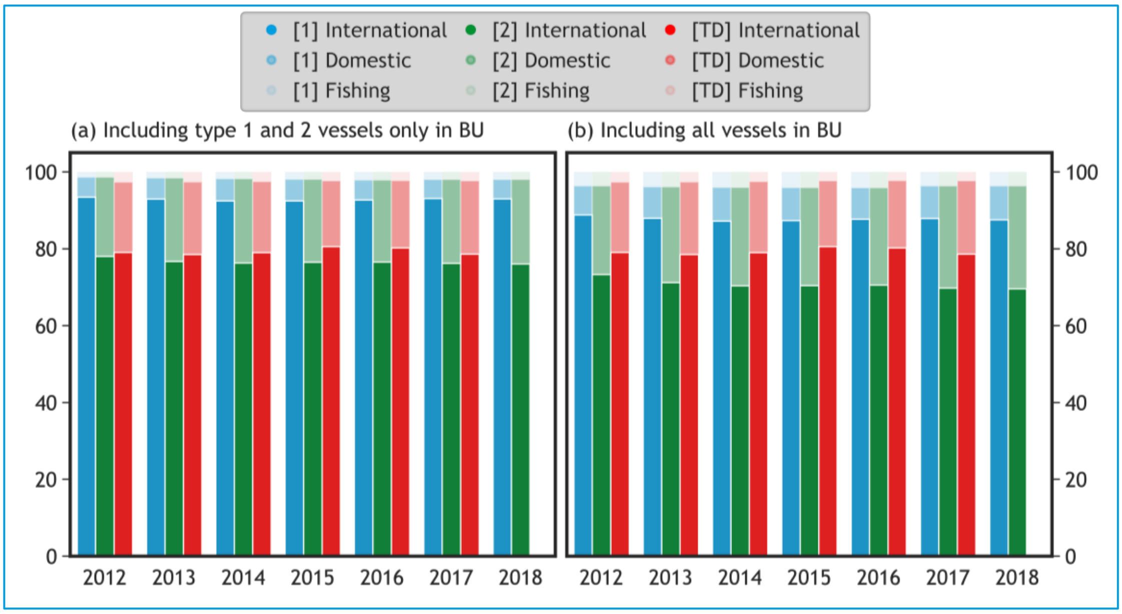
Figure 54 - Proportion of time spent on international and domestic voyages on average by ship type and size in 2018 (%) (Only including Type 1 and 2 vessels)



To allocate these emissions to their respective international or domestic split whilst keeping fishing vessels as a separate category, the approach which the consortium has taken forward in the reported results of this study is the voyage-based allocation, Option 2, leveraging AIS-derived ship voyages to determine the nature of a ship's activity, fuel consumption, and emissions, while the vessel-based allocation, Option 1, is presented alongside for the sake of continuity with previous inventories, where relevant.

As a further justification for this decision, this study finds that Option 2 shows a closer alignment to the top-down methodology's split between international and domestic HFO-equivalent fuel consumption estimates than Option 1, where the latter, as expected from Figure 54, underestimates the proportion of domestic ship activity. When considering only those vessels for which their international and domestic split is purely based on AIS-derived voyages, also referred to by Type 1 and 2 vessels, Option 2 is much more closely aligned with the top-down split, with an average of 2.7% difference between respective proportions of international shipping's estimated fuel consumption across the years 2012-2017, whereas this is a 13.2% difference between Option 1 and the top-down international shipping's estimated fuel consumption. When considering the entire fleet where international and domestic emissions for Type 3 have been modelled upon Type 1 and 2 vessel type and size averages (see Section 2.2.6), the individual proportions are slightly less aligned yet still in favour of Option 2, with a 8.7% difference between Option 2 and top-down international fuel proportions versus a 9.7% difference between Option 1 and top-down estimates, across the six years, where Option 1 is consistently overestimating the proportion of international ship activity and Option 1 underestimates compared to the top-down results.

Figure 55 - Comparison of bottom-up Option 1 and 2 with top-down international, domestic and fishing split of shipping's HFO-equivalent fuel consumption, year by year (where (a) includes only Type 1 and 2 vessels and (b) includes all vessels in the bottom-up splits)



As an additional justification, this methodology is in line with the IPCC's 2006 guidelines, which argue that shipping's split between international and domestic ought to be based on port of departure and port of arrival data, and that this criterion applies to each segment of a voyage calling at more than two ports (IPCC, 2006). The guidelines recognize that there are difficulties in distinguishing between domestic and international emissions with an absence of good data, and allows for alternative methods with clear assumptions, as described in the Third IMO GHG Study 2014. Leveraging AIS data further using Option 2, new data has become available and the QA process for this method provides good evidence that the derived split in activity is reliable, and a valuable contribution to the accurate assessment of the nature of shipping.

2.2.5 Estimating ship emissions

The methodology applied in this study remains conceptually similar to that applied in the Third IMO GHG Study 2014. Depending on the pollutant, hourly emissions (*EM*) are the product of either power demand ($\dot{W}$) and energy-based emission factors (EF_e) or fuel consumption (*FC*) and fuel-based emission factors (EF_f), for each of the three types of on-board machinery covered: the main engine (*ME*), auxiliary engine *(AE)*, and auxiliary boiler (*AB*).

While the overall approach to calculate ship emissions remained the same in this study, some of the methods to obtain the key operational variables have changed compared to the Third IMO GHG Study 2014. Some of the key changes are listed here and this section discusses both the similarities and the differences between the two studies:

1. **Main Engine Power**: Through the assessment of noon reports, the Third IMO GHG Study 2014 concluded that a speed-power correction factor had to be applied to estimate the ME power demand at any given hour. By reviewing new data, this study has opted to apply this correction factor **only** to a selection of vessel types and sizes.

2. **Operational phase assignment**: Based on the work of Olmer et al. (2017a; 2017b), distance from port and coast has been added as an additional criterion to SOG and engine load within the criteria to assign a vessel's operational phase.
3. **Auxiliary engine and boiler power tables**: Several sources of data have been used to update the power lookup tables to reflect the changes in the power demand of auxiliary machinery between 2012 and 2018.
4. **Specific fuel consumption**: Based on new findings in the literature, some *SFC* values have been updated and new ones added for LNG-fuelled vessels.
5. **Emission factors**: Based on new literature, the energy-based emission factors have been updated (see Annex B). In terms of method, fuel-based emissions are obtained by converting the same SFC value used to estimate fuel consumption and are no longer corrected by engine load (see Annex M).

Estimation of main engine operational power demand

Under design conditions, it is assumed that a ship's hull is clean, and the weather is calm. This allows for a good correlation between a ship's speed (v) and its resistance (R_T). For a ship to travel at the desired speed, it must provide a force of equal magnitude to the total ship resistance (R_T) and hence multiplying these two characteristics allows one to estimate the power required by the ship ($\dot{W}_i$):

$$\dot{W}_i = R_T \cdot v \tag{7}$$

The R_T can be divided further into hydrodynamic resistance (R_h) and aerodynamic resistance (R_a). When a ship navigates through water at any given speed, a force is applied onto the wetted surface of the ship's hull and this is known as hydrodynamic resistance. The hydrodynamic resistance is formed by the frictional resistance (R_f) and residual or wave-making resistance (R_r). The frictional resistance is dependent on the length of the ship, roughness of the hull and speed, among others; and it can represent up to 75% of R_h. The R_r is formed by the water's change of direction due to hull interaction; by abrupt changes in the water's streamline due to the hull's form; and to the formation of waves when the ship moves in the water (Stroke, 2003). The aerodynamic resistance — albeit less predominant than the hydrodynamic resistance on both calm and rough weather — is caused by the ship's exposed surfaces going through the air while in motion.

Both hydrodynamic, mainly the residual resistance, and aerodynamic forces are modified by the weather due to the change this has on the speed, direction and frequency of winds and waves. Another influencing factor on the hydrodynamic resistance is related to the hull surface conditions through its operational cycles. During operation, a hull rarely stays in its design conditions (i.e. clean and smooth) and its surface properties change over time as coatings deteriorate, fouling grow and as the plating deforms through wear and tear. Due to these changes on the hull surface, the frictional resistance has a significant increase which needs to be taken into account when quantifying this ship's fuel consumption and emissions.

Additional variables that need to be considered for the ship's propulsive needs are the ship loading condition. For any given ship loading condition, there is a draught and trim level. For example, an increase in the cargo transported will cause the ship to sink deeper or in other words increase its draught, the hull's wetted surface area and the ship's overall hydrodynamic resistance. On the other hand, having a ship on ballast conditions will cause the ship to have a lower draught with less wetted area producing a reduction in the hydrodynamic resistance and hence on the total resistance.

The equation to quantify a ship's propulsive power demanded when it is navigating at a particular speed, which combines the previously discussed effects, is the Admiralty formula:

$$\dot{W}_i = \frac{\delta_w \cdot \dot{W}_{ref} \cdot \left(\frac{t_i}{t_{ref}}\right)^m \cdot \left(\frac{v_i}{v_{ref}}\right)^n}{\eta_w \cdot \eta_f} \tag{8}$$

Where $\dot{W}_{ref}$ is the reference power as given in the IHS dataset, t_i and v_i are the instantaneous draughts and speeds respectively and they are given by the AIS dataset. The reference draught (t_{ref}) and speed (v_{ref}) are also from the IHS vessel dataset. The draught ratio exponent m is assumed to be 0.66 while the speed ratio exponent n is assumed to be 3, these represent the relationship between draught and power and speed and power, respectively. These values were considered in some detail in the Third IMO GHG Study 2014, and the justification remains the same. In the denominator, η_w represents the weather modifier to the ship's propulsive efficiency and η_f is the fouling modifier. A correction factor, δ_w, to $\dot{W}_{ref}$ is applied to certain ship types and sizes to adjust the speed-power relationship, as provided by the IHS dataset.

Weather correction factor (η_w)

In the Third IMO GHG Study 2014, it was assumed that weather effects alone were responsible for approximately 15% of additional power on top of the theoretical propulsion requirements of ocean-going ships defined as ships operating at a greater distance of five nautical miles from the nearest shore (Smith, et al., 2013). A 10% additional power requirement is added for coastal ships defined as ships operating less than or equal to five nautical miles from the nearest shore. The value required for η_w to represent a 10% increase in power demand is 0.909 and for 15% is 0.867. Johansson et al. (2017) questioned this method and did not implement such a scaling factor, while Olmer et al. (2017a) followed the lead of Smith et al. (2014). In a recent adaption of the Ship Traffic Emission Assessment Model (STEAM), propelling power is determined by wave height and directions, accounting for the environmental conditions in a highly detailed manner. Explicitly resolving wind and wave conditions and then estimating how these increase a ship's resistance introduces both significant computational cost and additional uncertainty (uncertainty both due to the environmental data used and the algorithms to estimate how the weather conditions modify fuel consumption).

In this study, the η_w for different ship classes (i.e. ship types and sizes) are the same as in the Third IMO GHG Study 2014 since they are deemed adequate for the time frame and scope of the work. The values are presented in more detail in Appendix L.

Fouling correction factor (η_f)

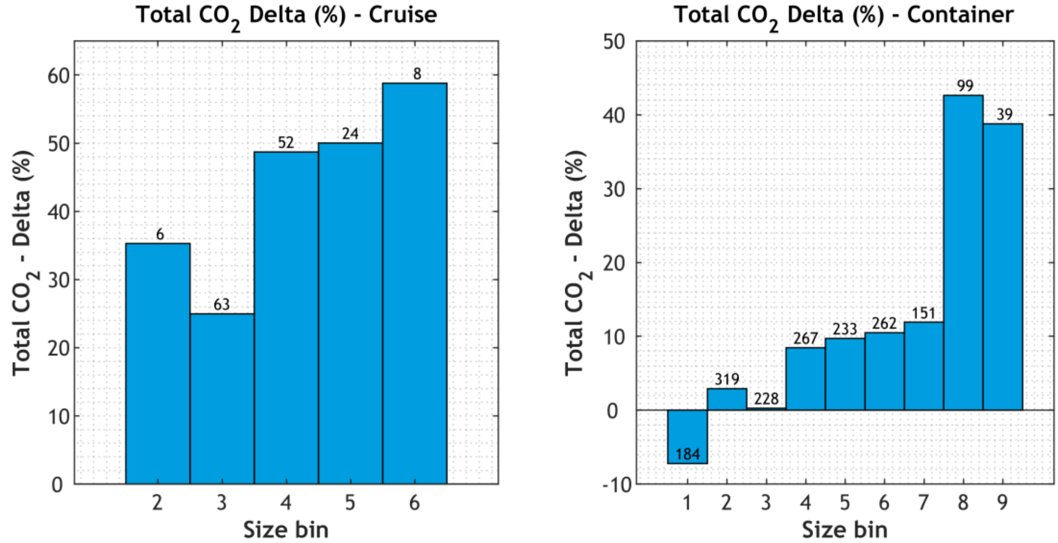
The Third IMO GHG Study 2014 applied a constant 9% resistance (and therefore fuel consumption and emissions) penalty in the form of a correction factor, η_f, to reflect the impacts of hull fouling. The value of η_f to represent a 9% increase in resistance is 0.917. Olmer et al. (2017a; 2017b) apply a variable hull fouling factor that is a function of the ship's length (measured between perpendiculars), its initial roughness when, its age (as roughness increases with age) and the number of years since drydocking (as roughness increases between drydocking due to biofouling). This approach accounts for how hull fouling affects resistance over time on a ship-by-ship level. As explained in Olmer et al. (2017a) the hull fouling factor increased the main engine power demand by 7% on average, ranging from 2%-11% depending on each ship's age and maintenance schedule. In the absence of additional empirical data, this study uses the η_f from the Third IMO GHG Study 2014. The η_f values for each ship type and size are presented in more detail in Appendix L.

Speed-power correction factor (δ_w)

The speed reported in the IHS dataset is called "speed." IHS defines speed as follows: "Maximum vessel Speed in knots when the ships engine is running at Maximum continuous rating (MCR)." In this report, it was assumed that on average "speed" was reporting the ship's maximum speed at the ship maximum continuous rating (MCR).

However, there are some ship types and sizes where this study observes that the "speed" value likely relates to a speed corresponding to a lower engine loading. The following corrections were identified by comparison with the MRV dataset. The validation included a detailed investigation into certain ship types and sizes, which identified a small number of outliers in an otherwise good agreement between the bottom-up model and MRV data. However, two candidates were recognized for the application of correction factors because of the explanation derived from this investigation. The fuel consumption related to large container vessels above 14,500 TEU (Size 8 and 9) and cruise ships were observed to be significantly overestimated as shown in
Figure 56.

Figure 56 – Percentage difference between MRV CO_2 emissions and the Fourth IMO GHG Study's CO_2 estimates for container vessels and cruise ships, by size category (pre correction), represented by 'Delta'.



Large container (sizes 8 and 9). Large vessels are designed with larger engines to be able to operate at higher speeds which is not normally done in practice. It seems that for the larger containers, many in the IHS database have "speed" values that relate to their service speed, which could be closer to 75% MCR instead of 100% MCR. For that reason, a δ_w of 0.75 is applied.

Cruise (all sizes). There is considerable uncertainty due to hotel load which represents a large proportion of the fuel consumption. Additionally, cruise ships tend to have novel propulsion layouts (significant hybridisation of power trains and use of diesel-electric configuration) which are difficult to model using the same approach as the majority of the remainder of the fleet, thus the bottom-up model tends to overpredict the power output. A δ_w of 0.70 is used for this ship type to accommodate these design features. For the remaining ships, δ_w was set to 1.00.

Other main engine powering aspects

In some cases, the estimated main engine load factor can be greater than 100% MCR, implying that a ship is using more than its installed main engine power, which is not possible. To avoid this, the bottom-up model removes SOG readings that are 1.5 times larger than the design speed, replacing it with maximum speed. In the particular case where, after applying the hull, weather, draught, and speed-power adjustment factors, the main engine load factor is still above 100% MCR then the bottom-up model assigns to this case a load factor of 98% MCR.

On-board the ship, shaft generators/motors can take shaft power in or out to either support the on-board auxiliary engine or to complement the propulsive needs. These systems modify, by taking or giving power, the main engine power demand at any given speed and loading condition. Other not uncommon systems on-board commercial ships are Waste Energy Recovery Systems (WERS) that convert non-used energy from an engine, depending on the ship needs, into useful thermal, mechanical or electrical power. From the IHS database, it is difficult to determine if a ship has shaft generators/motors installed and there is no information for the use of WERS for any type of power production. In addition, the WERS performance is dependent upon uncertain and route-dependent variables, such as weather conditions, which could introduce large levels of uncertainty to the emission inventories (Suárez de la Fuente, et al., 2017). For these reasons, and similar to the Third IMO GHG Study 2014, this study assumes that only the ME will be the propulsive power supplier while auxiliary engines cover solely the electrical demand on-board.

It is considered that assumptions made on shaft generators/motors and WERS should not significantly impact the total power produced on-board (Smith, et al., 2016) but to a certain extent will have an impact on the emissions produced from the auxiliary engines (Smith *et al.*, 2014).

Operational phase assignment

As done in the Third IMO GHG Study 2014, as well as Olmer et al. (2017b), this study assumes that while in service, a ship is operating in one of five defined phases: at berth, at anchor, maneuvering, in slow transit or at sea. This study combines operational phase assignment criteria from Olmer et al. (2017a; 2017b) and the Third IMO GHG Study 2014 and determines a ship's phase by its proximity to land or port, its speed over ground and its main engine load power. Table 16 describes how these features define the ship's phase, where liquid tankers represent a special case because they often are lightered offshore and hence can berth within 5 nautical miles from port. Minimum distances are measured between the vessel's AIS-recorded position and the world's coastal lines, freely available from Natural Earth data (shapefiles), and the port dataset, discussed in detail in Section 2.7.1, where each port is represented by a single point.

Table 16 - Operational phase assignment decision matrix.

SOG (knots)	ME load	Port distance (nm)		Coast distance (nm)		
		≤ 1	1 - 5	≤ 1	1 - 5	≥ 5
1≤	-	At berth	At berth*	Anchored	Anchored	Anchored
1 - 3 (incl. 3)	-	Anchored	Anchored*	Anchored	Anchored	Anchored
3 - 5	≤ 0.65	Manoeuvring	Manoeuvring*	Manoeuvring	Manoeuvring	Slow transit

(incl. 5)	**> 0.65**	Manoeuvring	Manoeuvring*	Manoeuvring	Manoeuvring	Normal cruising
> 5	**≤ 0.65**	Manoeuvring	Slow transit*	Slow transit	Slow transit	Slow transit
	> 0.65	Manoeuvring	Normal cruising*	Normal cruising	Normal cruising	Normal cruising

** Applicable to chemical tankers, liquified gas tankers, oil tankers and other liquids tankers only.*

Estimation of auxiliary engine and boiler operational power demand

Power demand by the auxiliary engine and boiler systems per ship type, size, and operational mode are scarce in shipping data services such as IHS. Furthermore, access to a representative sample for the whole fleet from on-board Ship Performance Monitoring systems is currently very limited. To tackle this, the Second IMO GHG Study approximated the powering demand by the auxiliary engine and boiler by assuming the ship class number and load of auxiliary engines operated and based the rated auxiliary engine power on the limited data provided by IHS. The Third IMO GHG Study 2014 used Starcrest's Vessel Boarding Program (VBP) (Starcrest Consulting Group LLC, 2013) data that has been collected at different ports in the United States to improve the auxiliary engine and boiler powering demands. For this study, the main purpose has been to build the profiles of each by using the information included in the Third IMO GHG Study 2014, while updating the power demands with available literature and data published between 2012 and 2018. To that end, the sources used are the following:

1. Third IMO GHG Study 2014 (Smith, et al., 2015a).
2. Starcrest's VBP reports from 2012 to 2018 (Starcrest Consulting Group LLC, 2020).
3. Auxiliary engine and boiler fuel consumption data provided by ClassNK.
4. Auxiliary engine fuel consumption provided by continuous monitoring data.
5. Expertise/Professional judgement from experts on the field.

The advantage of using the Third IMO GHG Study 2014 as a starting point is that the ship categorisation is relatively similar to the Fourth IMO GHG Study, allowing for a smooth update on both auxiliary engine and boiler power output. Additionally, the data provided has been peer-reviewed, verified by experts and validated against noon-reports. Following the Third IMO GHG Study 2014, this report uses the VBP annual reports which collect operational data from more than 1,200 different ships allowing for a representative sample of their powering needs. Ship types that are monitored include containers, bulk carriers, tankers of different types, Ro-Ro, cruise, general cargo among others.

This study also has access to on-board data, albeit, for a reduced number of specific ships, for fuel consumption and power output. The data from ClassNK is in the form of fuel consumption covering both auxiliary engines and boilers at different operational modes, to be converted to power output. The continuous monitoring data provided hourly observations for the auxiliary machinery power demanded on-board liquefied gas tankers. The hourly observations provide speeds and main engine MCR, allowing for the auxiliary engine power output to be classified per operational modes.

Finally, the tentative power output for both auxiliary engines and boilers at different operational modes have been sent to ship operators and experts to fine-tune the numbers.

Existing ship classes

The first step compares VBP reports between 2012 and 2018 for all available ships. The comparison found that there are not any spatial trends which can define an operational evolution on the auxiliary and boiler power output. This is mainly due to the sampling process which is conditioned to the ships that are inside the geographical areas of study (e.g. Port of Los Angeles) which produces considerable changes on the year-on-year power outputs.

Considering this, the year-on-year power outputs are averaged and compared to the numbers in the Third IMO GHG Study 2014. If the numbers are found to be similar, then the 2012-2018 power outputs are used.

In some instances, due to the VBP's sample size, certain ship types display larger power outputs on smaller ships than in their larger counterparts. To correct this, the Third IMO GHG Study 2014 proportions between sizes for similar ship types is maintained but using the updated power outputs.

Updated vessel size category bins

As shown before, the Fourth IMO GHG Study uses new ship sizes to existing ship types to have a more accurate description of the global fleet. In general, the additional size classes can be allocated to one of the following two strategies:

a To split previous size bins into multiple size bins.
b To add size bins to represent the trend of the fleet growth, i.e. the building of larger ships (e.g. containers).

For the case of a newly founded size class, where there is no data from any of the data sources mentioned above, this study opts for copying the same auxiliary and boiler operational power output, from the closest related size class. Available auxiliary engine and boiler power outputs from these data sources are subsequently used to infill the new ship sizes. However, if the power output has a difference larger than ±20% from the previous (case a. and b.) and forthcoming (only case a.) existing size then the previous size bin power output was used.

This study assumes that boilers are not used during open-ocean operations (i.e. at sea operation mode) since the ships are assumed to have a Waste Heat Boiler (WHB) installed on-board that reuse the waste heat coming from the main engine and fully covers the heating demand in the manner of an economiser (Baldi et al. 2018). To this general assumption, there are some exceptions:

- Various types of tankers still need the assistance of their boiler to fulfil their thermal needs, hence these ships still have a boiler power output while at sea (Baldi, et al., 2018; González Gutiérrez, C. et al., 2020).

Some ship classes typically do not have a boiler installed on-board, such as fishing ships and small general cargo. For these ship classes, the boiler power output is given as 0 kW for all operational modes.

Other relevant aspects

Table 17 presents the auxiliary engine and boiler power outputs per ship class and operational mode. At a per-ship level, the bottom-up model implements a decision tree which can override the values from Table 17 to better represent the auxiliary and boiler powering demand in small ships. The decision tree is based on the main engine installed power as follows:

- when main engine power is between 0 and 150 kW then auxiliary engine and boiler are set to zero;
- when main engine power is between 150 and 500 kW then the auxiliary engine is set to 5% of the main engine installed power while the boiler power output is based on Table 17;

– when the main engine power is larger than 500 kW then the auxiliary engine and boiler values shown in Table 17 are used.

Table 17 - Auxiliary engine and boiler power output, by ship type, size and operational mode.

Ship Type	Size	Unit	Auxiliary Boiler Power Output (kW)				Auxiliary Engine Power Output (kW)			
			At berth	Anchored	Manoeuvring	Sea	At berth	Anchored	Manoeuvring	Sea
Bulk carrier	0-9,999	dwt	70	70	60	0	110	180	500	190
	10,000-34,999		70	70	60	0	110	180	500	190
	35,000-59,999		130	130	120	0	150	250	680	260
	60,000-99,999		260	260	240	0	240	400	1,100	410
	100,000-199,999		260	260	240	0	240	400	1,100	410
	200,000-+		260	260	240	0	240	400	1,100	410
Chemical tanker	0-4,999	dwt	670	160	130	0	110	170	190	200
	5,000-9,999		670	160	130	0	330	490	560	580
	10,000-19,999		1,000	240	200	0	330	490	560	580
	20,000-39999		1,350	320	270	0	790	550	900	660
	40,000-+		1,350	320	270	0	790	550	900	660
Container	0-999	TEU	250	250	240	0	370	450	790	410
	1,000-1,999		340	340	310	0	820	910	1,750	900
	2,000-2,999		460	450	430	0	610	910	1,900	920
	3,000-4,999		480	480	430	0	1,100	1,350	2,500	1,400
	5,000-7,999		590	580	550	0	1,100	1,400	2,800	1,450
	8,000-11,999		620	620	540	0	1,150	1,600	2,900	1,800
	12,000-14,499		630	630	630	0	1,300	1,800	3,250	2,050
	14,500-19,999		630	630	630	0	1,400	1,950	3,600	2,300
	20,000-+		700	700	700	0	1,400	1,950	3,600	2,300
General cargo	0-4,999	dwt	0	0	0	0	90	50	180	60
	5,000-9,999		110	110	100	0	240	130	490	180
	10,000-19,999		150	150	130	0	720	370	1,450	520
	20,000-+		150	150	130	0	720	370	1,450	520
Liquefied gas tanker	0-49,999	cbm	1,000	200	200	100	240	240	360	240
	50,000-99,999		1,000	200	200	100	1,700	1,700	2,600	1,700
	100,000-199,999		1,500	300	300	150	2,500	2,000	2,300	2,650
	200,000-+		3,000	600	600	300	6,750	7,200	7,200	6,750

Ship Type	Size	Unit	Auxiliary Boiler Power Output (kW)				Auxiliary Engine Power Output (kW)			
			At berth	Anchored	Manoeuvring	Sea	At berth	Anchored	Manoeuvring	Sea
Oil tanker	0-4,999	dwt	500	100	100	0	250	250	375	250
	5,000-9,999		750	150	150	0	375	375	560	375
	10,000-19,999		1,250	250	250	0	690	500	580	490
	20,000-59,999		2,700	270	270	270	720	520	600	510
	60,000-79,999		3,250	360	360	280	620	490	770	560
	80,000-119,999		4,000	400	400	280	800	640	910	690
	120,000-199,999		6,500	500	500	300	2,500	770	1,300	860
	200,000-+		7,000	600	600	300	2,500	770	1,300	860
Other liquids tankers	0-999	dwt	1,000	200	200	100	500	500	750	500
	1000-+		1,000	200	200	100	500	500	750	500
Ferry-pax only	0-299	gt	0	0	0	0	190	190	190	190
	300-999		0	0	0	0	190	190	190	190
	1000-1999		0	0	0	0	190	190	190	190
	2000-+		0	0	0	0	520	520	520	520
Cruise	0-1,999	gt	1,100	950	980	0	450	450	580	450
	2,000-9,999		1,100	950	980	0	450	450	580	450
	10,000-59,999		1,100	950	980	0	3,500	3,500	5,500	3,500
	60,000-99,999		1,100	950	980	0	11,500	11,500	14,900	11,500
	100000-149999		1,100	950	980	0	11,500	11,500	14,900	115,00
	150000-+		1,100	950	980	0	11,500	11,500	14,900	11,500
Ferry-RoPax	0-1999	gt	260	250	170	0	105	105	105	105
	2000-4999		260	250	170	0	330	330	330	330
	5000-9999		260	250	170	0	670	670	670	670
	10000-19999		390	380	260	0	1,100	1,100	1,100	1,100
	20000-+		390	380	260	0	1,950	1,950	1,950	1,950
Refrigerated bulk	0-1999	dwt	270	270	270	0	520	570	560	570
	2000-5999		270	270	270	0	1,100	1,200	1,150	1,200
	6000-9999		270	270	270	0	1,500	1,650	1,600	1,650
	10000-+		270	270	270	0	2,850	3,100	3,000	3,100
Ro-Ro	0-4999	dwt	260	250	170	0	750	430	1,300	430

Ship Type	Size	Unit	Auxiliary Boiler Power Output (kW)				Auxiliary Engine Power Output (kW)			
			At berth	Anchored	Manoeuvring	Sea	At berth	Anchored	Manoeuvring	Sea
	5000-9999		260	250	170	0	1,100	680	2,100	680
	10000-14999		390	380	260	0	1,200	950	2,700	950
	15,000-+		390	380	260	0	1200	950	2,700	950
Vehicle	0-9,999		310	300	250	0	800	500	1,100	500
	10,000-19,999		310	300	250	0	850	550	1,400	510
	20,000-+		310	300	250	0	850	550	1,400	510
Yacht	0-+	gt	0	0	0	0	130	130	130	130
Service - tug	0-+	gt	0	0	0	0	100	80	210	80
Miscellaneous - fishing	0-+	gt	0	0	0	0	200	200	200	200
Offshore	0-+	gt	0	0	0	0	320	320	320	320
Service - other	0-+	gt	0	0	0	0	220	220	220	220
Miscellaneous - other	0-+	gt	110	110	90	0	150	150	430	410

Operational fuel correction due to ECA

As explained in Section 2.2.3, fuel switching can occur in ECAs to comply with the regulations set in the respective geographic area. To capture this, a vessel's fuel types — asserted by the infilled IHS vessel database (as explained in Section 2.2.1) — are switched to an ECA-compatible fuel when the vessel is sailing within an ECA and usually operates on non-compliant fuels. This switch is applied to a vessel's main engine, auxiliary engine and boiler fuel types, where for ship activity before 2015, HFO is replaced by low-sulfur HFO (1%), while from 2015 onwards all types of HFO are replaced with MDO (0.1%). The latter assumption is a simplified perspective because there are some ultra-low sulfur fuel oils (ULSFO) on the market which may be used to comply with the 0.1% m/m stringent ECAs. In 2018, fewer than 2% of FO sales had sulfur content less than 0.5% (IMO, 2019d), which clarifies the use of ULSFO for ECA compliance is small and justifies this simplification.

Table 18 - Fuel type switches due to ECA regulation.

Sulfur regulation stringency	Vessel's standard fuel type	Vessel's fuel type when in ECA
1.00% (10,000 ppm)	HFO	LSHFO 1%
	MDO	MDO
	LNG	LNG
	Methanol	Methanol
0.10% (1,000 ppm)	HFO	MDO
	MDO	MDO
	LNG	LNG
	Methanol	Methanol

Fuel consumption and emissions estimation

This section explains the process of how a vessel's hourly engine power ($\dot{W}_i$) is converted to fuel consumption leveraging the specific fuel consumption (*SFC*) for main engines and auxiliary machinery. It also covers how emissions are estimated specific to each pollutant and provides an introduction to how this step is different from the methodology of the Third IMO GHG Study 2014.

Calculation of fuel consumption

The vessel's hourly fuel consumption (FC_i), specific to its main engine, auxiliary engine and boiler are described by the same estimation method using the following equation:

$$FC_i = SFC_i \cdot \dot{W}_i \quad (9)$$

Where $\dot{W}_i$ is the power demand for each hourly observation of the given system main engines SFC_i is the hourly specific fuel consumption for each system.

Baseline specific fuel consumption

Similar to the Third IMO GHG Study 2014 (and adapted from (Jalkanen, et al., 2012)), this work uses the concept of baseline SFCs (SFC_{base}) to find SFC_i shown in Equation (9). Where SFC_{base} is the main engine, auxiliary engine and auxiliary boiler lowest SFC seen in their loading curve - in other words, the most fuel-efficient point - and they are given in Table 19.

The SFC_{base} varies based on engine/system age, fuel type, engine type, and system.

Table 19 has as a starting point the values used in the Third IMO GHG Study 2014. However, several of the SFC_{base} values have been updated with the latest sources available. Pavlenko et al. (2020), while researching the climate implications of using LNG as a marine fuel, included an extensive literature review on the fuel consumption of LNG-fuelled engines and the most recent SSD and MSD engines. It is assumed that the dual-fuel LNG engines always operate on LNG as their primary fuel while the mass of pilot fuel injected remains constant across engine loads. This assumption could be updated in future studies given that the amount of pilot fuel needed varies with engine load. The steam turbines SFC assumptions are taken from sources from the forthcoming study on steam-power LNG carriers by González Gutiérrez et al. (2020).

Table 19 - The SFC_{base} given in g/kWh for different engine and fuel types, and year of built

Engine Type	Fuel Type	Before 1983	1984-2000	2001+
SSD	HFO	205	185	175
	MDO	190*	175*	165*
	MeOH**	N/A	N/A	350*
MSD	HFO	215	195	185
	MDO	200*	185*	175*
	MeOH**	N/A	N/A	370*
HSD	HFO	225	205	195
	MDO	210*	190*	185*
LNG-Otto (dual-fuel, medium-speed)*	LNG	N/A	173*	156*
LNG-Otto (dual-fuel, slow-speed)*	LNG	N/A	N/A	148 LNG + 0.8 MDO (pilot)*
LNG-Diesel (dual-fuel)*	LNG	N/A	N/A	135 LNG + 6.0 MDO (pilot)*
LBSI*	LNG	N/A	156*	156*
Gas Turbines**	HFO	305	305	305
	MDO	300	300	300
	LNG	N/A	N/A	203*
Steam Turbines (and boilers)**	HFO	340*	340*	340*
	MDO	320*	320*	320*
	LNG	285*	285*	285*
Auxiliary engines	HFO	225	205*	195*
	MDO	210*	190*	185*
	LNG	N/A	173*	156*

* *Refer to a change from the Third IMO GHG Study 2014.*

** The conversion of SFC_{base} between fuels was done using the following assumed energy densities: For HFO is 40,200 kJ/kg; MDO uses 42,700 kJ/kg; LNG uses 48,000 kJ/kg and Methanol is assigned 19,900 kJ/kg (International Maritime Organization, 2018).

Main engine specific fuel consumption assumptions

The main engine SFC (SFC_{ME}) is assumed to vary as a function of its load in a parabolically: at low loads, the SFC tends to be at its highest level, to then decreases until it reaches a minimum (e.g. 75% MCR), and finally, after this point, the SFC begins to rise again.
The dependency of the SFC_{ME} to the main engine load is taken from the Third IMO GHG Study

2014, where several SFC curves against the main engine load were used to find an empirical equation that could estimate SFC_{ME} at any given engine load.

The resultant main engine SFC empirical equation, which is as well used in this study, is given as follows:

$$SFC_{ME,i} = SFC_{base} \cdot (0.455 \cdot Load_i^2 - 0.710 \cdot Load_i + 1.280) \quad (10)$$

Where $Load_i$ is the hourly main engine loading given as a proportion (i.e. from zero to one). This equation gives the main engine's most efficient load at around 80% MCR. The parenthetic component of Equation (10) is known as the main engine load correction factor (CF_L). This quadratic term is kept as a variable for convenience in future sections where the results between the Third and Fourth IMO GHG Studies are compared.

It is important to highlight that Equation (10) only applies to propulsion systems that use internal combustion engines, highlighted as engines one to eight in Table 10. Unlike for oil and LNG engines, SFC_{ME} values for gas and steam turbines are assumed to be not dependent on the engine load and, hence the SFC_{ME} for these engine types are always assumed to be the SFC_{base}.

As highlighted in the Third IMO GHG Study 2014, Equation (10) satisfactorily describes the SFC changes as a function of engine load when SFCs are optimized at 80% load. However, for some ships with electronically controlled engines, especially in case of slow steaming, the engine tuning could be optimized for engine loadings lower than 80% MCR. Unfortunately, the scale of this practice in the global fleet is unknown and out of the scope of this report.

Auxiliary engines and boiler specific fuel consumption assumptions

For auxiliary engines and boilers it is assumed, similar as in the Third IMO GHG Study 2014, that they are not dependent on their load and, hence, are not corrected by CF_L. Therefore, their fuel consumption is governed solely on the power demand and their SFC_{base} as shown in Equation (11):

$$FC_{AE|BO,i} = SFC_{base} \cdot \dot{W}_{AE|BO,i} \quad (11)$$

Where $FC_{AE,i}$ and $FC_{BO,i}$ are the hourly fuel consumption for the auxiliary engines and boiler respectively, $\dot{W}_{AE,i}$ and $\dot{W}_{BO,i}$ is the power output for the auxiliary engines and boilers respectively.

Other relevant aspects for fuel consumption

At engine loads below 7%, fuel consumption and all the emissions derived from the main engine are assumed to be zero. These low levels of engine loads normally occur while ships are at berth or anchorage, hence, in such cases fuel consumption and emissions are derived from the auxiliary engine and boiler.

Emissions Calculation:

For the Fourth IMO GHG Study the hourly emissions for each system (i.e. main engine, auxiliary engine and boiler) have been divided into two groups based on how the emissions are more commonly calculated:

1. Energy-based: Pollutants that are calculated depending on the engine's/boiler's power output ($\dot{W}$) using an energy-based emission factor (EF_e) in g pollutant/kWh. The hourly emissions (EM_i) then are calculated as follow:

$$EM_i = EF_e \cdot \dot{W}_i \tag{12}$$

   - The following emissions enter into this group: nitrogen oxides (NO_x), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), particular matter ($PM_{2.5}$ and PM_{10}) and non-methane volatile organic compounds (NMVOC).

2. Fuel-based: Pollutants that are calculated depending on the amount of pollutant found in the fuel and engine type. The EM_i are obtained by multiplying the hourly fuel consumption (FC_i) by the fuel-based emission factor (EF_f) in g pollutant/g fuel:

$$EM_i = FC_i \cdot EF_f \tag{13}$$

   - In this group of emissions enter CO_2, sulfur oxides (SO_x) and BC for marine diesel engines. LNG engines, steam turbines, and gas turbines have only energy-based BC emission factors, but they can be converted to fuel-based by virtue of the specific fuel consumption assumptions.

A list of all emission factors is provided in Appendix M. Moreover, a numerical example describing the fuel consumption and emissions estimation process is presented in Appendix B.

Other relevant aspects of total emissions estimation

Although the methodology to estimate fuel consumption and emissions explained in this section is similar to that used for the Third IMO GHG Study 2014, there are substantial differences in how emissions factors are estimated. These differences explain changes of up to 30 % on total emissions — depending on the pollutant — for 2012 and are addressed in detail in Appendix B. Here are the most relevant points:

- The Third IMO GHG Study 2014 obtained the majority of their energy-based emission factors (EF_e) from Cooper and Gustaffson (2004), who performed extensive testing on different engine types consuming HFO and MDO with a range of loads. The methodology further suggested converting from EF_e to their fuel-based counterparts (Ef_f). To align with the findings from Cooper and Gustaffson (2004), the EF_e were divided by the SFC used in Cooper and Gustaffson (2004), referenced to here as SFC_{CG}. Integrating this conversion into Equation (13) creates an age-dependent correction factor to the EF_e of all emissions except for CO_2. To provide an example using the Third IMO GHG Study 2014 data, the SFC_{base} for an SSD built after 2001 was given as 175 g/kWh while SFC_{CG} was 195 g/kWh for any EF_e. When calculating EM_i as in Equation (13), a reducing factor of 0.90 (≈ 175/195) is added. This factor is one of the principal differences between the studies.
- During the conversion from EF_e to EF_f, the Third IMO GHG Study 2014, due to how the equations were developed, also corrected SFC_{CG} by the engine load correction factor, CF_L, described previously. Since these are in the denominator, when used in conjunction with Equations (9) and (10), the effect of engine load on FC is eliminated, further reducing the

estimated emissions. In the following set of equations this is demonstrated by starting from Equation (14):

$$EM_{i\_IMO3} = FC_i \cdot EF_f = \left(SFC_{base} \cdot CF_L \cdot \dot{W}_i\right) \cdot \left(\frac{EF_e}{CF_L \cdot SFC_{CG}}\right)$$

$$EM_{i\_IMO3} = EF_e \cdot \frac{SFC_{base}}{SFC_{CG}} \cdot \dot{W}_i \qquad (14)$$

Equation (14) differs from this study's approach, which directly applies directly the EF_e (Equation (12)) and for the emissions that use EF_f that are either constant — CO_2 — or change with the engine load — BC — according to the literature (Olmer, et al., 2017a; 2017b)The decision to shift the method to estimate GHG emissions to an energy-based approach, except for CO_2 and BC, for the current study was made after consulting engine manufacturers and experts in emissions estimation:

- While the Third IMO GHG Study 2014 used unique specific fuel consumption values (i.e. SFC_{CG}) and energy-based factors obtained from emissions directly compared against FC (Cooper & Gustaffson, 2004), the Fourth IMO GHG Study has updated the energy-based factors to the newest available literature. Now, to calculate EM_i, it is not required to convert from EF_e to EF_f, eliminating the age-dependent SFC factor seen in Equation (14).

According to engine manufacturers and emission experts consulted for the report, there is no need for an age-based modifier/factor for the EF_e (i.e. PMs, N_2O, CO and NMVOC) since the age-related change in emissions is already captured in the SFC_{base} from the different engine generations. This means that changes seen in these EF come from the SFC_{base} change - which includes the generational efficiencies.

For fuel-based emission factors (i.e. CO_2, SO_x and BC) their dependency is in the number of molecules found in the fuel. For SO_x the time-dependency is captured through IMO's sulfur monitoring program since the average sulfur content changes year on year. However, the main age-dependency for these pollutants is observed when quantifying the total emissions through the engine SFC_{base}.

For BC is a mix of fuel- and energy-based emission factors depending on what the fuel is being consumed. Still, the emission factors will have an age-related relationship with the engine through the SFC_{base} as explained previously for each of the different emission factor approaches.

In the case of NO_x, the EF age-dependency is captured by the different Tiers while for CH_4 it is embedded by the different emission factors assigned to each gas-engine technology considered in this report and as given by Pavlenko et al. (2020).

Emission factors

This section covers the bottom-up emission factors and their estimation methodology with their relevant nuances. This section starts with the Low Load Factors (LLF) and then it follows by presenting each of the pollutants indicating what EF approach was used. The emission factors used in this study can be found in Appendix B.

Low load factors

Emission factors increase at different rates when engine loads are below 20% due to lower combustion efficiency. To recreate this behaviour, best fit lines are used to adjust the pollutants EF at these loads. For these, Table 20 presents the LLF used to define them. Please note that although the values project a line between 2 and 10%, the model has been set to not report any fuel consumption and emissions for the main engine below 7% MCR.

Table 20 - Low load adjustment factors used.

Engine load	PM	NO_X	SO_X *	CO_2 *	CO	CH_4	N_2O	NMVOC	BC *
<=2%	7.29	4.63	1.00	1.00	9.7	21.18	4.63	21.18	1.00
10%	1.38	1.22	1.00	1.00	1.97	2.18	1.22	2.18	1.00
20%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

* These pollutants vary directly as a function of fuel consumption, which itself is a function of engine load, so LLFs are not applied.

Carbon dioxide (CO_2) - Fuel-based emission factor

For CO_2 emissions it was used the mass-based EF per fuel type as given by the 2018 EEDI Guidelines (IMO, 2018a) as shown in Table 21.

Table 21 - Different fuels' fuel-based emission factors (EF_f) and their carbon content.

Fuel type	Carbon Content	EF_f (g CO_2/g fuel)
HFO	0.8493	3.114
MDO	0.8744	3.206
LNG	0.7500	2.750
Methanol	0.3750	1.375
LSHFO 1.0%	0.8493	3.114

Note that 'MDO' refers to distillate marine fuels in general, which would include marine gas oil (MGO). For low-sulfur HFO fuels it was assumed the same carbon content and EF_f than with HFO. Particularly for engines that have pilot fuel, the amount of CO_2 produced by the pilot fuel is incorporated into the EF_f by weighting the fuel mix of main and pilot fuels by CO_2 mass emitted.

Sulfur oxides (SO_x) - Fuel-based emission factor

SO_X emissions vary with fuel consumption and fuel sulfur content or, if installed, with the use of exhaust gas cleaning systems. For the Fourth IMO GHG Study the SO_X emission factor was estimated assuming that the global fleet did not use scrubbers between 2012 and 2018. Halff, Younes and Boersma (2019) asserted that by 2018 less than 1% of the global fleet had installed a scrubber. The fuel-based SO_X emission factor (g SO_x/g fuel) is calculated as follows:

$$EF_{f,SO_x} = 2 \cdot 0.97753 \cdot S \tag{15}$$

This equation reflects an assumption that 97.753% of the sulfur in the fuel is converted to SO_x (the rest is converted to sulphate/sulfite aerosol and classified as a part of particulate matter) and the "2" reflects the ratio of the molecular weight of SO_2 to sulfur because, for ship emissions, the vast majority of SO_x is SO_2. S is the fuel sulfur content fraction given as g of SO_x by g of fuel and they are presented in Table 22 as percentage. An important fact to consider is that yearly global sulfur content for HFO and MDO is never constant. This is seen in the IMO's annual sulfur monitoring program presented at different MEPC. The Fourth IMO GHG Study takes the values from the IMO's 2018 program to establish the value of $\%S$ in Equation (15) for each of the years covered and these are presented in Table 22. This table reflects SECAs and the EU Sulfur Directive applied at the time which required ships to switch to LSHFO pre-2015 — assumed to contain 1.0% sulfur — and from 2015 onwards to MDO.

Table 22 - Global average fuel sulfur content in percentage per year (IMO, 2019d, p. 6)

Fuel type	2012	2013	2014	2015	2016	2017	2018
HFO	2.51	2.43	2.46	2.45	2.58	2.60	2.60
MDO	0.14	0.13	0.12	0.08	0.08	0.08	0.07

The sulfur content for LSHFO used to estimate emissions in SECA areas before 2015 assumes a nominal value of 1.0% across all years. For LNG, following the Third IMO GHG Study 2014, it is assumed that the sulfur content was $8.29x10^{-4}$%. For methanol-fueled engines, the source of sulfur is associated with the pilot fuel, normally low-sulfur MDO, and required to ignite the fuel mix inside the combustion chamber. There are no SO_X measurements from the combustion of methanol in marine engines so far, only bench trials by engine manufacturers. MAN Diesel & Turbo (2014) states that methanol engines can reduce SO_X by between 90 and 97% when compared to their HFO counterparts. Under that light, the Fourth IMO GHG Study assumes that the SO_X emission factor for methanol-fueled engines is 10% of the SSD and MSD engines SO_X emission factor when consuming HFO.

Nitrogen oxides (NO_x) - Energy-based emission factor

For NO_x emissions from engines using the Diesel cycle, the EF_e is a function of the engine speed and tier (i.e. the year when the engine was manufactured), whether or not the vessel is operating in a NECA, since it was assumed that no engine could have a higher EF_e than the stipulated by IMO MARPOL Annex VI Regulation 13 (IMO, 2013b). Table 23 presents the different NO_x EF_e per engine speed and tier.

Table 23 - Engine tier differentiation with their respective limits depending on engine speed

Tier	Earliest Ship Construction Date	EF_{e},NO_x (g/kWh) *n* = engine's rated speed (RPM)		
		n < 130	130 <= n < 2,000	*n* >= 2,000
I	1st of Jan 2000	17.0	$45*n^{-0.2}$ e.g. n = 500 RPM -> 12.984	9.8
II	1st of Jan 2011	14.4	$44*n^{-0.23}$ e.g. n = 500 RPM -> 10.536	7.7
III	1st of Jan 2016	3.4	$9*n^{-0.2}$ e.g. 500 = RPM -> 2.597	2.0

For medium-speed engines, the emission factor was obtained at an engine speed of 500 rpm, similar to the Third IMO GHG Study 2014. For low-pressure injection LNG internal combustion engines (LNG-Otto MS, LNG-Otto SS and LBSI), a constant 1.3 g NO_x/kWh EF_e is assumed. For methanol-powered engines, the same approach as with SSD and MSD is used, with EF_e being the NO_x limit imposed by Regulation 13.

It is important to highlight that NO_x emissions can be reduced by after-treatment technologies such as EGR, SCR, scavenge air moisturising among others. As well, it was assumed for vessels with Tier III engines, and to reflect current practices, that when they are operating outside NECA their emission levels will be the same as a Tier II engine while in NECA they will comply with the Tier III NO_x emissions.

Particulate matter (PM_{10} and $PM_{2.5}$) – Energy-based emission factor

The PM_{10}'s EF_e are a function of the fuel's sulfur content and are therefore reduced when operating on lower sulfur fuels (e.g. when operating in ECAs). For engines being fueled by HFO and MDO/MGO, this study estimates PM_{10} EF_e based on the sulfur content reported in Table 22 and by using the following formulas:

HFO

$$EF_{e,PM_{10}} = 1.35 + SFC_i \cdot 7 \cdot 0.02247 \cdot (S - 0.0246) \quad (16)$$

MDO/MGO

$$EF_{e,PM_{10}} = 0.23 + SFC_i \cdot 7 \cdot 0.02247 \cdot (S - 0.0024) \quad (17)$$

The number 7 in Equations (16) and (17) comes from the molecular weight ratio between sulfate PM and Sulfur and 0.02247 reflects the proportion of the sulfur in the fuel that is converted to sulfate PM (Office of Transportation Air Quality , 2020).

In the case of engines that burn LNG, the PM_{10} EF_e are 0.01 g PM_{10}/kWh for Diesel engines and 0.02 g PM_{10}/kWh for LBSI, LNG-Otto SS and MS, and auxiliary engines. For boilers, steam and gas turbines, an $EF_{e,PM_{10}}$ of 0.03 g PM_{10}/kWh was used (Office of Transportation Air Quality , 2020).
The PM_{10} emission factor for methanol is considered to be 10% of the SSD and MSD engines PM_{10} emission factor when consuming HFO (MAN Diesel & Turbo , 2014). Finally, to calculate the EF_e for $PM_{2.5}$, this study assumes it makes up 92% of PM_{10} (EPA, 2019).

Methane (CH_4) – Energy-based emission factor

In this study it is assumed that the EF_e of CH_4 vary by engine type. For LNG-fueled engines the EF_e are taken from Pavlenko, et al. (2020), for methanol-fueled engines from MAN Diesel & Turbo (2014), and for the remaining engines taken from the Third IMO GHG Study 2014.

Pavlenko et al. (2020) assume EF_e values that account for variations in methane slip between engine technologies, designed to represent methane emission factors from marine engines on the E2/E3 test cycle. CH_4 EF_e values for LNG-fuelled engines are as follows: LNG-Otto SS (2.5 g/kWh), LNG-Otto MS (5.5 g/kWh), LBSI (4.1 g/kWh), LNG-Diesel (0.20 g/kWh). Actual methane emissions from these engines could be higher or lower depending on engine load. For that reason, and as referred to previously, a low load adjustment factor below the main engine's 20% MCR is applied. The base CH_4 emission factor for methanol-fueled engines has the same approach as with other EF_e, where $EF_{e,CH4}$ is 10% of the SSD and MSD $EF_{e,CH4}$ when consuming HFO or MDO (i.e. 0.001 g CH_4/kWh). The $EF_{e,CH4}$ by engine type can be found in Appendix B.

Carbon monoxide (CO) – Energy-based emission factor

The same CO EF_e values in the Third IMO GHG Study 2014 are used for this study with regards to internal combustion engines (expanding the EF_e to HSDs), turbines and boilers consuming HFO or MDO. For LNG-fueled engines of the type Otto-SS, -MS, LBSI and auxiliary machinery, the $EF_{e,CO}$ is assumed to be 1.30 g CO/kWh was taken from the Third IMO GHG Study 2014. For LNG-Diesel, $EF_{e,CO}$ is 1.04 g CO/kWh and for turbines and boiler, the emission factor is given as 0.20 g CO/kWh (Office of Transportation Air Quality , 2020). As with other EF_e for methanol engines, $EF_{e,CO}$ is 10% of the SSD and MSD $EF_{e,CO}$ when consuming HFO or MDO.

Nitrous oxide (N_2O) – Energy-based emission factor

For engines powered by HFO, their N_2O EF_e is taken from the Third IMO GHG Study 2014. For MDO-fueled engines, the $EF_{e,N2O}$ are taken from Office of Transportation Air Quality (2020) which gives for all diesel-cycle engines an EF_e of 0.03 g N_2O/kWh and 0.04 g N_2O/kWh for turbines and boilers. When engines being fueled by LNG, the $EF_{e,N2O}$ for Otto-SS, -MS, LBSI, auxiliary machinery, turbines and boilers is given as 0.02 g N_2O/kWh while for LNG-Diesel is 0.03 g N_2O/kWh (Office of Transportation Air Quality , 2020). Finally, when consuming methanol, $EF_{e,N2O}$ is 10% of the N_2O $EF_{e,N2O}$ from an SSD and MSD consuming HFO or MDO.

Non-methane volatile organic compounds (NMVOC) - Energy-based emission factor

For NMVOC, the EF_e used the values from the Office of Transportation Air (2020) for SSD, MSD, HSD, Auxiliary machinery, turbines and boiler when consuming HFO or MDO. The same reference was used for LNG-Diesel, auxiliary machinery turbines and boilers when consuming LNG. For the rest of the LNG-fueled engines, the Third IMO GHG Study 2014 was used. Finally, for methanol engines, the same assumptions as with the other EF_e was used.

Black carbon (BC) – Fuel- and energy-based emission factor

In this study, the main engine BC EF_f developed by ICCT are applied to estimate BC emissions. Here, the same approach used by Olmer et al. (2017a) and Comer et al (2017)is applied. For a detailed explanation on BC emission factor please refer to Olmer et al. (2017b). It is important to highlight that fuel-based emission factors are used for any internal combustion engine consuming any fuel except with LNG. For engines consuming LNG or any turbine, the emission factors are given as energy-based.

While the factors influencing BC emissions are not limited to engine type, fuel type, and engine load, these three parameters help understand the behavior of BC emissions in a manner that is useful for generating bottom-up emission inventories where these parameters are known. Other fuel parameters including the aromatic content and hydrogen content also likely influence BC emissions, but are out of the scope of this study. The BC emission factors in this study are based on measured Filter Smoke Number (FSN) values that have been then converted to BC mass using a mass absorption coefficient. While the BC EF_f have a degree of uncertainty and they can be improved over time, for the Fourth IMO GHG Study they are useful for understanding trends in BC emissions from ships over time.

In this study, the $EF_{f,BC}$ (g BC/ g fuel) vary as a function of fuel type (residual, such as HFO or distillate, such as MDO), engine stroke type (2-stroke or 4-stroke), and engine load. No LLF are applied because $EF_{f,BC}$ are allowed to vary as a function of all engine loads, including those less than 20% MCR. This study estimates BC emissions as follows:

Two-stroke engines operating on residual fuel (e.g., HFO)

$$\mathbf{EF_{f,BC} = 1.500x10^{-4} \cdot (Load^{-0.359})} \quad (18)$$

Two-stroke engines operating on distillate fuel (e.g., MDO or MGO)

$$\mathbf{EF_{f,BC} = 3.110x10^{-5} \cdot (Load^{-0.397})} \quad (19)$$

Four-stroke engines operating on residual fuel (e.g., HFO)

$$\mathbf{EF_{f,BC} = 2.500x10^{-4} \cdot (Load^{-0.968})} \quad (20)$$

Four-stroke engines operating on distillate fuel (e.g., MDO or MGO)

$$\mathbf{EF_{f,BC} = 1.201x10^{-4} \cdot (Load^{-1.124})} \quad (21)$$

For methanol-fueled engines, the fuel-based BC emission factor is assumed to be 90% less than the HFO fuel-based BC emission factor (IMO, 2017) and it is assumed that the same reduction would be seen in the energy-based emission factor.

When consuming LNG, any engine (except LNG-Diesel), turbine or boiler are assigned an EFe of 0.003 g BC/kWh while for LNG-Diesels it takes a value of 0.002 g BC/kWh. For gas turbines consuming HFO, EFe is assumed as 0.005 g BC/kWh while when consuming MDO EFe is assumed 0.004 g BC/kWh. For steam turbines and boilers consuming HFO, the EFe is assumed as 0.080 g BC/kWh and when consuming MDO, EFe is 0.060 g BC/kWh.

Final note on emission factors for low sulfur heavy fuel oil

Low Sulfur Heavy Fuel Oil (LSHFO 1.0%) uses the same emission factors as conventional HFO for all pollutant types, apart from SO_x, PM_{10} and $PM_{2.5}$. For these pollutants, the appropriate proportions of sulfur content as given in Table 20 should be used in Equations (15) to (17).

2.2.6 Type 3 and Type 4 emissions estimation methodology

Type 3 vessels are defined as those vessels that have at least 24 hours of AIS observations in a given year; valid MMSI numbers (9-digit numbers starting with 2-7); have not been matched with the IHS ship registry data; can be matched with the Global Fishing Watch (GFW) data; and are more than 100 gross tonnes based on GFW estimates. The estimation of activity and emissions from Type 3 vessels required a more extensive methodology to make up for their lack of coverage in the IHS dataset. The estimated emissions of Type 3 vessels were derived as follows:

1. Using the generic vessel type estimate made available by GFW, the Type 1, 2, and 3 vessels were classified into one of six vessel groups: Fishing, Passenger, Cargo, Reefer, Tanker and Other. These correspond with the previously defined IMO vessel types:
   a **Fishing:** Miscellaneous – fishing.
   b **Passenger**: Cruise, Ferry – ro-pax, Ferry - pax only.
   c **Cargo**: Bulk carrier, Container, General cargo, Ro-Ro, Vehicle carrier.
   d **Reefer**: Refrigerated bulk.
   e **Tanker**: Oil tanker, Chemical tanker, Liquified gas tanker, Other liquid tankers.
   f **Other**: Service-other, Service-tug, Offshore, Yacht, Miscellaneous – other.
2. The interquartile range of gross tonnage for Type 3 vessels by ship group was calculated. This range was then used to select a subset of Type 1 and Type 2 vessels by ship group for use as emission proxies.
3. For each ship group of filtered Type 1 and Type 2 vessels, the following variables were calculated:
   - average within-group emission rates (g/hour) for each pollutant;
   - average within-group fuel consumption rates (g/hour) for each fuel type;
   - average within-in group international/domestic activity split (% of total hours) based on Option 2.
4. These variables were then applied to the set of Type 3 vessels, according to ship group.
5. The hours of activity for the Type 3 vessels were estimated before calculating their emissions by:
   - Identifying the first and last AIS signal for each vessel, which gives an estimate of the maximum operating hours in a given year, but does not reflect actual vessel operating hours, which would be lower.
   - Matching this study's Type 3 vessels with the same vessels in the ICCT's inventory based on MMSI numbers. The data used in the ICCT inventory published in Olmer et al. (2017a) contains the observed hours of Type 3 ship vessels for 2013, 2014 and 2015, rather than only the time between the first and last received AIS signal.
   - Calculating the ratio of observed hours in the ICCT inventory to the total hours between first-seen and last-seen signals for the matched vessels.
   - Summarizing the above ratios by ship group for each common year: 2013, 2014, and 2015.
   - Applying the ratio to the hours between first- and last-seen AIS signals for Type 3 vessels in this study to estimate their actual operating hours, based on ship group for each year. For 2013, 2014, and 2015, the ratios corresponding to each year were applied. Because there were no common years for 2012, 2016, 2017, and 2018 between the ICCT inventory and this study, 2012 used 2013 activity adjustment ratios and 2016, 2017, and 2018 used the 2015 activity adjustment ratios. This introduces some additional uncertainty for Type 3 emissions for these years.
6. Emissions were calculated by multiplying the emission rates and adjusted activity hours; fuel consumption was calculated by multiplying the fuel consumption rates and adjusted activity hours.
7. The split of emissions and fuel consumption between international and domestic operations were calculated by multiplying the total emissions and fuel consumptions with corresponding international/domestic activity split (Option 2).

Table 24 - Number of Type 3 vessels by group, 2012-2018

	2012	2013	2014	2015	2016	2017	2018
Fishing	6,536	8,485	12,021	12,163	14,025	15,662	17,583
Passenger	3,569	5,209	6,336	7,108	8,307	9,842	10,722
Cargo	5,927	6,603	7,580	7,362	7,601	8,534	8,953
Reefer	411	583	664	693	787	1,067	1,201
Tanker	7,236	9,734	10,849	10,468	11,025	13,640	14,347
Other	22,000	40,494	48,249	46,891	55,225	81,387	86,247
Total	**45,679**	**71,108**	**85,699**	**84,685**	**96,970**	**130,132**	**139,053**

Table 25 - Ratio of observed hours versus hours between first-seen and last-seen signals, 2013-2015

Ship group		Fishing	Passenger	Cargo	Reefer	Tanker	Other
Activity adjustment ratio	**2013**	0.096	0.174	0.273	0.154	0.261	0.172
	2014	0.117	0.211	0.334	0.201	0.293	0.190
	2015	0.130	0.214	0.373	0.289	0.347	0.239

Finally, in order to distribute the activity, emissions, and fuel consumption estimates calculated for each ship group by IMO vessel type and size, the percentage of vessels counts per type and size bin were calculated for each ship group of filtered Type 1 and Type 2 vessels. This composition was applied to the Type 3 vessels under the assumption that the vessel type compositions would be roughly the same between types.

The number of Type 3 vessels is seen to have grown over time, but this primarily reflects the improved AIS coverage from year to year (illustrated in section 2.7.1), and to a lesser extent the improved GFW ship database quality, rather than the true year-on-year growth in the Type 3 fleet. The increased Type 3 coverage is expected to produce a spurious increasing trend in Type 3 emissions year on year and will not be representative of a true increase in the size of the Type 3 fleet. It was decided that the Type 3 fleet and its emissions should be included without a modification to correct for this perception of increased coverage.

This decision was driven by the absence of reliable sources of information to control for the true increase in fleet size, or estimate what coverage is still not yet included for these types of emissions. It was therefore preferable to include the more transparent uncertainty and quality challenges that can be demonstrated through the data describing the evolution of the observed fleet size over time. Type 3 emissions are shown to be significant only to the estimation of the domestic emissions inventory, not the international emissions when Option 2 for the allocation of domestic and international voyages is applied, and therefore their unedited inclusion is of minimal significance to the international emissions inventory.

Type 4 vessels are defined as having a gross tonnage greater than 100 tonnes but less than 300 tonnes, and are listed as “in service” in the IHS database during a given year yet did not have any identifying signals recorded in the AIS dataset. The estimation process for Type 4 vessels was as follows:

1. Using observed activity and emissions data from Type 1 and Type 2 vessels with a gross tonnage of between 100 and 300 tonnes, an average number of operational hours and an average hourly emissions rate for each pollutant was calculated for each vessel type and size.
2. These values were used as proxies for the annual operational hours and emissions rate for the Type 4 fleet and multiplied together to give a representative total annual emissions figure for each vessel type and size.

3. These emissions estimates were allocated to international or domestic sets by assuming that the proportion of international and domestic hours were identical to the average Type 1 and Type 2 vessel per type, and with a gross tonnage of between 100 and 300 tonnes.

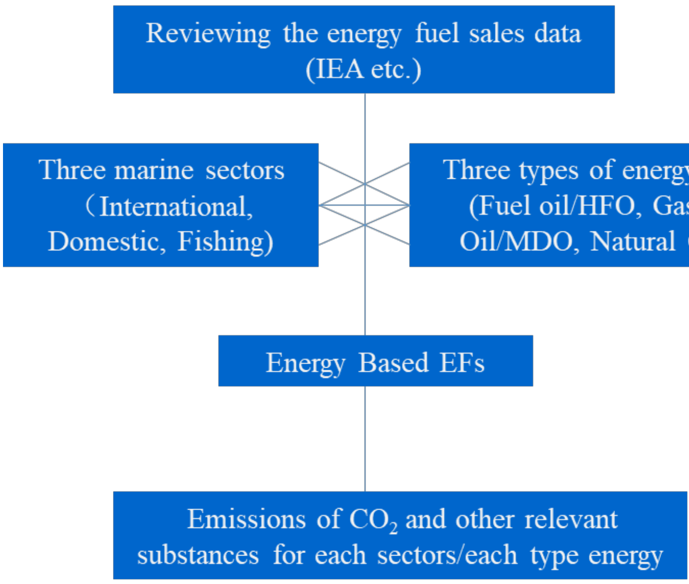
The number of Type 4 vessels totaled between 26,000 and 28,000 vessels per year from 2012 to 2018, although the number of Type 4 vessels is lowest in recent years, likely because some would-be Type 4 ships are able to be identified in the AIS data, resulting in them matching as Type 1 or Type 2 ships.

2.3 Top down methodology and data sources

2.3.1 Overview of the top-down estimations

The aim of this Task is to estimate the energy related GHG emissions of shipping based on fuel sales statistics and energy-based emission factors of GHGs. The total fuel consumption by shipping is estimated from world-wide sales of bunker by summing up per country. These so-called top-down results provide a comparator with bottom-up results. The long-run statistics for three types of of energy products (Fuel oil/HFO, Gas diesel oil/MDO, and Natural Gas/NG) and three marine sectors (international, domestic and fishing) over the period 2007-2011 are reported. The methodology and assumptions used in this task conform to International Energy Agency energy allocation criteria. The overall pathway is shown in Figure 57.

Figure 57 - The pathway of Top-Down methodology



Estimation results and calculation methods of emissions using top-down fuel consumption data are presented. A comparison of estimation results calculated in this study and in the Third IMO GHG Study is also provided.

2.3.2 Fuel data and energy consumption

Methods for review of IEA data

This study uses the World Energy Statistics energy balance statistics provided by IEA, which were also used in the Second and Third IMO GHG Studies.

This study uses IEA data within the period 2012-2017 to estimate top-down emissions.
The Third IMO GHG Study mainly used three types of energy products (fuel oil, gas/diesel and natural gas) and three sectors (international marine bunkers, domestic navigation and fishing). Since IEA data for year 2012 was not available in the Third IMO GHG Study and no projection was provided, this study covers the year 2012 to fill up the missing estimates.

Figure 58 illustrates the long-run trend for total marine consumption of different energy products (international, domestic and fishing) over the period 1971-2017. During the period 2012-2017, total marine energy consumption is relatively stable with a slight increase from 247.9 million tonnes to 259.3 million tonnes.

The IEA statistics report data for fuels most used by ships: fuel oil, gas diesel oil, motor gasoline, lubricants, non-specified fuel and natural gas fuel. For oil products such as motor gasoline, lubricants and non-specified fuel, their total consumption volume accounts for around only 0.1% of total fuel oil consumption. For other energy products statistics reported by IEA, their total equivalent consumptions accounts for around only 0.2-0.3% of total fuel oil consumptions.

Following the Third IMO GHG Study, this study's scope covers the three main energy products used in shipping: fuel oil (HFO), gas diesel oil (MDO) and natural gas (NG).

Figure 58 - Oil products and products from other sources used in shipping (international, domestic and fishing) 1971-2017

The most up-to-date statistics available from IEA are for year 2017 at the time of this study. For year 2018, 33 nations/regions have reported non-zero data to IEA, the sum-up fuel consumptions of these nations/regions in 2017 represent 19 and 23% of total consumptions for fuel oil and gas/diesel respectively (see Table 26). Since there exists significant gaps in the current IEA statistics for year 2018, this study excludes year 2018 from the top-down analyses.

Table 26 - Comparison of 2017 and 2018 marine fuels reporting to IEA (ktonnes)

	2017		2018	
Nations reporting	**Fuel oil**	**Gas/diesel**	**Fuel oil**	**Gas/diesel**
33 reporting nations/regions in 2018 (Algeria, Austria, Belarus, Belgium, Benin, Brazil, Bulgaria, Chinese Taipei, Costa Rica, Croatia, Cyprus, Ecuador, Egypt, France, Georgia, Guatemala, Hungary, Indonesia, Ireland, Italy, Jordan, Latvia, Lithuania, Poland, Portugal, Republic of Moldova, Romania, Senegal, Serbia, Slovenia, Thailand, Tunisia, United Kingdom, United States, Uruguay)	36,846	14,249	38,778	22,647
Total consumption in 2017	**19,6518**	**625,65**		
Percent of 2017 fuel reported by 33 nations/regions reporting in 2018	**19%**	**23%**		

2.3.3 Emission factors of GHGs and other relevant substances in top-down methodology

There are two types of emission factors used in the top-down method:
1. Emission factors that relate to the chemical composition of the fuel: CO_2, SO_x. These can be calculated directly from the fuel sales statistics. And
2. Emission factors that depend on the type of engine and the engine load: NO_x, CH_4, N_2O, etc., which depend on.

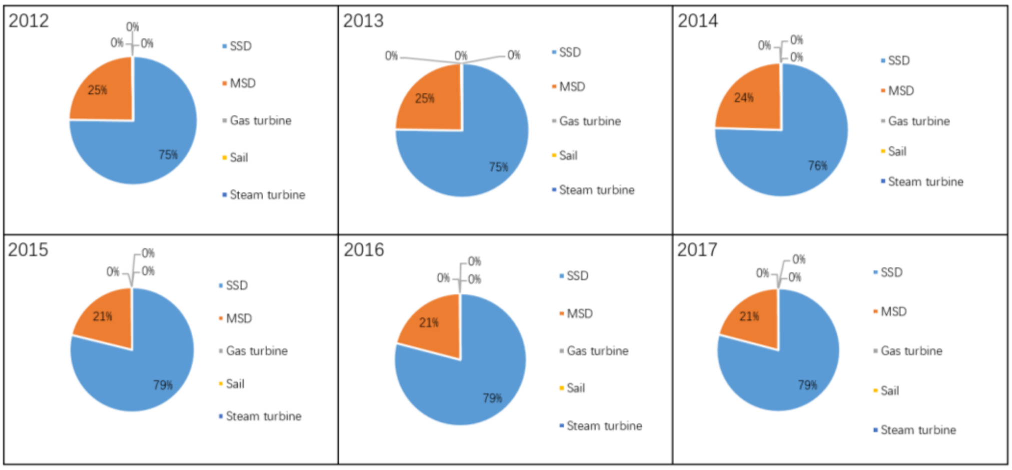
In view of the variable proportions of engine types for each type fuel in use based on the statistical data (Figure 59), the combined fuel-based emission factor considering engine composition will be more reasonable. So we used information from databased about engine types, as well as the results from the bottom-up modelling about engine loads, to arrive at emission factors. The schematic approach is described as the below:

Based on the bottom-up approach, the fuel consumption and emissions were estimated by fuel type, the total mass of pollutant by the total mass of fuel consumption to generate an appropriate mass-based emission factor, which then was multiplied by the IEA total fuel consumption for each fuel to calculate the top-down emissions. The mass-based emission factors and the top-down emissions was estimated for each year during 2012 to 2017.

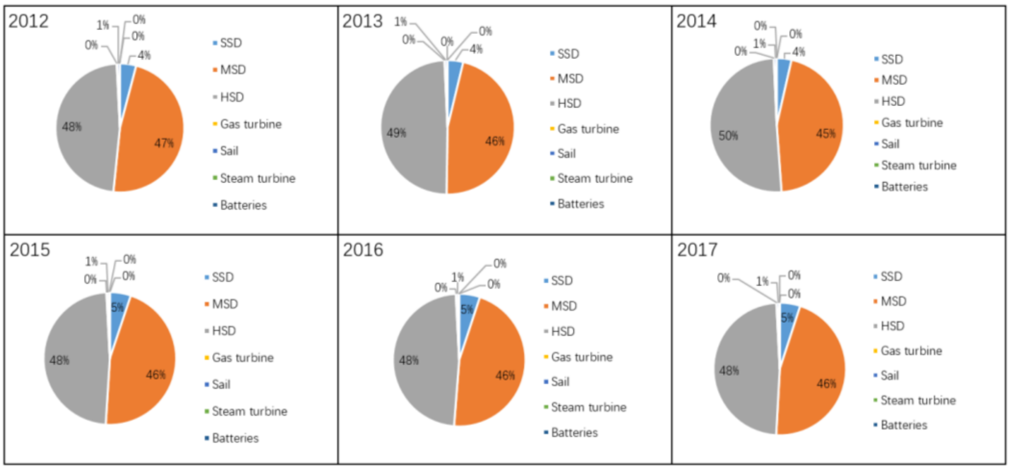
The benefit is that the emissions would already take into account changes in fleet composition, engine age distribution, SFC, and sulfur content. The emission factors used in top-down emissions in this study were more realistic one rather than just choosing someone engine (like SSD)-based emission factor for the specific fuel type used in the previous IMO GHG study. Also, this study uses a year-on-year (2012-2017) dynamic statistical emission factors of GHG and relevant pollutants for different type fuels. The emission factors for the period 2007-2011 are listed in
Table 27, which also makes a comparison with emission factors used in the Third IMO GHG Study in Section 2.6.6.

Figure 59 - Proportion of engine types for different types of fuel burning (2012-2017)

a HFO



b MDO



c LNG

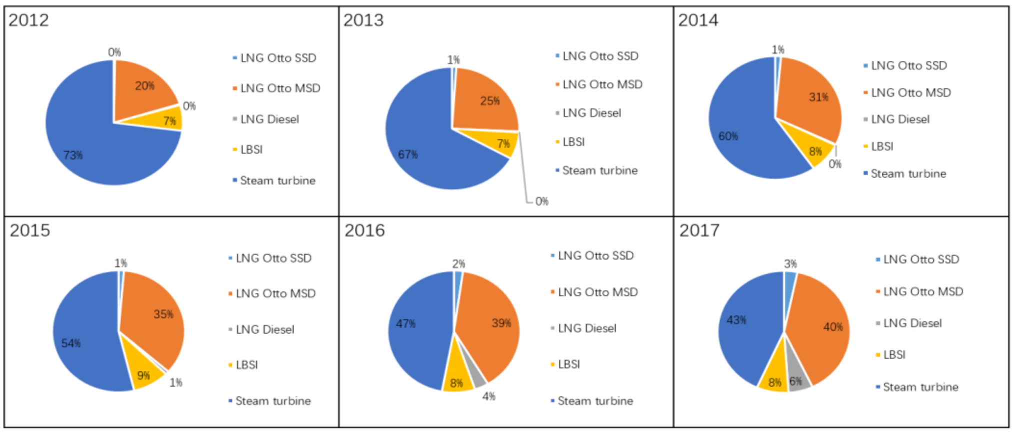


Table 27 - Emissions factors used in this study for top-down estimation (unit: kg pollutant/tonne fuel)

Pollutants	Fuel Type	The Fourth IMO GHG Study						
		2012	2013	2014	2015	2016	2017	2018
CO_2	HFO	3,114	3,,114	3,114	3,114	3,114	3,114	3,114
	MDO	3,206	3206	3,206	3,206	3,206	3,206	3,206
	LNG	2,750	2,750	2,749	2,749	2,750	2,753	2,755
CH_4	HFO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	MDO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	LNG	5.31	6.00	7.35	8.48	10.20	11.22	11.96
N_2O	HFO	0.17	0.17	0.17	0.17	0.18	0.18	0.18
	MDO	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	LNG	0.08	0.08	0.08	0.09	0.09	0.10	0.10
NO_x	HFO	78.61	77.18	76.19	76.98	76.71	76.67	75.90
	MDO	53.12	52.51	52.14	57.68	57.45	57.62	56.71
	LNG	5.60	5.90	5.82	5.99	7.46	10.95	13.44
CO	HFO	2.84	2.83	2.84	2.86	2.86	2.87	2.88
	MDO	2.48	2.47	2.47	2.58	2.58	2.60	2.59
	LNG	1.88	2.07	2.38	2.64	3.10	3.57	3.97
NMVOC	HFO	3.14	3.13	3.13	3.17	3.18	3.19	3.20
	MDO	2.16	2.15	2.15	2.39	2.39	2.42	2.40
	LNG	0.81	0.88	0.99	1.09	1.26	1.44	1.59
SO_x	HFO	46.63	44.80	45.31	47.90	50.44	50.83	50.83
	MDO	2.74	2.54	2.35	1.56	1.56	1.56	1.37
	LNG	0.03	0.03	0.03	0.03	0.03	0.03	0.03
PM	HFO	7.11	6.96	7.01	7.26	7.48	7.53	7.55
	MDO	0.97	0.96	0.94	0.92	0.92	0.92	0.90
	LNG	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$PM_{2.5}$	HFO	6.54	6.41	6.45	6.68	6.88	6.93	6.94
	MDO	0.90	0.88	0.87	0.84	0.84	0.85	0.83
	LNG	0.10	0.10	0.10	0.10	0.10	0.10	0.10
BC	HFO	0.26	0.27	0.27	0.26	0.26	0.26	0.26
	MDO	0.43	0.43	0.43	0.37	0.37	0.37	0.38
	LNG	0.019	0.019	0.019	0.019	0.019	0.019	0.019

2.4 Fugitive emissions

Emissions from non-combustion sources are estimated using the same methods used in the Second and Third IMO GHG studies, where fugitive HFCs and HCFCs from refrigeration and cooling activities and NMVOCs from oil transportation were estimated with a top-down approach, using a fleet-wide methodology for refrigerants specifically. For consistency and continuation, this study focuses on estimating fugitive HFCs and NMVOCs, but does not estimate fugitive PFC, SF6, or NF_3 emissions for the following reasons (for more context see Third IMO GHG Study 2014):

- PFCs have been used on-board ships in aqueous film forming foam (AFFF) fire-fighting foams. Manufacturers however have been phasing them out under the prohibition to produce them by the Montreal Protocol; as such, they are not considered further in this study.
- SF_6 gas is sometimes transported by ship, but this does not occur in large quantities and its leakage is expected to be negligible.

— NF_3 gas has recently been added to the list of GHGs under the UNFCCC framework. However, as with SF_6 gas, any leakage of NF_3 gas either from any activities onboard or any material used onboard is expected to be negligible and therefore NF_3 emissions are not considered further in this study.

2.4.1 Refrigerant emissions from ships

HFC and HCFC emissions are primarily fugitive emissions from refrigerant and air conditioning gas releases. Fishing vessels and passenger ships carry larger amounts of refrigerants than other ship types, in order to cool or freeze their catch or to provide comfort to passengers and crew with air conditioning (Hafner, et al., 2019). For older vessels, HCFCs (R-22) are still in service, whereas new vessels use HFCs (R134a/R404a). As in the Third IMO GHG Study 2014, HFC and HCFC fugitive emissions are estimated per ship per year, varying by ship type, leveraging key findings from the European Commission (EC) on the amounts of refrigerants carried by various types of ships (Schwarz & Rhiemeier, 2007), taking into account more recent results from the Nordic Council of Ministers looking at the Nordic fleet alone (Hafner, et al., 2019) (see Table 28). For vessels built before 2000, refrigerants are assumed to be ozone-depleting R-22 for both air conditioning and cooling, while for newer vessels R134a is assumed to be the refrigerant for air conditioning, and R404a for provisional cooling purposes (Smith, et al., 2015a). A range of 20-40% refrigerant loss is reported in both UNEP's report (UNEP Technical Options Committee, 2011) and the EC's study (Schwarz & Rhiemeier, 2007). This refrigerant loss can be attributed to the permanent exposure of refrigerated systems to continuous motion (waves), which can cause damage and leaking pipes. This range is confirmed by a more recent study by the Nordic Council of Ministers (Hafner, et al., 2019)and therefore a refrigerant loss of 30% is assumed for all ships, except for passenger vessels for which 20% annual loss of refrigerants is assumed, as in the Third IMO GHG Study 2014.

Table 28 - Key input variables in estimating HCFCs and HFCs from ship (amounts of refrigerants carried by various types of ships from DG ENV report) (Hafner, et al., 2019; Smith, et al., 2015a)

Ship type	Key input variables			
	AC (kg)	Refrigeration (kg)	Annual leakage	Percentage of vessels built after 1999
Chemical tanker	150	10	30.0%	71.5%
Container	150	10	30.0%	66.0%
General cargo	150	10	30.0%	34.0%
Liquified gas tanker	150	10	30.0%	55.5%
Oil tanker	150	10	30.0%	55.2%
Other liquids tanker	150	10	30.0%	12.0%
Ferry - pax only	500	20	20.0%	23.6%
Cruise	6,000	400	20.0%	37.7%
Ferry - RoPax	500	20	20.0%	30.1%
Refrigerated bulk	150	2,500	30.0%	8.8%
Ro-Ro	500	20	20.0%	45.4%
Vehicle	150	10	30.0%	64.1%
Yacht	150	10	30.0%	57.3%
Service - tug	150	10	30.0%	46.7%
Miscellaneous - fishing	150	210	30.0%	17.4%
Offshore	150	10	30.0%	45.3%
Service - other	150	10	30.0%	30.4%
Miscellaneous - other	150	10	30.0%	28.0%

Furthermore, refrigerants can be found in the cooling systems of reefer containers. According to the EC's study each reefer container carries 6 kg refrigerant charge (80% R134a and 20% R404) of which 15% is lost annually. The number of refrigerated containers has been estimated to be 1.6 million TEU in 2006 and 1.7 million TEU in 2012, by the EC's study and the Third IMO GHG Study 2014 respectively. The Third IMO GHG Study 2014 based the reefer container count on the IHS vessel database for 5,400 containers, relying on reefer plug installations rather than reefer TEU counts. This study also leverages reefer plug installations to estimate reefer containers, which comes with inherent uncertainty. However, for the sake of completeness, it counts the reefer plugs of all vessel types found active in AIS during the year in question.
When applying the above described process, the estimated annual total refrigerant loss in 2018, excluding reefer containers, amounts to 8,028 tonnes (the breakdown by ship type and the subsequently derived fugitive HCFC and HFC emissions can be found in Table 29).

Table 29 - Annual loss of refrigerants from the global fleet and derived HCFC and HFC emissions during 2018 (excluding reefer containers)

Ship type	Total annual loss of refrigerants (tonnes)		HCFC and HFC emissions (tonnes)		
	AC	Refrigeration	R-22	R134a	R404
Bulk carrier	510.7	34.0	75.8	439.7	29.3
Chemical tanker	237.5	15.8	52.5	188.3	12.6
Container	232.8	15.5	42.8	192.7	12.8
General cargo	474.6	31.6	267.2	224.1	14.9
Liquified gas tanker	88.2	5.9	25.2	64.6	4.3
Oil tanker	320.6	21.4	110.2	217.3	14.5
Other liquids tanker	6.5	0.4	5.5	1.4	0.1
Ferry - pax only	422.8	16.9	307.3	127.3	5.1
Cruise	804.0	53.6	490.2	344.4	23.0
Ferry - RoPax	274.2	11.0	172.1	108.7	4.3
Refrigerated bulk	33.8	563.3	519.9	4.4	72.8
Ro-Ro	143.7	5.7	59.5	86.5	3.5
Vehicle	38.0	2.5	9.6	28.9	1.9
Yacht	111.0	7.4	43.7	70.0	4.7
Service - tug	886.2	59.1	420.1	492.3	32.8
Miscellaneous - fishing	876.2	1,226.6	1,589.4	213.9	299.4
Offshore	250.7	16.7	104.3	153.0	10.2
Service - other	206.1	13.7	120.1	93.6	6.2
Miscellaneous - other	8.9	0.6	5.3	3.9	0.3
Total	**5,926.5**	**2,101.9**	**4,420.9**	**3,054.8**	**552.7**

In addition to these total estimates, there are an estimated 2.49 million reefer containers in 2018, which, using the 80:20 ratio, contribute 1,793 tonnes of R134a and 448 tonnes of R404 to the shipping fleet's fugitive refrigerant emissions (see Table 30).

Table 30 - Annual emissions of refrigerants from the global fleet and the estimated number of reefer containers

Year	Vessel-specific HCFC and HFC emissions			Reefer container HCFC and HFC emissions	
	R-22 (tonnes)	R134a (tonnes)	R404 (tonnes)	R134a (tonnes)	R404 (tonnes)
2012	4,635.8	2,059.7	375.5	1,401.3	350.3
2013	4,574.6	2,284.5	409.4	1,495.3	373.8
2014	4,625.7	2,498.4	449.4	1,582.0	395.5
2015	4,573.2	2,683.5	484.8	1,671.2	417.8
2016	4,495.8	2,789.9	507.1	1,728.7	432.2
2017	4,432.1	2,880.4	523.2	1,749.0	437.2
2018	4,420.9	3,054.8	552.7	1,793.2	448.3

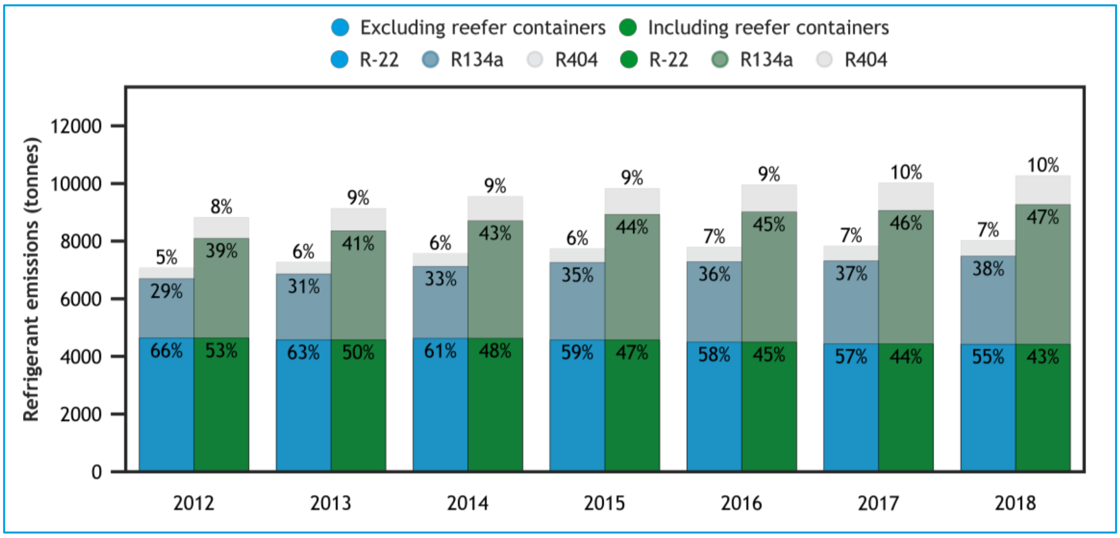
These updated results show a continued reduction in the share of R-22. As highlighted by the Third IMO GHG Study 2014, the balance of refrigerant shares will shift towards R134a when old vessels using R-22 as a cooling agent are replaced by new ships using HFCs (R134a). Using the global warming potential of refrigerants commonly used in shipping, the total refrigerant emissions correspond to 18.2 million tonnes in CO_2-equivalent emissions (using warming potentials as defined by IPPC (Forster, et al., 2007) and listed in Table 31), which is an increase from the 15.7 million tonnes in CO_2-equivalent emissions emitted in 2012.

Table 31 - Global warming potential of refrigerants commonly used in ships, relative to CO_2 warming potential (IPCC, 2006)

Refrigerant	Warming potential (relative to CO_2), 100 year horizon
R-22	1,810
R134a	1,430
R404a	3,260

The emissions of refrigerants from ships are mainly affected by changes in the size and composition of the global fleet, as well as an increase in reefer containers.

Figure 60 - Estimated refrigerant emissions of the global fleet, showing both totals when including and excluding reefer containers



2.4.2 Non-exhaust emissions of NMVOCs from ships

In addition to refrigerant emissions, this study also estimates shipping's NMVOC fugitive emissions, which can occur when transporting oil and gas. The Second and Third IMO GHG Studies estimated fugitive NMVOC emissions from crude oil transport based on top-down crude oil transport data from UNCTAD. Given the complexities of estimating bottom-up fugitive emissions and the need to account for the nature of the cargo, the temperature, the turbulence in the vapor space, sea conditions, ship design, etc., this study continues to estimates NMVOC fugitive emissions from transporting oil and gas using a top-down approach by assuming a standard volume of loss.

Non-exhaust emissions of NMVOCs are generated mainly during loading, unloading and transport of oil and fuels. The total emissions are the sum of the emissions during loading, unloading and transport. The specific calculation method and adopted emission factors are as follows (equations (22) to (25) and

Table 32).

$$Emission_{loaded} = Fuel_{loaded} * EF_{loaded} \quad (22)$$
$$Emission_{unloaded} = Fuel_{unloaded} * EF_{unloaded} \quad (23)$$
$$Emission_{transport} = Fuel_{transport} * EF_{transport} \quad (24)$$
$$Emission_{non-exhaust} = Emission_{loaded} + Emission_{unloaded} + Emission_{transport} \quad (25)$$

Table 32 - Emission factors for non-exhaust emissions of NMVOCs

Loaded	Unloaded	Transport
0.1% (mass%)	129 mg/L	150 mg/L*week

The VOC emission factors for unloading and for transport are based on emission factors from US-EPA known as the "AP-42 emission factors" (129 mg/L and 150 mg/week/L respectively).

The VOC emission factor during loading is based on a review of data for emission of hydrocarbons and factors presented by EMEP/CORINAIR (0.1% of loaded mass), and it should be noted that this study assumes that the average duration of transport is 7 days (one week). Fuel statistics are from UNCTAD Review of Maritime Transport 2019.

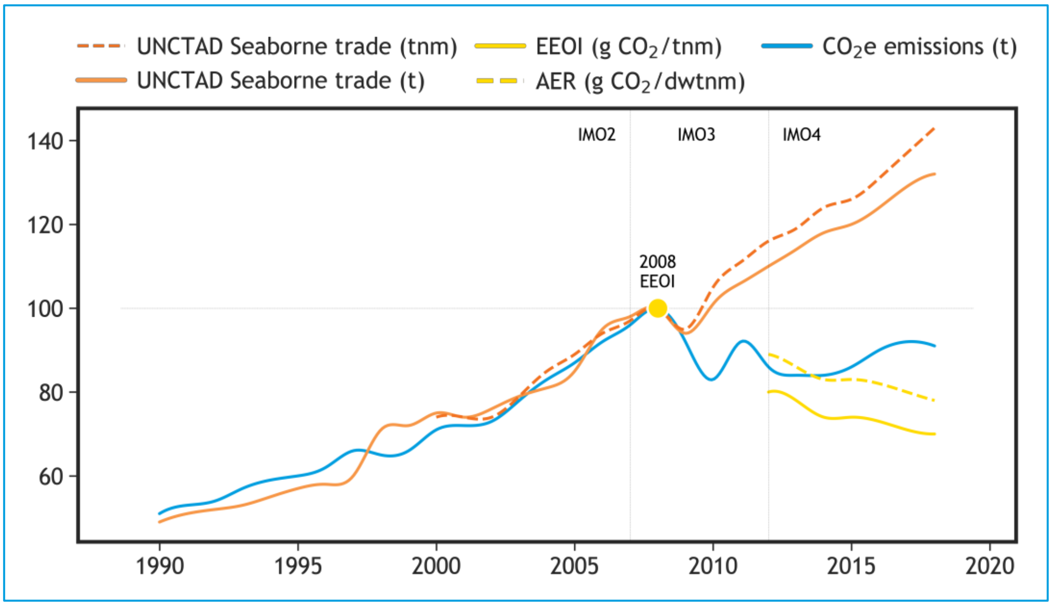
Based on the above method, the estimated non-exhaust emissions of NMVOCs ranged from 2.28 to 2.51 million tons in 2012-2017 (Table 33). The result corresponds to 0.124% mass loss and results in VOC emissions of 2.4 million tons, which is very close to the value in 2006 (crude oil transport 1941 million tons, VOC emissions 2.4 million tons) reported the IMO GHG study 2009.

Table 33 - Top-down non-exhaust emissions of NMVOCs estimates (million tonnes)

Year	Fuel statistics			Emissions
	Loaded	Unloaded	Transport	(million tonnes)
2006	1,783.4	1,931.2	1,931.2	2.38
2007	1,813.4	1,995.7	1,995.7	2.43
2008	1,785.2	1,942.3	1,942.3	2.39
2009	1,710.5	1,874.1	1,874.1	2.29
2010	1,787.7	1,933.2	1,933.2	2.39
2011	1,759.5	1,896.5	1,896.5	2.35
2012	1,785.7	1,929.5	1,929.5	2.38
2013	1,737.9	1882	1,882	2.32
2014	1,706.9	1,850.4	1,850.4	2.28
2015	1,771	1,916.2	1916.2	2.37
2016	1,831.4	1,990	1990	2.45
2017	1,874.9	2,035	2035	2.51

2.5 Bottom-up estimates of shipping emissions

Figure 61 - Trends in seaborne trade, carbon, carbon intensity metrics (EEOI and AER) and CO_2-equivalent emissions for international shipping, 1990-2018, indexed to 2008



Source: UMAS.

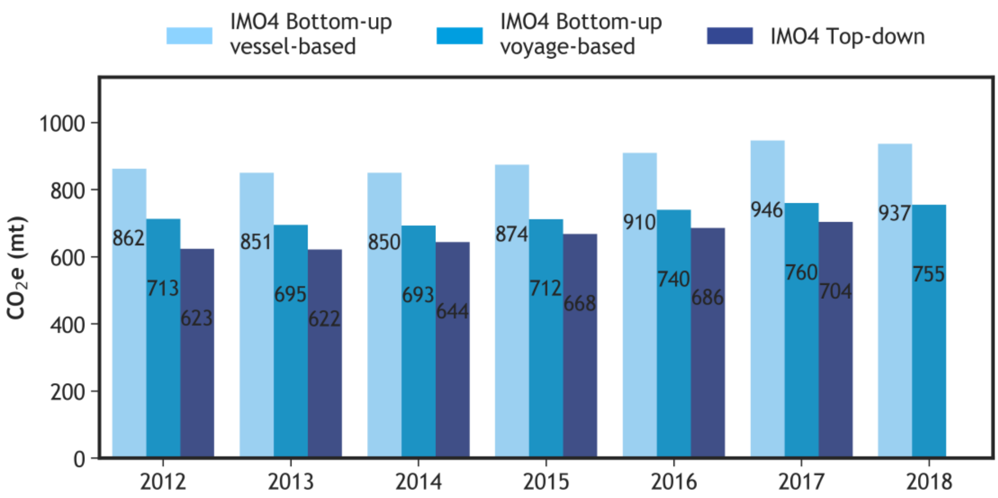
Figure 61 presents emissions, trade and carbon intensity trends as estimated across this and the two previous IMO GHG Studies. For all three studies, the consensus results that have been used to produce this plot are from the bottom-up inventory. There are differences in data and method between studies, but these have mostly been small and explainable and of negligible consequence to the use of the data to estimate the trend over time. One exception is that in this study, a key development in the way international and domestic shipping emissions are allocated has created a larger change in the emissions inventory for the year overlapping with IMO3. Because this is a change in allocation of emissions, it is assumed to also be relevant to apply retrospectively to the results of the previous two studies and enabled the plotting of this continuous long-run trend in CO_2. The carbon intensity results for all the years plotted (including 2008) are those results calculated in this study only.

These results show that against a long-run backdrop of steadily increasing demand for shipping (growth in seaborne trade), the three studies approximately align with three discrete periods for international shipping's GHG emissions:

- 1990 to 2008 – emissions growth, and emissions tightly coupled to growth in seaborne trade.
- 2008 to 2014 – emissions reduction in spite of growth in demand, and therefore a period of rapid carbon intensity reduction that enabled decoupling of emissions from growth in transport demand.
- 2014 to 2018 – a period of continued but more moderate improvement in carbon intensity, but at a rate slower than the growth in demand. And therefore a return to a trend of growth in emissions.

2.5.1 Greenhouse gas emissions (in CO_2e) and fuel consumption (2012-2018) - international shipping

Figure 62 - Annual greenhouse gas emissions (in CO_2e) for international shipping, according to the vessel-based and voyage-based allocation of international emissions (excluding black carbon (BC) emissions). For more detail on uncertainty ranges, see Section 2.7.1.



Source: UMAS.

Figure 62 presents the absolute values and trends in GHG emissions (expressed in CO_2e) of international shipping over the period 2012-2018. These CO_2-equivalent emissions are presented using 100-year Global Warming Potential (GWP) for GHGs emitted from ships. We assume 100-year GWPs of 1 for CO_2, 28 for CH_4, and 265 for N_2O (IPCC, 2006). Figure 62 excludes BC emissions to maintain comparability of GHG emissions between IMO GHG studies, as this is the first IMO GHG Study to estimate BC emissions. Including BC emissions, with a 100-year GWP of 900 (Comer, et al., 2017; Olmer, et al., 2017a; 2017b), the voyage-based international GHG emissions for shipping in 2018 would be 7% higher, totaling 810 million tonnes CO_2e.

Estimations are presented for both the bottom-up method, both assignment options for international shipping, and top-down method. The bottom-up method estimates absolute values which are consistently higher than the estimates in the top-down method, but the estimates demonstrate convergence over the time period, as also observed in the Third IMO GHG Study 2014. Greater explanation for the differences and the convergence between the bottom-up and top-down results is provided in Section 2.7

The year-on-year international shipping GHG emissions (in CO_2e) trend is similar but not identical between the bottom-up and top-down inventories. In particular, the 2012 totals show a larger discrepancy and higher value for the bottom-up method than the top-down method. As is discussed in the quality analysis in Section 2.7.1, there is perceived to be lower quality and higher uncertainty in the estimate in this specific year of the bottom-up inventory because of the quality of the AIS data available for 2012. The top-down and remaining years of the bottom-up method's estimates are more consistent in their input data quality and as a result are expected to be more reliable. The overall trend shown is for reduction in emissions to a minimum annual emission in 2014. Emissions then increase with a maximum for the period in 2017 and a small reduction in emissions (0.7-1%, considering both assignments of international emissions) between 2017 and 2018 is demonstrated in the bottom-up inventories.

Explanation and consequences to the bottom-up inventory results of the improved estimation of international and domestic shipping emissions

The absolute value of international GHG emissions (in CO_2e) in 2012, according to the voyage-based allocation, is estimated to be 13% lower than the estimate for the same year in the Third IMO GHG Study 2014. The main driver of this is the adoption of this voyage-based method for the differentiation of shipping emissions between international and domestic shipping, which the consortium finds to be in better agreement with the IPCC Guidelines. The discrepancy is significantly lower (5% higher) when the same vessel-based allocation is applied. Following the approach and justification described in Section 0, this study analyses emissions for each ship on discrete voyages before aggregating to international totals only those emissions which occur between two ports in different countries. The consequence of this method development is presented graphically in Section 0. Relative to the Third IMO GHG Study 2014 method for allocation of international shipping emissions, the key implications are:

There is some reduction in the allocation to international shipping emissions by all ship types and sizes, given even ships involved predominantly in international trade can visit more than one port in the same country before sailing to a different country.

There is a particularly significant reduction in the allocation to international shipping emissions in the smallest of each ship type's sizes. In the Third IMO GHG Study 2014, differentiation was applied between international and domestic shipping by assuming different type and size categories were either wholly international or domestic activity. The Third IMO GHG Study 2014's definition of domestic emissions were those from ship types mainly involved in coastal activity (e.g. Ro-Pax), while the smallest size categories of the major freight carrying ship types (e.g. oil tankers, bulk carriers and containers) were assumed to completely serve international routes. This study shows this approach likely overestimates international shipping's emissions according to the consortiums understanding of the IPCC guidelines because the latter ship types sometimes/often operated between two ports in the same country.

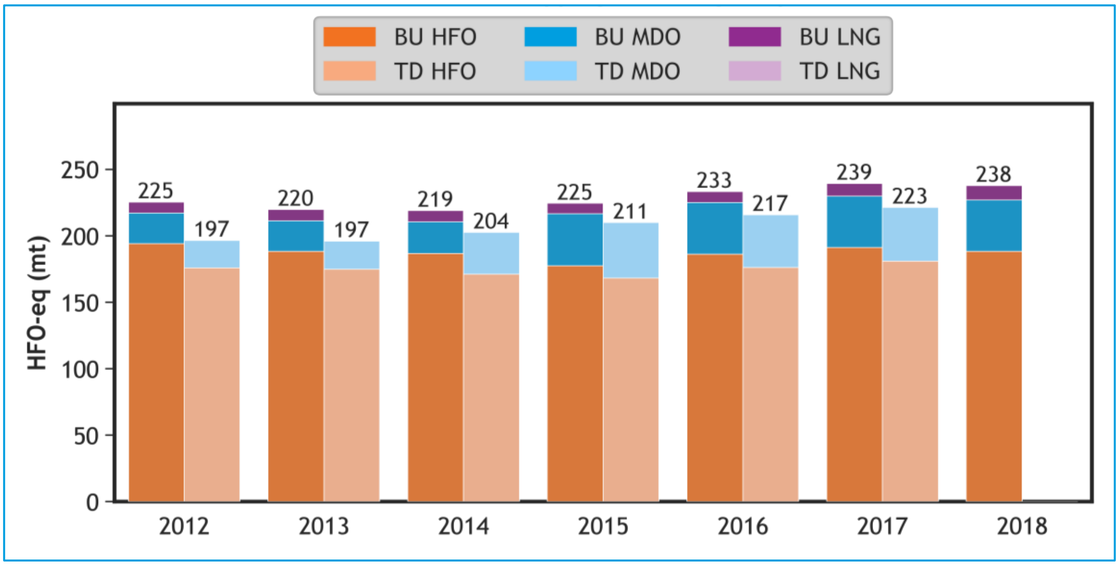
Detailed results, including breakdowns by fuel type, ship type, energy use onboard and phase of ship operation

Figure 63 presents the results for the consumption of different fuels over the period 2012-2018. The dominant marine fuel uses during this period is HFO, according to the bottom-up inventory results, this accounted in 2018 for 79.3% of the total fuel consumption of voyage-based international shipping (75.1% when considering the vessel-based allocation). By contrast, the HFO use in 2012 is 86.3% of voyage-based international shipping's HFO-equivalent fuel consumption (84.0% according to vessel-based allocation), showing a reduction of 7-9% in the proportion of HFO consumption.

In the following comparisons, the voyage-based allocation of international emissions is used in discussing fuel share alignments between top-down and bottom-up estimations. Both method's results show broad agreement in the proportion of HFO and MDO use over the period, and both show a significant increase in MDO use between 2014 and 2015, consistent with the entry into force of 0.1% sulfur ECA zones in Europe and North America, which increases the incentivization of MDO use by ships. The bottom-up model uses modelling assumptions to estimate the fuel use and compliance as a function of whether a ship is sailing inside or outside an ECA. This similarity in the trend change between 2014 and 2015 in both the bottom-up and top-down results is therefore an important validation of those modelling assumptions. However, a greater discrepancy in HFO/MDO split in 2016 and 2017 is observable between bottom-up and top-down inventories.

The top-down results have no significant inclusion of LNG consumption, whereas a small and consistent portion of LNG consumption can be seen in the bottom-up results. This discrepancy is discussed in greater detail in Section 2.7 and is predominantly due to the majority of LNG consumption in the bottom-up estimate originating from LNG as boil-off gas used by tankers carrying LNG as cargo[5]. This component of energy consumption in shipping is not captured in the top-down method because it only includes the fuels sold to ships explicitly as fuels, and not the discrepancies between cargos of energy commodities loaded and unloaded.

Figure 63 - HFO-equivalent fuel consumption per year for the three most important fuel types used (HFO, MDO and LNG), where bottom-up estimates are according to voyage-based allocation of international emissions.



Source: UMAS.

Figure 64 provides similar information but summarising the change in total and average GHG emissions (in CO_2e) for each ship type over the period. Given the similarity of the emissions factors of GHG species of both HFO and MDO, the percentage changes in GHG emissions closely follow the changes in fuel consumption. During the period of this study, most ship types saw both an increase in total GHG emissions, as well as a reduction in average GHG emissions per vessel. The change in average GHG emissions is a function of changes in average ship sizes within the fleet, as well as technical and operational trends in the fleet. The change in total GHG emissions is a function of the total number of ships and their average technical and operational trends. More detail of the explanations behind those changes with a particular focus on the three ship types with highest emissions is included in Section 2.5.4 and Annex O presents the results for the bottom-up inventory of international

[5] LNG stored as a cargo boils off due to the low boiling point of LNG. This boil-off can be reliquefied, combusted (in a gas consumption unit), or used as an energy source for the ship. Where the LNG is used as an energy source for the ship, it is included as a fuel consumption and source of emissions in the bottom-up modelling.

shipping fuel consumption, according to the voyage-based allocation also referred to by 'Option 2' and broken down by ship type and year.
For the purpose of clearly communicating the relative magnitudes of fuel consumption and emissions, and some of the year-on-year trends, only one assignment concept (voyage-based) is used. If derived from vessel-based allocation, the trends and relative magnitudes would be similar, with some small differences in absolute values. The results are for the average fuel consumption per ship and total fuel consumption, respectively. The average fuel consumption shows the fleets which contain (on average) the largest 'per ship' fuel consumption. However, due to the difference in the number of ships of different types, this is not a consistent ranking with the fuel consumption totals.

Containers, cruises, and vehicle carriers have the largest 'per average ship' fuel consumption. Cruises would have the largest 'per average ship' fuel consumption if both domestic and international shipping emissions were considered in combination. This is because on average a cruise ship spends 45% of its time on domestic voyages, across the 7 years, almost an even split between domestic and international shipping. Liquid gas tankers and vehicle carriers' both spend 80% or more of the average ship's activity allocated to international shipping, which represents some of the higher values across different ship types. Their high average fuel consumption as shown in Figure 63 is therefore partly a consequence of the high allocation of their activity to international shipping.

The trends in average fuel consumption over the period 2012-2018 vary significantly between ship types. For many ship types, notably for cruises, ferries and refrigerated bulk ships, fuel consumption falls consistently over the period, but for others the average fuel consumption increases starting in 2014. These differences are due to a combination of changes in average design parameters (including average installed power), average operational parameters (including average speeds and days at sea), and in average ship sizes over the years, which are presented and discussed in greater detail in Section 2.5.4.

Contrasting with the insights on average ship fuel consumption, a different set of ship types make up those with the greatest contribution to total fuel consumption, consistent with the Third IMO GHG Study 2014's findings. These are containers, bulk carriers and oil tankers. With the exception of containers, which also have the highest per-ship average international fuel consumption, the number of ships of each type is a strong determinant of how much fuel they consume in aggregate. This explains why regardless of more modest increases or decreases in average ship fuel consumption over the period, many of the ship types show increases in total fuel consumption (since 2014), during which time trade and therefore demand for the services of these fleets have grown.

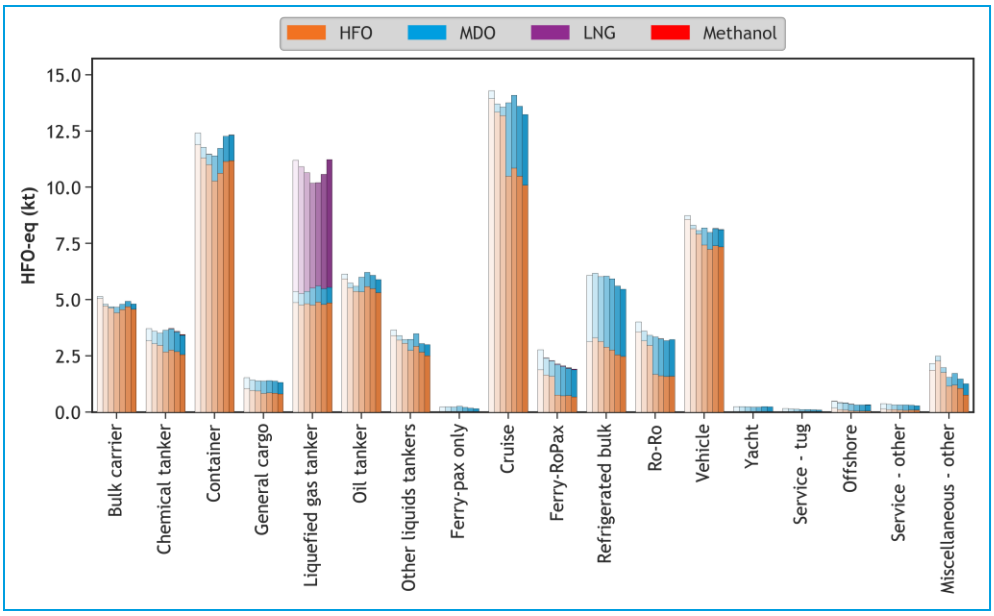
In combination with the next three most significant ship types to total fuel consumption (chemical tankers, liquified gas tankers and general cargo ships), the top six fuel-consuming ship types account for 85.4% of international shipping fuel consumption in 2018, according to the voyage-based allocation of international emissions.

Only one ship type, LNG carriers, has any significant consumption of LNG over the period and in 2018. The majority of this consumption is related to LNG boil-off gas arising from the carriage of LNG as a cargo, as opposed to LNG sold to a ship as a bunker fuel. It is estimated that during this period, LNG consumption in LNG carriers reduced, albeit with some reversal of that trend in 2018.

The increased use of MDO in 2015 observed in Figure 63 varies by ship types due to differences in the number of operational hours in ECA zones, with cruise ships on average seeing the most

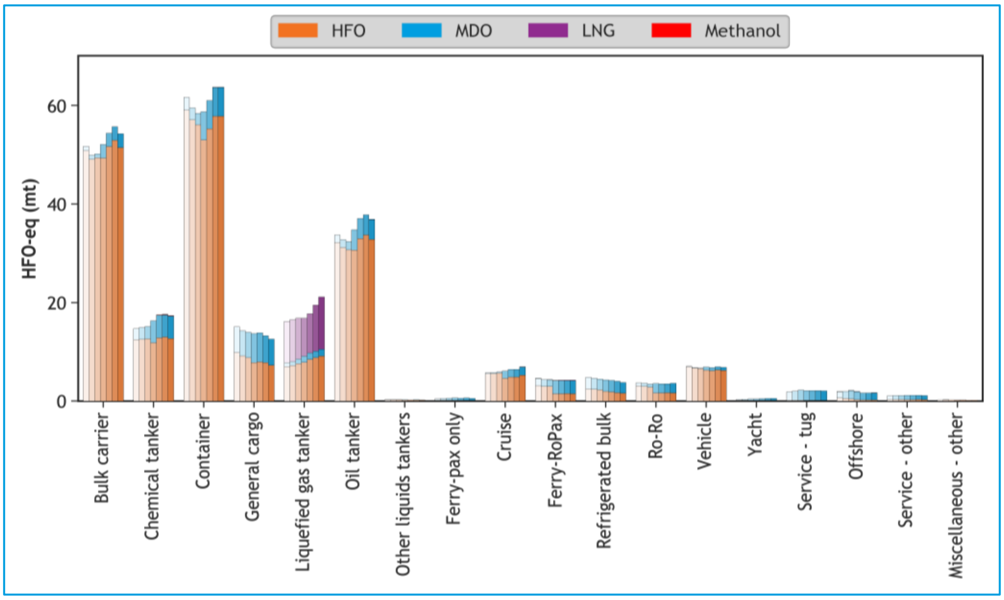
pronounced increase in MDO use. This implies that these are ship types that on average spend more time within ECA zones than other ship types.
The consumption of methanol starts in 2015, for which only two vessel type and size categories are responsible. Namely, the largest ferry RoPax and chemical tanker categories.

Figure 64 - Average annual HFO-equivalent fuel consumption per ship, split by fuel type, on international voyages only.



Source: UMAS.

Figure 65 - Total annual HFO-equivalent fuel consumption per ship type, split by fuel type, on international voyages only



Source: UMAS.

Figure 66 provides similar information but summarising the change in total and average GHG emissions (in CO_2e) for each ship type over the period. Given the similarity of the emissions factors of GHG species of both HFO and MDO, the percentage changes in GHG emissions closely follow the changes in fuel consumption. During the period of this study, most ship types saw both an increase in total GHG emissions, as well as a reduction in average GHG emissions per vessel. The change in average GHG emissions is a function of changes in average ship sizes within the fleet, as well as technical and operational trends in the fleet. The change in total GHG emissions is a function of the total number of ships and their average technical and operational trends. More detail of the explanations behind those changes with a particular focus on the three ship types with highest emissions is included in Section 2.5.4.

Notable exceptions to the general observation include:

General cargo, other liquids tankers, ferry RoPax, refrigerated bulk ships, Ro-Ro, vehicle, miscellaneous fishing, offshore and miscellaneous other, which all saw both a reduction in total GHG emissions and in average GHG emissions per vessel,

Liquid gas tankers which saw the second largest increase in total GHG emissions as well as an increase in average GHG emission per vessel.

Figure 66 - Change in total international greenhouse gas emissions (in CO_2e) and average vessel-specific greenhouse gas emissions (in CO_2e) between 2012 and 2018

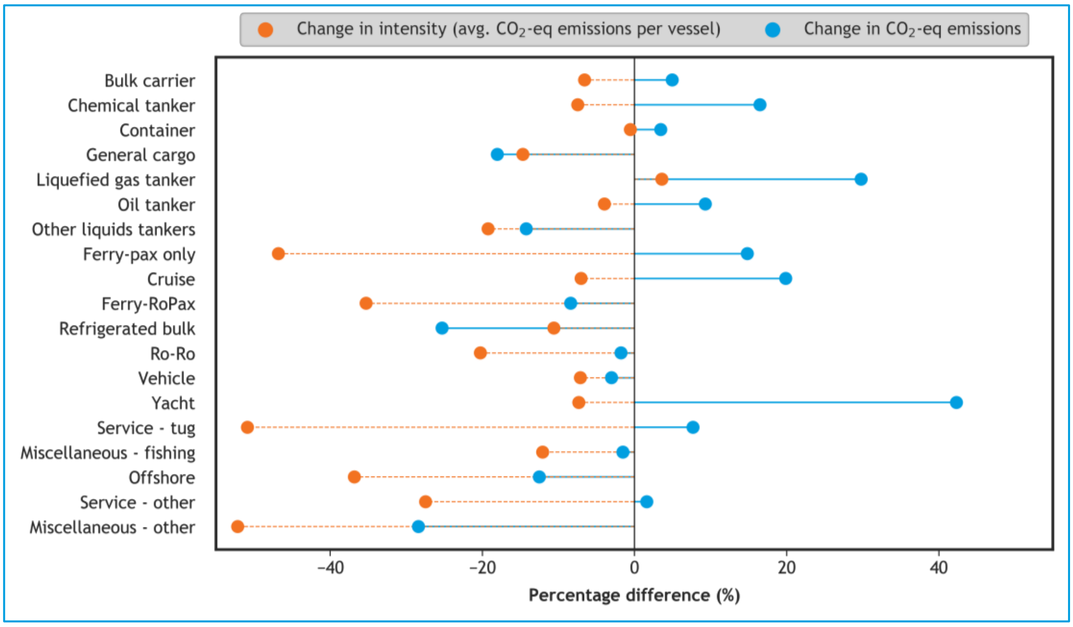
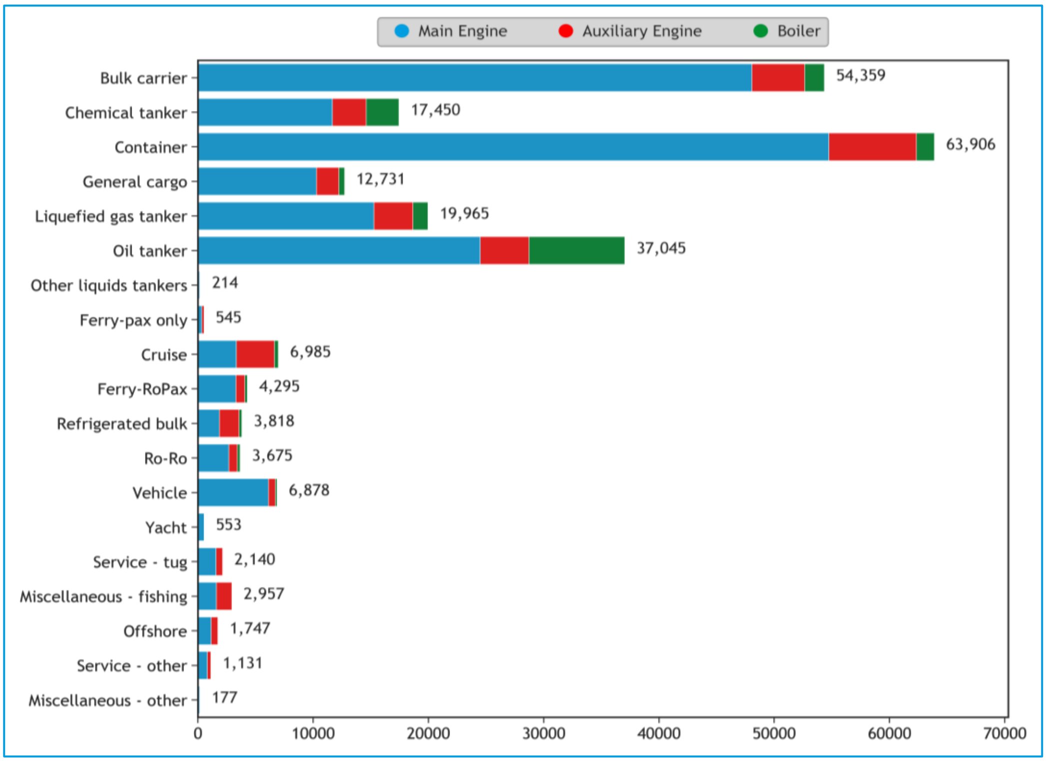


Figure 67 - International HFO-equivalent fuel consumption, according to voyage-based allocation of emissions 'Option 2' (thousand tonnes), 2018, split by main engine, auxiliary engine and boiler



Notable exceptions to the general observation include:

General cargo, other liquids tankers, ferry RoPax, refrigerated bulk ships, Ro-Ro, vehicle, miscellaneous fishing, offshore and miscellaneous other, which all saw both a reduction in total GHG emissions and in average GHG emissions per vessel,

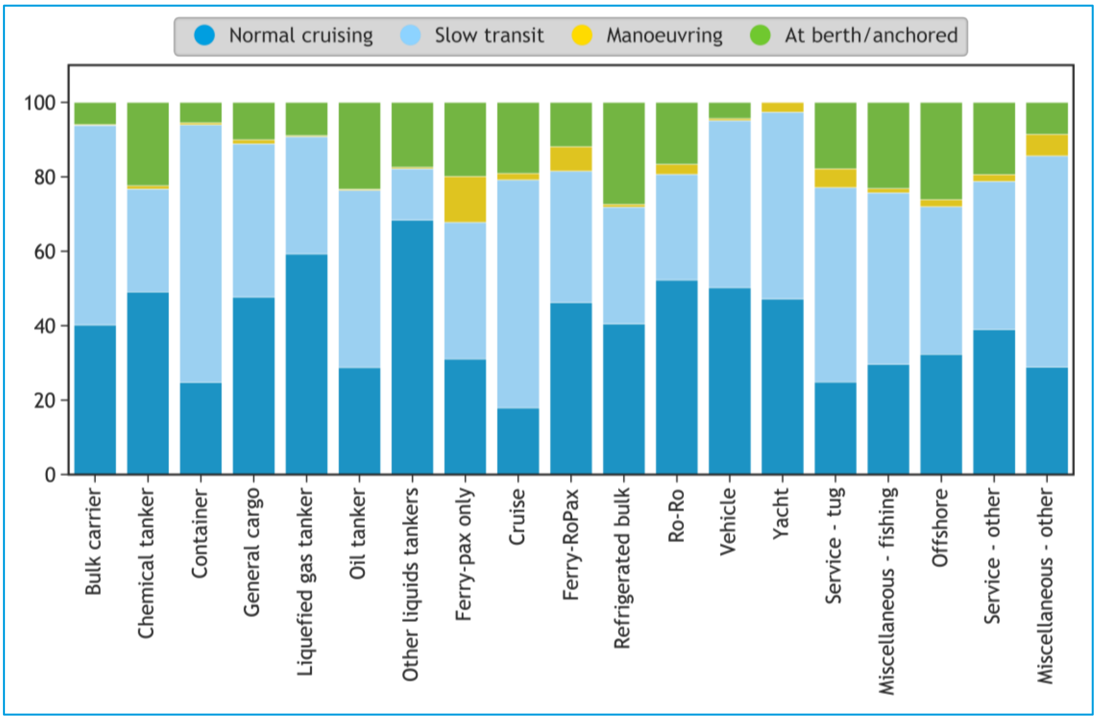
Liquid gas tankers which saw the second largest increase in total GHG emissions as well as an increase in average GHG emission per vessel.

Figure 66 - Change in total international greenhouse gas emissions (in CO_2e) and average vessel-specific greenhouse gas emissions (in CO_2e) between 2012 and 2018

Figure 67 presents the breakdown of the total fuel consumption by ship type, between the different uses onboard: main engine (propulsion), auxiliary engines (electricity generation), boiler (heat). The dominant energy demand generally is the main engine and propulsion energy demand, as also observed in the Third IMO GHG Study. This continues to be the case in spite of widespread use of slow steaming (Section 2.5.4) which predominantly reduces the main engine fuel consumption. Ship types with larger shares of auxiliary engine fuel consumption are cruise ships, refrigerated bulk carriers, miscellaneous-fishing.

Figure 68 presents the breakdown of GHG emissions across different phases of operation for each ship type, as defined by Table 16. Depending on the ship type, there are differences in the share of emissions that occur at sea on passage, as opposed to during a manoeuvring, anchorage or berthed phase of operation. Of the six ship types most important to the emissions inventories, chemical tankers and oil tankers have on average the largest portion of their total emissions (greater than 20%) associated with phases at or near the port or terminal. Container ships, cruise ships and oil tankers have the smallest share of their total emissions associated with cruising (definition) due to dominance of time spent slow cruising and/or phases at or near port, with liquefied gas tankers and other liquids tankers showing the largest share of their emissions associated with cruising.

Figure 68 - Proportion of international greenhouse gas emissions (in CO_2e) by operational phase in 2018. Proportions assigned according to voyage-based allocation of emissions. More information on operational phases and respective criteria can be found in Table 16



2.5.2 Implications of a revised calculation approach for the estimate of international shipping emissions in 2008

One of this study's methods for estimating the share of total emissions from shipping that should be allocated to international shipping differs to that used in the Third IMO GHG Study. The difference has occurred due to improvements in data and method since the Third IMO GHG Study, the method selection at that time was made on the basis of what was technically possible. The consequence of this method development, discussed in detail in Section 2.2.4, is a reduced estimate of international shipping emissions.

Given the importance of the year 2008 in the IMO's Initial GHG Reduction Strategy as a reference year for both GHG emissions and carbon intensity. This study's method development suggests that the values for the 2008 should be reconsidered.

A recalculation for 2008 using this study's method is not possible because of the challenge of accessing historical data from so far back. Even if 2008 data could be sourced, it would be limited to terrestrial AIS receiver sources only, which would significantly increase the uncertainty of a deployment of this study's method (which requires high quality global AIS coverage). However, the inventory results for 2012-18 can provide a means to hindcast the split for 2008. A method to enable that hindcast is developed and deployed in section 2.2.4, in order to produce the detailed results for the voyage based international emissions 2008. Using the outputs of that method, an update of the key 2008 inventory totals relevant to the IMO Initial Strategy on GHG Reduction is also possible. These are:

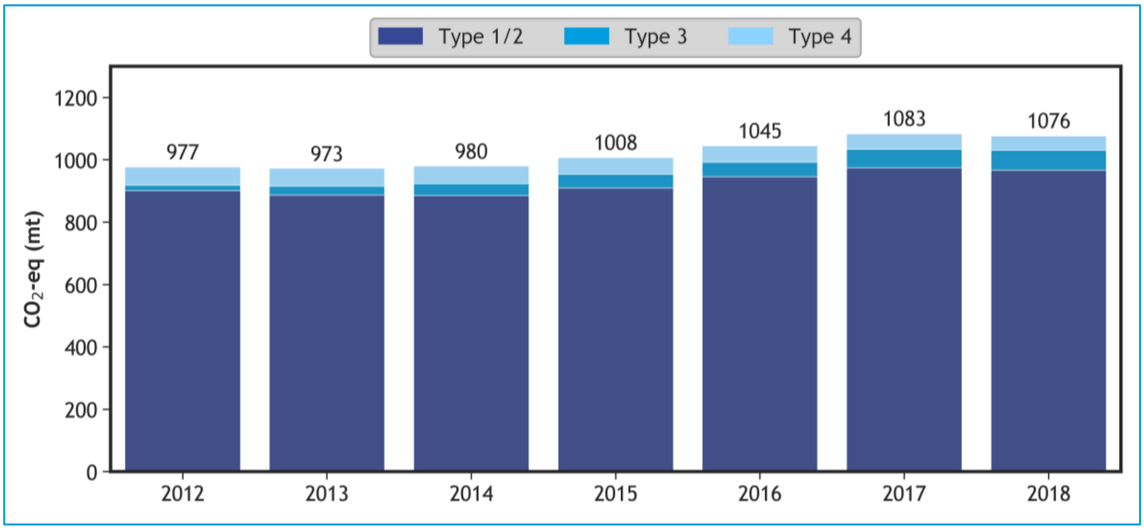
- International shipping total CO_2 emissions: 775.7 million tonnes.
- International shipping total GHG emissions (in CO_2e) : 794.1 million tonnes.

Consistent with this studies bottom-up results, these revised inventory calculations are closer to, but also remain above, the equivalent top-down estimates in this year.

2.5.3 Greenhouse gas emissions (in CO_2e) and fuel consumption for total shipping (international, domestic and fishing)

Inventories are also produced for total shipping, inclusive of international shipping, domestic shipping and fishing activity. These are shown in Figure 69 (GHG emissions (in CO_2e) broken down by calculation type), and Figure 70 (fuel consumption, broken down by fuel type). In order to produce quantifications of GHG emissions, we assume 100-year GWPs of 1 for CO_2, 28 for CH_4, and 265 for N_2O (IPCC, 2006). BC emissions are not included in this plot as a GHG. Table 34 includes the total fuel consumption for each of the main fuel types in use across international shipping, domestic shipping and fishing.

Figure 69 – Total greenhouse gas emissions (in CO_2e) for total shipping, including break down by calculation method

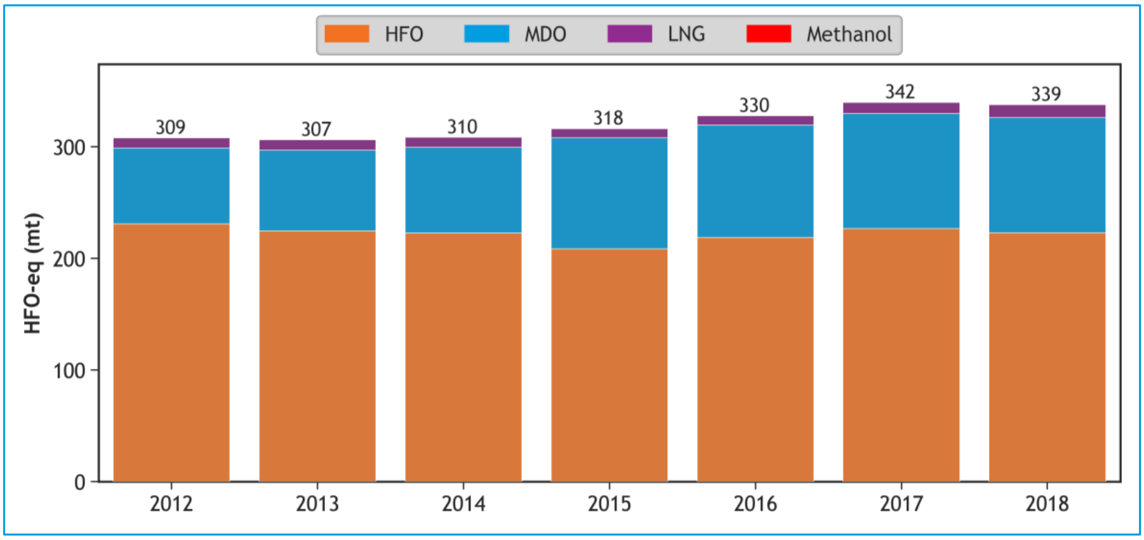


Source: UMAS.

The trend for total shipping GHG emissions (in CO_2e) is similar to the trend for international shipping, albeit with approximately constant emissions to 2014 (as opposed to a small reduction), followed by a period of steady increase from 2014 to 2018 (a total increase during this period of 9.4%). The calculated increase in GHG emissions (in CO_2e) is greater than the increase in international shipping over the same period. This trend similarity is explained because total shipping emissions are dominated and predominantly explained by international shipping emissions trends.

Figure 70 shows that some of the trend for increase in total GHG emissions (in CO_2e) is driven by the significant growth over the period of the total emissions calculated using the Type 3 method. For the reasons discussed in Section 2.7.1 this trend is thought to be significantly driven by the method and the improved coverage in AIS data of ships that are not recorded in the IHS database and that do not have an IMO number.

Figure 70 - Annual HFO-equivalent fuel consumption for total shipping, including break down by fuel type



Source: UMAS.

For the international shipping, domestic shipping and fishing vessels that are captured by the bottom-up method, the breakdown of fuel consumption also shows similar trends to that of international shipping. HFO use saw a small absolute reduction (-3.5%), whilst MDO and LNG use increased (41% and 23.4% respectively). Methanol is a new entrant fuel in the inventory with no use recorded in 2012, but approximately 160,000 tonnes used across international shipping, domestic shipping and fishing.

International shipping's share of the fuel consumption across international, domestic and fishing varies as a function of fuel type. Voyage-based international shipping accounts for 95% of LNG consumption (predominantly driven by consumption in LNG carriers, where the cargo is used as an energy source), 84% of HFO consumption, 81% of Methanol consumption and 37% of MDO consumption.

Table 34 - International, domestic and fishing fuel consumption by fuel type, where totals represent HFO-equivalent fuel consumption (in million tonnes)

Fleet sector		Fuel	2012	2013	2014	2015	2016	2017	2018
Option 1 - Vessel-based allocation	International shipping	HFO	228.69	222.54	220.45	207.02	217.29	225.34	221.78
		LNG	8.89	9.11	8.92	8.16	8.47	9.9	11.34
		MDO	34.86	37.02	38.87	59.94	60.43	62.32	61.47
		METHANOL	0.0	0.0	0.0	0.02	0.13	0.16	0.16
		Total	**272.43**	**268.7**	**268.34**	**275.95**	**287.04**	**298.32**	**295.16**
	Domestic navigation	HFO	2.14	1.99	1.93	1.31	1.28	1.25	1.13
		LNG	0.05	0.06	0.09	0.07	0.07	0.06	0.1
		MDO	21.43	23.47	25.57	26.71	26.53	28.34	29.16
		METHANOL	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total	**24.25**	**26.21**	**28.33**	**28.86**	**28.65**	**30.48**	**31.25**
	Fishing	HFO	0.17	0.16	0.19	0.15	0.16	0.15	0.14
		LNG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		MDO	11.61	11.79	12.34	12.86	13.38	12.27	12.35
		METHANOL	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total	**12.12**	**12.3**	**12.9**	**13.39**	**13.94**	**12.78**	**12.86**
Option 2 - Voyage-based allocation	International shipping	HFO	194.22	188.35	186.82	177.48	186.24	191.21	188.33
		LNG	8.42	8.57	8.39	7.8	8.09	9.51	10.9
		MDO	22.79	22.93	23.77	39.19	38.88	38.65	38.46
		METHANOL	0.0	0.0	0.0	0.0	0.1	0.13	0.13
		Total	**225.12**	**219.52**	**218.7**	**224.71**	**233.45**	**239.46**	**237.62**
	Domestic navigation	HFO	36.61	36.18	35.56	30.85	32.33	35.38	34.58
		LNG	0.52	0.6	0.62	0.42	0.45	0.46	0.54
		MDO	33.5	37.57	40.67	47.46	48.08	52.0	52.18
		METHANOL	0.0	0.0	0.0	0.02	0.03	0.03	0.03
		Total	**71.56**	**75.39**	**77.97**	**80.1**	**82.24**	**89.34**	**88.79**
	Fishing	HFO	0.17	0.16	0.19	0.15	0.16	0.15	0.14
		LNG	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		MDO	11.61	11.79	12.34	12.86	13.38	12.27	12.35
		METHANOL	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Total	**12.12**	**12.3**	**12.9**	**13.39**	**13.94**	**12.78**	**12.86**
Total bottom-up estimate		HFO	230.99	224.7	222.57	208.48	218.73	226.74	223.05
		LNG	8.94	9.17	9.01	8.23	8.54	9.96	11.44
		MDO	67.91	72.28	76.78	99.51	100.34	102.93	102.99
		METHANOL	0.0	0.0	0.0	0.02	0.13	0.16	0.16
		Total	**308.8**	**307.21**	**309.57**	**318.2**	**329.63**	**341.58**	**339.27**

2018 detailed results.

Table 35 describes the detailed results for each ship type and size. Versions of this table for all years can be found in Appendix O.

Table 35 - Detailed results for 2018 describing the fleet (international, domestic and fishing) analysed using the bottom-up method

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	696	680	70	4,271	1,796	11.8	178	56	19	9.3	25.5	1.0	0.3	0.1	3.8	3.7
	10000-34999	dwt	2,014	0	0	27,303	5,941	13.8	177	255	34	11.0	7.3	2.8	0.3	0.1	20.3	20.0
	35000-59999	dwt	3,391	0	0	49,487	8,177	14.3	184	266	25	11.4	5.4	3.7	0.4	0.2	46.4	45.7
	60000-99999	dwt	3,409	0	0	76,147	9,748	14.4	214	302	30	11.4	4.1	4.9	0.7	0.3	63.9	63.0
	100000-199999	dwt	1,242	0	0	169,868	16,741	14.5	252	334	13	11.2	2.7	9.2	0.7	0.2	39.6	39.0
	200000-+	dwt	516	0	0	251,667	20,094	14.6	258	336	3	11.8	2.3	12.7	0.7	0.2	22.3	22.0
Chemical tanker	0-4999	dwt	1,032	4,908	127	4,080	987	12.2	168	21	46	9.6	65.7	0.8	0.3	0.9	15.0	14.8
	5000-9999	dwt	844	18	0	7,276	3,109	12.9	185	217	50	10.3	28.7	1.6	0.8	0.7	8.2	8.1
	10000-19999	dwt	1,088	0	0	15,324	5,101	13.8	190	249	57	11.4	17.9	2.7	0.8	1.0	15.6	15.3
	20000-39999	dwt	706	0	0	32,492	8,107	14.7	202	280	63	12.1	11.1	4.5	1.2	1.3	15.6	15.3
	40000-+	dwt	1,289	0	0	48,796	8,929	14.6	201	274	55	11.9	7.7	4.7	1.2	1.2	28.7	28.2
Container	0-999	teu	861	165	1	8,438	5,077	16.0	196	163	43	11.8	23.9	2.6	0.7	0.4	10.2	10.0
	1000-1999	teu	1,271	0	0	19,051	12,083	19.0	210	270	30	13.4	17.2	5.1	1.5	0.4	28.5	28.0
	2000-2999	teu	668	0	0	34,894	20,630	21.1	220	275	24	14.2	11.4	7.9	1.5	0.6	21.2	20.9
	3000-4999	teu	815	0	0	52,372	34,559	23.1	246	271	29	14.7	10.3	12.7	2.4	0.5	40.1	39.4
	5000-7999	teu	561	0	0	74,661	52,566	24.6	258	280	39	15.7	9.8	20.3	2.4	0.5	41.3	40.7
	8000-11999	teu	623	0	0	110,782	57,901	23.9	261	301	38	16.3	8.3	26.4	2.9	0.5	58.8	57.9
	12000-14499	teu	227	0	0	149,023	61,231	23.8	246	297	33	16.3	6.8	27.2	3.3	0.6	22.3	22.0
	14500-19999	teu	101	0	0	179,871	60,202	20.2	250	309	51	16.5	5.4	26.7	3.7	0.6	9.9	9.7
	20000-+	teu	44	0	0	195,615	60,210	20.3	210	292	43	16.3	5.3	21.0	3.6	0.9	3.5	3.5
General cargo	0-4999	dwt	4,880	6,926	1,490	2,104	1,454	11.1	170	71	55	8.8	24.3	0.6	0.1	0.0	19.2	18.9
	5000-9999	dwt	2,245	0	0	6,985	3,150	12.7	176	238	44	9.8	19.1	1.4	0.3	0.2	13.0	12.8
	10000-19999	dwt	1,054	0	0	13,423	5,280	14.0	192	267	39	11.4	16.8	2.8	0.8	0.2	12.9	12.7
	20000-+	dwt	793	0	0	36,980	9,189	15.0	197	269	38	11.9	8.5	4.5	0.8	0.2	14.0	13.7
Liquefied gas tanker	0-49999	cbm	1,085	1,589	11	8,603	2,236	14.2	190	87	42	11.7	38.0	2.4	0.4	1.1	16.1	15.8
	50000-99999	cbm	308	0	0	52,974	12,832	16.4	229	324	22	14.1	9.3	8.9	3.0	0.8	12.3	12.1
	100000-199999	cbm	436	0	0	83,661	30,996	19.0	271	339	8	14.9	10.3	22.2	4.4	1.0	41.3	37.5

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	200000-+	cbm	46	0	0	121,977	36,735	19.2	252	364	5	16.0	10.3	26.3	11.7	1.9	5.8	5.7
Oil tanker	0-4999	dwt	1,734	7,310	648	3,158	966	11.4	135	17	14	8.7	79.5	0.5	0.4	0.7	23.5	23.2
	5000-9999	dwt	779	0	0	6,789	2,761	12.1	142	136	11	9.1	36.7	0.9	0.6	0.9	6.0	5.9
	10000-19999	dwt	235	0	0	14,733	4,417	12.9	136	149	18	9.8	24.3	1.4	0.9	1.4	2.8	2.8
	20000-59999	dwt	615	0	0	43,750	8,975	14.6	166	202	26	11.2	10.6	3.4	1.0	2.8	14.0	13.8
	60000-79999	dwt	429	0	0	72,826	11,837	14.8	194	278	45	11.6	6.7	5.2	1.0	2.8	12.2	12.1
	80000-119999	dwt	1,029	0	0	109,262	13,319	14.8	195	289	61	11.2	4.9	5.4	1.2	3.1	31.5	31.1
	120000-199999	dwt	597	0	0	155,878	17,446	15.1	220	313	44	11.4	4.1	8.0	1.8	3.5	25.1	24.7
	200000-+	dwt	755	0	0	307,866	27,159	15.5	252	342	10	11.9	2.6	14.5	1.7	3.1	46.0	45.3
Other liquids tankers	0-999	dwt	26	443	64	3,450	687	9.6	98	8	30	7.5	1,577.8	0.1	0.6	2.1	1.5	1.5
	1000-+	dwt	27	79	0	10,813	2,034	13.6	207	59	37	11.6	82.9	4.8	0.9	1.2	0.7	0.7
Ferry-pax only	0-299°	gt	663	8,607	1,410	4,034	1,152	19.3	162	11	104	14.1	1,280.2	0.4	0.3	0.0	8.6	8.4
	300-999°	gt	666	0	0	102	3,182	26.2	161	53	70	14.7	926.9	0.7	0.3	0.0	2.1	2.1
	1000-1999°	gt	51	0	0	354	2,623	14.5	135	38	88	9.3	314.0	0.6	0.3	0.0	0.1	0.1
	2000-+	gt	55	0	0	1,730	6,539	16.2	199	77	28	12.4	169.0	3.5	0.9	0.0	0.8	0.8
Cruise	0-1999	gt	126	641	45	3,115	911	12.7	93	17	74	8.1	3,770.5	0.1	0.4	2.2	1.7	1.7
	2000-9999	gt	110	0	0	867	3,232	13.8	148	109	63	9.2	513.4	0.5	0.8	1.8	1.1	1.1
	10000-59999	gt	105	0	0	4,018	19,378	19.0	206	232	63	13.4	147.3	5.0	6.4	1.4	4.3	4.2
	60000-99999	gt	98	0	0	8,249	51,518	21.8	256	272	94	15.3	155.2	16.1	20.3	1.0	11.6	11.4
	100000-149999	gt	61	0	0	10,935	67,456	21.3	250	295	96	16.0	140.5	24.4	20.0	1.0	8.8	8.6
	150000-+	gt	21	0	0	13,499	73,442	22.0	236	301	58	16.4	109.6	23.2	19.8	1.2	2.9	2.9
Ferry-RoPax	0-1999°	gt	1,040	1,474	340	2,720	1,383	13.0	165	9	95	9.0	458.1	0.6	0.2	0.5	5.7	5.6
	2000-4999	gt	400	0	0	832	5,668	17.4	167	64	94	11.4	257.3	1.8	0.6	0.4	3.5	3.5
	5000-9999	gt	227	0	0	1,891	12,024	21.6	155	83	88	13.2	205.0	3.2	1.2	0.5	3.5	3.4
	10000-19999	gt	231	0	0	3,952	15,780	20.3	190	124	80	15.1	123.0	7.9	1.9	0.6	7.6	7.5
	20000-+	gt	282	0	0	6,364	28,255	22.6	219	203	145	16.5	105.1	15.2	3.3	0.5	17.1	16.7
Refrigerated bulk	0-1999	dwt	93	1,201	77	2,409	793	12.1	147	29	22	9.1	175.8	0.4	1.0	0.5	1.9	1.9
	2000-5999	dwt	213	0	0	3,986	3,223	14.7	149	284	24	11.1	76.1	1.2	2.1	0.5	2.6	2.5
	6000-9999	dwt	182	0	0	7,476	6,206	17.4	150	313	16	13.6	48.2	2.6	2.8	0.5	3.4	3.3

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	10000-+	dwt	157	0	0	12,612	11,505	20.2	218	340	51	16.3	37.1	7.1	5.3	0.3	6.3	6.2
Ro-Ro	0-4999	dwt	615	1,175	384	1,406	1,618	11.2	129	56	24	8.1	226.2	0.7	0.9	0.5	6.8	6.7
	5000-9999	dwt	200	0	2	6,955	9,909	17.6	201	183	73	14.2	50.7	6.1	1.4	0.4	5.0	4.9
	10000-14999	dwt	135	0	0	12,101	15,939	19.6	218	264	137	15.5	39.3	10.0	1.9	0.5	5.3	5.2
	15000-+	dwt	89	0	0	27,488	19,505	19.1	199	299	171	15.2	22.4	11.1	1.8	0.5	3.8	3.7
Vehicle	0-29999	gt	168	7	0	5,151	7,264	17.3	213	167	63	13.6	53.9	4.6	0.9	0.4	3.2	3.1
	30000-49999	gt	189	0	0	13,571	11,831	19.4	254	297	36	14.7	21.8	7.1	1.0	0.3	5.0	4.9
	50000-+	gt	487	0	0	20,947	14,588	19.9	281	309	47	15.5	16.4	10.4	0.9	0.2	17.8	17.5
Yacht	0-+°	gt	1,665	7,914	542	1,077	1,116	16.7	78	36	64	10.7	405.8	0.4	0.0	0.0	4.9	4.9
Service - tug	0-+°	gt	8,805	58,478	8,983	1,218	1,086	11.9	80	14	82	6.6	422.7	0.3	0.2	0.0	41.0	40.3
Miscellaneous - fishing	0-+°	gt	9,140	17,583	9,807	468	983	11.7	164	42	89	7.5	304.3	0.3	0.3	0.0	40.7	40.0
Offshore	0-+°	gt	4,322	11,696	875	4,765	2,010	13.9	80	25	111	8.5	152.8	0.6	0.5	0.0	20.9	20.5
Service - other	0-+°	gt	3,157	8,104	1,158	2,496	1,620	13.6	96	25	90	8.1	205.3	0.6	0.4	0.0	14.3	14.1
Miscellaneous - other	0-+°	gt	138	55	56	11,496	15,301	18.2	102	70	154	10.7	31.6	2.1	0.4	0.2	1.3	1.3

* Based on type 1 and 2 vessels only.

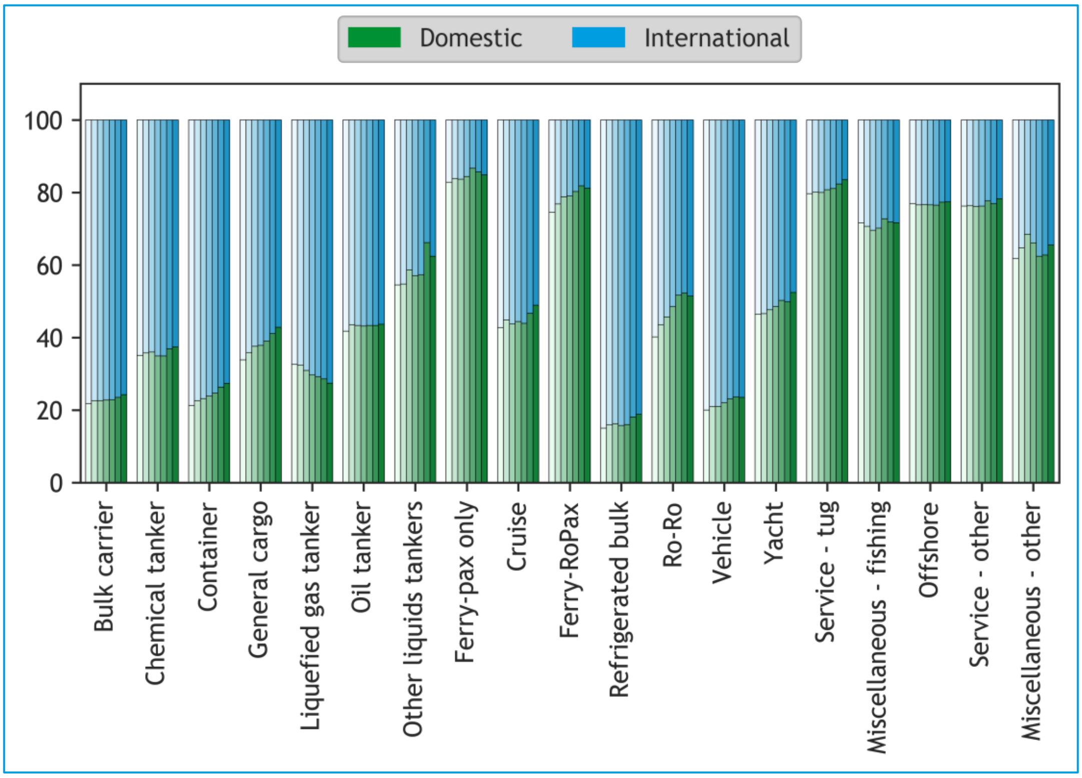
° These ship types are classified 'domestic' in the vessel-based method to distinguish domestic from international emissions. All other ship types are considered international in that option (see **Table 15**)

2.5.4 Greenhouse gas emissions (in CO_2e) trends/variability and drivers of trends and variability (2012-2018)

The voyage-based international shipping GHG emission (in CO_2e) inventories are the consequence of a series of underlying drivers and trends. Some insight into the results can therefore be obtained by looking at individual components and identifying how these interact with the aggregated results.

This work is unique in how it allocates international and domestic shipping activity as a function of the discrete voyages undertaken by ships. Changes over time in the allocation are shown in Figure 71 For the majority of ship types, including the dominant emission sources (bulk carriers, containers and oil tankers), the proportion of days spent in domestic activity increased over the period of this study. Only one ship type (liquefied gas tanker) decreased its share of domestic activity during this period.

Figure 71 - Proportion of days spent in domestic and international shipping activity (2012-2018), where individual voyages are not highlighted here but rather aggregated hours spent on either international or domestic voyages. Individual voyages can widely vary in duration. The x-axis groups the years 2012-2018 together for each of the vessel types in this study



Source: UMAS.

Figure 72 presents the trends over the period of this study for a number of parameters that are of high significance in the inventory. These are presented both as trends for the average ship and for the total fleet. The latter is inclusive of the trend in fleet growth over the period. Across the three ship types, bulk carriers, containers and oil tankers, the same general trends in averages are observable but in different magnitudes. The average bulk carrier and oil tanker increased in deadweight by approximately 5.7 and 6.5%, respectively, whereas the average container increased by approximately 20.6%. The size increase is accompanied by a less than proportional increase in average installed power for each ship type, with the container ship installed power increasing by 7.1% over the same period. In combination, this drives a reduction in the potential carbon intensity of the fleet because it can transport more mass with less power, all else being equal.

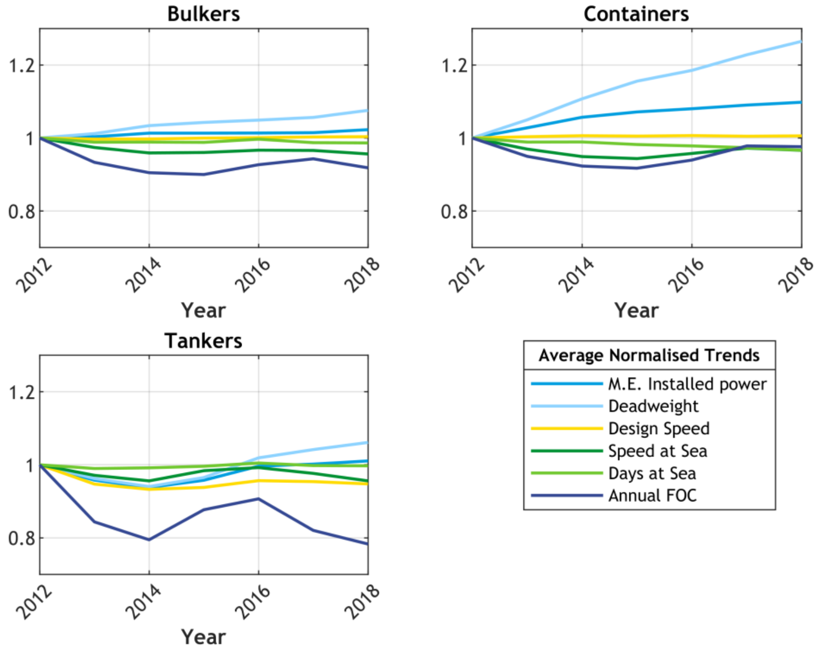
Trends in the average annual fuel consumption of these three ship types are less definitive, with some volatility over the time period studied. In all fleets, the annual fuel consumption falls in spite of the growing total installed power. Some of this is explained by a reduction in the average number of days at sea relative to 2012. However, some of the reduction is also due to falling average speeds over the period.

In summary, all three fleets by 2018 were, relative to 2012, composed of larger ships with a greater installed power, but despite these increases, with lower per-ship fuel consumption due to fewer sailing days and lower average speeds.

The total trends for the fleets, which includes their increase in number of ships over the period, show similar characteristics. The total deadweight of bulk carriers, containers and oil tankers increased by 17.2%, 24.5% and 19.4% respectively. Consistent with the trends in average parameters, the total installed power increased by less: 12.7%, 11.1%, and 16.8%, respectively. Also consistent with the trends in the average parameters, changes in total international fuel consumption are observed to be slightly flatter, increasing by 4.9%, 3.4% and 9.3% for bulk carriers, containers and oil tankers respectively.

These results continue the trends observed in the Third IMO GHG Study 2014. The reduced fuel consumption on average and for total fleets is a positive sign that the fleet is becoming more efficient. However, that these trends continue to occur at the same time as increased installed power implies that the fleet in 2018 has an even larger latent emissions potential than it did in 2012. This latent emissions potential refers to the potential for the trends in emissions to be rapidly reversed without changes to the fleet's composition. This can occur because a significant driver of the small deviation in emissions trends are operational parameters (reductions in operating speed and in this case also days at sea), which are a function of behaviour and market conditions as opposed to design parameters.

Figure 72 - Trends for fleet and average ships for the three most high emitting fleets over the period 2012 to 2018, where international fuel consumption is presented according to the voyage-based allocation of international ship activity (Option 2)



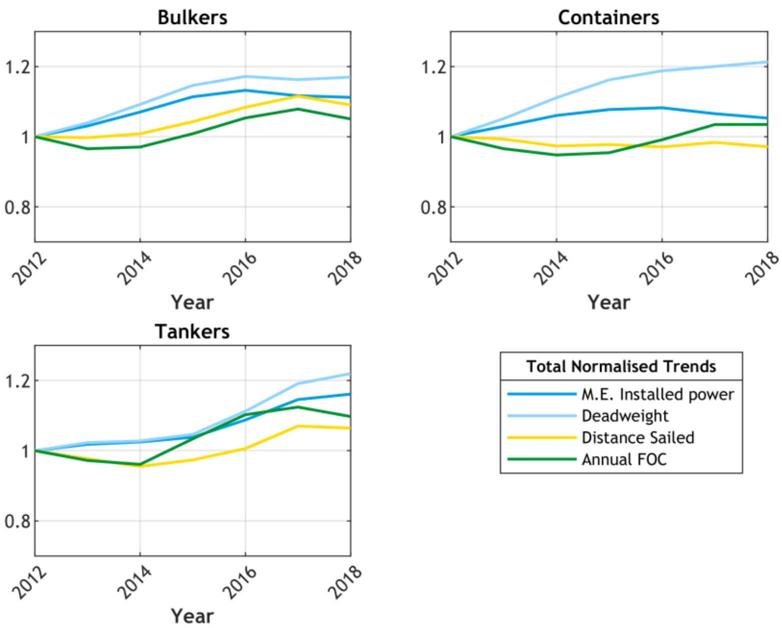
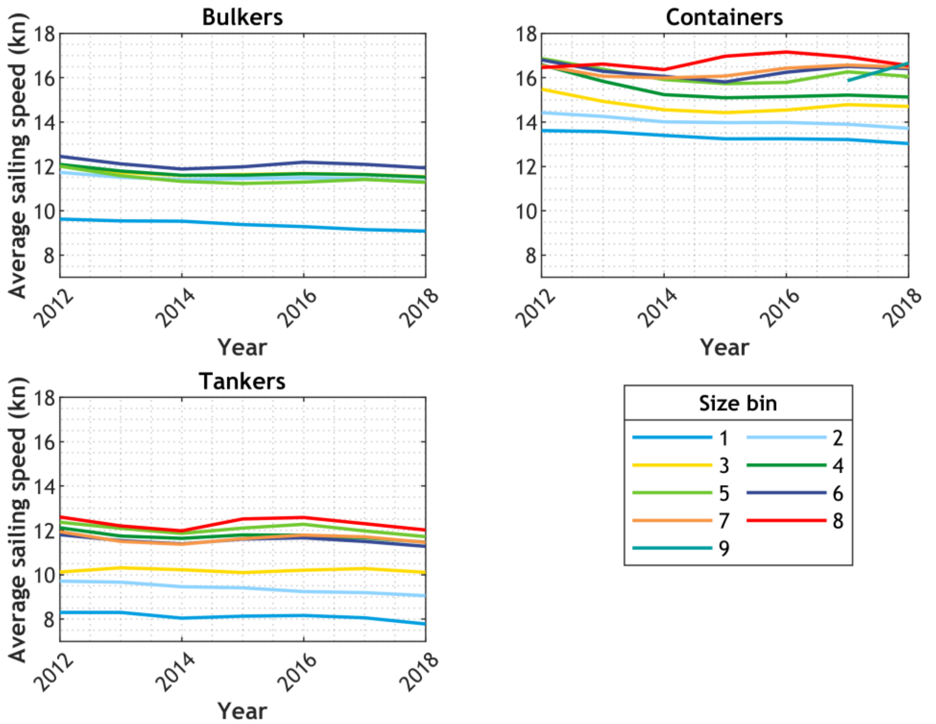


Figure 73 provides further breakdown in the trends of operating speed for the different ship types and their component ship size categories over the period 2012 to 2018. All three ship types when aggregated show reductions in average sailing speeds. Less obvious trends and more volatility are visible in the individual ship type and size categories. Ship speeds consistently fell for all of the ship types and sizes from 2012 to 2014. However, many sizes then sped back up on average in 2015 relative to 2014, as seen in an increase of 0.5 knots for the largest oil tankers, and an increase of 1 knot for the size 8 container fleet. Increases in average speeds for some ship size categories continue until 2017, but across all types and size categories, speeds are then either constant or fell from 2017 to 2018. Potential explanations for this variability in operating speed include the oil price fluctuations during this period, where significantly lower oil prices and therefore fuel costs occurred in 2015-17 relative to 2012-14, and trends in the use of containers of different sizes during a period of high average ship size growth (Figure 73).

Figure 73 - Speed trends for the three highest emitting fleets aggregated (top left) and broken down for each ship type's size categories.



Source: UMAS.

The consequence of the trends in operating speeds is the power outputs required for ship propulsion. These are often expressed as “loads” corresponding to the proportion of overall installed propulsion power that is used. Average main engine loads for each ship type and size category are listed in Table 36. They are influenced both by the average operating speed in each fleet, and the average design/reference speed. The data show that by 2018, the majority of the ship type and size categories listed are on average operating at between 40 and 60% load relative to their installed propulsion power. Nearly every fleet is operated at lower engine load in 2018 than in 2012 (with the exception of the larger container ship sizes, discussed below).Most oil tanker fleets saw a peak in engine loads in 2016, consistent with the trends in average operating speed.

The container fleets are consistently being operated at lower loads than the oil and bulk carrier fleets, especially those of 2000 TEU capacity and above. One exception to that rule in the container fleets is the largest ships (14500-19999 TEU) where engine load increases significantly over the period. This is in spite of the average speed remaining approximately 16-17 knots throughout the period. This implies that new builds entering over the period have lower design/reference speeds so operate at higher load to achieve similar operating speeds.

Table 36 - Main engine loads for bulk carriers, containers and oil tankers, where the average vessel specific main engine loads at sea have been weighted by the days spent at sea by vessel (only including type 1 and 2 vessels)

Ship type and size category		Average main engine loads at sea						
		2012	2013	2014	2015	2016	2017	2018
Bulk carrier	0-9,999	0.61	0.6	0.59	0.59	0.59	0.57	0.52
	10,000-34,999	0.64	0.62	0.61	0.61	0.61	0.61	0.6
	35,000-59,999	0.61	0.58	0.57	0.58	0.58	0.58	0.57
	60,000-99,999	0.6	0.56	0.54	0.54	0.55	0.55	0.54
	100,000-199,999	0.58	0.52	0.49	0.48	0.48	0.51	0.5
	200,000-+	0.63	0.59	0.56	0.56	0.58	0.58	0.56
Container	0-999	0.55	0.54	0.52	0.51	0.51	0.5	0.48
	1,000-1,999	0.5	0.48	0.46	0.46	0.47	0.46	0.46
	2,000-2,999	0.42	0.37	0.35	0.35	0.37	0.39	0.39
	3,000-4,999	0.41	0.36	0.33	0.32	0.33	0.33	0.33
	5,000-7,999	0.37	0.34	0.32	0.31	0.31	0.34	0.34
	8,000-11,999	0.35	0.34	0.34	0.33	0.38	0.4	0.4
	12,000-14,499	0.36	0.34	0.35	0.36	0.4	0.42	0.41
	14,500-19,999	0.26	0.29	0.35	0.54	0.6	0.6	0.56
	20,000-+	N/A	N/A	N/A	N/A	N/A	0.34	0.51
Oil tanker	0-4,999	0.55	0.54	0.53	0.54	0.55	0.52	0.46
	5,000-9,999	0.54	0.52	0.53	0.53	0.51	0.5	0.49
	10,000-19,999	0.53	0.55	0.54	0.53	0.55	0.54	0.54
	20,000-59,999	0.58	0.56	0.54	0.56	0.56	0.54	0.51
	60,000-79,999	0.58	0.56	0.54	0.57	0.6	0.56	0.53
	80,000-119,999	0.51	0.48	0.47	0.51	0.52	0.5	0.48
	120,000-199,999	0.49	0.45	0.45	0.48	0.51	0.5	0.48
	200,000-+	0.54	0.49	0.47	0.54	0.56	0.52	0.48

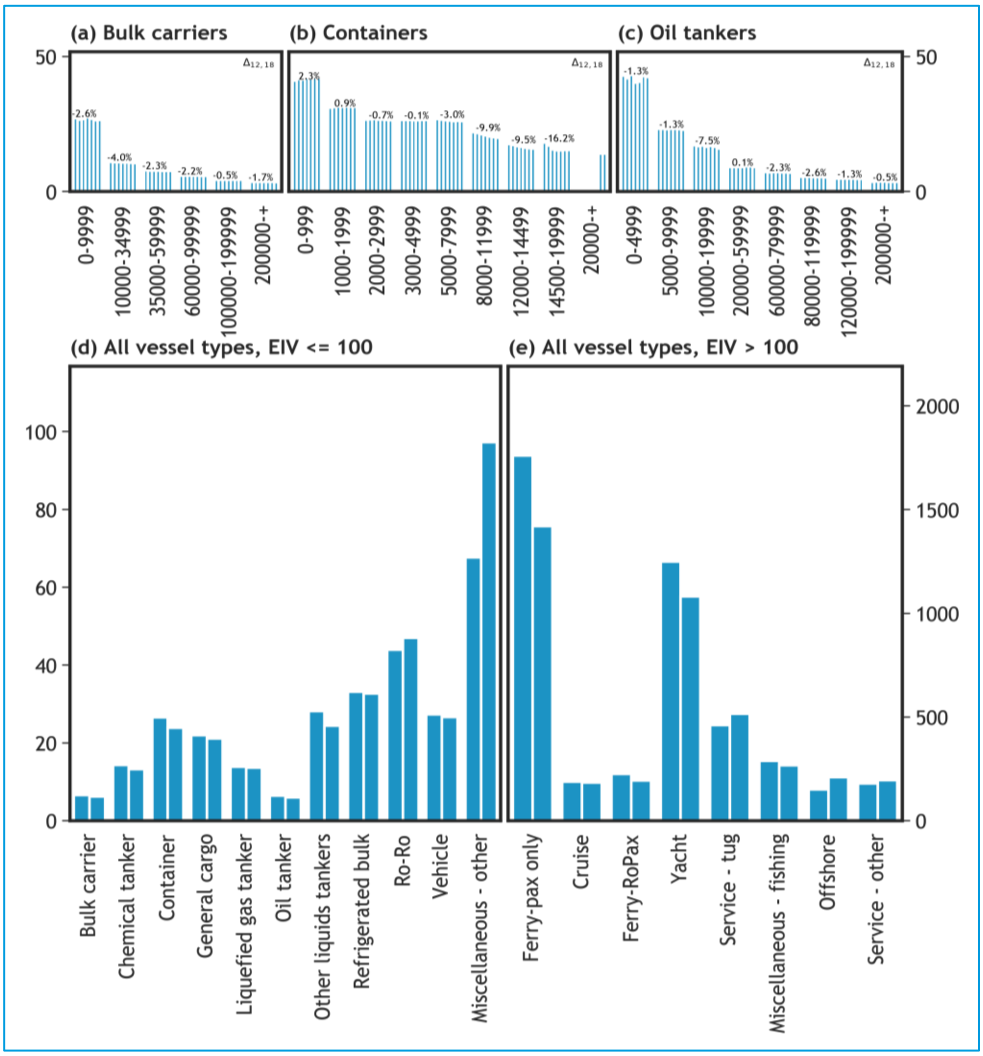
Figure 74 presents trends over the period in one means of estimating the technical efficiency, Estimated Index Value (EIV). EIV is an approximation of EEDI calculated from IHS data. It does not include the same details and correction factors that are included in the calculation of EEDI, but in the absence of a publicly available record of EEDI statistics for every ship, it is the best means for obtaining a comprehensive view of technical efficiency.

The period of this study encompasses both phase 0 (2013-2015) and the first part of phase 1 (2015-2018) of the EEDI regulation which requires newbuild ships within specific fleets and size ranges to be built to a maximum value of technical carbon intensity (gCO_2/tnm). The regulation is only applied to new builds, whereas Figure 74 presents the average for the total fleet in operation, many of which will have been built before the regulation entered into force. Trends in EIV reduction can be driven both by regulation, but also market forces and technological development.

For the three ship types that dominate international shipping's GHG emissions, there is mostly little change, if any, in fleet average EIV over the period within the specific ship type size ranges (plots a, b and c). The exception to this observation is the larger container size categories (8000 TEU capacity and above) which see significant improvements which are likely to be due to a combination of market factors and the younger average age of these fleets given the emergence and growth of these size categories during the period of this study. The first ship in the 20,000+ TEU category appears in 2017 so this category does not have a trend.

Overall trends in EIV aggregated to ship type level can also be seen in Figure 74, in plots d and e. The plots show a general improvement in technical efficiency over the period of this study, particularly across the ship types that are dominant sources of GHG emissions. The trends are a composite of the trend within given fleets across all size ranges, and therefore also represent any trend in the ship type's composition of different sized ships. For example, if there is increased use of larger ship sizes, then the EIV advantage of larger ship size contributes to a reduction in the fleet average EIV. Figure 74 shows that at least for the ship types oil tanker, bulk carrier and container ship, there was a trend of increased ship size during the period, most notably for containers. In combination with the results across all plots in Figure 74 this implies that for these ship types at least, a source of the modest fleet average EIV improvement has been the increase in average ship size.

Figure 74 - Trends across the 7 years in EIV for (a) bulk carriers, (b) containers (c) oil tankers by size category, where (d) and (e) show the difference in EIV between 2012 and 2018, aggregated by ship type, weighted by total voyage-based international shipping fuel consumption

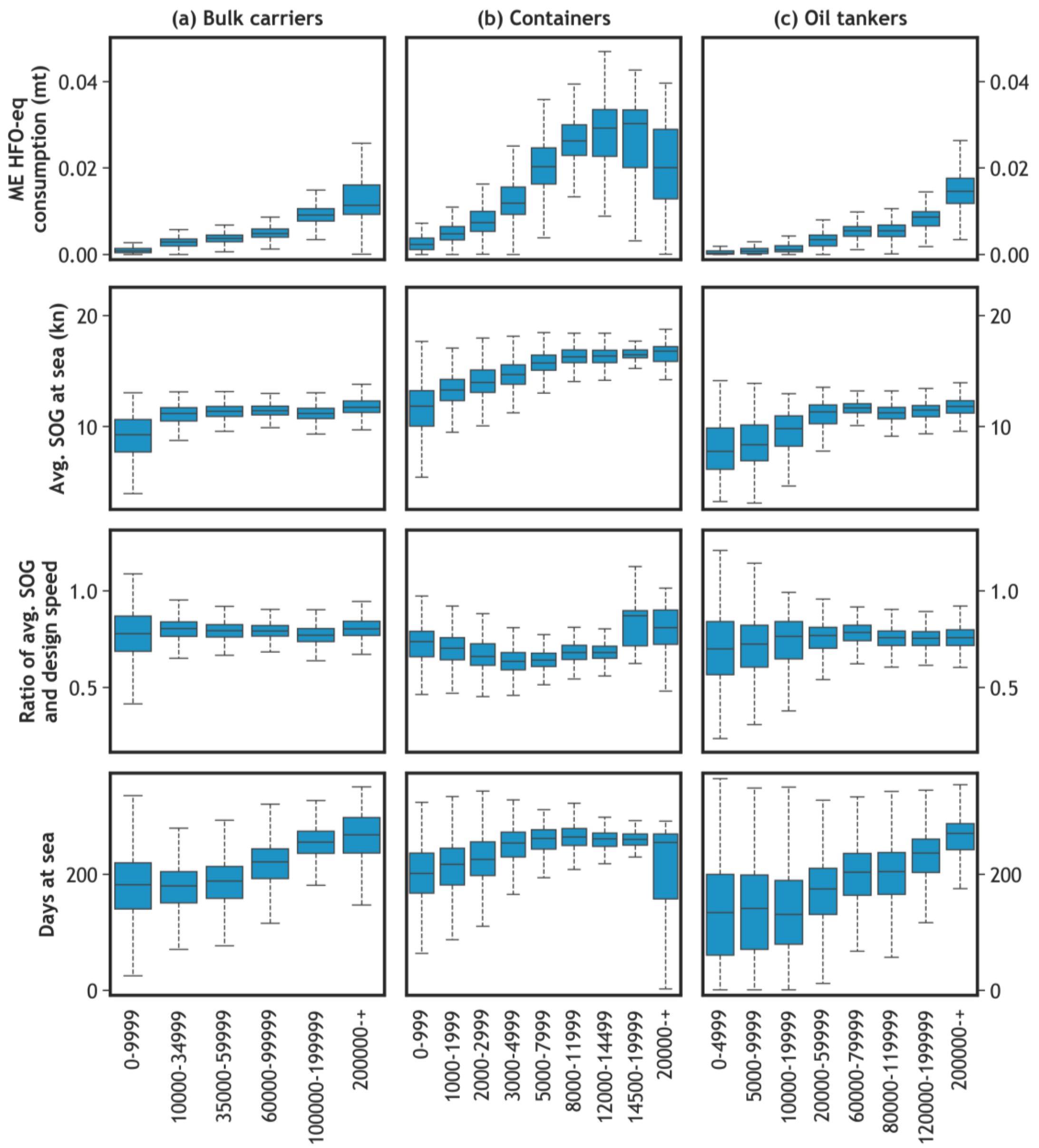


Source: UMAS.

Figure 75 presents the variability within ship type and size categories of key drivers of CO_2 emissions using a "box and whisker" plot. The central line represents the median value, the upper and lower edge of the "box" are the 1st and 3rd quartile of the sample, whereas the range of the whiskers is defined as a function of the interquartile range, applying a multiplication by 1.5. The figure indicates greater homogeneity in operational parameters for larger ships, as indicated by the relative variability in speed, days at sea, and the ratio of operating to design speed falling as ship size increases. Variability in main engine fuel consumption (normalised to HFO-equivalent fuel consumption) is less sensitive to ship size. Consistent with other explanations of observed trends, the exception to these generalisations is the larger containers which are less homogenous in specifications, given the new builds that appear in these fleets during the period 2012-2018.

For a given ship size, main engine fuel consumption can show significant variability, even for the larger ship sizes. For example, using the interquartile range as an indication of variability, the total annual main engine fuel consumption of the largest size category for the three ship types shown in Figure 75, i.e. sized larger than 200,000 DWT for both bulk carriers and oil tankers and 20,000 TEU for containers, vary widely with ranges from 9,290-16,050, 11,790-17,640 and 12,880–28,930 tonnes respectively. Assuming that the variability is not solely explained by weather impacts, this indicates a large potential to reduce fuel use and GHG emissions without significant changes in technology, and within the existing fleets. This indicates a large potential to reduce fuel use and GHG emissions without significant changes in technology, and within the existing fleets. This would require a more detailed explanation of the cause of variability in fuel consumption within a fleet, and the development of policy to incentivise operation towards the lower bound of these main engine fuel consumption ranges.

Figure 75 - Variability in emissions drivers across the three highest emitting ship types, 2018



Source: UMAS.

2.5.5 All species, bottom-up results

Figure 76 - Emissions species trends, all species 2012-2018, showing both the estimates for voyage-based and vessel-based international shipping emissions.

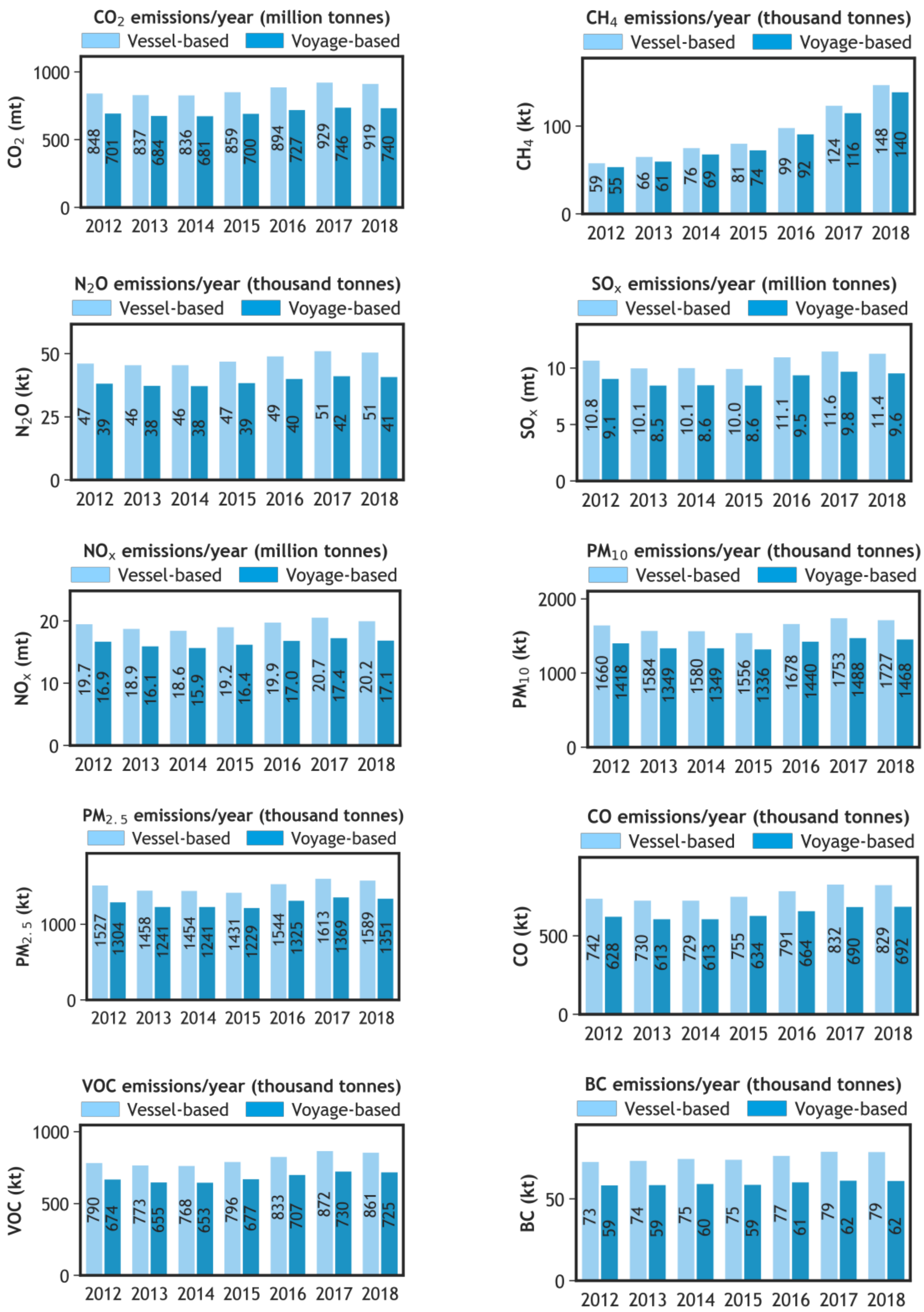
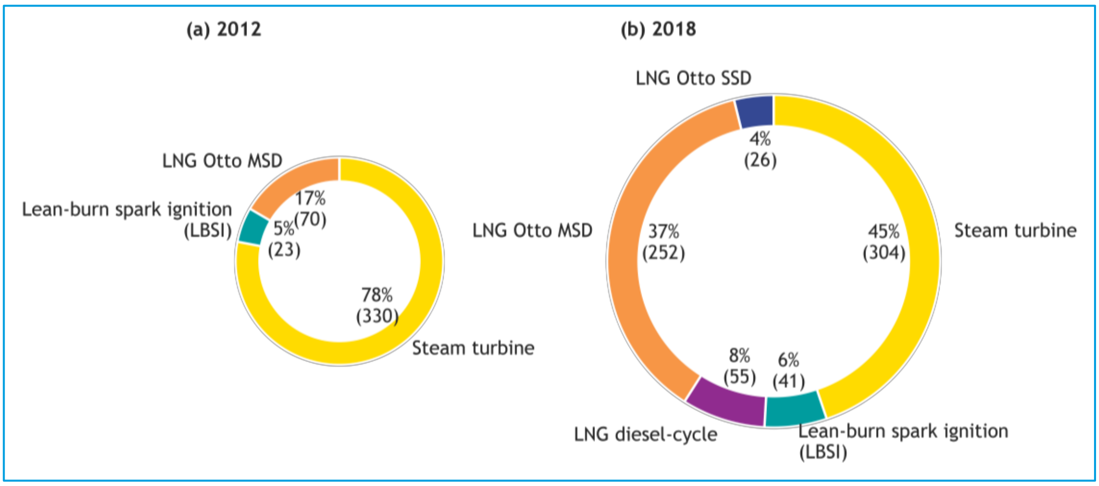


Figure 76 presents results for all emissions species, aggregated for each year and representing total emissions from international shipping according to the same definitions as used for the main GHG inventories.

Of all the species analysed, CH_4 emissions increased most strongly over the period studied, in particular growth was large relative to the increase in use of LNG as a fuel. Total LNG use in international shipping increased by 28-30% over the period 2012-2018, but over the same period emissions of methane are estimated to have increased by 151-155%, where the range includes both vessel-based and voyage-based allocations. The explanation for the difference in growth rates for fuel consumption and methane emissions is associated with a shift in the mix of machinery being used across the fleet during this period and shown in Figure 77. In 2012 most LNG consumption was from LNG carriers that used their cargo as fuel in steam boilers. Over the period, other ship types, including container ships, cruise ships and offshore vessels, have started to use LNG as a fuel, and the LNG carrier fleet has increasingly moved from steam turbine propulsion to use of LNG in internal combustion engines. Low-pressure injection, Otto-cycle engines were the most popular technology for these ships over the study period, with other ships using high-pressure injection, Diesel-cycle engines. The low-pressure injection engines emit more unburned methane than the high-pressure injection engines, and both technologies emit more methane than steam turbines. Figure 78 shows the change between 2012 and 2018 with respect to the uptake of the key LNG-fueled engines, for more information on engines specifically see Section 2.2.1.

Figure 77 - Comparison of LNG-fuelled engine types in 2012, where size of chart represents number of engines and those engines representing less than 1% have been omitted



Together, the growth of the LNG fuelled fleet, and the shift away from steam turbines to dual-fuel internal combustion engines has resulted in faster growth in methane emissions than the use of LNG itself, and compared to other GHGs. This outcome of rapid growth in CH_4 emissions was foreseen in the Third IMO GHG Study scenarios.

Figure 78 - Comparison of the contribution of individual species to voyage-based international greenhouse gas emissions (in CO_2e) in 2018, highlighting the impact the inclusion of black carbon has.

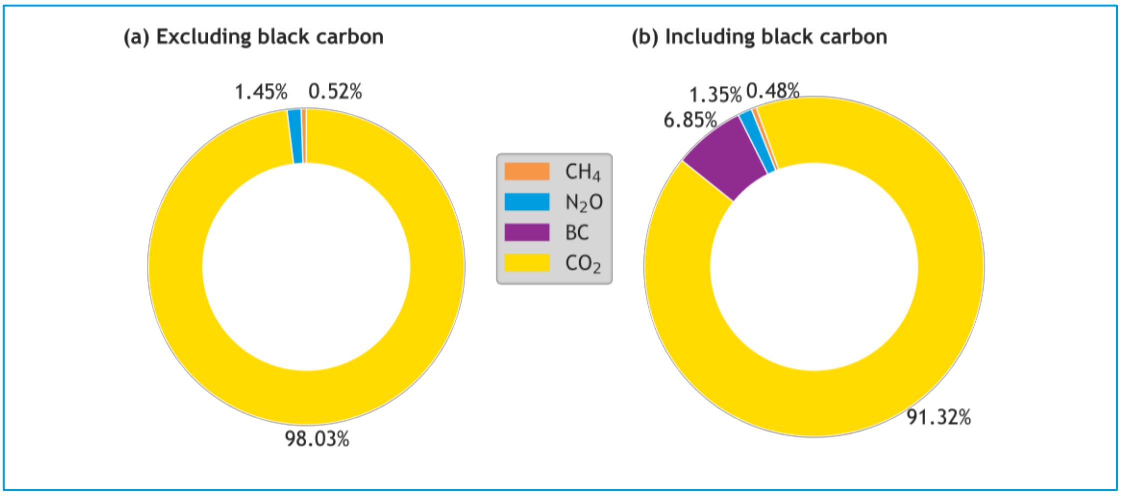


Figure 78 presents the overall breakdown of CO_2-equivalent emissions by species type for voyage-based international shipping emissions. By 2018, the contribution from each of the GHG emissions species (CO_2, CH_4, N_2O) to overall CO_2-equivalent emissions is 98.03, 0.52, 1.45% respectively when considering voyage-based international emissions, where the vessel-based proportions differ marginally (98.12, 0.44 and 1.44%). If BC emissions are also included in the calculation of CO_2-equivalents, using a 100-year GWP of 900, then these shares become 91.32, 0.48, 1.35% (for CO_2, CH_4 and N_2O), with BC representing the second most significant contribution at 6.84%, for voyage-based international emissions (where shares are 91.17, 0.41, 1.34 and 7.08%, respectively, for vessel-based international emissions). In both accountancies, CO_2 emissions continue, as observed in the Third IMO GHG Study 2014, to account for most of international shipping's GHG emissions (in CO_2e).

While not classified as a GHG, BC is a potent climate pollutant, with an especially large short-term warming effect. Total BC emissions, including international, domestic and fishing activity, have grown from 89 kt in 2012 to 100 kt in 2018, an 11.6% change, compared to an 9.4% increase in CO_2 emissions over that same period. The contribution of these BC emissions to total climate impacts from shipping emissions can be estimated by converting them into a CO_2-equivalent magnitudes. Significant debate remains on how the Global Warming Potential of BC should be calculated, so this is done using the best available science and is therefore still highlighted as a separate contributor to shipping's GHG emissions (in CO_2e).

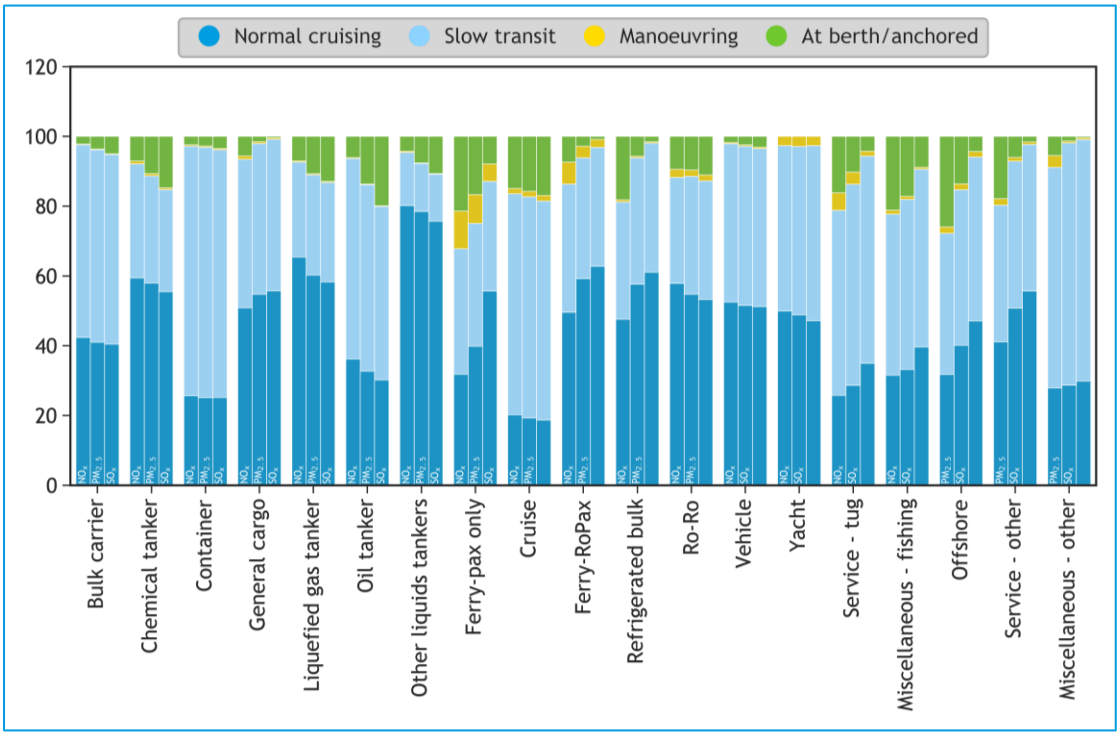
Figure 76 demonstrates that besides the rapid growth in CH_4 emissions, all other emissions species see only small fluctuations over the period 2012-18, more in line with the trend in total fuel consumption presented in Section 2.5.1.

The following description is for trends in other emissions species. All percentages are calculated for voyage-based allocation of international shipping, and are of negligible difference if a vessel-based allocation is applied. There is a trend of a small increase in total emissions for certain pollutant species (SO_x sees an increase of 5.5%, $PM_{2.5}$ sees an increase of 3.6%). This is against a backdrop of increased stringency during the period of regulations to reduce SO_x emissions (at least regionally). These regulations are part of the explanation that whilst total fuel consumption only increased by approximately 5.6% over the period, underlying this trend is a significant shift in the composition of total fuel consumption – a reduction in HFO use by 3% and a growth in MDO use by 69% and LNG by 30%. Given that MDO and LNG are both fuels with lower sulfur content than HFO, and therefore lower per unit energy emissions factors for both sulfur and PM emissions, it might be expected that overall the total species trends of these key pollutants improve over the period. The explanation for the observed trend increase comes from the evolution of the average sulfur content of HFO and MDO. These increased and decreased respectively over the period. The reduction in HFO use is countered by an increase in the average sulfur content of HFO (represented by increases in the magnitude of emission factors for SO_x and PM). With HFO still the dominant fuel in the total fuel mix (see Figure 63), the total emissions are more impacted by the average sulfur content increase of HFO than the increase in the fuel mix of MDO and LNG. One consequence of these trends is that on average for a given volume of international shipping traffic, those regions with ECAs have seen reductions in local SO_x and PM emissions (due to the ECA induced lower emissions). But those regions without ECAs will have seen an increase in SO_x and PM emissions (due to the increase in the HFO sulfur content).

During the period of this study, the fleet's machinery composition has also been affected by NO_x emissions regulation with increased penetration in the fleet of both Tier II and Tier III compatible machinery. In spite of that increased penetration, total NO_x emissions also increased during the period, by 1.2%. This increase was at a lower rate than the total fuel consumption increase (5.6%), so implies that some decoupling of NO_x pollution from fuel consumption was achieved. But it is a decoupling which is small, and unable to prevent an absolute increase against a trend of a small increase in fuel consumption.

Figure 79 presents a breakdown of some of the emissions species of particular relevance to health impacts, by operational phase. These show significant variations depending on the ship type and pollutant, regarding the percentage of the ship type's total emissions that occur at or near the port (e.g. at anchorage or at berth). This is explained by the different styles of operation, and also the different regulations on these pollutants, particularly in the Emission Control Areas.

Figure 79 - Proportion of species-specific emissions (NO_x, $PM_{2.5}$ and SO_x) by operational phase in 2018, according to voyage-specific assignment of emissions. Operational phases are assigned based on the vessel's speed over ground, distance from coast/port and main engine load (see Table 16).



2.5.6 Shipping as a share of global emissions

To quantify shipping's contribution to global anthropogenic total emissions, this study compares its estimated CO_2 emissions with its global counterpart as done in the Third IMO GHG Study 2014. Based on estimates provided by the IPCC, converted from elemental carbon to CO_2, total shipping CO_2 emissions have increased by 9.3% between 2012 and 2018, whereas its share of global CO_2 emissions over this period grew incrementally from 2.76 to 2.89% (see Table 37). International shipping's CO_2 emissions observe a smaller increase of 5.4% in absolute terms, which throughout the years represents a relatively constant share of global CO_2 emissions fluctuating around 2%.

Table 37 - Total shipping and voyage-based and vessel-based international shipping emissions 2012-2018 (million tonnes), as a share of global anthropogenic CO_2 emissions.

Year	Global anthropogenic CO_2 emissions	Total shipping CO_2	Total shipping as a percentage of global	Voyage-based International shipping CO_2	Voyage-based international shipping as a percentage of global	Vessel-based International shipping CO_2	Vessel-based international shipping as a percentage of global
2012	34,793	962	2.76%	701	2.01%	848	2.44%
2013	34,959	957	2.74%	684	1.96%	837	2.39%
2014	35,225	964	2.74%	681	1.93%	846	2.37%
2015	35,239	991	2.81%	700	1.99%	859	2.44%
2016	35,380	1,026	2.90%	727	2.05%	894	2.53%
2017	35,810	1,064	2.97%	746	2.08%	929	2.59%
2018	36,573	1,056	2.89%	740	2.02%	919	2.51%

2.6 Top-down estimates of shipping emissions

2.6.1 Top-down fuel consumption results

This section presents the Fourth IMO GHG Study top-down results for the period of 2012-2017.

Review of Fourth IMO GHG Study top-down energy estimates

The consortium reviewed the Third IMO GHG Study results, including updates based on current versions of IEA statistics. The IEA statistics explicitly designate fuel consumptions to three sectors: international marine bunkers, domestic navigation and fishing (including both international and domestic fishing activities). Table 38 presents results retrieved from the Third IMO GHG Study for the period 2007-2011 and new results for the period 2012-2017. Fuel consumption data are provided in million tonnes, where consumption data for natural gas were converted to tonnes oil equivalent using IEA unit conversions (1TJ = 0.0238845897 ktoe). The consumption trends are relatively smooth for all fuels at the break point between year 2011 and 2012 (see Figure 80, Figure 81, Figure 82,). For the data quality and uncertainty issues in IEA statistics, Sections 2.6.6 and 2.6.7 presents relevant comparison analyses.

Sales of gas/diesel increased significantly since 2014 and keep relatively stable after 2015. This trend may reflect the response to the introduction of 0.10% m/m Sulfur limit in Emission Control Areas (ECAs) in accordance with Annex VI of the MARPOL Conventions which started from January 1, 2015. Since the desulfurization of heavy fuel oils is too expensive in practice to make economic sense, currently, the more feasible way to meet the emission requirement is to use gas/diesel which is already low in Sulfur.

Table 38 - Top-down ship fuel consumption data used in two studies (million tonnes)

		Third IMO GHG Study					Fourth IMO GHG Study					
Marine sector	**Fuel Type**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
International marine bunkers	HFO	174.1	177.0	165.9	178.9	177.9	175.9	174.9	171.1	168.1	176.1	180.8
	MDO	26.0	22.7	24.9	28.2	29.6	20.7	21.1	31.6	41.9	39.6	40.6
	NG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.07
International total		**200.1**	**199.7**	**190.8**	**207.1**	**207.5**	**196.6**	**196.0**	**202.7**	**210.04**	**215.75**	**221.47**
Domestic navigation	HFO	19.9	14.2	15.3	14.3	12.7	13.2	13.8	14.7	12.2	12.2	15.3
	MDO	22.7	23.9	23.6	25.7	27.4	31.5	32.4	31.9	31.8	32.7	33.6
	NG	0.04	0.05	0.05	0.05	0.07	0.08	0.10	0.12	0.12	0.11	0.08
Domestic total		**42.64**	**38.15**	**38.95**	**40.05**	**40.17**	**44.78**	**46.3**	**46.72**	**44.12**	**45.01**	**48.98**
Fishing	HFO	1.1	1.1	1.0	0.8	0.8	0.8	0.7	0.7	0.5	0.4	0.5
	MDO	5.4	4.9	5.0	5.2	5.1	5.7	5.6	5.5	5.5	5.3	5.3
	NG	0.04	0.02	0.04	0.02	0.05	0.06	0.05	0.07	0.10	0.06	0.05
Fishing total		**6.54**	**6.02**	**6.04**	**6.02**	**5.95**	**6.56**	**6.35**	**6.27**	**5.9**	**5.76**	**5.85**
Total		**249.28**	**243.87**	**235.79**	**253.17**	**253.62**	**247.94**	**248.65**	**255.69**	**259.96**	**266.52**	**276.30**

Figure 80 - IEA fuel oil sales in shipping 2007-2017

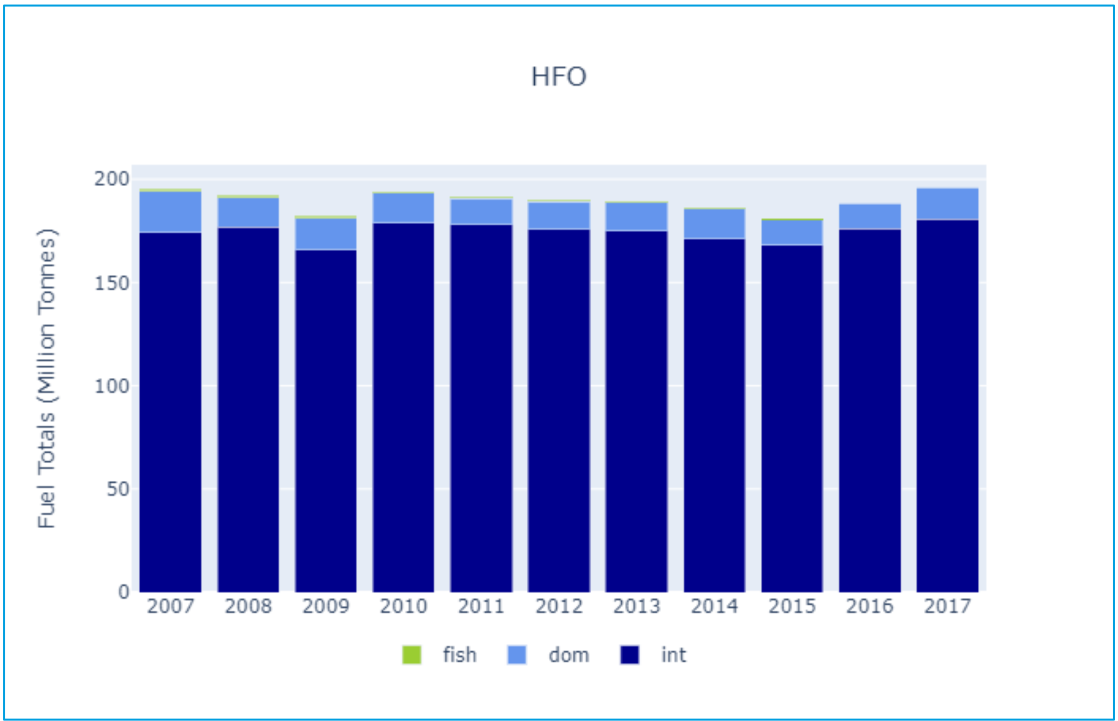
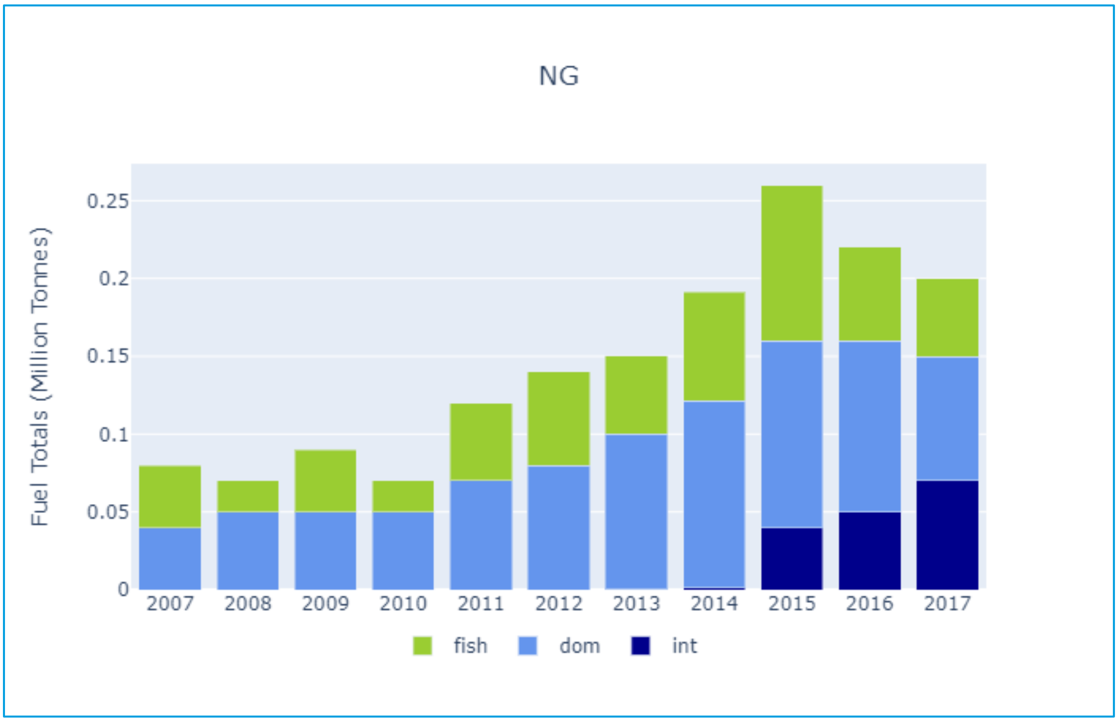


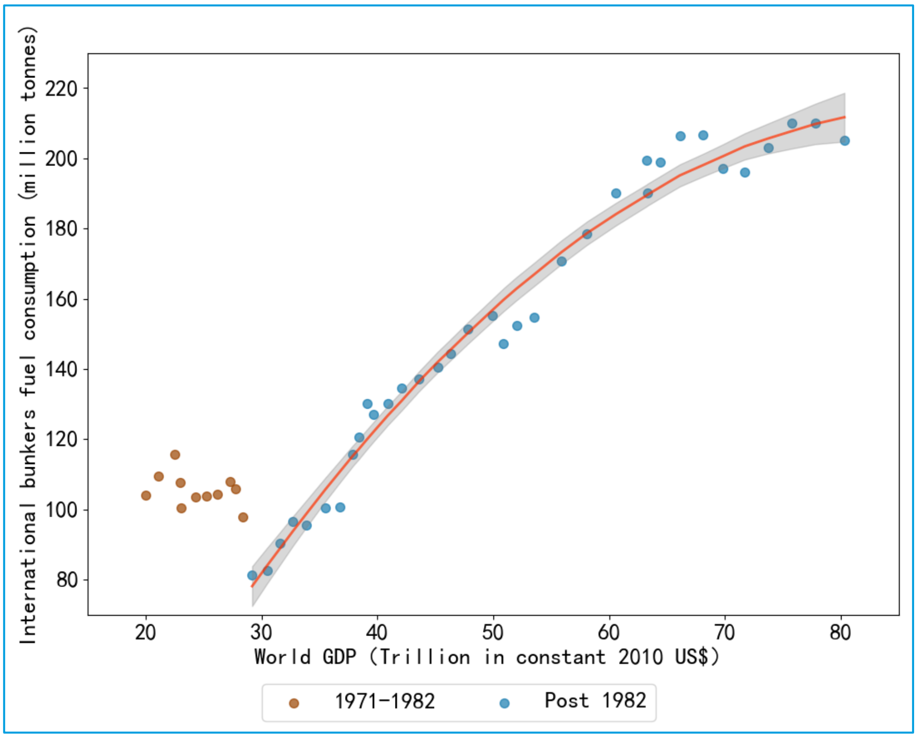
Figure 81 - IEA gas/diesel sales in shipping 2007-2017

Figure 82 - IEA natural gas sales in shipping 2007-2017



The world economy has been the main driver for international fuel consumption in a quite long period. The consortium evaluated the top-down consumption data trends for international bunkers fuel consumption and the world GDP trends as reported by the World Bank World Development Indicators. Unlike the strong linear relationship between international fuel oil consumption and world GDP found in the Third IMO GHG Study for the period 2000-2011, this study finds this linear relationship does not always hold. Total international bunkers fuel consumption, including both fuel oil and gas/diesel, are examined in this study. For the period 1971-1982, there is no clear relationship between international bunkers fuel consumption and world real GDP (in constant 2010 US$). The relationship between two data series in the post 1982 can be better depicted using a quadratic function (R^2 equals 0.979) rather than using a linear function (R^2 equals 0.945). This is because the increasing trend in total international bunkers fuel consumption after 2011 has been slowed down. The graphical relationships for two periods are illustrated in Figure 83. In-depth analysis of this topic is far beyond the scope of this study and will not be further discussed in this study.

Figure 83 - Correlation between world real GDP and international bunkers fuel consumption in 1971-2017



2.6.2 Fuel-based GHGs and other relevant substances emissions by top-down methodology

The emission inventories of CO_2, CH_4, N_2O, NO_x, CO, VOCs, SO_x, $PM_{2.5}$, PM, and BC was estimated by three types of energy products (Fuel oil/HFO, Gas diesel oil/MDO, and Natural

Gas/NG) and three marine sectors (international, domestic and fishing) over the period 2012-2017, as listed in Table 39-Table 48. The time series of emissions of GHG and relevant substances over the period 2012-2017 were also presented in Figure 84-Figure 85. It should be noted the real-world LNG consumption from ships might be higher than NG sales in IEA because many LNG-fueled ships are LNG carriers that are using their cargo as fuel. This also explains the large difference in bottom-up versus top-down LNG consumption and emissions estimates later in Section 2.7.

CO_2

Global CO_2 emissions rise then flatten around 2015, with the peak value reached to 868 million tonnes in 2016. International shipping account for the major part.

CH_4

Global CH_4 emissions rise after 2012, with the emission reached to approximately16 kilotonnes in 2017. The amounts of CH_4 were generally lower than in the IMO GHG Study 2014 due to the lower emission factors used in this study.

N_2O

Global N_2O emissions ranged from 43 to 48 kilotonnes and kept an increasing trend in 2012-2017.

NO_x

Global NO_x emissions rise from 2013, with the peak reached to 19 megatonnes in 2017. The estimated amounts of NO_x were generally lower than IMO GHG Study 2014 due to the lower emission factors used in this study.

CO

Global CO emissions ranged from 682 to 773 kilotonnes in 2012-2017.

NMVOCs

Global $NMVOC_s$ emissions rise after 2013, with the peak reached to 820 thousand tonnes in 2017.

SO_x

Global SO_2 emissions rise from 2013, with the peak reached to 10 megatonnes in 2017. While the SO_2 emissions of MDO declined from 2015 as a result of the ECA regulation, the average Sulfur content of HFO increased, causing the total SO_2 emissions to increase.

$PM_{2.5}$

Energy base Global SO_2 emissions rise from 2013, with the peak reached to 1.4 megatonnes in 2017.

PM

Global PM emissions rise from 2013, with the peak reached to 1.55 megatonnes in 2017.

BC

Global BC emissions ranged from 74 to 81 kilotonnes in 2012-2017.

Table 39 - International, domestic and fishing CO_2 emissions 2012-2017, using the top-down. Method (million tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	547.8	544.6	532.7	523.4	548.3	562.9
	MDO	66.2	67.6	101.5	134.4	126.9	130.3
	NG	0.0	0.0	0.0	0.1	0.1	0.2
Top-down international total	All	614.1	612.3	634.2	657.9	675.3	693.4
Domestic navigation	HFO	41.0	43.1	45.7	38.0	37.9	47.5
	MDO	101.0	103.9	102.3	102.0	104.9	107.7
	NG	0.2	0.3	0.3	0.3	0.3	0.2
Top-down domestic total	All	142.2	147.3	148.4	140.4	143.1	155.5
Fishing	HFO	2.3	2.2	2.3	1.7	1.4	1.5
	MDO	18.2	17.9	17.5	17.7	16.8	17.1
	NG	0.2	0.1	0.2	0.3	0.2	0.1
Top-down fishing total		20.7	20.3	20.0	19.7	18.4	18.8
All fuels top-down		**777.0**	**779.8**	**802.6**	**818.0**	**836.8**	**867.6**

Table 40 - International, domestic and fishing CH_4 emissions 2012-2017, using the top-down Method (tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	9,220.51	9,164.45	8,974.13	8,889.69	9,326.85	9,617.24
	MDO	936.31	954.07	1,429.80	1,983.81	1,871.83	1,942.50
	NG	0.00	2.10	10.95	332.41	546.69	837.71
Top-down international total	All	10,156.82	10,120.62	10,414.87	11,205.92	11,745.37	12,397.45
Domestic navigation	HFO	689.85	725.19	770.45	646.10	644.79	811.46
	MDO	1,427.98	1,465.38	1,442.21	1,505.89	1,547.64	1,606.46
	NG	446.64	594.16	852.54	1,018.25	1,098.01	934.46
Top-down domestic total	All	2,564.48	2,784.73	3,065.19	3,170.24	3,290.44	3,352.38
Fishing	HFO	39.52	36.84	39.08	28.51	23.15	26.07
	MDO	257.18	252.82	246.96	261.74	248.59	255.46
	NG	340.46	326.98	486.99	915.41	628.62	560.33
Top-down fishing total	All	637.16	616.64	773.03	1,205.65	900.36	841.87
All fuels top-down		**13,359**	**13,522**	**14,253**	**15,582**	**15,936**	**16,592**

Table 41 - International, domestic and fishing N_2O emissions 2012-2017, using the top-down Method (tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	30,559.1	30,449.1	29,833.9	29,380.2	30,813.7	31,689.9
	MDO	3,737.4	3,820.9	5,734.4	7,558.8	7,139.1	7,362.1
	NG	0.0	0.0	0.1	3.3	4.8	7.2
Top-down international total	All	34,296.5	34,270.0	35,568.4	36,942.3	37,957.5	39,059.2
Domestic navigation	HFO	2,286.4	2,409.5	2,561.3	2,135.3	2,130.2	2,673.8
	MDO	5,699.9	5,868.6	5,784.1	5,737.8	5,902.6	6,088.5
	NG	6.7	8.0	9.7	10.2	9.7	8.1
Top-down domestic total	All	7,993.0	8,286.1	8,355.1	7,883.4	8,042.6	8,770.4
Fishing	HFO	131.0	122.4	129.9	94.2	76.5	85.9
	MDO	1,026.6	1,012.5	990.4	997.3	948.1	968.2
	NG	5.1	4.4	5.5	9.2	5.6	4.8
Top-down fishing total	All	1,162.6	1,139.3	1,125.9	1,100.7	1,030.1	1,059.0
All fuels top-down		**43,452**	**43,696**	**45,050**	**45,926**	**47,030**	**48,889**

Table 42 - 7 International, domestic and fishing NO_x emissions 2012-2017, using the top-down Method (thousand tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	13,829.89	13,498.33	13,033.53	12,938.71	13,506.94	13,860.03
	MDO	1,097.46	1107.88	1,650.06	2,418.14	2,273.50	2,341.07
	NG	0.00	0.00	0.01	0.23	0.40	0.82
Top-down international total	All	14,927.35	14,606.21	14,683.60	15,357.09	15,780.84	16,201.92
Domestic navigation	HFO	1,034.72	1,068.14	1,118.96	940.38	933.77	1,169.45
	MDO	1,673.75	1,701.61	1,664.38	1,835.58	1,879.74	1,936.09
	NG	0.47	0.58	0.68	0.72	0.80	0.91
Top-down domestic total	All	2,708.94	2,770.33	2,784.01	2,776.68	2,814.32	3,106.44
Fishing	HFO	59.27	54.26	56.76	41.49	33.52	37.57
	MDO	301.44	293.58	285.00	319.04	301.94	307.88
	NG	0.36	0.32	0.39	0.65	0.46	0.55
Top-down fishing total	All	361.07	348.16	342.15	361.18	335.92	346.00
All fuels top-down		**17,997.36**	**17,724.70**	**17,809.76**	**18,494.95**	**18,931.08**	**19,654.36**

Table 43 - International, domestic and fishing CO emissions 2012-2017, using the top-down Method (thousand tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	498.94	495.65	484.97	480.20	503.58	519.55
	MDO	51.22	52.18	78.20	108.12	102.02	105.68
	NG	0.00	0.00	0.00	0.10	0.17	0.27
Top-down international total	All	550.15	547.83	563.17	588.43	605.77	625.49
Domestic navigation	HFO	37.33	39.22	41.64	34.90	34.81	43.84
	MDO	78.11	80.14	78.88	82.07	84.35	87.40
	NG	0.16	0.21	0.28	0.32	0.33	0.30
Top-down domestic total	All	115.60	119.57	120.79	117.29	119.50	131.53
Fishing	HFO	2.14	1.99	2.11	1.54	1.25	1.41
	MDO	14.07	13.83	13.51	14.26	13.55	13.90

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
	NG	0.12	0.11	0.16	0.29	0.19	0.18
Top-down fishing total	All	16.33	15.93	15.78	16.09	14.99	15.48
All fuels top-down		**682.08**	**683.32**	**699.74**	**721.81**	**740.26**	**772.51**

Table 44 - International, domestic and fishing NMVOC emissions 2012-2017, using the top-downMethod (thousand tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	551.89	547.24	535.09	532.81	559.22	577.21
	MDO	44.54	45.34	67.95	100.11	94.46	98.12
	NG	0.00	0.00	0.00	0.04	0.07	0.11
Top-down international total	All	596.44	592.58	603.04	632.97	653.75	675.44
Domestic navigation	HFO	41.29	43.30	45.94	38.72	38.66	48.70
	MDO	67.93	69.64	68.54	75.99	78.10	81.15
	NG	0.07	0.09	0.12	0.13	0.14	0.12
Top-down domestic total	All	109.29	113.03	114.59	114.85	116.90	129.97
Fishing	HFO	2.37	2.20	2.33	1.71	1.39	1.56
	MDO	12.23	12.01	11.74	13.21	12.55	12.90
	NG	0.05	0.05	0.07	0.12	0.08	0.07
Top-down fishing total	All	14.65	14.26	14.13	15.03	14.01	14.54
All fuels top-down		**720.38**	**719.88**	**731.76**	**762.85**	**784.66**	**819.95**

Table 45 - International, domestic and fishing SO_x emissions 2012-2017, using the top-down Method (thousand tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	8,203.63	7,835.26	7,751.01	8,050.98	8,881.37	9,188.80
	MDO	56.55	53.63	74.24	65.57	61.89	63.54
	NG	0.0000	0.0000	0.0000	0.0012	0.0017	0.0024
Top-down international total	All	8,260.18	7,888.89	7,825.25	8,116.55	8,943.27	9,252.3
Domestic navigation	HFO	613.77	620.01	665.44	585.14	613.99	775.31
	MDO	86.24	82.37	74.89	49.77	51.17	52.55
	NG	0.0027	0.0031	0.0037	0.0038	0.0034	0.0026
Top-down domestic total	All	700.02	702.39	740.33	634.92	665.17	827.86
Fishing	HFO	35.16	31.50	33.76	25.82	22.04	24.91
	MDO	15.53	14.21	12.82	8.65	8.22	8.36
	NG	0.0020	0.0017	0.0021	0.0034	0.0020	0.0016
Top-down fishing total	All	50.69	45.71	46.58	34.47	30.26	33.27
All fuels top-down		**9,010.89**	**8,636.99**	**8,612.16**	**8,785.94**	**9,638.7**	**10,113.5**

Table 46 - International, domestic and fishing $PM_{2.5}$ emissions 2012-2017, using the top-down Method (thousand tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	1,150.94	1,120.20	1,102.69	1,122.43	1,210.89	1,252.59
	MDO	18.51	18.59	27.44	35.30	33.33	34.45
	NG	0.00	0.00	0.00	0.00	0.01	0.01
Top-down international total	All	1,169.45	1,138.79	1,130.14	1,157.73	1,244.22	1,287.05
Domestic navigation	HFO	86.11	88.64	94.67	81.58	83.71	105.69

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
	MDO	28.23	28.56	27.68	26.79	27.56	28.49
	NG	0.01	0.01	0.01	0.01	0.01	0.01
Top-down domestic total	All	114.35	117.21	122.36	108.38	111.28	134.19
Fishing	HFO	4.93	4.50	4.80	3.60	3.01	3.40
	MDO	5.08	4.93	4.74	4.66	4.43	4.53
	NG	0.01	0.01	0.01	0.01	0.01	0.01
Top-down fishing total	All	10.02	9.44	9.55	8.27	7.44	7.93
All fuels top-down		**1,293.82**	**1,,265.43**	**1262.05**	**1,274.38**	**1,362.94**	**1,429.17**

Table 47 - International, domestic and fishing PM emissions 2012-2017, using the top-down Method (thousand tonnes)

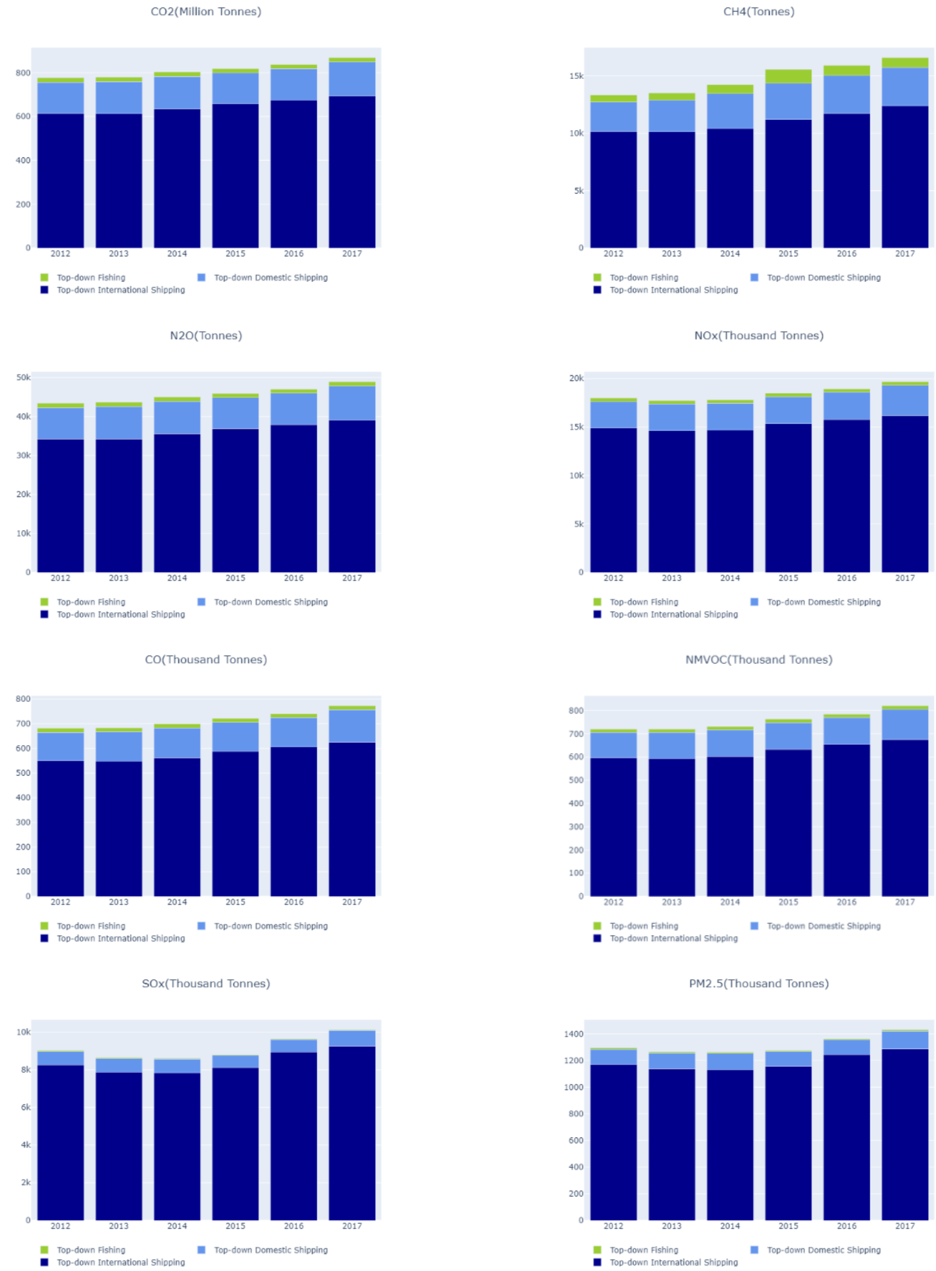
Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	1,251.04	1,217.61	1,198.49	1,219.92	1,316.18	1,361.60
	MDO	20.12	20.21	29.83	38.37	36.23	37.45
	NG	0.00	0.00	0.00	0.00	0.01	0.01
Top-down international total	All	1,271.16	1,237.82	1,228.32	1,258.29	1,352.41	1,399.05
Domestic navigation	HFO	93.60	96.35	102.89	88.66	90.99	114.89
	MDO	30.69	31.04	30.09	29.12	29.95	30.97
	NG	0.01	0.01	0.01	0.01	0.01	0.01
Top-down domestic total	All	124.30	127.40	132.99	117.80	120.96	145.86
Fishing	HFO	5.36	4.89	5.22	3.91	3.27	3.69
	MDO	5.53	5.35	5.15	5.06	4.81	4.92
	NG	0.01	0.01	0.01	0.01	0.01	0.01
Top-down fishing total	All	10.90	10.26	10.38	8.99	8.08	8.62
All fuels top-down		**1,406.36**	**1,375.48**	**1,371.69**	**1,385.08**	**1,481.45**	**1,553.54**

Table 48 - International, domestic and fishing BC emissions 2012-2017, using the top-down Method (thousand tonnes)

Marine sector	Fuel type	2012	2013	2014	2015	2016	2017
International marine bunkers	HFO	45.55	46.63	46.39	44.44	46.04	47.02
	MDO	8.86	9.13	13.67	15.46	14.62	15.15
	NG	0.0000	0.0000	0.0000	0.0001	0.0002	0.0002
Top-down international total	All	54.41	55.76	60.06	59.90	60.67	62.17
Domestic navigation	HFO	3.41	3.69	3.98	3.23	3.18	3.97
	MDO	13.51	14.03	13.79	11.73	12.09	12.53
	NG	0.0003	0.0003	0.0003	0.0004	0.0003	0.0002
Top-down domestic total	All	16.92	17.72	17.77	14.96	15.27	16.50
Fishing	HFO	0.20	0.19	0.20	0.14	0.11	0.13
	MDO	2.43	2.42	2.36	2.04	1.94	1.99
	NG	0.0002	0.0002	0.0002	0.0003	0.0002	0.0001
Top-down fishing total	All	2.63	2.61	2.56	2.18	2.06	2.12
All fuels top-down		**73.96**	**76.08**	**80.40**	**77.04**	**78.00**	**80.80**

Time series of top-down results

Figure 84 - a) CO_2, b) CH_4 , c) N_2O, d) NO_x , e) CO, f) NMVOC, g) SO_x ,h) PM2.5, i) PM, h) BC, delineated by international shipping, domestic navigation and fishing



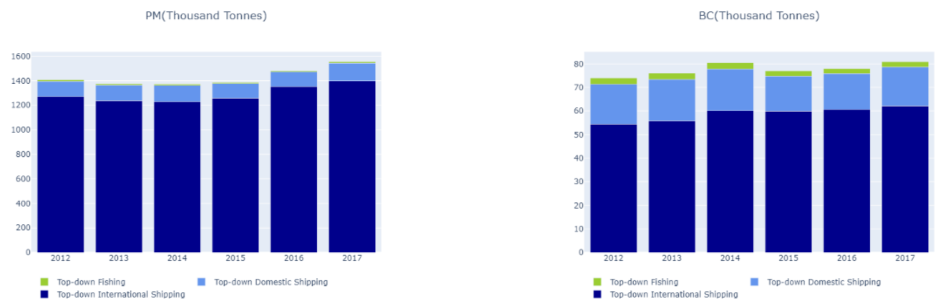
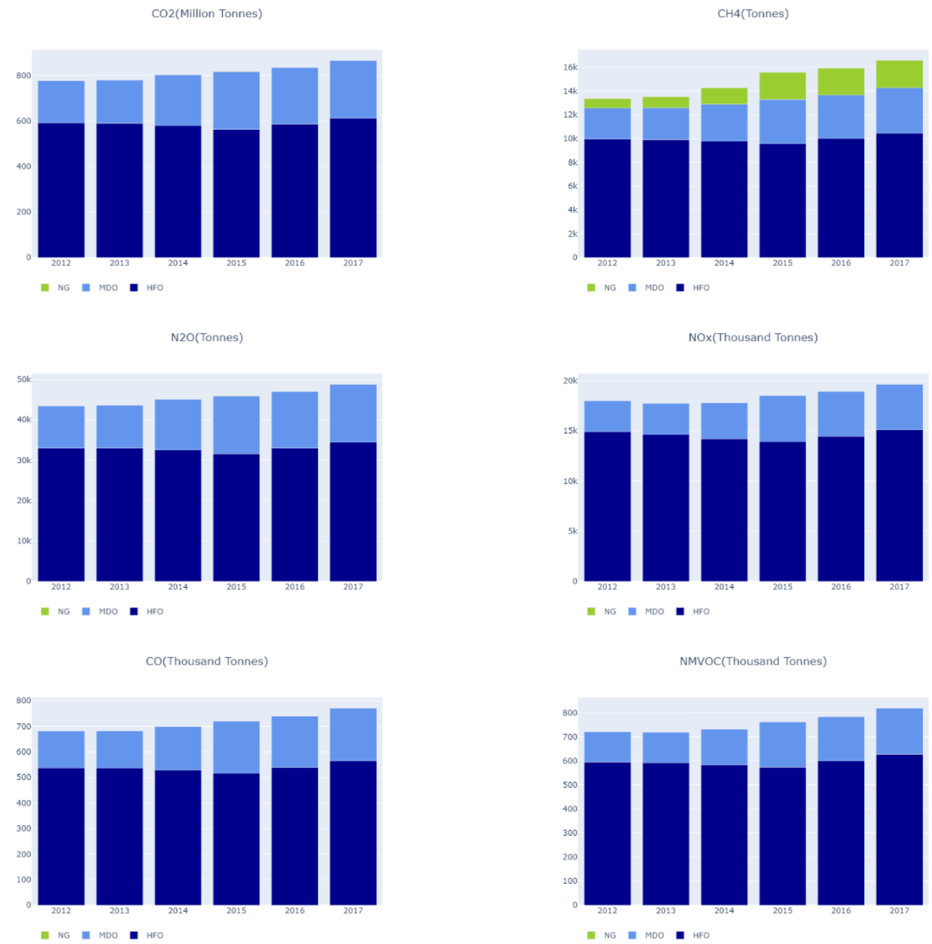
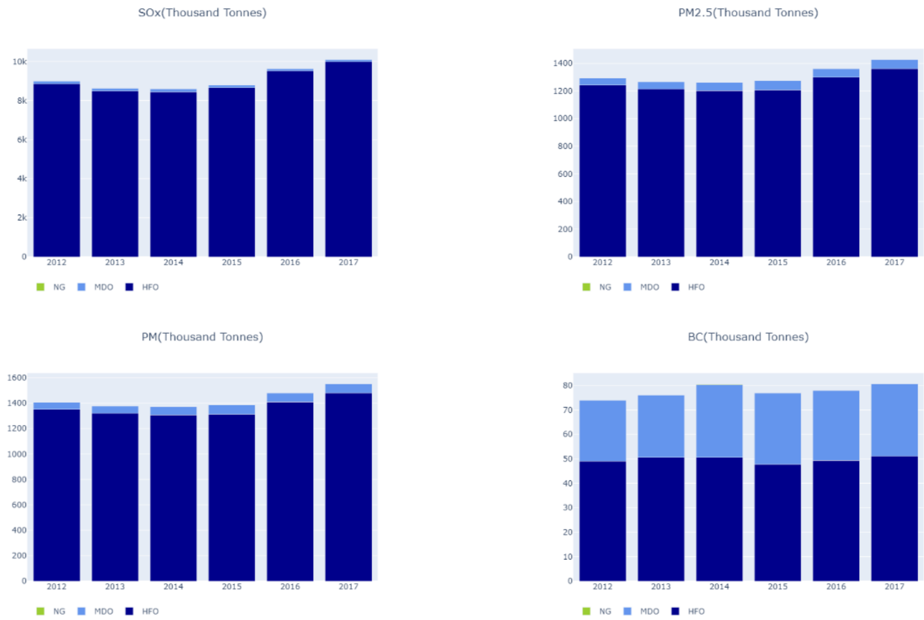


Figure 85 - a) CO_2 , b) CH_4 , c) N_2O, d) NO_x , e) CO, f) NMVOC, g) SO_x ,h) $PM_{2.5}$, i) PM, h) BC, delineated by HFO, MDO and NG





2.7 Comparison of top-down and bottom up estimates

Three main comparators are essential to understanding the results derive from the top-down and bottom-up inventories:

1. Comparison on the fuel totals for conventional fossil fuel (HFO, MDO).
2. Comparison on the alternative fuel (LNG and methanol). And
3. Comparison on total emission of GHGs and relevant substances.

Comparison on the fuels totals of conventional fossil fuel (HFO and MDO)

Total fuel consumption estimates for 2012–2018 by bottom-up and top-down approach is presented in Figure 86 and Figure 87 (the former for for all ships, and the later for international shipping according to Option 2). IEA has not yet issued the statistics on 2018.
In all cases, the bottom-up results for conventional fossil fuel are greater than the top-down statistics. However, the all top-down values are in the range of each error bars of bottom-up approach.
During the period of 2012-2017, the increment from bottom-up to top-down for total marine sectors remained as constant at approximately 20%. On the other hand, increment for international ship is slightly decreased from 10% to 4%. As IEA did not report any methodology changes in this statistics, nor report notification on uncertainties during the period, the less difference may be caused by the better s-AIS coverage during the period.
Allocation of fuel inventories by fuel type of conventional fossil fuel is important. The fuel split between residual (HFO) and distillate (MDO) for the top-down approach is explicit in the

fuel sales statistics. However, the HFO/MDO allocation for the bottom-up inventory is based on our assumptions.

Figure 88 presents comparison on fuel type allocation of top-down and bottom-up approaches. The application ECA in 2015 seems to be appropriate implemented in both approach.

Figure 86 - Top-down and bottom-up comparison on conventional fossil fuel (HFO and MDO) for all marine sectors

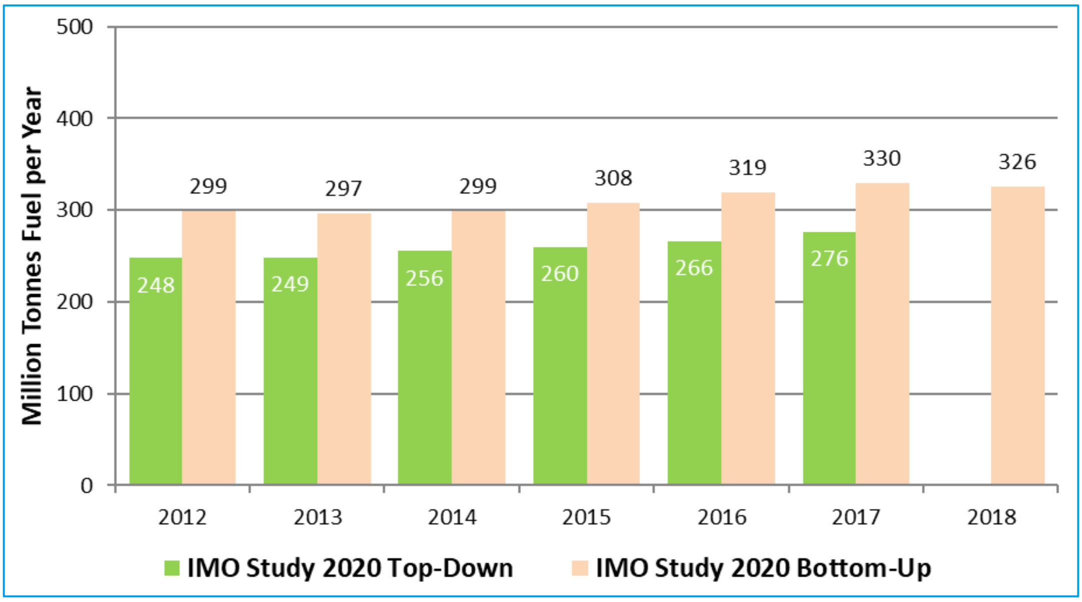


Figure 87 - Top-down and bottom-up comparison on conventional fossil fuel (HFO and MDO) for all marine sectors

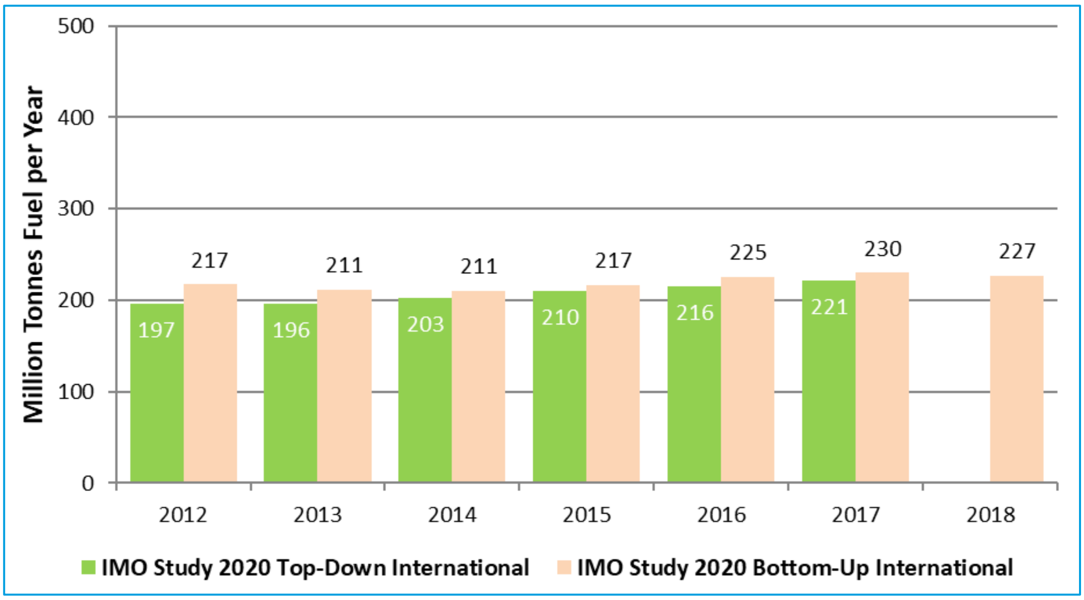
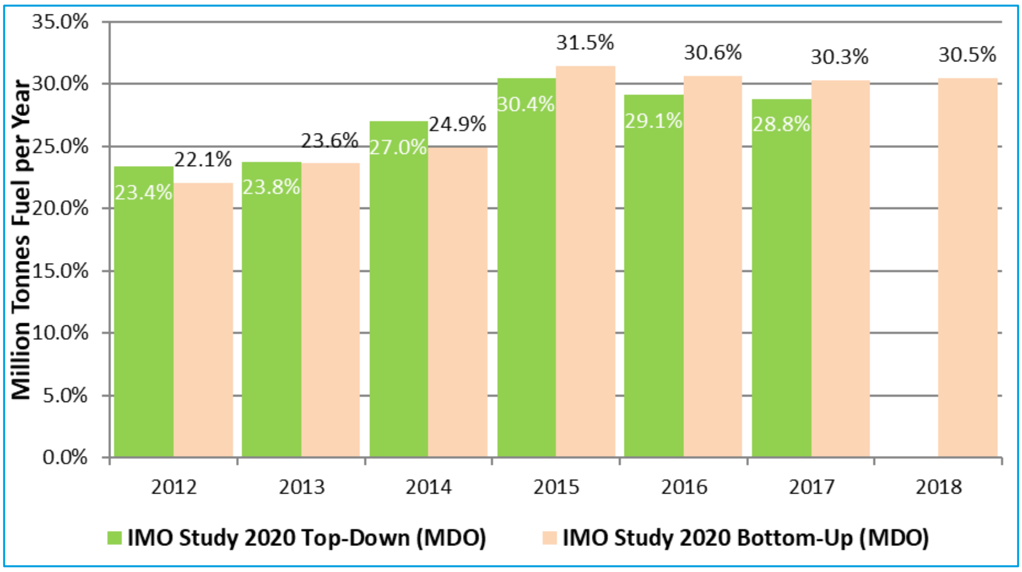


Figure 88 - Top-down and bottom-up comparison on the ration of MDO to total conventional fossil fuel for all marine sectors



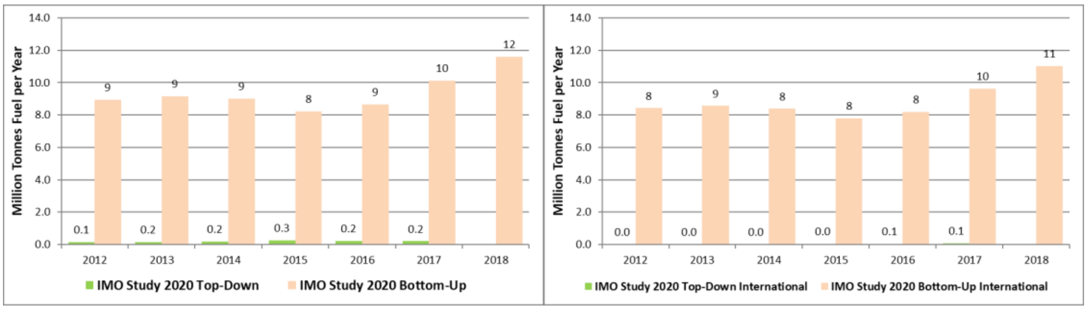
Comparison on the alternative fuel (LNG and methanol)

Total fuel consumption estimates for 2012–2018 by bottom-up and top-down approach is presented in Figure 89. It is obvious that volumes reported in IEA statistics is quite underestimated. This is mainly because how the boil off gas (BOG) should be implemented in the IEA statistics. In LNG carriers, certain amount of BOG will be vapored from their cargo tanks. IEA statistics, the amount of BOG will be expressed the difference between Import and Export and regarded as 'Loss'. On the other hands, the BOG in the bottom-up approach is regarded as fuel, and be sum-up in the figure. The consortium considered that this implication on BOG could not be changed, because of complexity of business practices.

It should be noted that IEA recently count up the volume of LNG which was used as fuel by non-LNG carrier, which has LNG fuel tanks separated from their cargo tanks.

For methanol as fuel, IEA does not count the duel in their statistics, therefore, it is impossible to make the comparison on it.

Figure 89 - Top-down and bottom-up comparison on LNG



a) all marine sectors b) for international shipping

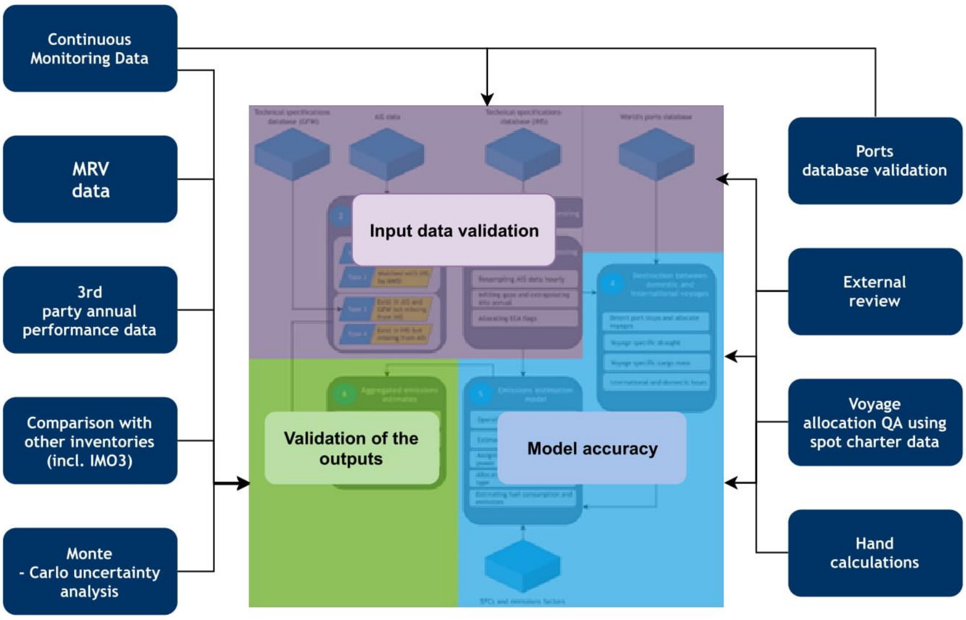
Comparison on total emission of GHGs and relevant substances

In this study, the emission factor for all fugitive GHGs and relevant substances is established for bottom-up approach by engine types and engine loads for each ship type/size bins. Then aggregated Emission factors for each fuel type (HFO, MDO LNNG and methanol) are calculated and applied to the top-down approach. Therefore, there is no deviation of relationship between Top-down and bottom-up approach, if compared with fuel consumption or with amount of GHG and relevant substances.

2.7.1 Bottom-up Quality Assurance and Quality Control

Extensive Quality Assurance (QA) and Quality Control (QC) efforts have been undertaken to ensure that the results presented in this report are of the highest possible quality and with a clear characterization of that quality. The volume of data available for validation for the current study far exceeds the data available at the time of the Third IMO GHG Study 2014. This has been used to its maximum potential to further increase the confidence in the quality of the bottom-up method and its outputs.

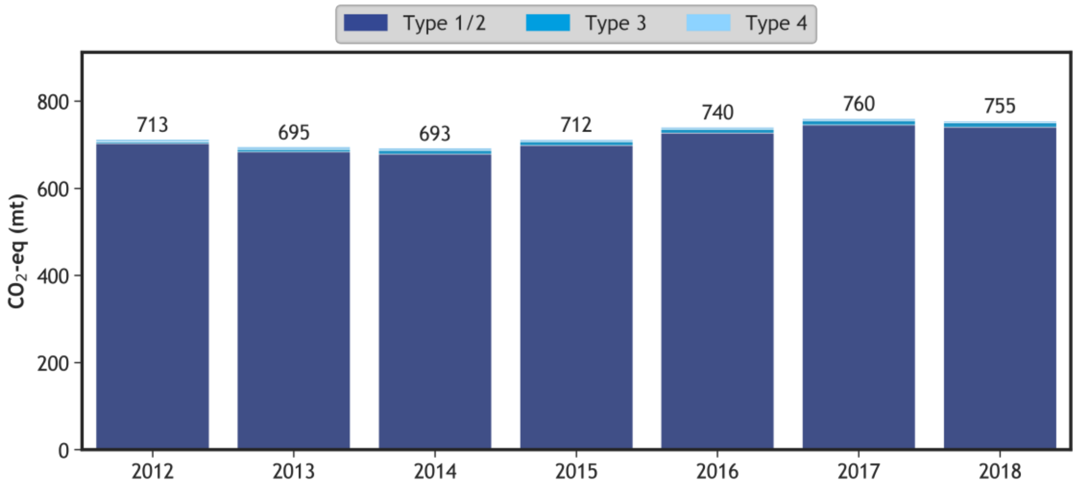
Figure 90 - Overview of the QAQC procedure of bottom up model completed for this study



Source: UMAS.

In order to clarify the calculation method of the bottom-up inventory of international shipping emissions, and as evidence of this method's overall quality, Figure 90 presents a break-down of the international shipping inventory for the period 2012-18, according to the different calculation types. Type 1 and 2 calculations are performed with the highest-quality input data and matching between the fleet technical specifications (derived from IHS data) and operational parameters (derived from AIS data). Type 3 and 4 calculations are undertaken with poorer-quality input data. The bottom-up emissions inventory is obtained almost exclusively using the highest-quality input data, and the total CO_2 emissions have a very low sensitivity to the lower-quality Type 3 and 4 calculations. This explains why some of the quality issues observed in the Type 3 input data (Section 2.2.6) are insignificant to the uncertainty in absolute values or trends observed in the inventory results.

Figure 91 - Origins of the estimates of voyage-based international shipping GHG emissions (in CO_2e), broken down by estimation method type.



In summary, confidence in quality is assured because:

- As shown in Figure 90, QA and QC procedures were undertaken at all stages of the modelling process, covering the input data and assumptions, the implementation accuracy of the model, and the resulting quantitative outputs.
- The outputs were validated at several different levels, including by detailed analysis of the key driving parameters (e.g. speed, days at sea) of the inventory's emissions estimates.
- AIS-derived speed and draughts were validated using a high frequency continuous monitoring dataset, showing a good agreement that ensures confidence in the bottom-up model's principal input parameters.
- To validate the domestic and international split, the port call detection methodology and the ports database used as input datasets were separately and independently validated. The port calls detection model outputs were validated against shipping manifests as well as third-party vessel-specific port call and voyage data samples, showing a good agreement.
- The accuracy of the bottom-up model's methodology and its implementation was validated with hand calculations and an external review of the input paraments, including emissions factors and SFC values.
- The resulting inventories were validated against a range of datasets including high frequency continuous monitoring data, third-party annual vessel performance data and, most importantly, a Monitoring, Reporting, and Verification (MRV) dataset covering more than 11,000 vessels (before filtering).

- The validation results for most of the principal components that influence CO_2 and other emissions showed excellent agreement with all validation datasets.
- The CO_2 and distance travelled at sea estimates across the entire fleet covered by MRV are showing a small overestimation error of 5.5 and 3.4% respectively.
- When breaking down the MRV based comparison by vessel type, the CO_2 emissions for three major vessel types are showing only -0.2% error for bulk carriers, 6% for container vessels, and 3% for oil tankers.
- These three vessel types contribute to over 65% of the international CO_2 emissions in 2018 and so are representative of global international shipping.
- Those vessel types for which the agreement is not as good are of negligible influence on the inventory's overall accuracy as their overall contribution to the international CO_2 emissions is no more than 3%.
- The difference in total fuel consumption figures with the previous Third IMO GHG study is 3% in the overlapping 2012 confirming the correct execution of the basic model and appropriate assumptions used in this study.
- To support the QA and QC processes, a Monte-Carlo analysis was performed to quantify the level of uncertainty in the results, which is of particular value when comparing the bottom-up inventory results with the top down estimations and using this comparison to further understand and explain this inventory's quality.

Specific details underpinning this summary are described in the subsequent sub-sections.

Validation of voyage specific draughts

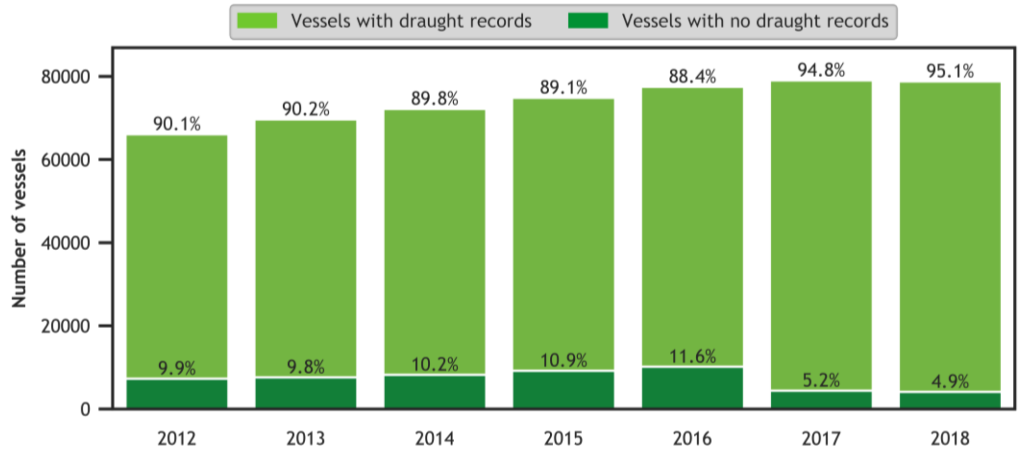
A vessel's draught records are important for a) the estimation of the vessel's energy demand and resulting emissions, and b) the cargo mass it is carrying, for use in the carbon intensity metric estimation outlined in Section 3.2. As described in detail in Smith, et al. (2015a) and Olmer, et al. (2017b), a vessel's draught influences the underwater hull surface area and hull form, which in turn affects a vessel's water resistance and therefore power demand. It is among the key input variables in the bottom-up model feeding into the Admiralty formula to estimate a vessel's power demand. The source data used in the bottom-up model is derived from the AIS-transmitted messages, where the records have been infilled and spurious records are dampened. This section discusses the key uncertainties involved with AIS draught measurements and their significance.

The two key sources of uncertainty identified are those vessels without any observed draught measurements, and the general uncertainty involved with the measurement of AIS draught records on board a ship. As was concluded in the Third IMO GHG Study 2014, draught records from AIS datasets tend to overestimate a ship's actual draught. This is primarily due to their submissions being prone to human error and rounding. While the influence of this is negligible within the fuel consumption method because the Admiralty formula is less sensitive to a vessel's draught records than its SOG, it has a much bigger impact in the estimation method of cargo masses and the derived EEOI estimates. The cargo estimation process has benefited from a voyage-based draught, as this implies a single cargo mass is estimated per voyage, but the cargo estimation method based on draught records remains a very uncertain process, as discussed in Section 3.2.

As explained in Section 2.2.3 draught measurements are obtained from the data reported in AIS static messages, which are linked with their dynamic counterpart through the MMSI number reported in both message types. Draught measurements are entered manually on some ships (from draught mark readings or a loading computer), while on others they are reported from sensors. Rarely is a ship's draught reporting audited for quality, causing null observations and spurious draught records within the unprocessed AIS messages, causing AIS-reported draught records to be highly uncertain in general (Smith, et al., 2015a). As static messages appear less frequently than dynamic messages, more draught measurements are infilled than SOG and location. However, compared to these two dynamic AIS-reported variables, draught does not have the same variability hour to hour and is typically only altered at the beginning of new voyages, leading to a reduced range of uncertainty (Smith, et al., 2015a).

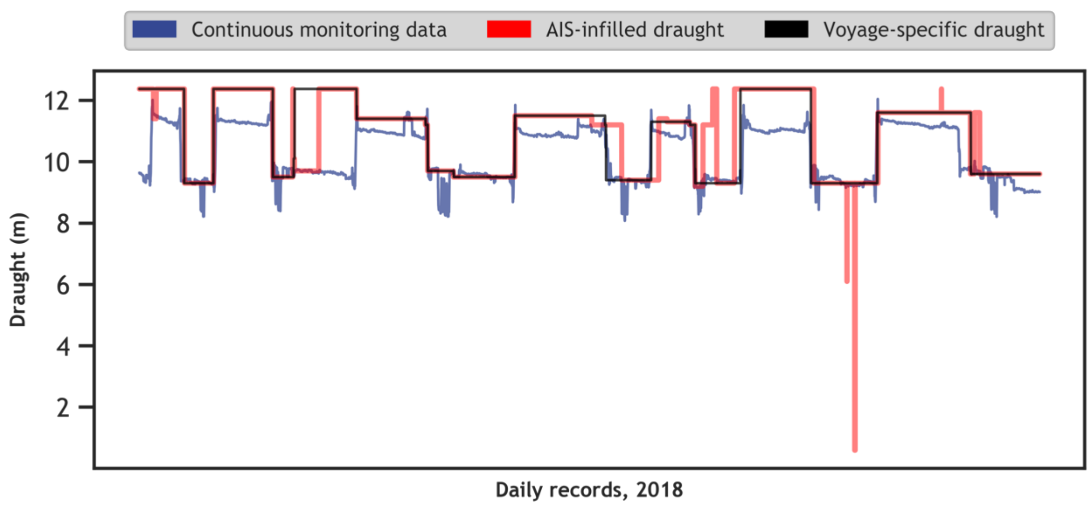
Overall, between 2012 and 2016 the proportion of vessels with no AIS-reported draught records increases, while in 2017 a sudden improvement is observed, as shown in Figure 92. In 2017, exactEarth reportedly experienced disruptions that manifested in a drop in coverage due to switching terrestrial data providers. It is unclear why the number of vessels without any draught messages has dropped simultaneously in the same year. It is possible that the terrestrial data provider has an improved coverage of static messages, allowing for better matching between a vessel's static and dynamic messages.

Figure 92 – Number of vessels with no AIS-reported draught records in relation to total number of Type 1 and Type 2 vessels, highlighting a steady increase in proportion, with a sudden drop in 2017 and 2018.



On a per-vessel level, spurious draught records are occasionally observed, and those which are above the design draught of the vessel are removed and infilled following the methodology described in Section 2.2.1. To dampen out erroneously reported draught values that have not been removed because they fall within the feasible draught range, this study introduces a voyage-specific draught. An example application of the voyage-specific draught can be seen in Figure 93, where a sudden drop in draught measurement is observed in the AIS-infilled draught reports in the fourth quarter of the year, in the middle of a voyage. By aligning draught records with voyages, draught changes can only be observed at loading and unloading of the vessel, not in the middle of a voyage, as is the expected behaviour of a vessel. This voyage-specific draught affects both fuel estimates and cargo estimates.

Figure 93 - Timeseries of an individual vessel's AIS-reported draughts.



Source: UMAS.

Further detail is provided following a comparative analysis between the hourly AIS-infilled draughts and a sample of continuous monitoring data averaged at a daily level below.

Voyage allocation/ports detection

The current study is the first of its kind to allocate emissions to international and domestic inventories according to an individual vessel's voyages. Accurate voyage allocation and port stop detection is of high importance in order to isolate these domestic and international voyages and their associated emissions, as the quantity of shipping activity classified as international has a direct influence on the inventory of international shipping emissions, a key output of this study.

The three key sources of uncertainty identified with respect to the stop identification process are a) the port dataset itself, b) the AIS-transmitted GPS and SOG messages and c) the assumptions used to identify a stop. A separate QA process was applied to the port dataset used in this study, and is described below. It finds a very good correspondence with two key global port datasets. To assess the quality of the port call modelling itself, this study's port calls have been compared to a small sample of verified vessel-specific stops, as well as a larger sample of shipping manifests. While it is crucial that the correct stops are identified, the most important factor is the nature of the identified voyage. Overall, a good correspondence is found between the stops identified and the validation stops. Across all vessel types, 88.4% of shipping manifest port calls were matched by this study's identified port stops, with container vessels the worst matched at 83%, which is explainable by their different operational pattern.

Port database QA

Key to the stop detection process is the port database containing the individual ports, to which a vessel's potential stops are assigned. The port database used in this study has been internally collated by UMAS International and contains approximately 13,000 global ports, their unique identifier, GPS coordinates, and country (see Figure 94). Many of these ports may not be within the scope of this study as they may primarily serve domestic and/or inland shipping only. To validate the coverage of the port dataset, it was cross-referenced with the World Port Index dataset (ESRI Deutschland, 2019) and the World Food Program port dataset (World Food Programme, 2019). Both validation datasets contain approximately 3,500 ports, with their coverage focusing on coastal ports. The coverage of this study's port dataset has been assessed by attempting to match the ports disclosed in each respective validation dataset based on their GPS-coordinates, allowing for a catchment radius of 20, 40 and 80 nautical miles. This process provides a good first indicator of the quality of the methodology used, with an approximately 95% coverage of both validation datasets when considering a 40 nautical mile catchment radius. The validation results are described fully in Figure 94 and Table 49.

Figure 94 – World maps showing the geographic coverage of main port dataset and the two validation datasets.

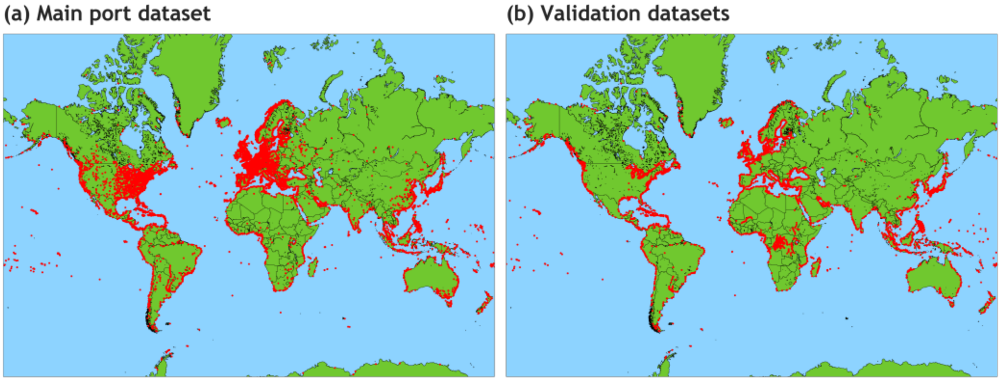


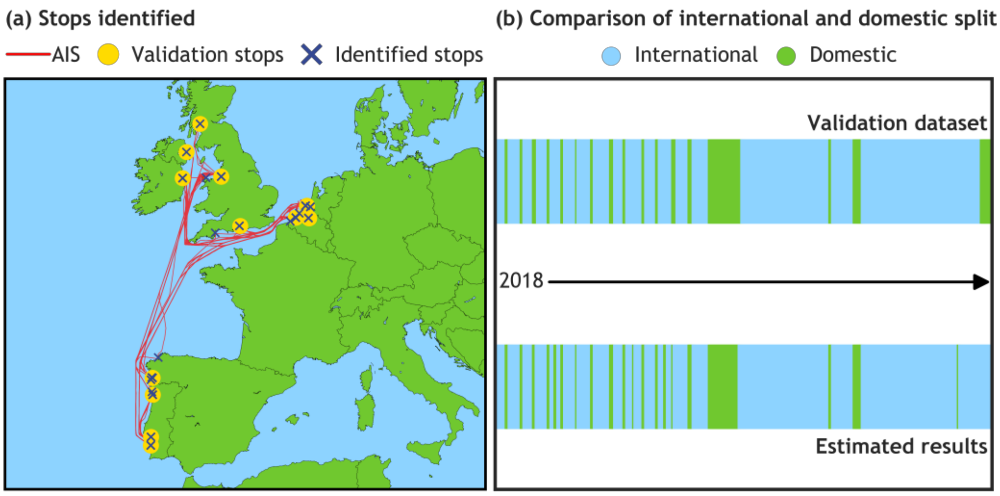
Table 49 – Assessment results of port dataset coverage.

Dataset source	Size	Percentage covered by port database, used in this report		
		20 nm	40 nm	80 nm
World Port Index (*Esri Deutschland*)	3,669	92.7 %	97.6 %	98.8 %
World Food Program (*data.world*)	3,571	84.3 %	94.4 %	97.6 %

Stops modelling QA

In addition, shipping manifests, vessel-specific port call and voyage data samples have been used to validate the stops and voyages estimated for particular vessels. As this process feeds into the split of international and domestic shipping activity, focus was given to the accurate identification of stops to highlight over- or under-identification. Figure 95 illustrates a detailed comparison of the stops identified for a vessel, as well as its split in international and domestic voyages, throughout 2018. Component (a) shows the satellite-observed trajectory of each vessel and compares the identified stops with the vessel's reported stops. Component (b) compares the temporal international-domestic split of the vessel's voyages over the course of 2018. Although limited in coverage, this comparison shows the detailed capability and reliability of the algorithms developed and the value of a voyage-based perspective when assessing shipping activity to be international or domestic in nature.

Figure 95 - Vessel-specific comparison of stops identified and international/domestic nature of voyages

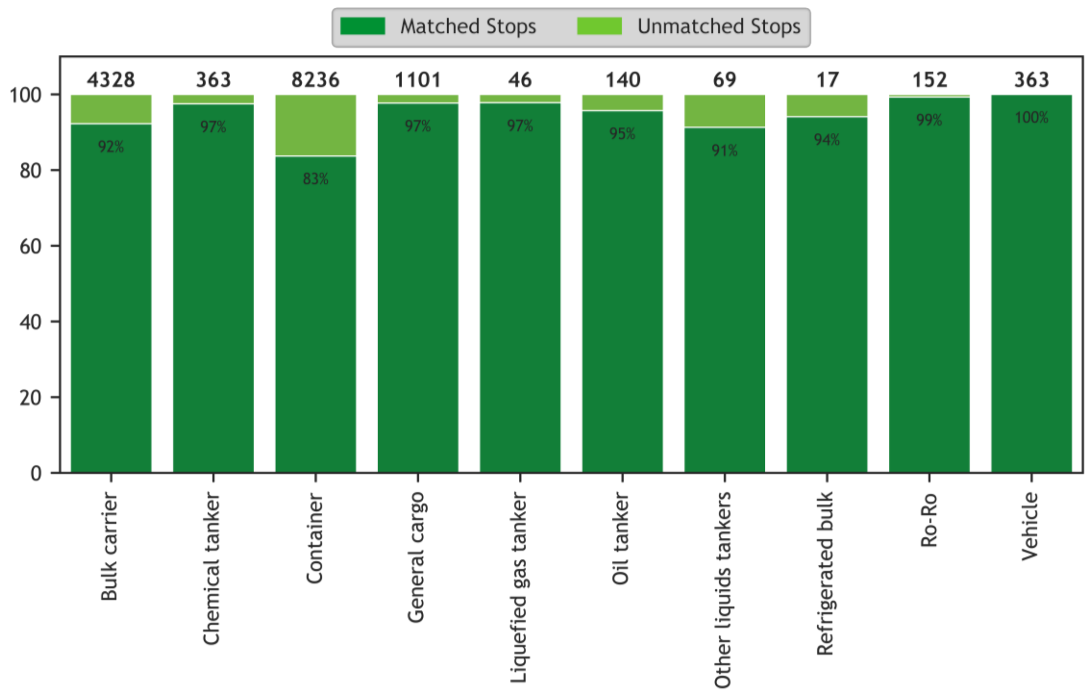


Source: UMAS.

The AIS-derived stops were further validated by matching them with a sample of stops sourced from shipping manifests, from which a relatively larger scope was provided. This validation sample contained almost 15,000 unique stops at 47 different ports, including partial shipping activity for approximately 4,000 vessels. This dataset only included shipping activity linked to outgoing volumes of trade for a single region in 2014, and due to this regional focus, it does not contain a vessel's complete sequence of stops. Therefore, this validation exercise explored the risk of under- rather than over-identifying port stops.

Figure 96 shows the matching results per vessel type, where the total number of stops are highlighted alongside matching rates. Across all vessel types, 88.4% of shipping manifest port calls were matched by this study's identified port stops. Container vessels are the worst matched with 83%. This is because container vessels behave differently to other vessel types with respect to port calls, and that for the purpose of computational efficiency, the port identification algorithm does not differentiate between vessel types. Its criteria have been developed to maximize accurate port stop identification across the fleet.

Figure 96 – Comparison of identified port stops with shipping manifest reported port calls, including only those vessel types consisting of sample size larger or equal to 10



Comparison with a high-frequency continuous monitoring data

Shipowners and operators are increasingly using Continuous Monitoring Datasets (CMDs) to understand and optimize their fleet's performance. If executed well, these datasets are both high-resolution and high-quality for a range of parameters that are also estimated and used within the bottom-up method, as well as being present in the bottom-up method's outputs. This data source provides an opportunity for deep quality analysis, albeit limited to the sample of ships for which CMD has been sourced. Using this approach led to the following conclusions for the data and methodology applied in the current study:

- On an annual aggregated level, all the principal components that influence CO_2 and other emissions, namely AIS speed, voyage specific draught, and fuel consumption, showed a very good correlation with the CMD.
- On daily observations of the same parameters, the correlation is of a poorer quality, which is explainable as a reflection of the hourly AIS operational coverage. The fact that the correlation dramatically improves when aggregated annually is an expected result and a key indication of the quality and appropriateness of the method used for annual inventories.
- For the annualized estimate of main engine fuel consumption, there is evidence of a systematic bias in the bottom-up method causing a small over-estimation relative to the sample of ships for which CMD was available.

- A key explanation for the observed overestimation is that the majority of the vessels within this sample are shown to have their reference or design speed reported at lower than 100% of the Maximum Continuous Rating (MCR) of the installed power reported in the © technical specifications database. The 100% MCR reference power is confirmed ©IHS and is a generalized assumption applied in the bottom-up model. Because of this, the bottom-up model will systematically assume a higher power output from machinery, and therefore higher fuel consumption, for a given operational speed.
- Supporting this explanation that the CMD comparison is indicative of the quality for this specific non-representative sample, and that it is not evidence of a systemic quality issue or bias in the inventory, is the superior agreement obtained from the MRV data comparison, undertaken on a much larger and therefore more representative sample of vessels.
- There is generally a poor agreement between the bottom-up method's estimate of auxiliary engine fuel consumption, but with a better agreement on annualized rather than daily statistics (consistent with other parameters and a positive indication for the quality of annualized inventories). Because auxiliary fuel represents a significantly smaller proportion of overall fuel consumption than main engine fuel, this observed lower quality has little significance to the overall inventory's quality.

Overall statistics

In this subsection, the bottom-up model is compared with a high-frequency CMD. Given that the CMD set in question is limited, the main purpose of this exercise is not to validate the overall performance of the model, but to provide a better understanding of how primary components of the model influence the fuel consumption figures and the consequences on quality. This is achieved through a detailed analysis of the behavior of these components on an individual vessel basis.

CMD systems record sensor data on-board and handle ship information related to its performance and operation, such as shaft power and fuel lines. These systems have the capacity to measure many performance parameters at high frequency and accuracy while allowing for a more transparent recording of ship operation when compared to noon reports. Although the CMD system records information every 15 seconds, the datasets used in this section were provided as averaged hourly or daily aggregations using a rolling average between recordings, resembling noon reports. The bottom-up calculations were averaged daily to have the same time scale.

This study had access to the CMDs of 94 ships with hourly recordings for the year 2017, representing 49 ships with more than 320,000 hourly observations, and 45 ships with more than 14,000 daily observations in 2018. For the 2017 dataset, the hourly observations were averaged daily to match the 2018 dataset aggregation. While the number of ships from the CMD are not representative of the global fleet, they are suitable to validate the bottom-up model and to understand the model's uncertainties.

The CMD allows for comparison across ship type, fuel, or machinery. The evaluation method compares the daily- and annually-averaged CMD observations and bottom-up results and adds a linear regression model to the pair points to assess the degree of correlation between the predicted values and the CMD. The linear regression analysis highlights the sources of the model's uncertainties and general differences to what was observed by the CMD. The sensors used for monitoring the ship performance to generate the CMD have associated measurement errors of between 0.1% and 5.0% depending on the sensor (González Gutiérrez, C. et al., 2020). These errors can be higher due to the sensor operational state and maintenance periods. Additionally, by using the averaged performance per day, the effect of weather on ship performance is smoothed out. It is important to highlight that to properly represent the fuel-mix consumption, the CMD and bottom-up daily observations and calculations were converted to HFO-equivalent mass using the fuels' gravimetric energy content.

Table 50 presents the linear regression results for each of the parameters for the comparison between the CMD recording and the Fourth IMO GHG Study. In general, the closer the linear regression slope *β* gets to 1.00, the closer it is to the observed CMD behavior. The larger the value of R^2, the better the linear regression explains the data observed. The intercept α on the linear regression model shows the average value of the variable in the y-axis when the value in the x-axis is zero. For variables that never reach zero, such as draught, α is meaningless. For variables that do have values at zero, α is the result of the interactions and differences between x, the CMD observations, y, the bottom-up model results, and the regression errors minimized by the linear model. The meaning of α is therefore more a mathematical artefact rather than a descriptor of the differences in the model. For that reason, α will be shown for statistical completeness but will not be discussed further.

Table 50 - Linear regression model results for the available ship types considering each daily observation and average of all daily observations. The intercept is represented by the Greek letter *α*, and the slope by β

Variable	2017						2018					
	Daily Observations			Annually-Averaged Daily Observations			Daily Observations			Annually-Averaged Daily Observations		
	α	β	R^2	α	β	R^2	α	β	R^2	α	β	R^2
Speed (kn)	2.86	0.80	0.84	2.07	0.86	0.94	1.35	0.88	0.91	0.31	1.00	0.95
Draught (m)	3.76	0.64	0.57	1.83	0.83	0.75	2.14	0.87	0.90	0.47	1.02	0.97
ME Power (kW)	2,812.93	0.88	0.79	1,434.62	1.01	0.68	1,335.15	1.17	0.90	602.22	1.27	0.97
ME FOC (kg/h)	48.99	0.94	0.73	1011.81	0.63	0.66	295.46	1.01	0.84	354.79	0.97	0.91
AE FOC (kg/h)	352.91	0.00	0.06	346.57	0.00	0.21	125.29	0.64	0.70	28.39	1.06	0.92

In the following subsections, the linear regression model results for the daily observations and annually averaged variables are presented in graphical form and discussed in more detail. In general, the dark lines represent the trend that a perfect match between the bottom-up model and the values observed in the CMD would have. Any point that lies above this line indicates that the bottom-up model is overpredicting the variable depicted in question, and underpredicting if the observation is below. The red line is the line that minimizes the distance to each observed point, with the light red area representing the 95% confidence interval. The term bias is used in this subsection to explain the behavior of the differences between the bottom-up model and CMD observations.

Complementing the linear regressions are the box-and-whisker plots, here referred to as box plots, per ship type per year. The box plots visualize the data dispersion between the bottom-up results and the CMD, allowing for a clear understanding of the similarities and differences between the observed data and the model results. The box plots have a red dotted line that represents the average value and a solid black line that represents the median. The box bounds the middle 50% of the data, and the whiskers indicate the 5th and 95th percentile datums observed. Anything beyond the whiskers is considered an outlier and is represented by a dot (Chambers, et al., 1983).

Speed

Figure 97 presents the AIS SOG used in the bottom-up model against the SOG recorded by the CMD and disaggregated by ship type. For the daily SOG observation, a slope of 0.80 is calculated for 2017 with a variable bias while for 2018 the slope was found to be 0.88. For the 2017 result comparison Figure 92 (a) it can be seen that there is a small variable bias that causes the bottom-up model to overpredict SOG at low ship speeds and then crossing at around 12.0 knots when the model starts to under-predict the speed. Moving to Figure 92 (c), it can be seen that the median and average of both the bottom-up and CMD values are almost the same, increasing the confidence in the bottom-up model to correctly estimate the SOG. The strong correlation between the AIS SOG used in the bottom-up model and CMD can be explained by an improvement in AIS coverage in 2017 and 2018, as well as the similarity between the SOG sensing equipment used to measure the CMD and AIS data. A comparison between daily records in Figure 98 shows that the patterns in observed speeds between the two datasets are very similar, except for a day where the CMD recorded an unusually high speed. This type of difference between the speed recording systems highlights that errors can be caused by speed sensor errors, the CMD system being turned off for a short time affecting the daily average, and the methodology to deal with outliers.

Looking at Figure 97 (d), the linear regression model is more closely aligned with the CMD, but with a variable bias where the bottom-up model overpredicts slightly at low SOGs, but then crossing at around 9.0 knots to start underpredicting SOG. The strong correlation between the bottom-up values and the CMD is further seen in the box plots from Figure 92 (f), where the CMD range, median, and average of each ship type are each closely matched to the bottom-up model.

Figure 97 - Plots that show the difference between the Fourth IMO GHG Study and the CMD for a) the daily speed, b) the annually-averaged daily speed for different ship types and, c) a box plot showing the average daily SOG in the year 2017. The plots a) to c) present this data for 2017, whereas d) to f) present the 2018 comparison. For a), b), d) and e) the linear regression is plotted in red, whereas the red dotted lines in the boxplots represent mean value of the respective samples

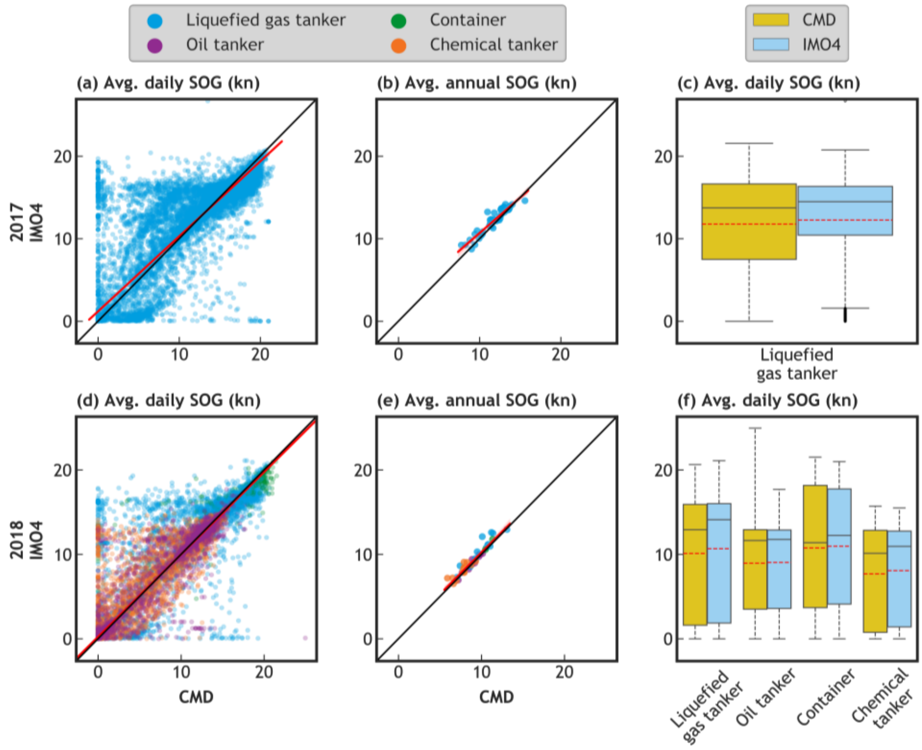
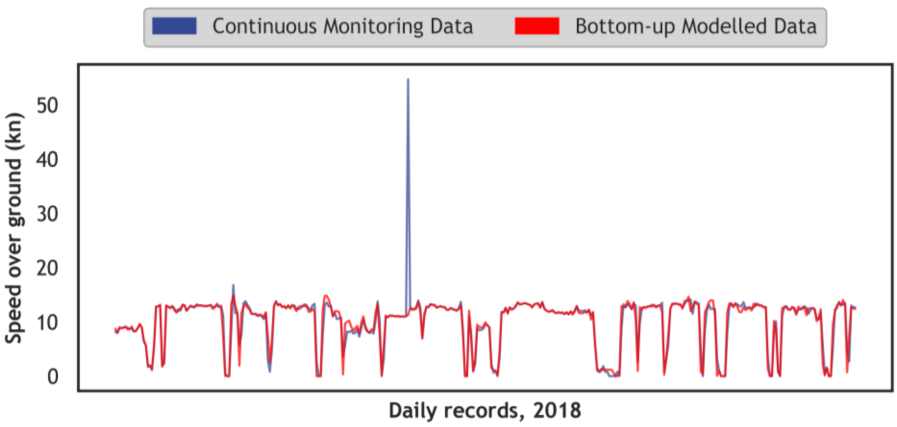


Figure 98 - SOG daily record comparison between the bottom-up model based on AIS data and CMD for an individual ship



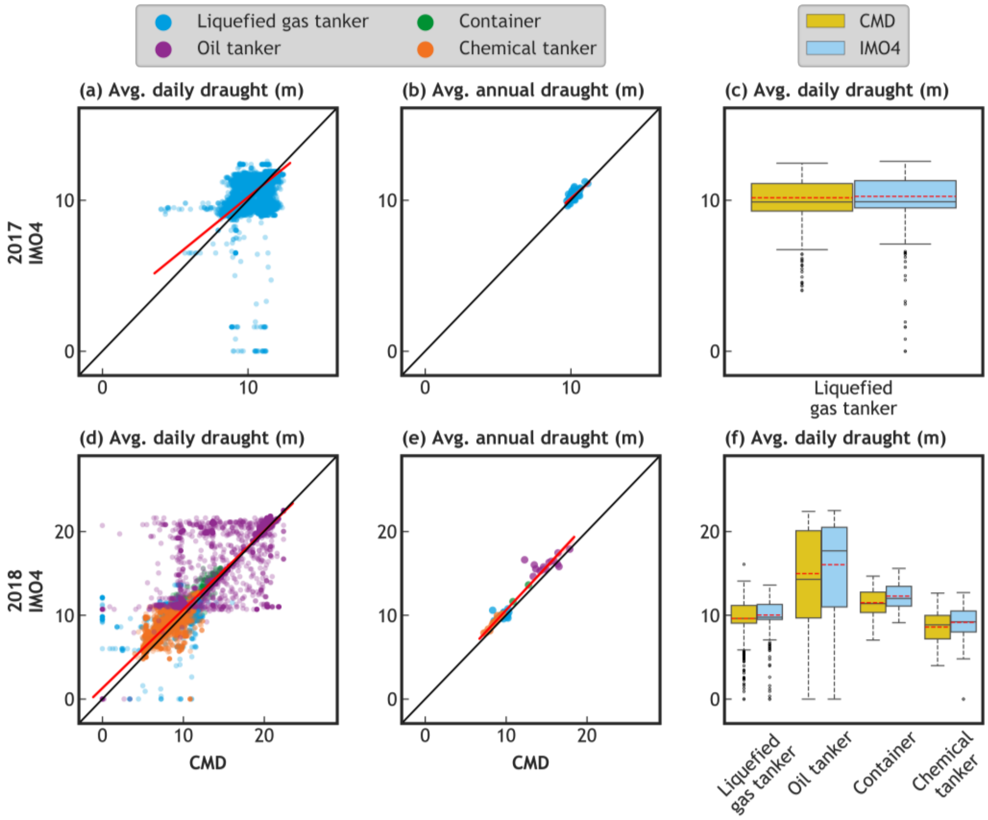
When annually averaging the daily speeds by vessel, it is seen in Figure 97 (b) and (e), that ß increases to 0.86 for the year 2017 and 1.00 in the case of the 2018 dataset, slightly overpredicting the CMD average with a narrow confidence interval and a high R^2 (as seen in Table 50). This confirms that the AIS SOG has an overall good agreement with the high-frequency speed measurements from the CMD.

Draught

The draught for the bottom-up model is taken from AIS data, which is recorded manually from tank readings on-board. This makes it prone to inaccuracies (Harati-Mokhtari, et al., 2007), 2007). On the other hand, CMD draughts are taken directly from the tank sensors, introducing inaccuracies due to sensor maintenance issues, or the CMD system being turned off.

The *β* for the daily draught difference for the data in 2017 is 0.64, with a slight variable bias that causes the model to switch from overpredicting at smaller draughts to underpredicting at around 11.0m. The variable bias seen for the 2017 draught, Figure 99 (a), has a reduced impact since the largest differences are seen for draughts that are below 8.0m, which are draughts not typically seen in liquefied gas tankers. Due to the nature of the liquefied gas in cargo, this ship type tends to have large variations in the measurement of their draught, causing the lower prediction accuracy of the linear model in Table 50 (González Gutiérrez, C. et al., 2020).

Figure 99 - Difference between the Fourth IMO GHG Study and the CMD for a) the daily draught and, b) the annually-averaged daily draught for the year and c) a box plot showing the average daily draught in 2017. The plots a) to c) present this data for 2017, whereas d) to f) present the 2018 comparison. For a), b), d) and e) the linear regression is plotted in red, whereas the red dotted lines in the boxplots represent mean value of the respective samples



For the year 2018, the slope in Figure 99 (d) was 0.87 with a smaller variable bias when compared to 2017. The linear regression model shows that the bottom-up model tends to overpredict at smaller draughts, normally seen in this comparison for chemical and liquefied tankers, with a crossover point at around 16.0m when it starts to under-predict (Figure 99 (d)). The larger draughts observed in oil carriers, and the larger spread between their laden and ballast draught, as well as a strong correlation between the bottom-up and CMD data at the smallest and largest draughts of this ship type (roughly 10.5 and 20.0m respectively) lead to the variable bias seen in 2018, as their error minimization adds more weight to the linear regression model.

From the box plots (in Figure 99 (c) and (f)), it is evident that the bottom-up model tends to quantify a similar data dispersion as observed in the CMD, with closely-matched average and median draughts. This indicates the suitability of the bottom-up model to accurately predict the ships' draughts. Oil tanker draught differences tend to be larger when the draught is between 11.0 and 19.0m (Figure 99 (d)). These differences arise mainly from the dispersion found in the bottom-up model, as shown in Figure 99 (f). However, this is not a source of concern for the accuracy of the models since the whiskers indicate that all the observations and predicted values fall within the expected confidence interval.

The linear models in Figure 99 (b) and (e) show that the bottom-up model on average tends to slightly overpredict the ships' draught, with the oil tankers showing the largest average difference. However, the percentage difference between bottom-up and CMD in the annually averaged draughts are estimated to be 6% in 2018 and <2% in 2017 based on their median, as can also be observed in Figure 99 (c) and (f). This indicates that whilst estimates can be of a lower accuracy for short periods, they improve with the period average. For an inventory which is focused on the accuracy of aggregated annual parameters, this provides a key indicator of quality.

Moreover, the differences in draughts would not significantly affect the power estimation. By referencing the Admiralty equation, the 0.66 exponential factor for the draught reduces the differences between the bottom-up model and CMD even further. In other words, the influence of the draught error is reduced when the power is calculated. The consequences of draught error to calculations of cargo mass will be slightly larger than the consequences to power and emissions accuracy.

Main engine power

For the year 2017 in Figure 100 (a), the linear regression model shows that the bottom-up model tends to slightly overestimate the main engine (ME) power output at low powers. The model shows that there is a small variable bias which causes the bottom-up model to start overpredicting at higher ME power outputs of 25,000 kW. From Figure 100 (c) it is shown that the bottom-up model closely follows the CMD with similar box heights, means, and medians, but with some power overprediction at the upper extreme. This indicates the strong calculation capabilities of the bottom-up model for liquefied gas tankers.

For the year 2018 Figure 100 (d) shows for all ship types that the bottom-up model tends to more severely overpredict the ME power output as it increases. This is further illustrated in Figure 100 (c) where all bottom-up box heights, mean, median and upper whiskers are larger than those observed from the CMD. From the daily analyses of speed and draught, the bottom-up model showed a strong agreement with the data recorded by the CMD with speed, in general, being slightly underpredicted (Figure 99 (b) and (e)) and draught slightly overpredicted (Figure 99 (c) and (f)). Looking again at the Admiralty equation used in the bottom-up method, the difference in draughts between the bottom-up model and the CMD will not have a relevant impact on the ME power calculation. Further, the bottom-up model tends to under-predict the ship's speed which will have a small reductive effect, due to the slight difference of the ME power output. However, another plausible explanation could be that the higher than expected modelled shaft power is caused by a potential mismatch between the reference ME power and reference speed taken from IHS database. It is assumed that the IHS speed is the ship's maximum speed at 100% ME MCR, except for cruise ships and certain sizes of containers.

To test this on the sample cases, daily averaged observations were plotted against the daily averaged shaft power to generate their speed-power curve and capture the shaft power at which the curve reaches the reference speed reported in the IHS database.

Figure 101 illustrates that the majority of the ME MCR values at which the reference speed is reached occurs between the 60 and 100% ME MCR bins, with an average around the 80% MCR. This mismatch between the CMD and the bottom-up model assumption explains the overprediction seen in Figure 100, which is more prominent for oil and liquefied gas tankers that were found between the 60 and 80% MCR for the year 2018. Further, the liquefied gas tankers observed in 2017 were observed to have their reference speed at above 80% MCR, allowing for a better match with the CMD values seen in Figure 100 (c).

It is important to note that the number of CMD ships is small, and what is shown in Figure 101 may not be representative of the entire fleet. The consortium raised this point with IHS and was informed that by 2018 the majority of the reported speeds in the input dataset were maximum speeds given at 100% ME MCR. This is consistent with the assumption applied in the bottom-up model. This information was further tested and confirmed with the MRV dataset shown in the following section, providing further evidence that this CMD is less well-represented than the average ships and the data and methods employed in the bottom-up model.

Figure 100 - Difference between the Fourth IMO GHG Study and the CMD for a) the observed ME power output and, b) the annually-averaged ME power output and c) a box plots showing the observed ME power output in 2017. The plots a) to c) present this data for 2017, whereas d) to f) present the 2018 comparison. For a), b), d) and e) the linear regression is plotted in red, whereas the red dotted lines in the boxplots represent mean value of the respective samples

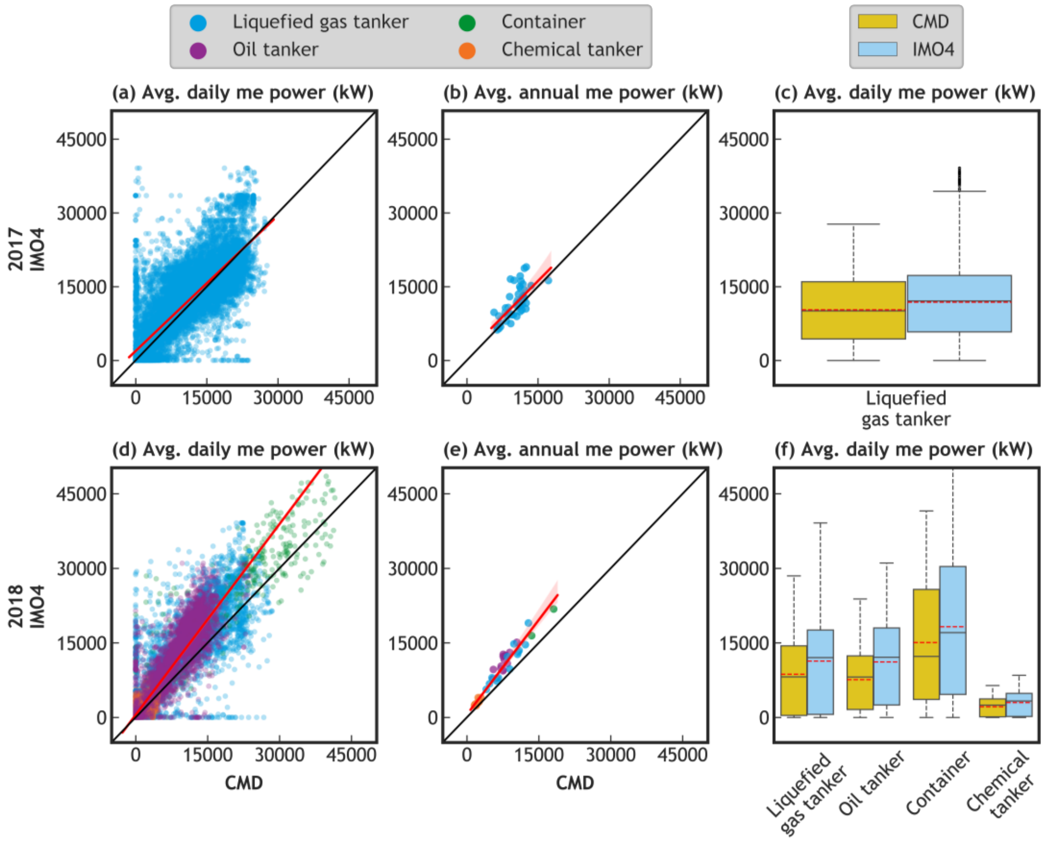
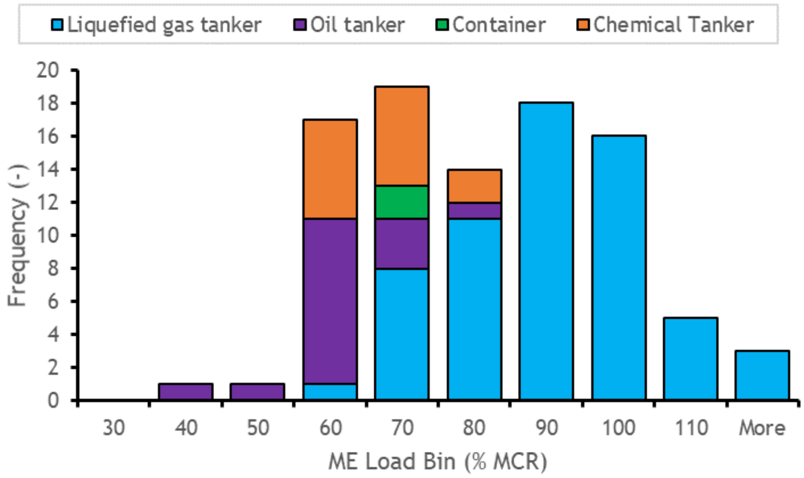


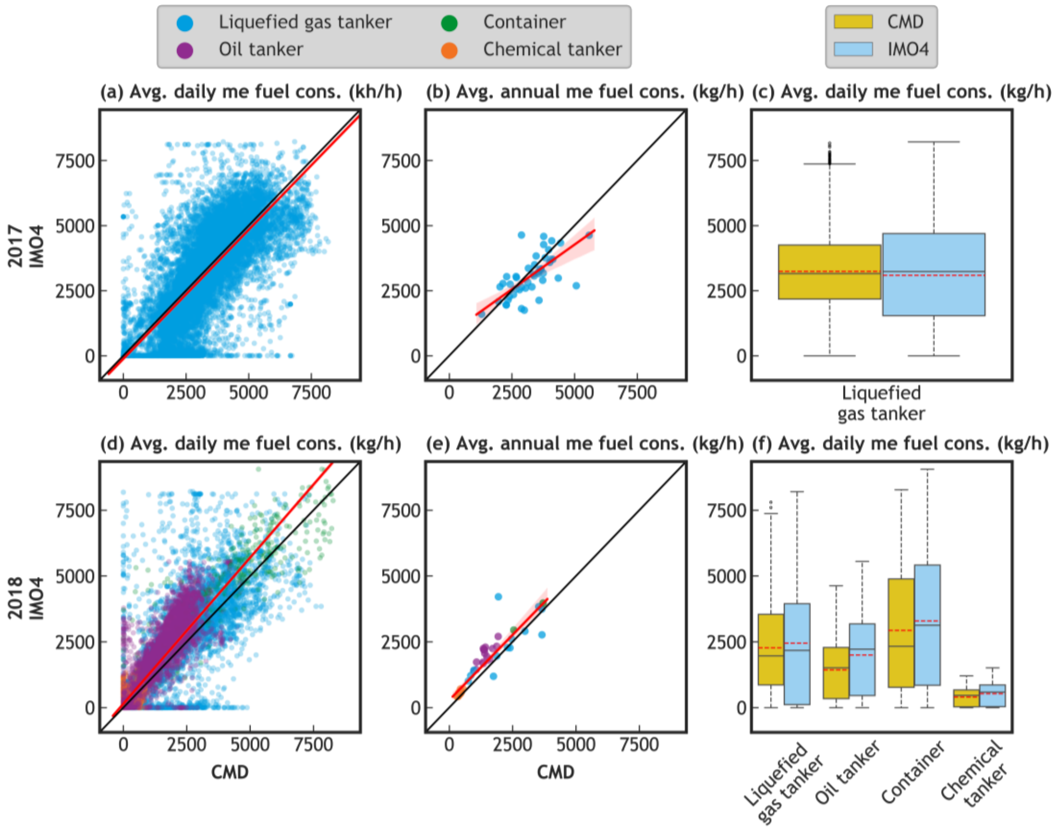
Figure 101 - Frequency plot of the ME percentage MCR by ship type at which the reference speed is reached, as observed from the CMD



Main engine fuel consumption

It is seen from Figure 101 and Figure 102 (a, c, d and f) that the bottom-up FOC model closely follows the ME power model behavior, evidencing the quality of the bottom-up model in calculating FOC. For the year 2017 in Figure 102 (a), the bottom-up model results slightly underestimate the FOC with an almost constant bias equal to the linear regression intercept of 49 kg/h. From Figure 102 (b) it is seen that the median and mean from both the bottom-up model and CMD are similar to the bottom-up results, though with a larger spread caused at the top by the ME power upper datum from the box plot, while at the lower end caused by the SFC being lower in the bottom-up model than in the CMD. This small difference is expected since the CMD will be capturing the SFC degradation which was outside the scope of the bottom-up model. Nevertheless, the box plot indicates a good agreement between the bottom-up model and the CMD.

Figure 102 - Difference between the Fourth IMO GHG Study and the CMD for a) the daily-averaged hourly ME fuel consumption, b) the annually-averaged hourly ME fuel consumption and, c) a box plot of the daily-averaged hourly ME fuel consumption in 2017. The plots a) to c) present this data for 2017, whereas d) to f) present the 2018 comparison. For a), b), d) and e) the linear regression is plotted in red, whereas the red dotted lines in the boxplots represent mean value of the respective samples



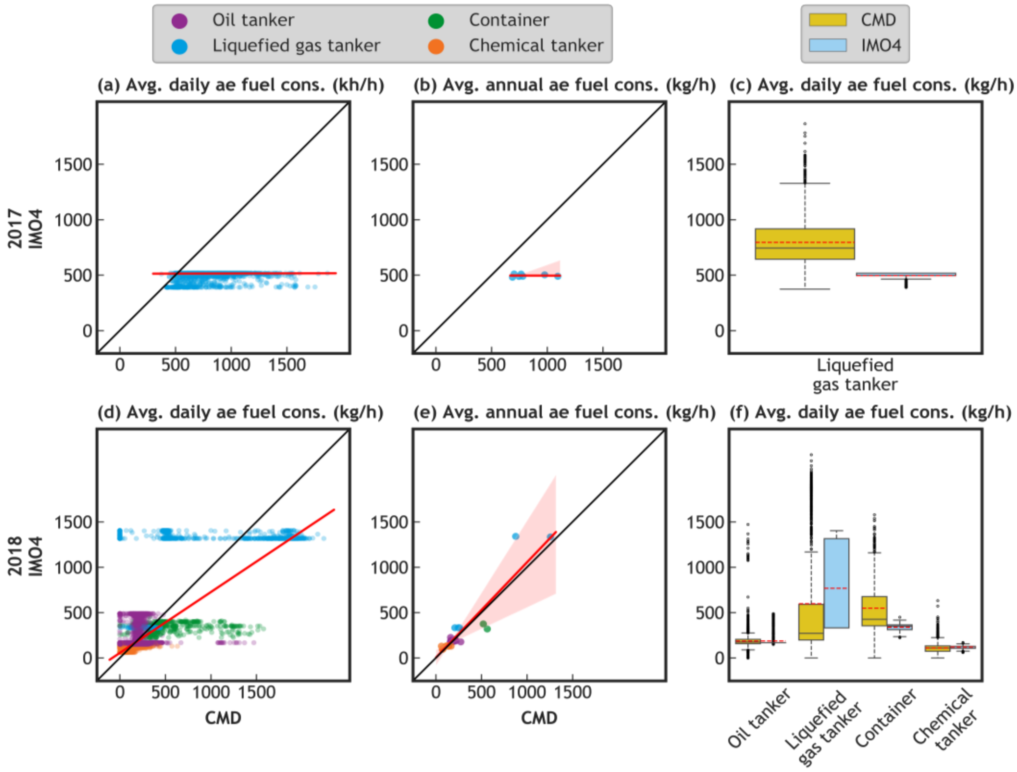
In the case of the 2018 comparison in Figure 102 (d), the bottom-up model slightly overestimates fuel consumption at low FOC while the difference increases with FOC. This is observed in the linear regression with a *β* of 1.01 and an *α* of 295 kg/h. From Figure 102 (f) it is seen that the same behaviour for liquefied gas tankers, where the bottom-up model has a larger spread but similar medians and means. For oil tankers and containers, the bottom-up model shows a larger spread in the upper box quartile, caused mainly by the larger ME power prediction. However, the distances between mean and median tend to stay at a similar distance. For chemical tankers, the differences in FOC follows the behaviour seen for its ME power comparison. The bottom-up model FOC behaviour, when compared to the ME power calculation, indicates the general adequacy of the assumed SFC and the generic SFC curve for this work. This was an important factor to quantify because the generic assumed SFC curve does not consider different engine models, tunings, compression ratios, and engine degradation which could introduce important differences with real performance data.

With regards to the annually-averaged hourly FOC, it is seen that the 2017 comparison Figure 102 (b) has a much larger variable bias than in the daily-averaged FOC, caused by the liquefied gas tankers that tend to have a constant fuel-mix consumption (i.e. they always consume two or more fuels in the same hour). This is a characteristic that is not modelled in the bottom-up model due to the complexity and the level of uncertainty it could introduce into the global inventories. For the year 2018, the bottom-up model slightly overpredicts the hourly FOC with a *β* of 0.97 with a bias almost constant and similar to *α* which is given around 355kg/h. In Figure 102 (b) and (e), an increasing range in the confidence interval is seen as FOC increases, relating to the large dispersion in Figure 102 (a) and (d).

Auxiliary engine fuel consumption

The daily-averaged hourly AE fuel consumption has the largest overall difference with the CMD in the bottom-up model results. However, because AE fuel comprises a smaller proportion of total fuel consumption than ME fuel, the impact to overall accuracy is relatively small. In general, the linear model under-predicts the fuel consumption with an R^2 of 0.06 for 2017 and 0.70 for 2018 (Figure 103 and Table 50). The large scatter seen from liquefied gas tankers (Figures 103 (a) and (d)), which tend to provide their auxiliary power through a mix of turbo-generators and diesel gen-sets (González Gutiérrez, C. et al., 2020) that are not captured by the bottom-up model, reduces the linear regression model's R^2. However, the largest root cause for the difference is how the AE power generation is modelled by operational mode. This limits the bottom-up model's ability to capture in-detail the more dynamic behavior of the auxiliary machinery. The behavior is seen in Figure 103 (a) where the bottom-up model's AE power calculation stays around 400 kW while the CMD captures a range between 400 kW and 1700 kW. This is further exemplified by the box plot in Figure 103 (c) where the bottom-up model's height is small, and in Figure 103 (b) and Table 50 where *α* stays relatively constant at around 350 kg/h. As discussed in previous sections and in past IMO GHG Studies, AEs are particularly difficult to model due to a lack of relevant information available in datasets, but also due to their operational diversity. This can be seen in the number of outliers in the CMD observations (Figures 103 (c) and (f)) and the increments in the confidence interval seen in Figure 103 (e).

Figure 103 - Difference between the Fourth IMO GHG Study and the CMD for a) the daily-averaged hourly AE fuel consumption and, b) the annually-averaged hourly AE fuel consumption and c) a box plots the daily-averaged hourly AE fuel consumption in 2017. The plots a) to c) present this data for 2017, whereas d) to f) present the 2018 comparison. For a), b), d) and e) the linear regression is plotted in red, whereas the red dotted lines in the boxplots represent mean value of the respective samples.



While it was not possible to obtain CMD for the auxiliary boiler system, it is expected that the results from the bottom-up model will display a similar behaviour and uncertainty as the AE system.

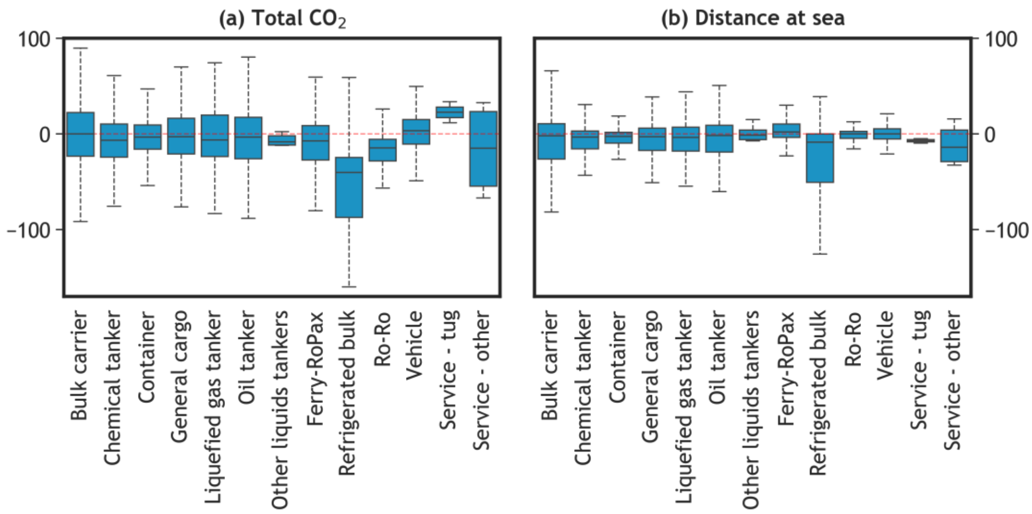
Comparison with EU MRV (Monitoring, Reporting and Verification)

Through the European Commission's (EC) MRV scheme (EU, 2015) the largest publicly-available measured and independently verified vessel performance dataset has been created. Although it has some limitations, the dataset is the most comprehensive and specifically targeted to evaluate fuel consumption and carbon intensity related to maritime trade, providing an ideal source for validating bottom-up estimates. The 2018 dataset available in this scheme has been used for validation.

Principal parameters including distance travelled at sea and CO_2 emissions are in general well correlated. The CO_2 and distance travelled at sea estimates across the entire fleet covered by MRV are overestimated by 5.5 and 4.7% respectively. However, when looking at the CO_2

emissions for three major vessel types, as shown in Figure 104, the differences vary, for example for bulk carriers the error is -0.2%, for container vessels 6%, and for oil tankers 3%. These vessel types contribute to over 65% of the international CO_2 emissions in 2018 and so are representative of global international shipping. For vessel types, where a poorer agreement of more than 10% deviation is observed, the overall effect on the overall inventory accuracy is rather marginal as their contribution to the international CO_2 emissions is no more than 3%. Therefore, a good agreement between the bottom-up estimations with the MRV dataset indicates a high-quality standard of the bottom-up CO_2 estimations and other relevant metrics.

Figure 104 - Variability in error in (a) total CO_2 and (b) distance at sea agreement between this study's estimates and MRV data 2018



MRV data matching and filtering

The European Union has set up an MRV system for vessels operating to, from, and between ports located in the European Economic Area, when transporting goods or passengers for commercial purposes. The first reporting year took place in 2018. Companies are required to monitor data at a voyage level including CO_2 emissions, fuel consumption, cargo transported, and distance sailed, as well as other relevant information about the technical and operational energy efficiency of their ship. Each year, companies submit verified aggregated data to the European Commission and to the authorities of the flag State concerned in the form of an emission report. Subsequently, the European Commission publishes all CO_2 emissions data and relevant information on the public section of the THETIS-MRV website. The published database provides a large body of measured and verified CO_2 emissions data across a variety of vessel types. Validation was carried out using version 179 of the 2018 EU MRV dataset (downloaded on 02/04/2020).

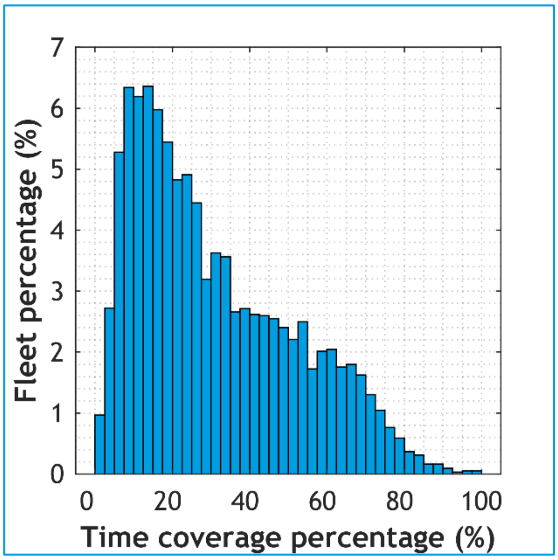
Because the MRV data set only covers voyages that interact with EEA ports, the time spent at sea reported by most vessels is less than the entire year (Figure 105). To allow for an accurate deployment of this data for verification and quality assurance purposes, an analogous dataset was created from the bottom-up method for like-for-like comparison to be made over 2018. This was possible by using the output from the voyage detection algorithm to identify voyages that interacted with EEA ports. Thus, the validation in this section is carried out with bottom-up data that overlaps directly with the MRV data for each vessel identified.

The sample includes data for over 11,000 vessels which, following basic filtering for the purposes of this study (Table 51), was reduced to 9,739 vessels (81.4% of the original MRV dataset). This accounts for around 10% of the world's fleet or more than 30% of the world's fleet over 5000 gross tonnage, making this measured and verified dataset a highly valuable resource for the validation of the results of this study. The reduction in dataset size is not a reflection of the MRV data quality but stems from the retention of the metrics of interest (e.g. transport expressed in t.nm).

Table 51 – MRV dataset filtering

Variable	Dataset	Lower Limit	Upper Limit
Sailing hours at sea	MRV, IMO4	0	8760
EEOI	MRV, IMO4	0	1,000

Figure 105 - EU MRV 2018 dataset coverage



CO_2 emissions estimate quality

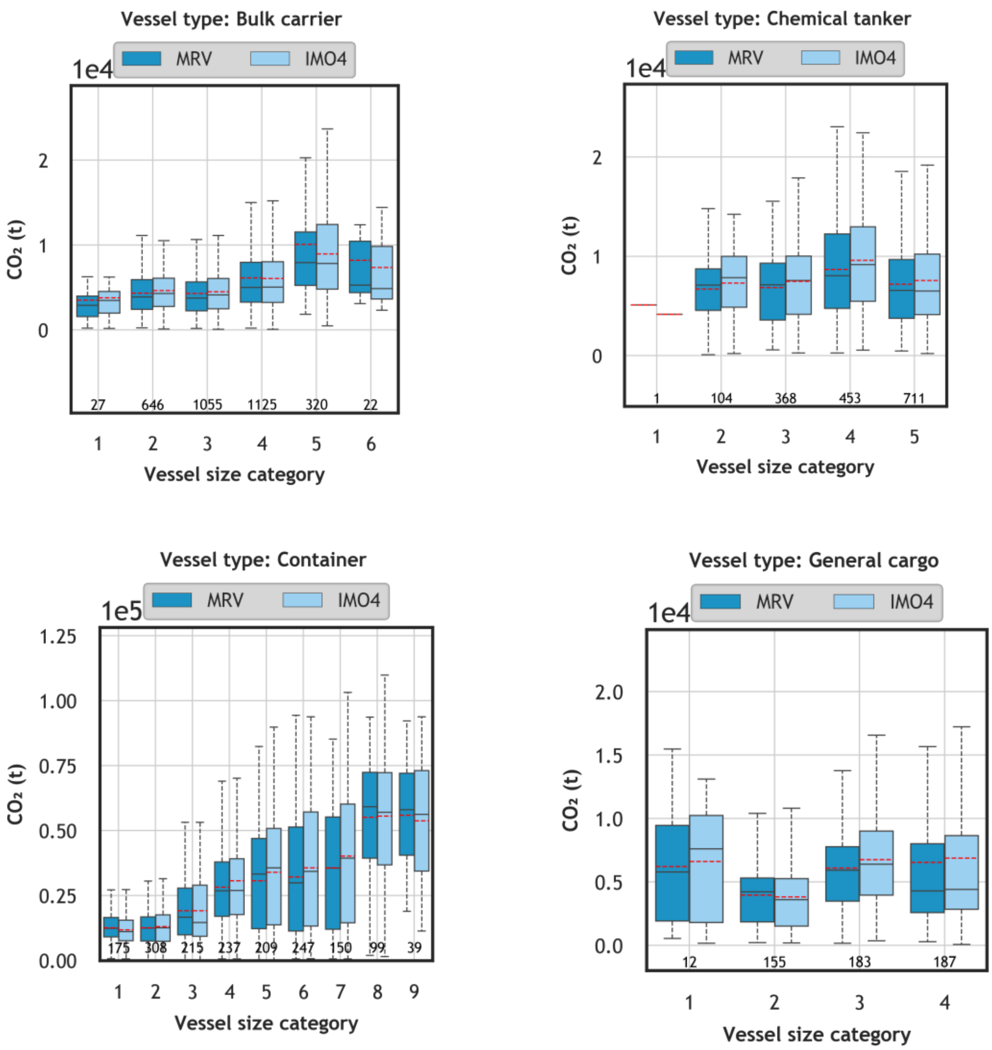
The boxplots in Figure 106 present the statistical equivalence between the CO_2 emissions estimated by the BU model data during operational periods covered by the EU MRV data for the matched vessels by type and size (outliers are removed for clarity of presentation). For this comparison, the BU data included accounts for CO_2 emissions as per EU MRV regulation, which clarifies that:

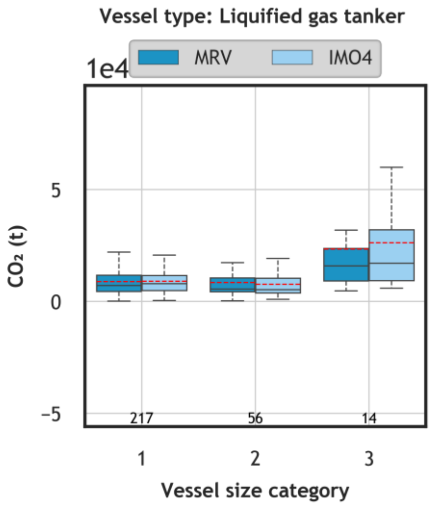
> *"monitoring and reporting shall be complete and cover CO_2 emissions from the combustion of fuels, while the ships are at sea as well as at berth" (Article 4, Regulation (EU) 2015/757)*

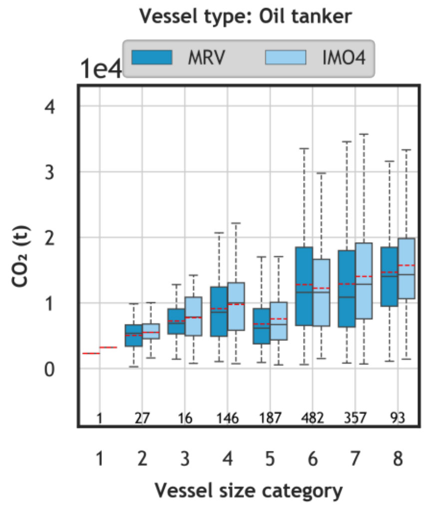
Thus, CO_2 emissions while berthing and from all machinery (main engine, auxiliary engine, and boiler) are included, but only from voyages under the MRV regulation. These graphical comparisons show that CO_2 emissions consistently have a good agreement and that the bottom-up model's outputs are of high quality, because:

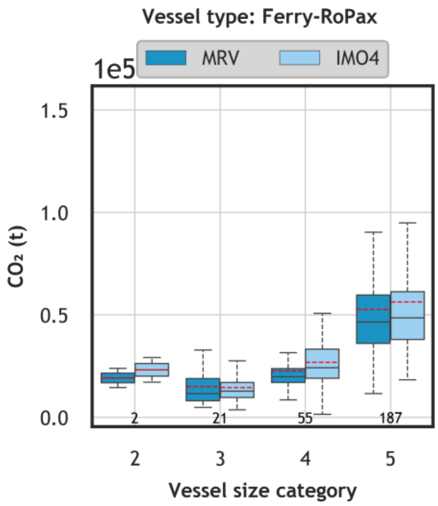
- Consistent agreement on the median values of CO_2 emissions across ship types and sizes is observed.
- Consistent similarities in range (variability) as shown by the similarities in the interquartile range and whiskers.

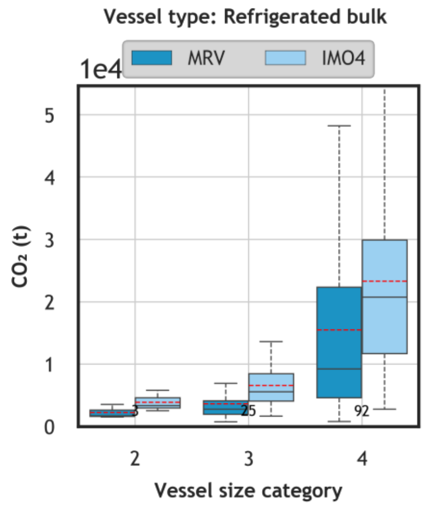
Figure 106 - CO_2 emissions estimate comparison by ship type and size

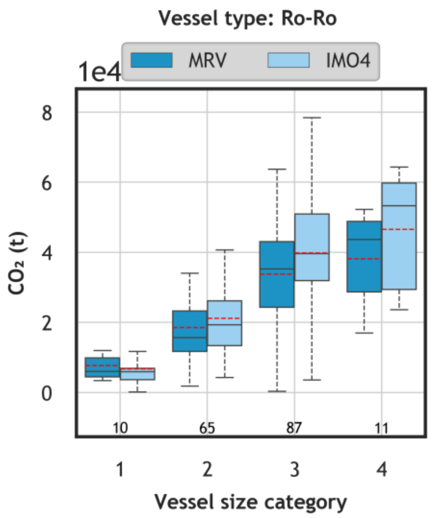


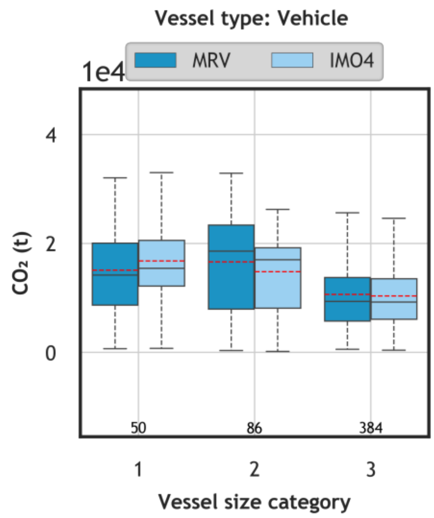

Vessel type: Liquified gas tanker
MRV
IMO4
1e4
5
0
−5
217
56
14
1
2
3
CO₂ (t)
Vessel size category


Vessel type: Oil tanker
MRV
IMO4
1e4
4
3
2
1
0
1
27
16
146
187
482
357
93
1
2
3
4
5
6
7
8
CO₂ (t)
Vessel size category


Vessel type: Ferry-RoPax
MRV
IMO4
1e5
1.5
1.0
0.5
0.0
2
21
55
187
2
3
4
5
CO₂ (t)
Vessel size category


Vessel type: Refrigerated bulk
MRV
IMO4
1e4
5
4
3
2
1
0
3
25
92
2
3
4
CO₂ (t)
Vessel size category


Vessel type: Ro-Ro
MRV
IMO4
1e4
8
6
4
2
0
10
65
87
11
1
2
3
4
CO₂ (t)
Vessel size category


Vessel type: Vehicle
MRV
IMO4
1e4
4
2
0
50
86
384
1
2
3
CO₂ (t)
Vessel size category

The box and whisker plots presented on **Figure 106** display the interquartile range as well as the minimum and maximum values are a function of the interquartile range, applying a 1.5 factor.

There are examples where the CO_2 fit is of poorer quality, but this is consistent with expectations based on the method used, which is focused on producing good accuracy for the fleets with the largest contribution to the emissions inventory. This necessarily requires some generalization of the technical and operational specifics for some of the ship types and sizes less significant to overall emissions. This is particularly seen for Ro-Ro vessels and refrigerated bulkers whose CO_2 emissions are overestimated by 16 and 41.5% respectively. The most appropriate explanations of the overestimation trend for these two vessel types are as follows:

1. **Refrigerated bulk**: The cooling load on these vessels is significant, therefore assumptions of the auxiliary power required are considerable. Additionally, power take-off from the main shaft may be used to provide power rather than separate generator sets. In the current study's modelling approach, the auxiliary energy assumptions assume cooling load is not changing throughout the period of operation, which may not be accurate and elevating the fuel consumption.
2. **Ro-Ro**: These vessels tend to have a variety of propulsion systems, with diesel-electric becoming increasingly common. This is difficult to model relative to conventional propulsion layouts in the approach taken in the bottom-up model, and information in the vessel database is not sufficient for accurate representation. Assumptions regarding engine and auxiliary loading appear from these comparisons to require further refinement.

Importantly, these vessel types only account for around 3% of international CO_2 emissions hence the observed overestimation trend is not representative of the global inventory.

Distance sailed and sailing hours

A detailed comparison of distance sailed at sea and sailing hours obtained from the matched MRV and bottom-up datasets is presented in Appendix P.

- **Distance sailed at sea:** Across ship types, distance sailed at sea is well comparable in terms of medians and interquartile ranges over the different sizes. However, a small discrepancy, observed in distance, is explainable by a small systemic bias in the port-call algorithm resulting in a longer (or shorter) period of operation, depending on a vessel type, included in the AIS derived estimate of MRV activity but not relevant for ship annual activity.
- **Sailing hours:** An underestimation in sailing hours is observed due to the ambiguity around the definition of sailing time. This is because the definition of "time at sea" used in the MRV regulations is not identical to what is applied in the current study. According to the MRV, the "time at sea" is based on "port departure and arrival data and excludes anchoring", while "fuel consumption, time at sea and distance sailed shall be monitored

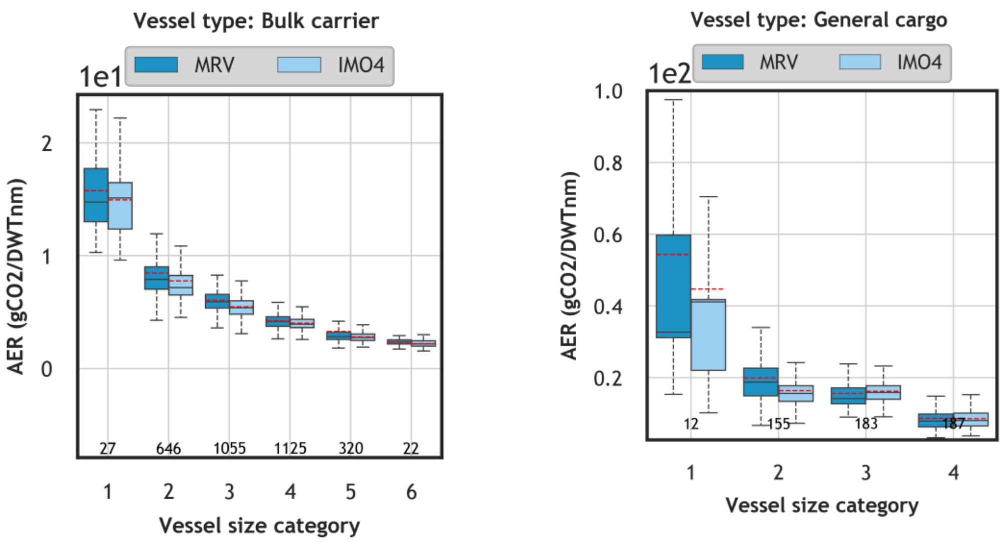
from berth to berth". However, drifting, waiting, and tank cleaning time are all considered as part of the voyage if happening prior to arrival at or after departure from the port of call, namely, "should the vessel be adrift while waiting for a berth the distance should be included as the vessel is underway". Even if the main propulsion is temporarily not required, there will be still auxiliary generators and boilers in operation" (EU, 2015). In this study, the anchoring time is strictly excluded from "time at sea", but since the "anchoring" phase is defined based on speed and distance from port, it most likely includes drifting whilst waiting for berth time. This subtle difference in "time at sea" definitions leads to underestimation of "time at sea" by 9.4% based on median time at sea, and overestimation of the TIME emissions per hour metric (gCO_2/hr) by 14%, based on the median when comparing the current study's time at sea with the MRV data.

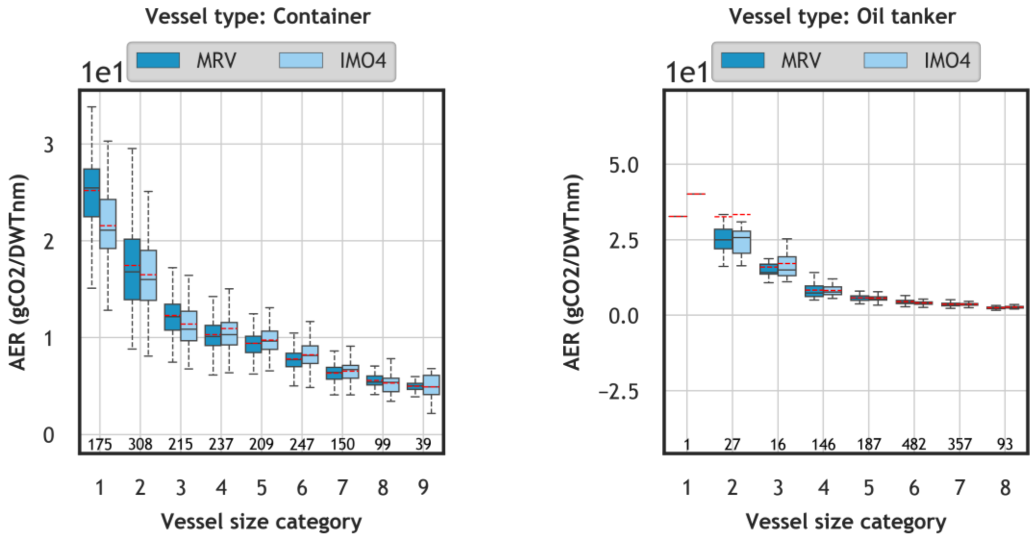
— This difference between "time at sea" definitions does not affect the distance travelled because this distance is estimated using AIS SOG which is normally very low during berth and anchoring phases.

Carbon intensity validation

Figure 107 presents box plots for the Annual Efficiency Ratio (AER, gCO_2/DWTnm). The AER correlates well with those values reported in MRV, where the discrepancy rate across the entire fleet is around 5%. This is expected as the CO_2 and distance variables are validated, and the deadweight is constant as defined by the technical specifications.

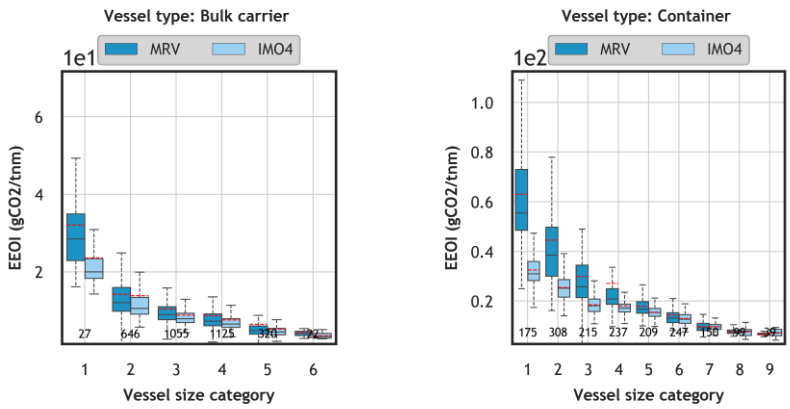
Figure 107 – AER comparison for major deep-sea cargo vessels

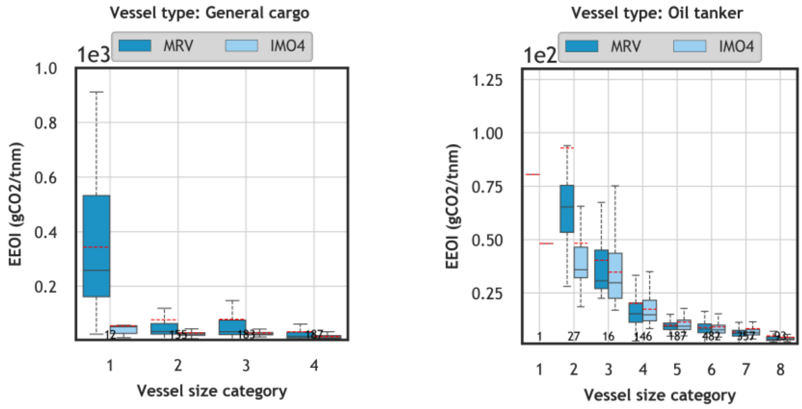




However, Figure 108 shows a systematic underestimation of carbon intensity as measured by the Energy Efficiency Operational Indicator (EEOI) for most vessel type and size categories. Since distance travelled and CO_2 emissions agree very well between the two datasets, this suggests that the explanation for this observation is the accuracy of the estimated cargo mass, namely a general overestimation of cargo masses transported.

Figure 108 - EEOI comparison for major deep-sea cargo vessels





The error in cargo estimation was found to be inversely proportional to vessel size. Error variation is larger for smaller sizes and minimal for most of the larger sizes. Thus, EEOI estimations for these larger vessel sizes are more accurate, suggesting that vessels usually engaged in international voyages are more accurately represented.

The volume of voyage cargo is not part of the publicly available MRV dataset; however, this can be derived by taking the ratio of DIST (gCO_2/nm) and EEOI, which are both provided. The EEOI (gCO_2/tnm) metric is not clearly defined for some vessel types such as Cruise, Ro-Ro, General Cargo and Ferry RoPax, whose cargo is not easily translated to a tonnage value. In these cases, the cargo is missing or only accounts for part of the load. This contributes to the wide variation in cargo estimates when compared to the bottom-up cargo estimates.

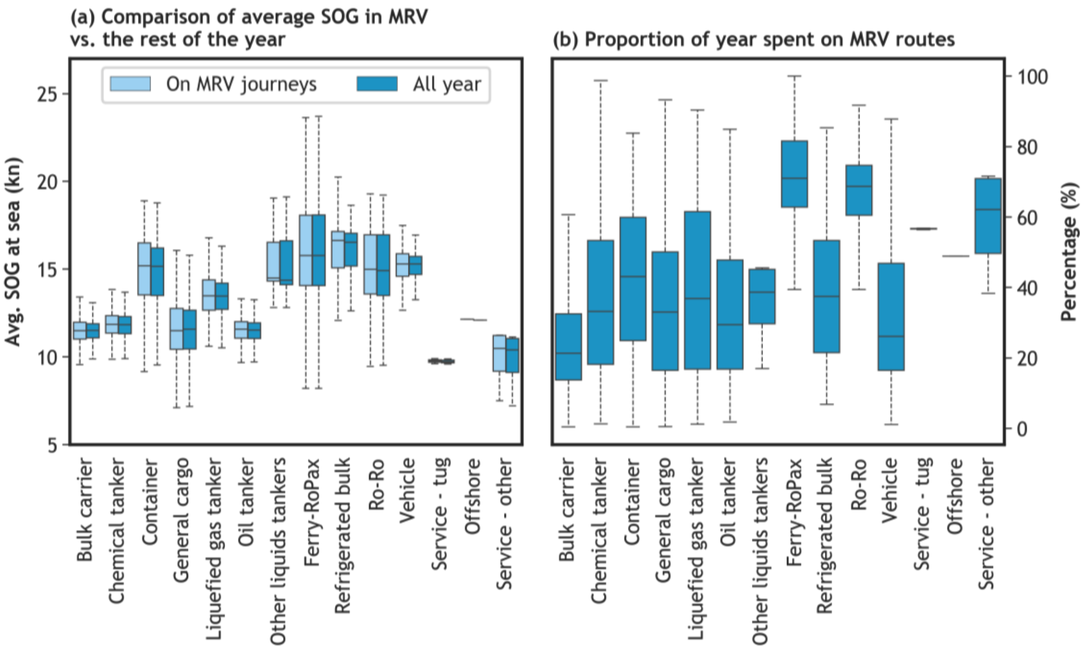
Bias and uncertainty in the MRV dataset

Given the geographical limitations to the MRV dataset, the representativeness of global shipping activity by the MRV dataset was carefully considered and tested. The investigations showed that both the operation and fleet coverage were highly representative of global equivalents and gave high confidence that the sample can be used to provide extensive insights into the quality of the bottom-up model. These investigations included:

— Whether the subset of a ship's operation as represented when interacting with European ports only was representative of the same ship's overall annual and global activity. This was to test whether the EU MRV data disproportionately captures coastal and internal trade, which is operationally different to long-haul, deep-sea voyages. A comparison of operating speeds of the vessels in the MRV dataset against their activity for the rest of the year showed that operating speeds within the time period covered by EU MRV data are very close both in terms of median value and the range of values experienced (Figure 109 (a)). This is a strong indicator that the operation documented in the MRV dataset is representative of global operation in terms of speed, one of the strongest predictors of CO_2 emissions.

— Figure 109 (b) illustrates how the MRV dataset covers a significant proportion of international fleets' annual operations, with median values ranging between 25-70% of total annual performance of the vessels included in the dataset, depending on vessel type.

Figure 109 - Key variables which describe the scope of the MRV dataset in 2018



There is also an inherent temporal limitation to the validation from this dataset, as it only covers the activity in 2018. Given the nature of the bottom-up model, the validation results based on this dataset can be assumed to apply to previous years. This is reinforced by the positive validation against the high frequency CMD in section 0.

Comparison between Third and Fourth IMO GHG Studies

As part of this study's bottom-up quality assurance and quality control, a detailed comparison is made with the Third IMO GHG Study 2014. By taking advantage of the availability of satellite AIS data to produce estimates of activity and emissions, the Third IMO GHG Study 2014's emissions inventory produced a significant advancement in methodology relative to earlier inventories. Its quality was extensively validated against data supplied by ship owners and operators, as well as long-range identification and tracking data. While the bottom-up approach in the current study is closely related to the approach used in the Third IMO GHG Study 2014, some important improvements have been implemented as discussed in Section 2.2.5. This section compares the coherency of the two bottom-up inventories for 2012, the year of overlap between the two studies, in order to evaluate whether any differences between the results can be explained by the specifics of the improvements made to the methodology of this study. This section focuses on the following key comparison metrics in the given order:

- Technical and operational indicators, including total number of ships and AIS coverage as well as vessel-type specific deadweight and installed power; and
- Fuel consumption (HFO-equivalent) and other emissions, for the whole and international fleet.

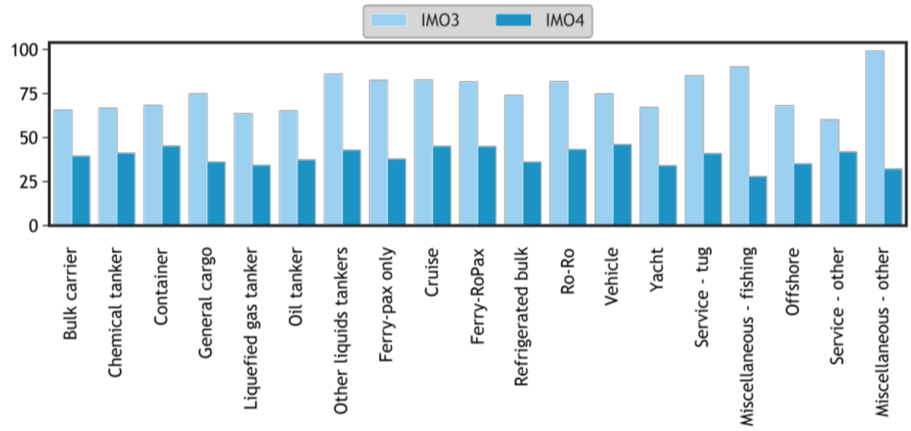
A crucial finding in this comparison is the differences in AIS coverage. This study has not been able to obtain the same quality of AIS data for 2012 as was used in the Third IMO GHG Study 2014, and is a likely explanation for the small discrepancy between the results of the two studies for that year, despite extrapolating the data temporally from May to December for the first four months of the year of 2012 as discussed in Section 2.2.3. Furthermore, the discrepancies in the comparative results can be attributed to several methodological differences specific to the manner in which the main engine, auxiliary engine and boiler fuel consumptions are estimated in this study. In combination with other components of this report's QA analysis, especially the considerable scope of analysis the MRV data has allowed this study to perform, there is evidence to justify why the 2012 results in this study diverge from those produced in the Third IMO GHG Study 2014, in addition to why there is no overall negative quality implication on this study's inventory of 2012 and the other years included in the scope of this study.

Technical and operational indicators

AIS coverage and derived parameter differences

Of all the parameters compared, the discrepancy between the two studies' AIS coverage, as highlighted in Figure 110, is the greatest. This can be explained by the fact that the Third IMO GHG Study 2014 leveraged a combination of three satellite-obtained AIS datasets, as well as four terrestrial AIS datasets. The Fourth IMO GHG Study, on the other hand, relies on only one source, namely exactEarth, an AIS data provider that supplies both satellite and terrestrial AIS signals. It is important to note that the AIS coverage for 2012 supplied for this study was an anomaly, where in addition to lower coverage, no terrestrial data was available for the first quarter of the year, and the coverage in coastal areas was sparse. The latter issue was resolved by extrapolating the data for these months, which improved coverage by approximately 10%.

Figure 110 - Comparison of Third and Fourth IMO GHG studies' AIS coverage in 2012 (%)

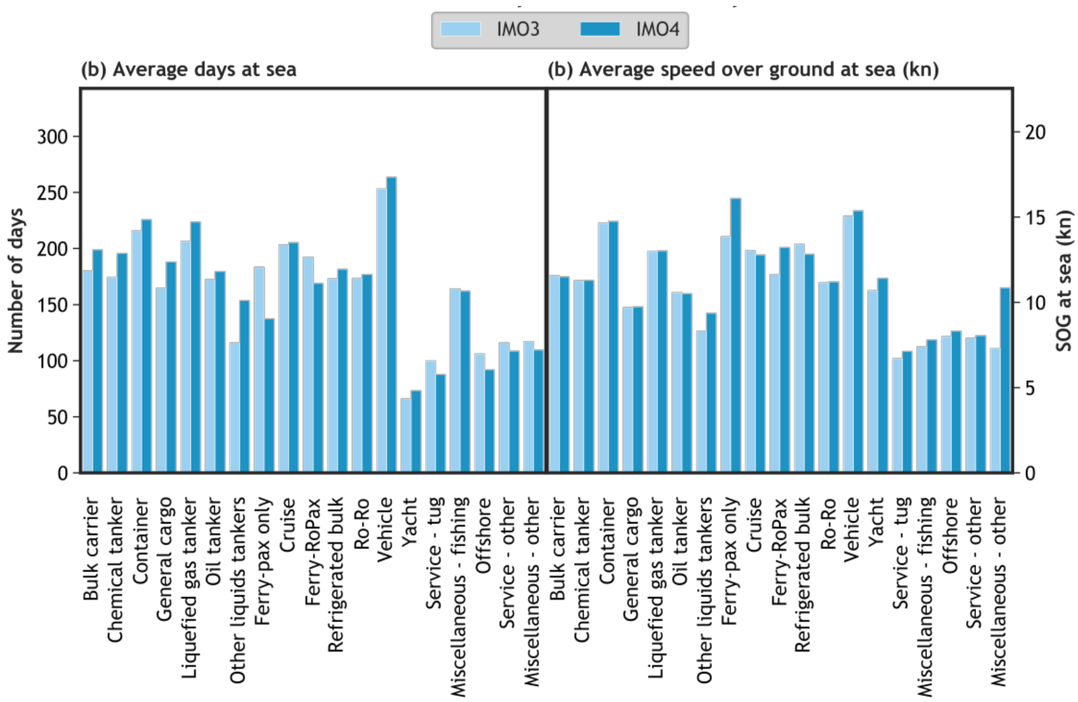


In terms of its impact on AIS-derived operational parameters, a discrepancy in the average number of days spent at sea per vessel type is observed, where this study estimates a higher proportion of the year spent at sea for most vessel types (see Figure 111). With the exception of ferries and domestic vessels, average days spent at sea are consistently lower in the Third IMO GHG Study 2014. While a difference in coverage is the predominant cause, its effect may be further exacerbated due to changes in phase assignment criteria, as explained in Section 2.2.5. This study's phase assignment methodology also considers proximity to port and coast when assigning a vessel's phase to one of 'at berth', 'at anchorage', and 'maneuvering', in addition to the vessel's main engine load factor and SOG, the two indicators used in the Third IMO GHG Study 2014. This could result in an increased proportion of hours at sea, because those hours, which under the Third IMO GHG Study 2014's phase assignment may have been classified as 'at port' are now classified as 'at sea', as they occurred over five nautical miles from the nearest coastline.

While the comparison of days spent at sea shows a visible discrepancy due to a difference in AIS coverage, as well as methodological changes, the difference in mean SOG at sea, where SOG is a key parameter to which emissions inventories are highly sensitive, is much smaller for many of the more relevant vessel types, particularly those that contribute significantly to the international emissions inventory (see Figure 111).

A comparison of average SOG at sea for both studies, as illustrated in Figure 111 across ship types, is mostly consistent with the exceptions of the more domestically active ferries, yachts, other liquid tankers, and miscellaneous vessels.

Figure 111 - Comparison between the Third and Fourth IMO GHG Studies' (a) average days at sea and (b) average speed over ground at sea

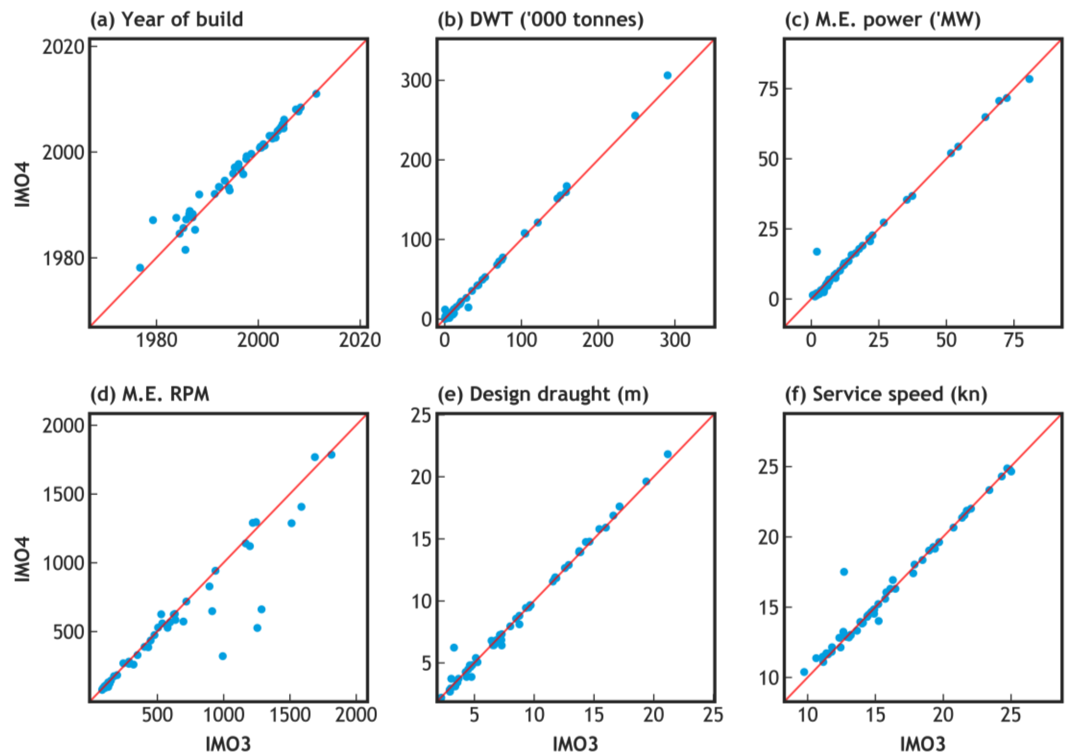


The global fleet and its technical specifications

To reflect the changes observed in the global fleet over the past decade, this study has re-classified certain size categories to take into account the observed trends in the distribution of vessel types and sizes (see Section 2.2.5). In this section, the original vessel-type specific size categories are applied in order to compare the observed fleet in both studies. While both studies use the same source for their vessel-specific technical specifications through the IHS database, this dataset itself has been modified and updated. As shown in Figure 111, both studies have a similar number of Type 1 and Type 2 vessels per vessel type. The Type 3 and Type 4 vessels have been excluded from this comparison as the counts are not presented separately in the Third IMO GHG Study 2014 report. Comparing Type 1 and Type 2 vessel counts for the most significant vessel types, only a marginal difference can be seen. However, there is a more pronounced deviation for miscellaneous — fishing, service — tugs, and offshore vessels, and marginally for bulk carriers. These discrepancies can be explained by two potential reasons, a) a difference in the AIS data sources which potentially contributed to a slight increase in the number of IHS vessels matched with AIS vessels in this study, and b) in the case of service — tug and offshore vessels, there is a possible mismatch in the type bin allocation procedure between the two studies given that it has been updated in this study to align with the new ship coding system as described in Section 0. However, given that these are mainly small vessels, the impact on the inventories is expected to be small.

To further understand what impact IHS modifications may have had within the bottom-up model, Figure 112 compares average vessel characteristics by ship type and size for vessels included in each of the inventories, as well as their respective IHS database for vessel Types 1, 2 and 4. The scatterplots compare average (a) year of build, (b) deadweight tonnage, (c) main engine power, (d) main engine revs per minute, (e) design draught, and (f) service speed per ship type and size category, where the diagonal slope represents a perfect match between the two datasets.
When comparing vessel type and size, the specific average indicators median year of built (Figure 112 (a)) , mean deadweight (Figure 112 (b)), mean engine power (Figure 112 (c)), and mean reference draught (Figure 112 (e)) are consistent for both studies across ships types and sizes. Finally, engine RPMs (Figure 112 (d)) and design speeds (Figure 112 (f)) also show a good matching with a few exceptions caused by the categories affected by changes in classification mapping.

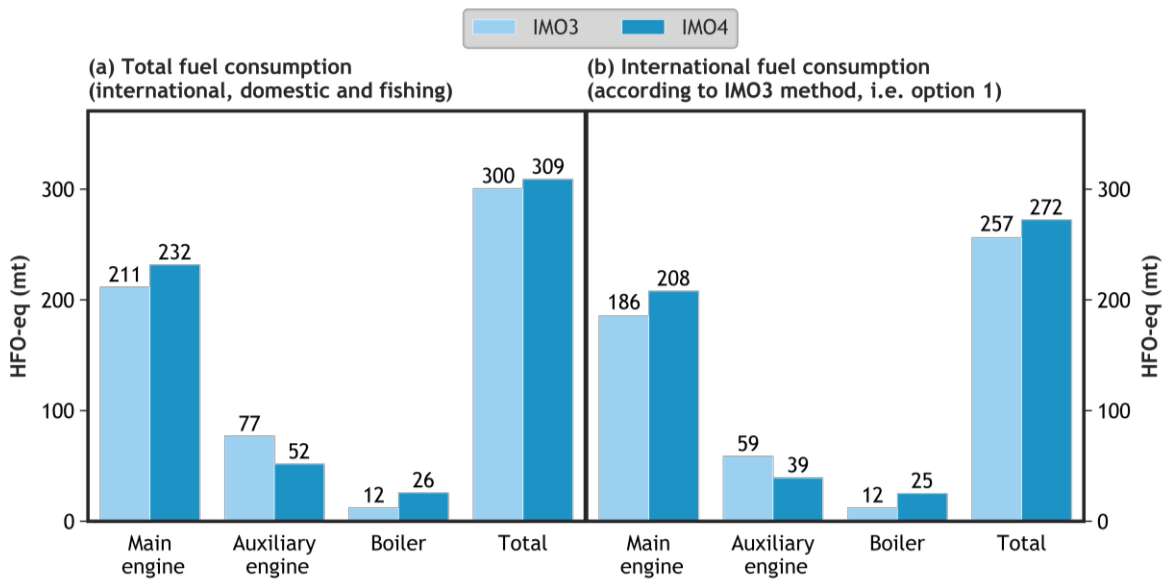
Figure 112 - Comparison between the Third and Fourth IMO GHG Studies' vessel-type and size specific technical indicators, averaged by size and type vessel



Fuel consumption and CO_2 emissions

Because of the very close relationship between fuel consumption and CO_2 emissions the discussion on the discrepancies between the two studies and their explanation applies to both fuel consumption and CO_2 emission estimates, despite the narrative in this subsection focusing on fuel consumption alone. In terms of total fuel consumption, 300 million tonnes of HFO-equivalent fuel was estimated to be consumed in 2012 by the Third IMO GHG Study 2014. This is approximately 3% less than this study's estimate of 309 million tonnes of HFO-equivalent fuel consumption, as shown in Figure 113 (a). The difference of 9 million tonnes is composed of an increase in main engine fuel consumption and a reduction in auxiliary fuel consumption, while boiler fuel consumption has also increased. Similar differences can be seen in the results for international shipping, as shown in Figure 113 (b).

Figure 113 - Comparison between the Third and Fourth IMO GHG Studies' HFO-equivalent fuel consumption estimates in 2012, where (a) includes total fuel consumption and (b) shows only international fuel consumption, according to vessel-based allocation of international emissions (Option 1).



The explanations for these changes observed in both are similar and are provided below. One key overarching factor that affects all of these components is the small difference in the estimated days at sea, as discussed above and illustrated in Figure 111. This slight increase in days at sea results in an increased time when the main engine is in operation and contributing to a higher fuel consumption, as its proportional impact on the total fuel consumption figures is larger than the auxiliary and boiler machinery.

Increase in main engine fuel consumption:

A significant share of the overall main engine fuel consumption increase in this study can be explained by a well justified and evidenced revision to a key input assumption in the bottom-up model. This study assumes that the service speed reported in the IHS database corresponds to a power output of 100% of the main engine's MCR for all vessel types, with the exception of the two largest container sizes and cruise ships. In contrast, the Third IMO GHG Study 2014 assumed that the reported values corresponded to 90% MCR. As a result, a factor of 0.9 was applied to the Admiralty equation when estimating the main engine power. In theory this means that the estimated main engine load in this report is around 10% higher than that of the Third IMO GHG Study 2014, however the speed reported in IHS dataset used in this study contains either service speed or max speed corresponding with 100% MCR making the load factors comparison rather difficult. Further explanation on the reasoning for changing the MCR correction factor method is addressed in Sections 2.2.5 and 2.7.1.

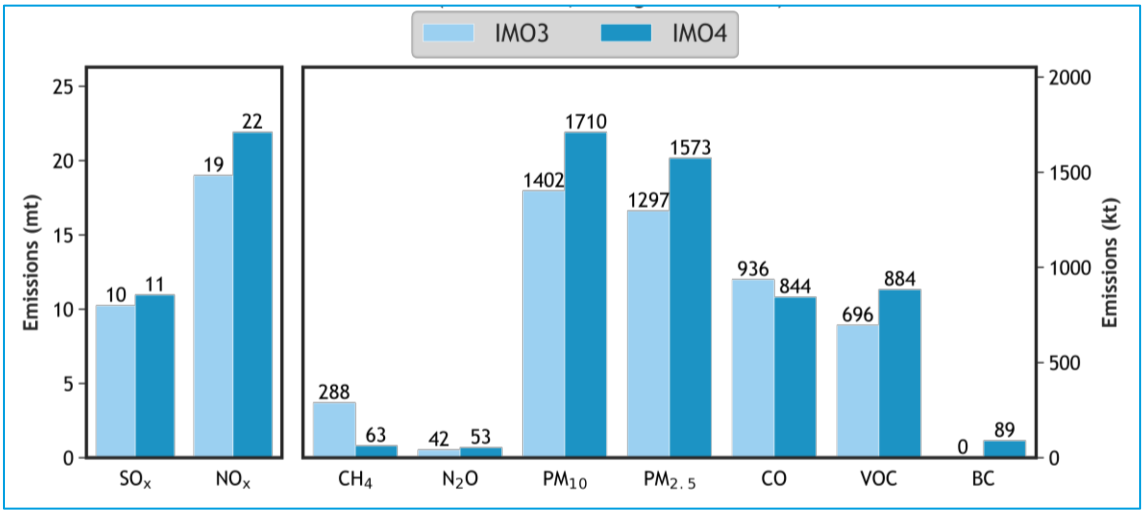
Significant differences in auxiliary engine and boiler fuel consumption: These differences are mainly associated with a) the updated auxiliary and boiler operational power demand look up table used in this study and b) improvements in the operational phase assignment methodology, both discussed in Section 2.2.5.

For many ship types, especially those requiring auxiliary and boiler power for cargo loading and unloading, the increased number of days at sea results in a reduction of the auxiliary engine's fuel consumption, *ceteris paribus*, as with the boiler fuel consumption.

All emissions species other than CO_2: black carbon (BC), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), oxides of nitrogen (NO_X), fine particles (PM_{10} and $PM_{2.5}$), sulfur oxides (SO_X) non-methane volatile organic compounds (VOC)

Figure 114 shows a comparison of total emissions for the different species covered in this study, compared with the results of the Third IMO GHG Study 2014.

Figure 114 - Comparison between the Third and Fourth IMO GHG Studies' total emissions for all species other than CO_2 in 2012



Results vary from an underestimation of 78 % for CH_4 to and overestimation of 27% for VOC. Detailed explanations for these discrepancies can be found in Appendix A. In summary:

- Some of the energy-based emission factors, the mathematical base from which emissions are estimated (see Appendix A), have been updated to reflect new research and are now considered to be more accurate.
- All pollutants were affected by omitting the 0.9 MCR correction factor in this study. This in theory, explains an approximate 10% increase of each respective total, in line with the increment observed for total fuel consumption.
- The Fourth IMO GHG Study used fuel- and energy-based emission factors depending on what pollutant was being estimated allowing for variation in load, carbon and sulfur content. In contrast, the Third IMO GHG Study 2014's converted all emission factors to fuel-based emission factors varied inversely proportional to the engine load factor (CF_L). As detailed with an example in Appendix M, this implies a varying reduction of emissions from 20% at engine loads of 10% to 1% at engine loads of 80% from the results of the Third IMO GHG Study 2014.
- This study opted not to correct the fuel-based emission factors as a result of an engine's age since the age-factor is captured already via the SFC, NO_x tiers, sulfur content per year and different machinery technologies. In contrast, the Third IMO GHG Study 2014 reduced emissions down to 90% for vessels built from 2001, 95% for vessels built between 1984 and 2000, and increased them by 5% for vessels built before 1984.
- Black carbon (BC) is one of the new contributions from the current report. As such, no results were reported in the Third IMO GHG Study 2014 to compare against.
- For methane (CH_4), this study estimates methane emissions to be 78% lower than the Third IMO GHG Study 2014. This is because, in this study, LNG-powered engines are sorted into four categories: Otto-SSD, Otto-MSD, LNG-Diesel and LBSI. In 2012, the predominant LNG

engine type was LNG-Diesel with a CH_4 base emission factor, low enough (0.002g/kWh) to render its methane emissions closer to 0. This compares with a generic methane base emission factor of 8.5 g/kWh for LNG vessels that are assumed to be Otto cycle only in the Third IMO GHG Study 2014.

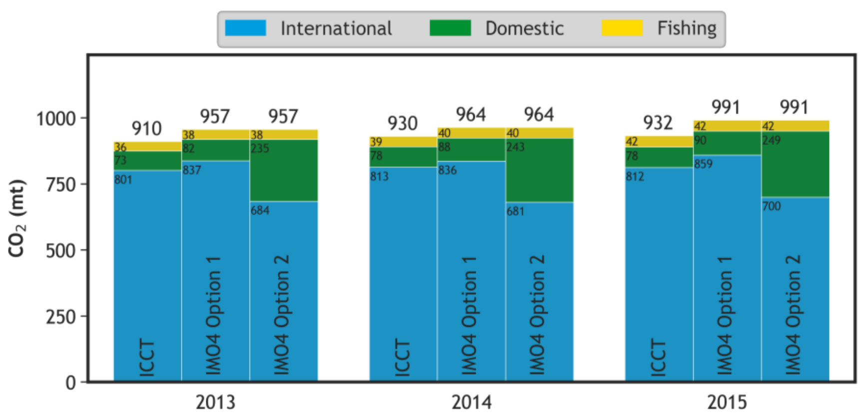
- In regards to carbon monoxide (CO), this study estimates 9% less CO emissions than the Third IMO GHG Study 2014. This is because of a change in the assumption for the CO emissions factor for gas and steam turbine vessels. While the Third IMO GHG Study 2014 used the same fuel-based emission factors of SSD engines for HFO and MDO fuels and a single value for all LNG vessels, this study allocated a specific factor, up to seven times lower, for each fuel and engine type.

Comparison with other inventories

This section compares this study's results to an independently produced model, which can provide insights in the quality of the bottom-up model applied. Overall, the results herein show good agreement when the same international/domestic allocation method is applied. Given the method differences described in previous sections, the differences are of an expected relative underestimation of international/total emissions in the ICCT inventory relative to this study's results. This is, therefore, additional confirmation of the appropriateness of this study's approach, given that its results agree well with an independent study for common years. Additional information on how to interpret and compare the results of these two studies follows.

This study overlaps with an ICCT inventory (Olmer, et al., 2017a) for the years 2013-2015. As illustrated in Figure 115, total shipping emissions estimates and trends over time are both well-aligned, although this study is consistently 4 to 6% higher than the ICCT inventory for the common years in both total and international emissions estimates, when international shipping emissions are calculated using Option 1, as explained in Section 2.2.4.

Figure 115 - Total shipping emissions for common years between ICCT and the current study



Comparing the two studies, the main difference is the share of international versus domestic shipping. In the ICCT inventory, international and domestic shipping were differentiated according to ship type and size per the Third IMO GHG Study 2014, with cargo ships operations defined as international and offshore, harbor craft, small passenger vessels, and other smaller craft operations defined as domestic. The consensus inventory for the Fourth IMO GHG Study (Option 2) took a different approach, whereby international and domestic voyages were identified based on port pairs, with a voyage between ports of different countries classified as international and a voyage between ports of the same country classified as domestic (Section 2.2.4). This approach roughly tripled the share of emissions attributed to domestic shipping. In the ship-level approach, where international and domestic shipping were determined by ship type and size, the share of emissions attributable to international or domestic shipping was similar to what had been estimated in the Third IMO GHG Study 2014 and by the ICCT.

This study estimates somewhat higher GHG emissions than the ICCT inventory published by Olmer et al. (Olmer, et al., 2017a) due to the following:

- The ICCT inventory estimates emissions only between the first observed and the last observed position for a ship in a given year, while this study assumes that each ship is emitting 8760 hours per year (except leap years), implying operations from the first of January to the thirty-first of December, even if the first AIS signal was observed in March of a given year and the last signal was observed in October of that same year. The ICCT would only estimate emissions for that ship between March and October.

- Auxiliary engine power demand assumptions: Auxiliary engine power demand for some ships, especially chemical tankers, liquefied gas tankers, oil tankers, and refrigerated bulk carriers, are assumed to be higher than in the ICCT inventory (see section 0).

- Differences in AIS processing and matching, including infilling missing technical specifications for ships; infilling speed over ground for interpolated positions when there are gaps in AIS data; and addressing situations where main engine load factors are greater than 1 (see section 0).

On average, a higher main engine power demand penalty due to hull fouling, as described in Appendix L.

Validation by hand calculations

This section discusses the hand calculations performed to ensure the bottom-up model's implementation accuracy. This exercise confirms that the model accurately estimates hourly fuel consumption and emissions with an overall error of less than 1%. For this validation exercise, a random row from the hourly model output is selected and compared against a hand-calculated process where the same input parameters are assumed, while applying an identical sequence of steps as in the computer-programed model. The decision tree and equations applied are as per the described bottom up methodology in Section 2.2.5.

This process ensured that the input parameters including SFC_{base}, AE/AB power demand, operational mode, and engine tier are defined appropriately based on the vessel's specifications and the operational profile at a given hour. For fuel consumption and emissions, a maximum error of 0.38% is obtained. This marginal discrepancy can be explained by the following:

- With the exception of NO_x, all main engine emissions estimates show an error of 0.38% from the hand-calculated emissions, which is associated with a calculation of fuel consumption. This is because the fuel consumption is estimated using a best fit line adjusted to replicate a shape of the engine load correction factor (CF_L). In this case, the approximate discrepancy between the best fit line and the hand-calculated value is 0.38% at an engine load of 62.64%. Since all emissions are the product of fuel consumption multiplied by constant values of EF_{fc}, the error is carried through all species, apart from NO_x.

- NO_x shows a lower error (-0.168%) because its fuel-based emission factor is corrected by the engine load correction factor (CF_L) in order to comply with the regulatory limits on NO_x emissions. In practice this means that the NO_x fuel-based emission factor is not constant and varies inversely proportionally to CF_L. Similar to fuel consumption, the value of EF_{fc} for NO_x used a best fitting polynomial curve with its own induced error. For this example, the curve induced errors compensate for each other and result in a difference of -0.168%.

Results for the auxiliary engine and boiler have a closer alignment with the hand-calculated value, producing a maximum discrepancy of 0.2%.

2.7.2 QA/QC analysis results in the top-down estimations

QA/QC analysis of energy data

In this section, energy statistics provided by the IEA were evaluated to check the data quality and to improve the transparency of the top-down estimation results.
The current version of World Energy Statistics provided by the IEA reported energy statistics of 150 countries/regions.

In the Third IMO GHG Study, the IEA energy statistics were compared to International Marine Bunker Fuel Oil data issued by US EIA for 2007-2010. Due to the data availability reason, the Third IMO GHG Study only compared the aggregated fuel oil consumption data in international marine bunkers sector between IEA data and EIA data.

In this section, we compare IEA energy statistics with energy statistics provided by the United Nations Statistics Division (UNSD). The UNSD started to publish world energy statistics since 2004, which covers energy data for different countries/regions from year 1997. In earlier publications of energy statistics, the UNSD did not separate detailed shipping sectors in energy balance statistics. Since 2005, however, the UNSD improved the reporting structure of energy balance statistics to cover information of more detailed sectors, and sectors such as international marine bunkers and domestic navigation are explicitly listed as separate sectors. Energy balance statistics with this new structure are available from 2011 onwards. As a result, this data source provides the great opportunities for comparison with IEA data.

Since the UNSD includes the fishing sector in “Agriculture, forestry, fishing”, it cannot be separated to conduct the comparison. However, since fuel consumption of fishing is small compared to other domestic and international navigation, this does not diminish the value of the comparison.

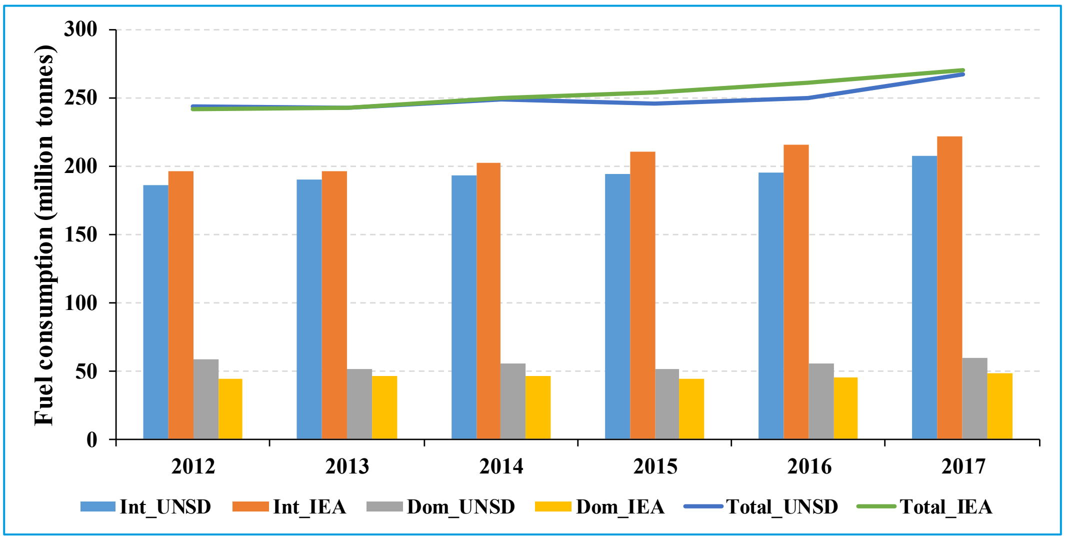
The energy balance statistics provided by the UNSD report total oil products consumption data. For the reason that fuel oil (HFO) and gas/diesel (MDO) consumption account for the majority of oil products used in shipping sectors, this sector adds up HFO and MDO consumption data in the IEA source to compare with total oil products consumption data in the UNSD source.

The QA/QC analyses cover the period 2012-2017, for each annual energy statistics, UNSD revises previous year’s energy data if more reliable data sources are available. Since energy data from UNSD for year 2017 are the latest version and thus have no revisions until next publication. As a result, this study uses the best available information to conduct the QA/QC analyses, i.e. revised data for the period 2012-2016 and data for year 2017 are used.
Table 52 and Figure 116 illustrate differences in statistical reporting between two data sources. From 2012 to 2017, the aggregated fuel consumptions in international marine bunkers reported by the UNSD are generally smaller than that reported by the IEA, while the aggregated fuel consumptions in domestic navigation reported by the UNSD are generally larger than that reported by the IEA. The net effects are largely offset so that the difference between the two data sources is a few percent at most.

Table 52 - Comparison of fuel consumption data between IEA and UNSD (million tonnes)

	Source	2012	2013	2014	2015	2016	2017
International marine bunkers	IEA	196.6	196.0	202.7	210.0	215.7	221.4
	UNSD	185.5	190.4	193.4	194.2	194.8	207.4
	Difference (%)	**-5.7%**	**-2.8%**	**-4.6%**	**-7.5%**	**-9.7%**	**-6.3%**
Domestic navigation	IEA	44.7	46.2	46.6	44.0	44.9	48.9
	UNSD	58.3	51.9	55.4	51.2	55.1	59.4
	Difference (%)	**30.6%**	**12.2%**	**18.9%**	**16.2%**	**22.7%**	**21.7%**
Total	IEA	241.3	242.2	249.3	254.0	260.5	270.3
	UNSD	243.8	242.3	248.8	245.4	249.9	266.9
	Difference (%)	**1.1%**	**0.0%**	**-0.2%**	**-3.4%**	**-4.1%**	**-1.3%**

Figure 116 - Illustration of differences between IEA and UNSD fuel consumption data



From the perspective of individual country/region, energy data of most countries/regions are similar to each other in two data sources, the significant discrepancies only exist in just a few countries/regions. Figure 117 and Figure 118 illustrate correlations of fuel consumption data of all countries/regions between two data sources using pooled data from the period 2012-2017.

Figure 117 - Correlations of international marine bunkers fuel consumption data between IEA and UNSD

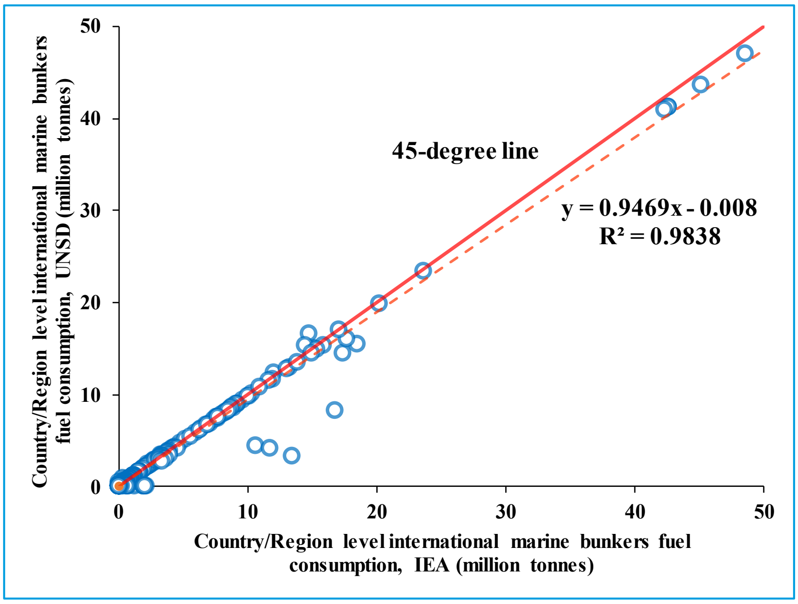
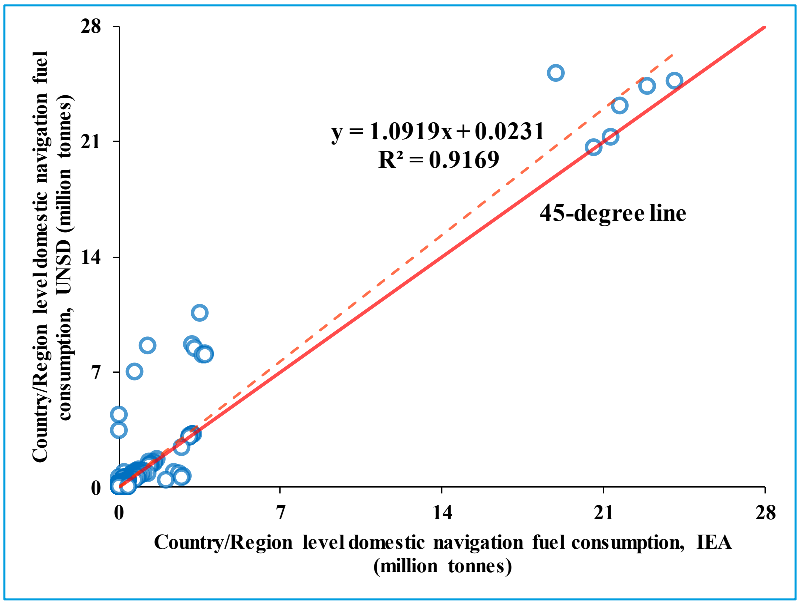


Figure 118 - Correlations of domestic navigation fuel consumption data between IEA and UNSD



Results of top-down QA/QC

The top-down QA/QC provides a thorough understanding of the quality and limitations of the top-down inventory estimates. This section uses the most up-to-date data sources provided by the UNSD, which are the most comparable data source with the IEA data, to conduct QA/QC analyses.

The comparison results indicate that the IEA tends to report more international marine bunkers fuel consumptions and less domestic navigation fuel consumptions during the period 2012-2017. However, the net effects are largely offset which leads to the aggregated fuel consumptions be quite consistent between IEA and UNSD.

Due to the difficulties in data collection and processing, there undoubtedly exists uncertainties in energy statistics. For example, misestimates of energy data could arise from allocation or classification errors and poor data qualities among reporting countries, just like the discussions given in the Third IMO GHG Study.

QA/QC analysis of fuel-based emission factors

The top-down emissions factors are based on the estimation by the bottom-up emissions and were described in Section 2.3.3. Generally, they have the same correlations to the previous GHG study presented in bottom-up emission factor Section 2.2.5. But for clarification of the emissions by top-down methodology between this study and, the emission factors used in this study has been compared with the third IMO GHG Study 2014 as the Table 53.

Table 53 - Comparison of emissions factors in this study with the Third IMO GHG study 2014 (unit of EFs: kg pollutant/tonne of fuel)

Pollutants	Fuel Type	EFs in this study	EFs in IMO GHG Study 2014	Correlation 2020/2014 EFs	Correspondence
CO_2	HFO	3,114	3,114	1.00	Good
	MDO	3,206	3,206	1.00	Good
	LNG	2,749~2,753	2,750	1.00	Good
CH_4	HFO	0.05	0.06	0.83	Moderate difference
	MDO	0.04-0.05	0.06	0.67~0.83	Moderate difference
	LNG	5.31~11.22	51.2	0.11~0.22	Significant difference
N_2O	HFO	0.17-0.18	0.16	1.06-1.12	Good
	MDO	0.18	0.15	1.2	Moderate difference
	LNG	0.08~0.10	0.11	0.73~0.91	Moderate difference
NO_x	HFO	75.90~78.61	93	0.82~0.84	Moderate difference
	MDO	52.14~57.62	87.25	0.60~0.66	Significant difference
	LNG	5.6~10.95	7.83	0.72~1.40	Significant difference
CO	HFO	2.83~2.87	2.77	1.01~1.02	Good
	MDO	2.39~2.54	2.77	0.86~0.92	Good
	LNG	1.9~3.57	7.83	0.24~0.46	Significant difference
NMVOC	HFO	3.13~3.19	3.08	1.01~1.04	Good
	MDO	2.15~2.42	3.08	0.70~0.79	Moderate difference
	LNG	0.82~1.44	3.01	0.27~0.48	Significant difference
SO_x	HFO	44.63~50.83	46.4~51.7*	0.97~0.98	Good
	MDO	1.56~2.74	2.64	0.59~1.04	Good
	LNG	0.03	0.02	1.5	Significant difference
PM	HFO	6.96~7.53	6.77-7.21*	1.02~1.04	Good
	MDO	0.92~0.97	1.02	090~0.95	Good
	LNG	0.11	0.18	0.61	Significant difference

Notes: good < 10%; moderate difference 10-25%; significant difference > 25%.

*EF changed for each year due to variable fuel sulfur content, thus the range of EFs was indicated.

In Table 53, most emission factors used for top-down estimations in this study remained within the same ranges used in the Third IMO GHG study 2014. However, some pollutant emission factors do not correlate well (va.3lues in red) between the two studies and particularly in LNG fuel type. The pollutants showing the significant difference are discussed further below:

CH_4

For CH4, new research has been conducted on emission factors by engine type. Overall, that are much lower for all engines than the static IMO GHG STUDY 2014 emission factor. In particular, unburned methane from dual fuel and steam turbine engines. Pavlenko et al. (2020) conducted an in-depth assessment of unburned methane from marine engines, which includes an exhaustive review of the literature on methane slip from different engine technologies. In IMO GHG STUDY 2014, Emissions of methane (CH4) were determined by analysis of test results reported in IVL (Cooper & Gustaffson, 2004) and MARINTEK (J.B. & Stenersen, 2010)Methane emissions factors for diesel-fuel engines, steam boilers and gas turbine are taken from IVL 2004, which states that CH4 emissions are approximately 2% magnitude of VOC. CH4 emission factors grow as the low-pressure dual-fuel 4-stroke, medium-speed LNG engines, which have the highest methane emissions, become more popular. In this study, the oil-based emission factors have not changed much. For LNG, the emission factors have dropped significantly.

NO_x

NO_x emissions are also a function of engine Tier and, for new ships that have Tier III engines, whether or not they are operating in a NECA. NO_x emission factors are a function of combustion temperature and are also be affected by after-treatment technologies such as EGR or SCR systems which may be used to comply with IMO MARPOL Annex VI Regulation 13 (IMO, 2013b). In this study, use the emissions limits in Regulation 13 as the emission factor for NO_x, which is consistent with the Third IMO GHG Study 2014 and Olmer et al. (2017a, 2017b).

CO

In IMO GHG STUDY 2014, emissions of carbon monoxide (CO) were determined by methods originally described in Sarvi (Sarvi, et al., 2008) Kristensen (2012) and IVL (Cooper & Gustaffson, 2004). In this study, the emission factors have been updated, which is consistent with the Third IMO GHG Study 2014 and Olmer et al. (2017a; 2017b). For LNG, the emission factors have dropped significantly.

NMVOC

In IMO GHG STUDY 2014, emissions factors for non-methane volatile organic compounds (NMVOC) were taken from ENTEC 2002 study and for LNG from Kristensen (2012) report. The LNG NMVOC emission factor have dropped significantly.

SO_x

SO_x emissions vary with fuel sulfur content or with the use of exhaust gas cleaning systems. SO_x emission factors for 2012-2018 are based on global average fuel sulfur content statistics from IMO, sulfur monitoring reports in accordance with resolution MEPC.192(61) and resolution MEPC.273(69) and will reflect SECAs and the EU Sulfur Directive. The fuel sulfur contents are listed in the Table 53. In this study, use the same approach as the Third IMO GHG Study 2014 and Olmer et al. (2017a; 2017b). For LNG, the emission factors have increased significantly.

PM

In this study, PM emission calculation similar to what has been done in the Third IMO GHG Study 2014 and other researchers (Olmer, et al., 2017b; Comer, et al., 2017; Starcrest Consulting Group, 2018).

2.8 Uncertainty analysis for both the bottom-up and top-down estimations

2.8.1 Uncertainty analysis of the bottom-up emissions estimations

The bottom-up modelling methodology incorporates data from a variety of derived sources, including technical specifications of individual vessels, physical relationships modelled as closed-form equations, and empirical measurements for expressing quantities such as emissions factors. The non-linearity of these embedded relationships, combined with the successive levels of aggregation applied at each step of the modelling process, implies that there is no simple relationship between the uncertainty of each individual input and the uncertainty of the final fleet-wide emissions estimates. It is common when modelling systems of this complexity to employ Monte Carlo analysis, a well-established method that generates output uncertainty estimates through the implicit characterization of the individual input and model uncertainties.

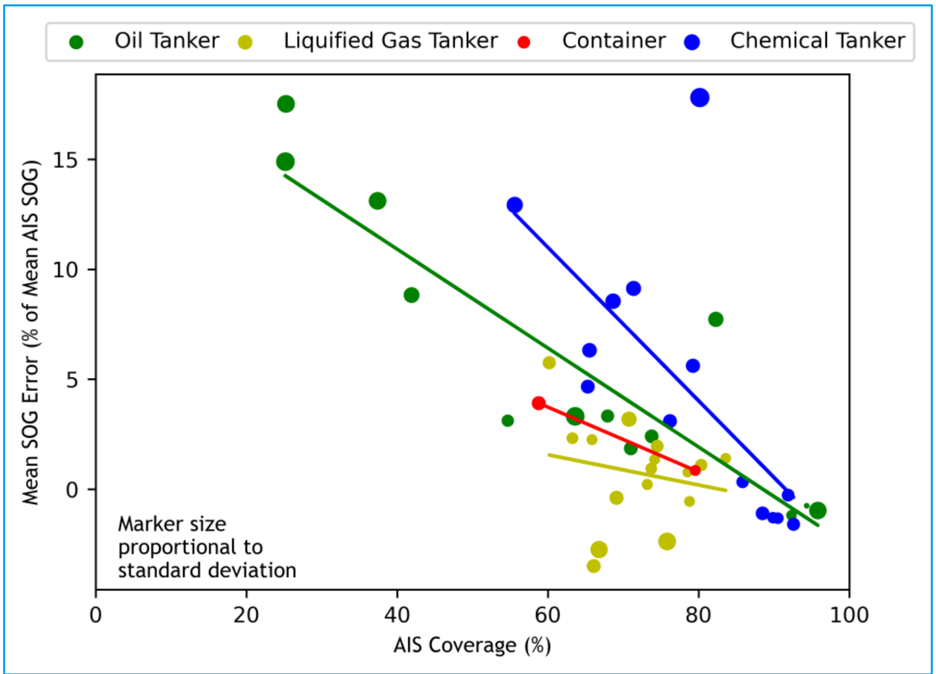
To the best of the consortium’s knowledge, the uncertainty analysis methodology presented in Annex 5 of the Third IMO GHG Study 2014 remains state-of-the-art, and is therefore applied largely unchanged in the current study. This section provides a brief overview of the methodology with figures illustrating the principal uncertainty characterizations as applied to the results of this study.

The uncertainty introduced into the model can be characterized at the point of introduction for each of the three main aggregation stages. These are at:

- Vessel Per-Hour: For a ‘given’ vessel in a ‘given’ hour, uncertainties in the speed, draught, and engine fuel consumption can arise due to the assumptions inherent in the AIS tracking calculations.

- Vessel Per-Year: When a vessel's emissions are aggregated up to an annual estimate, the principle source of uncertainty is introduced through the extrapolation of the number of days at sea and at port into the periods where the vessel is unobserved in the AIS dataset. The significant difference in the emissions rates when at sea and at port implies that variation in observational coverage is a key factor in emissions uncertainty. This (Johansson, et al., 2017) aggregation step is only applied to Type 1 and Type 2 vessels due to the availability of dense hourly data and observation state.
- Fleet Per-Year: Vessels that are marked as active for a given year in the IHS database but are not present in the AIS dataset (Type 4 vessels as defined in Section 2.2.2 have their technical specifications activity imputed from observed vessels of the same type and size. This introduces uncertainty not only from the source vessels, but also through the number of type 4 vessels that may not be genuinely active in a given year despite appearing so in the IHS database. Similarly, vessels that have been identified in the GFW database but not in the IHS dataset (Type 3 vessels as defined in Section 2.2.2) introduce uncertainty through the considerable lack of coverage of these vessels in earlier years, leading to a wide range of possible fleet sizes per year.
- The variability of the input variables at the vessel per-hour level is explored in detail in Section 2.7.1 using a set of continuous monitoring data for a subset of vessels. In addition to the analysis performed there, Figure 119 below illustrates the decreasing uncertainty in SOG measurements as the AIS coverage increases for these vessels. It can also be seen that the standard deviation of errors decreases with coverage.

Figure 119 - Variability of SOG Error with AIS Coverage



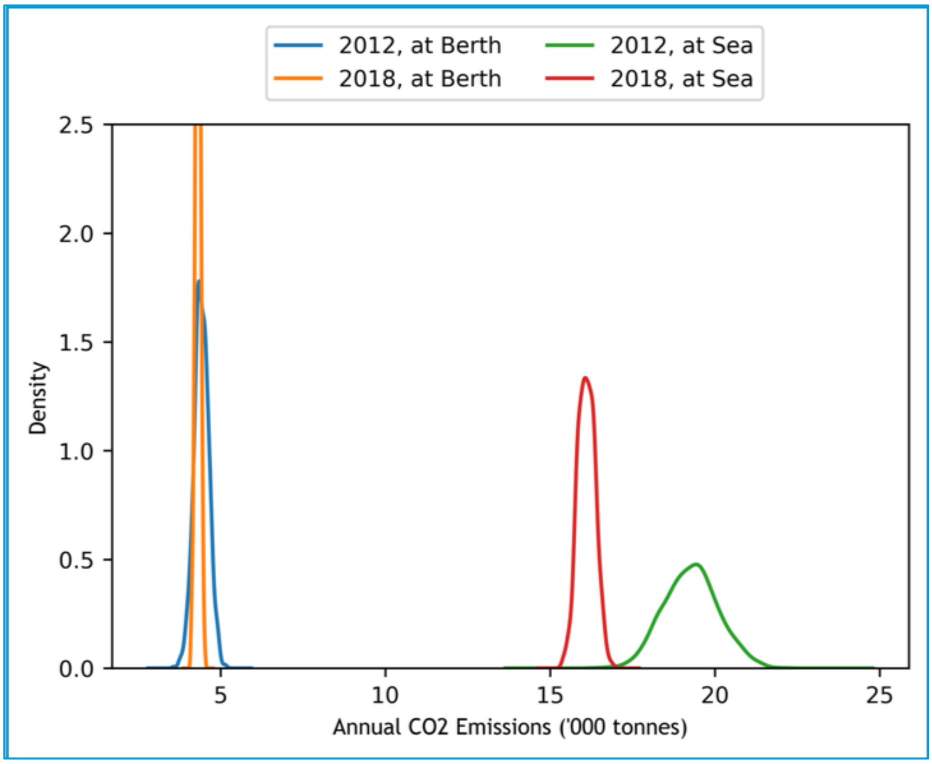
For each vessel, aggregated from an hourly to a yearly basis, this study calculates an effective average emissions rate per hour when observed and unobserved both at sea and at port, in addition to the mean number of hours spent in each of these states. These mean values are then aggregated per vessel type and size to generate a single representative vessel, with a mean and standard deviation for each observation state, emission, and fuel consumption values under the assumption of normally distributed inter-category variation. This assumption is justified by the central limit theorem and the large sample sizes in each vessel category.

Quantifying the uncertainty in the proportion of hours that the vessel was unobserved either at port or at sea in this manner makes it possible to sample 1000 annual emission instances from each representative vessel, with the variability increasing for those vessels with low average observed hours. This can be seen clearly in Figure 120, illustrating the kernel density estimates over 1,000 CO_2 emission samples from a 'Panamax'-size bulk carrier for 2012 and 2018. The average emissions are observed to have decreased from 2012 to 2018, in addition to the standard deviation of the emissions samples decreasing as the average AIS observational coverage rises from 38 to 60%.

Table 54 - Fleet-wide Monte Carlo results for CO_2-equivalent emissions

Year	Standard Deviation (tonnes)	Standard Deviation (% of mean)	Min-Max Width (tonnes)	Min-Max Width (% of Mean)	AIS Coverage (%)
2012	63,159,023	6.12	377,976,415	36.60	38.3
2013	48,230,485	4.91	320,298,774	32.60	42.2
2014	43,535,030	4.41	274,134,881	27.79	47.2
2015	40,718,007	4.05	258,314,316	25.68	52.8
2016	37,126,682	3.58	253,548,785	24.46	56.5
2017	36,433,363	3.45	220,568,039	20.90	52.3
2018	28,643,637	2.68	164,907,796	15.44	60.2

Figure 120 - Kernel density estimates for the emissions uncertainty of Panamax bulk carriers in 2012 and 2018, separated by mode of operation



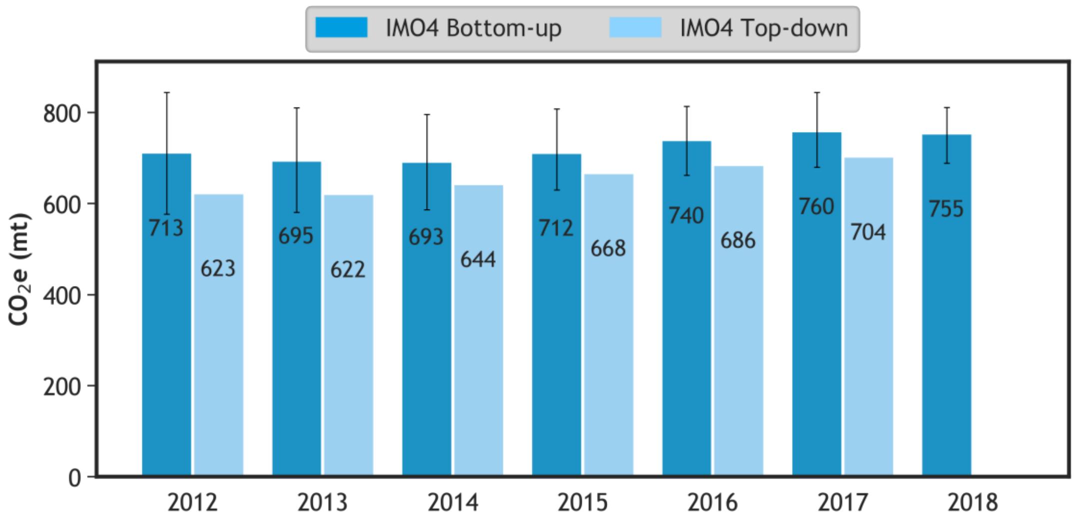
Aggregation to the whole fleet per-year level is performed for each vessel matching type individually, so that uncertainty can be more easily allocated to specific introduction sources. For Type 1 and Type 2 vessels, the emission distributions for each vessel type and size are aggregated to the fleet per-year level by sampling from each a number of times equal to the number of observed vessels per type-size category for each year.

The size of the Type 3 fleet each year is sampled from a uniform distribution bounded by 0 and the number of Type 3 vessels observed in 2018, when AIS coverage is observed to be highest. This bounding was chosen to account for the high likelihood that the sharp increase seen in the observed Type 3 fleet size from 2012 to 2018 is predominantly due to improved coverage rather than an increase in new builds. To avoid complexity, it is assumed that the maximum Type 3 fleet size is the same from year to year, but the proportion of vessels per type and size is kept equal to each year's observed Type 3 fleet. Likewise, the mean emissions per vessel type and size bin are recalculated for each year based on the observed fleet.
The size of the Type 4 fleet is also sampled from a uniform distribution, bounded by 0 and the total number of Type 4 vessels observed per year, to account for the likelihood of vessels not operating despite being listed as in-service in the IHS database. The upper bounding in this case is set to the 'observed' number of Type 4 vessels per year, as any additional

‘unobserved’ vessels not matched as Type 4 would presumably be seen in the Type 3 fleet.

This process was repeated 1,000 times for each matching type to generate a distribution of fleet-wide emissions from which to derive uncertainty ranges. The standard deviation and min-max sample ranges of the aggregated emissions for the international and domestic fleets for each year are included in the supplementary spreadsheets, divided also by matching type. These are further aggregated to give whole-fleet emission uncertainties per year by sampling uniformly from the 1,000 samples generated per matching type for each vessel type and size bin. This process ensures there is no unintended covariance between the orders of earlier sampling. The results from the Monte Carlo analysis are described in Figure 121 for fleet-wide CO_2-equivalent emissions, where ‘Min-Max Width’ represents the minimum and maximum fleet emissions estimates generated by the sampling process. The uncertainty bounds are seen to shrink as the AIS coverage increases from 2012 to 2018, as suggested by the reduction in SOG uncertainty shown in Figure 121.

Figure 121 - Range of uncertainty estimated for bottom-up GHG emissions (in CO_2e million tonnes) estimates, in relation to top-down estimates.



The results from the Monte Carlo analysis in Figure 121 are for the voyage-based assignment of international shipping emissions. Because of the similarity in the underlying method, the magnitude of the uncertainties in each year are proportionately equivalent for the estimates of vessel-based assignment international shipping emissions.

2.8.2 Uncertainty analysis of the top-down emissions estimations

The uncertainties involved with the fuel consumption data and the emission factors. The uncertainties associated with the emission factors have been discussed in Section 2.3.3

and generally follow the uncertainties of emission factors used in bottom-up methodology. Thus, the top-down uncertainty section mainly presents results of uncertainty analyses of the IEA energy consumption data. The basic methodology follows the Third IMO GHG Study, but provides one more part regarding to the uncertainty of data accuracy. This additional part is conducted by comparing the energy consumption data from UNSD with the IEA data.

This study followed the framework of the Third IMO GHG Study to do the uncertainty analyses. Four sources of uncertainties are as follows:

1. Maritime Sector Reporting: fuel sales distinguish between international and domestic navigation categories with uncertainty. Errors can be made when fuels reported under different categories are combined. This type of error can be spilt in two cases:
   a) Misallocations. Fuels that should be attributed to national navigation are allocated in international navigation or vice versa. In this case only the total (sum) of sales per type of fuel is correct, while the allocation is uncertain.
   b) Duplications. Fuel sales could be allocated in both categories, double counting the amount of fuel sold. In this case, the allocation and fuel totals can contain errors contributing to uncertainty.
2. Other Sector Misallocation: marine fuels might be allocated to other nonshipping categories e.g. export, loss, and agriculture. In this case, marine fuels would be under-reported and other sectors may have their fuels over-reported.
3. Transfers category reporting: according with IEA this category comprises inter-product transfers, which results from reclassification of products either because their specification has changed or because they are blended into another product. The net balance of inter-product transfers should be zero, however "National stocks" can be used in blending residual bunkers to specification. This could increase the volume of fuel delivered to ships sometimes without statistical documentation (IEA, 2013) resulting in underreporting.
4. Data accuracy: IEA data may suffer of intrinsic accuracy due to the ways the data are collected.

Maritime sector reporting

In Section 2.7.2, the comparison of UNSD data and IEA data clearly shows the possibilities that fuel consumptions may be misallocated between international navigation and domestic navigation. This will not cause additional uncertainties for total fuel consumption statistics.

Other sector misallocation

As identified in the Third IMO GHG Study, the export-import misallocation source contributes most to the uncertainties of the IEA fuel oil and gas diesel data. The average percentage of discrepancy (differences in export-import value divided by total reported fuel consumption) is 28% for the period 2007-2011. By using the same method, this study finds the average percentage of export-import discrepancy is 20% for the period 2012-2017 and Figure 122 illustrates the trend of export-import discrepancy rates from 2007 to 2017. Figure 123 illustrates the whole picture of the export-import discrepancy relative to the world fuel sales.

Figure 122 - Export-import discrepancy rates of the IEA fuel oil and gas diesel data

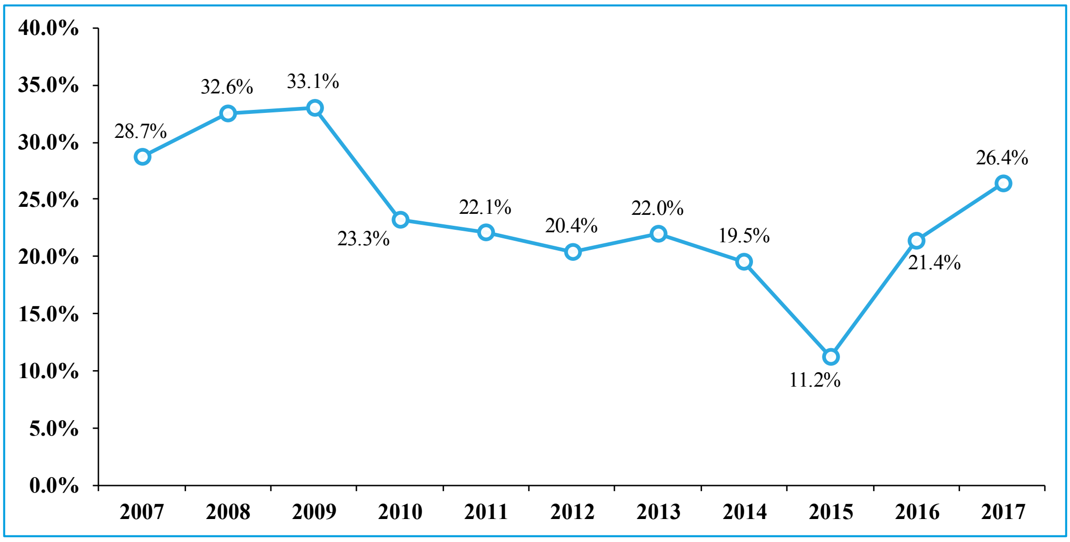
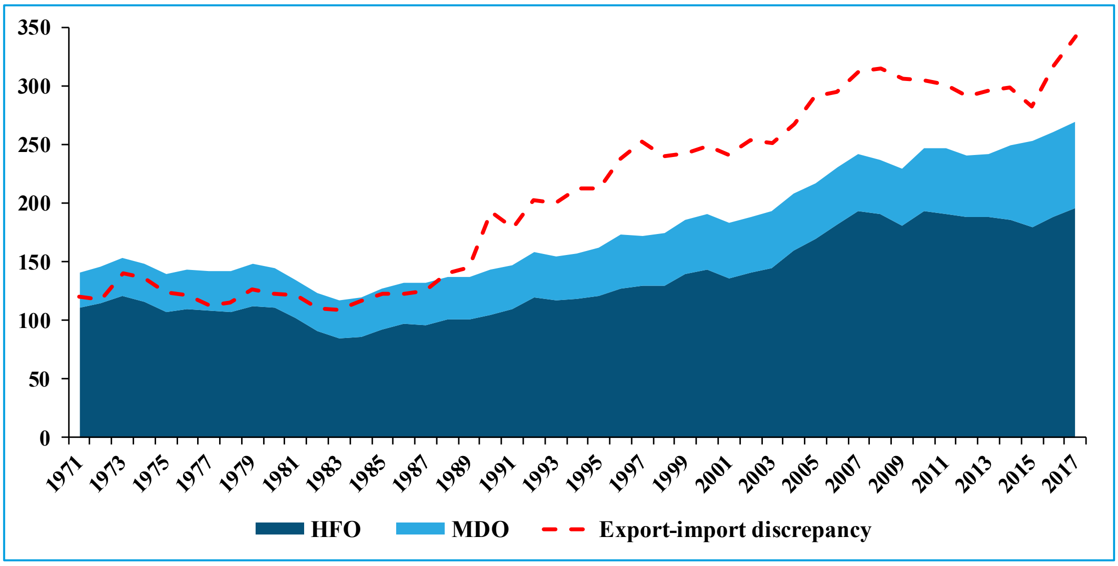


Figure 123 - HFO/MDO international marine bunker and domestic navigation sales, export-import discrepancy at world balance (million tonnes)



Transfers category reporting

Following the Third IMO GHG Study, this study recognizes the net balance of "Transfers" as an indicator of a potential maximum discrepancy in the net balance of inter-product transfers figure.

Data accuracy

In Section 2.6.6, this study uses the UNSD energy statistics to conduct the QA/QC analyses. This data source is slightly different to the IEA data for individual country/region, which may represent the potential uncertainties related to other sources such as data collection methods, data processing methods and so on.

Based on the data used in Section 2.7.2, differences in percentage between UNSD and IEA data for individual country/region are calculated. Figure 124 and Figure 125 illustrate the distribution of differences for HFO and MDO respectively. Discrepancies of gas diesel data are generally larger than fuel oil data.

Figure 124 - Distribution of differences in percentage between UNSD and IEA fuel oil data for the period 2012-2017

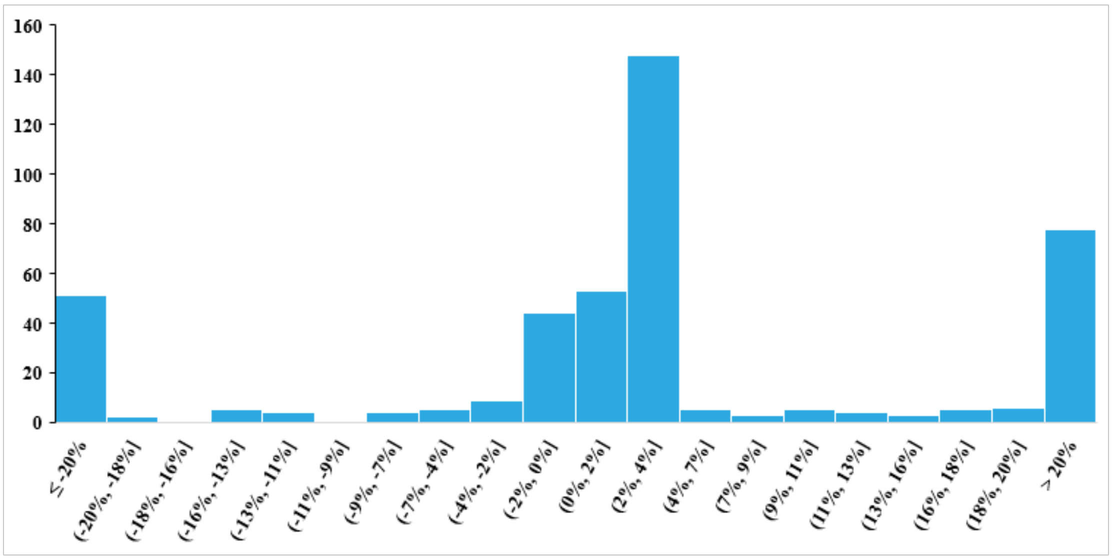


Figure 125 - Correlations between discrepancies and energy consumption levels for fuel oil data for the period 2012-2017. Sizes of circles represents degrees of discrepancies

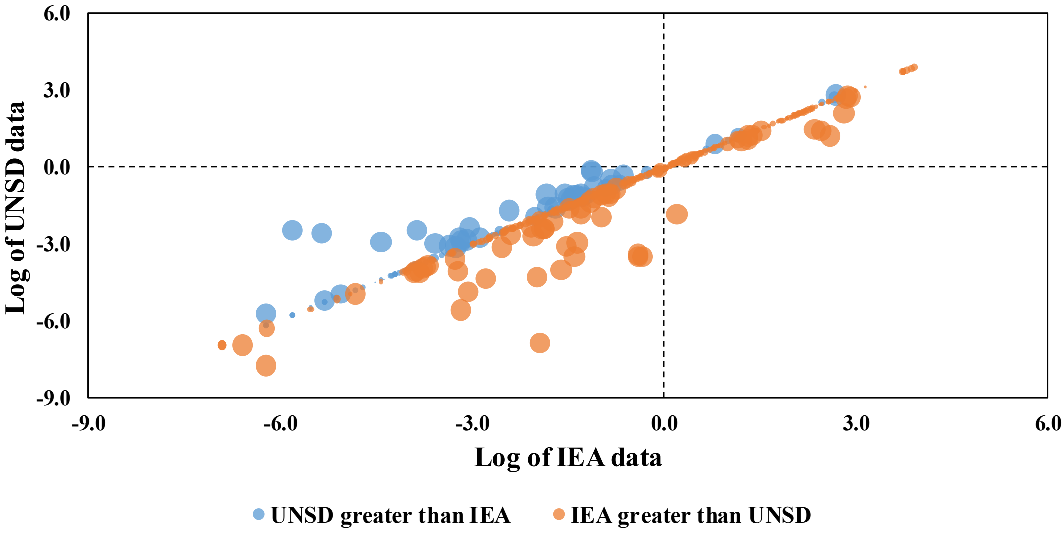
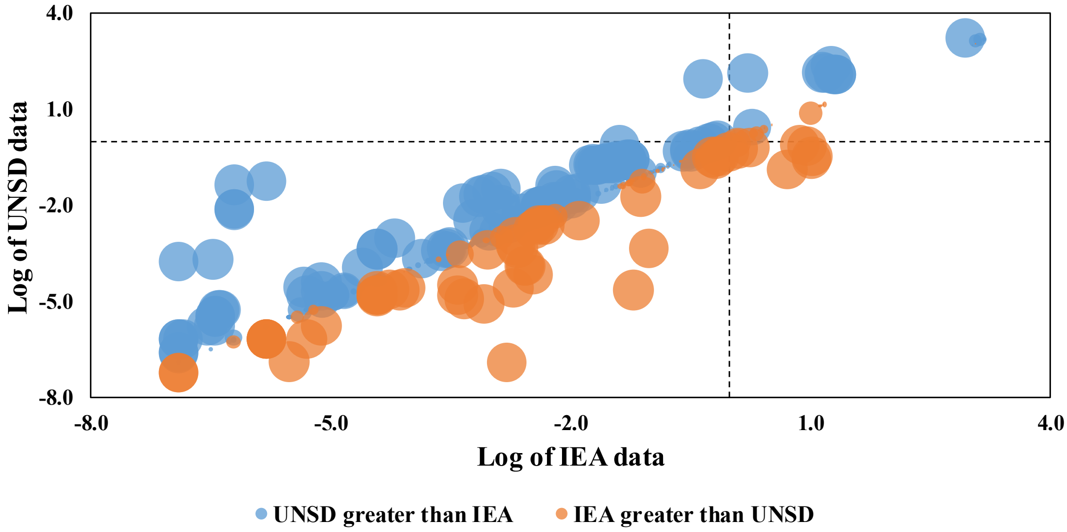


Figure 126 - Correlations between discrepancies and energy consumption levels for gas diesel data for the period 2012-2017. Sizes of circles represents degrees of discrepancies



Section 2.7 reveals that the net effects of discrepancies for two fuel types can be largely offset, but the net discrepancies still exist. This can be seen in Table 55 which shows the quantile statistics of discrepancies for HFO, MDO and summation of two fuel types.
By examining the aggregated value, countries/regions within the 25% quantile and 75% quantile have discrepancies range between -3.4 and 2.7%, which indicates the uncertainty will be around 6.1%. For countries/regions within the 10 percent quantile and 90% quantile, the discrepancies range between -20.9 and 13.0%. This indicates that the uncertainty will increase to around 33.9%.

Table 55 - Quantile statistics of discrepancies of HFO and MDO

	Quantiles				
Fuel type	10	25	50	75	90
HFO	-8.5%	-3.4%	-2.3%	0.6%	2.9%
MDO	-27.8%	-0.6%	2.7%	5.2%	106.6%
HFO+MDO	-20.9%	-3.4%	-1.5%	2.7%	13.0%

Results of top-down uncertainty analyses

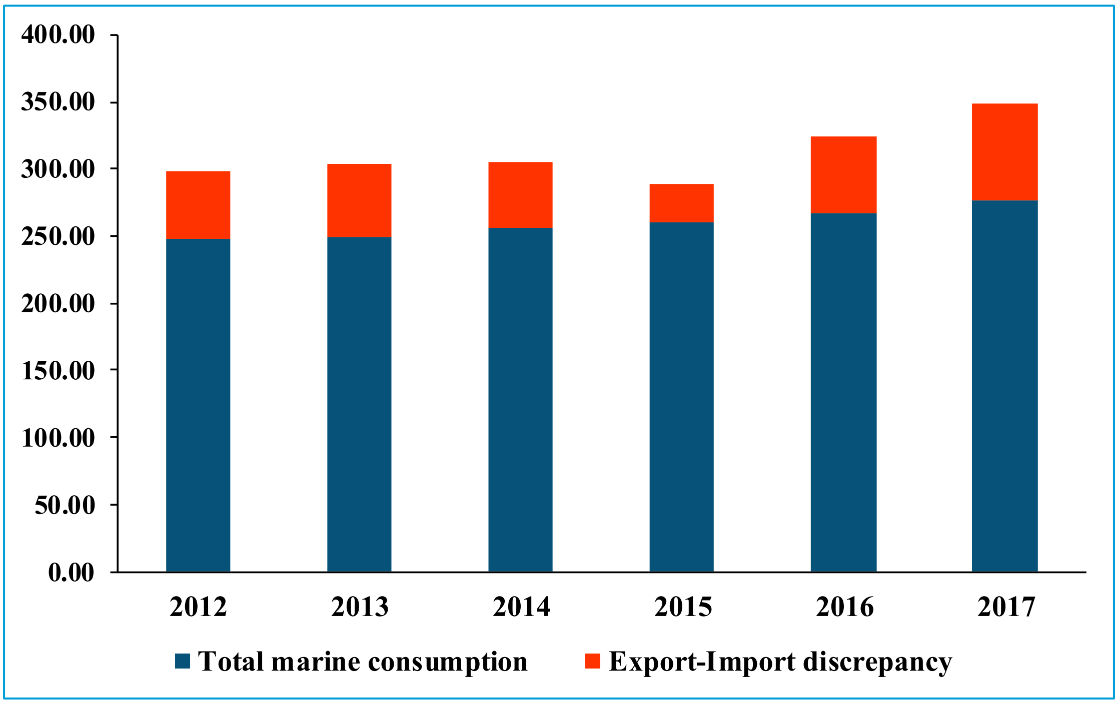
The adjusted estimates of top-down marine fuels are shown in Table 56 and Figure 127 illustrates the adjusted estimates for the period 2012-2017. Due to data for fuel transfers are not available at the time of this study, adjustment for fuel transfers balance are not shown in Table 56. According to the Third IMO GHG Study, the transfer discrepancies are typically around three percent of the total marine fuel consumption data, which is a small percentage compared to the export-import discrepancies. Therefore, it will not cause significant biases in the uncertainty analyses.

The adjusted marine fuel estimates is almost same as the data from bottom-up approach.

Table 56 - Results of quantitative uncertainty analysis on top-down statistics (million tonnes)

		2012	2013	2014	2015	2016	2017
Total marine fuel consumption (reported)	HFO	189.90	189.40	186.50	180.80	188.70	196.60
	MDO	57.90	59.10	69.00	79.20	77.60	79.50
	NG	0.14	0.15	0.19	0.26	0.22	0.20
Adjustment for Export-Import discrepancy	HFO	35.57	51.46	54.53	60.96	50.00	51.44
	MDO	15.07	3.20	-4.55	-31.94	6.97	21.40
Adjusted top-down marine fuel estimates		**298.58**	**303.31**	**305.66**	**289.28**	**323.49**	**349.14**
Bottom-up approach		298.9	296.98	299.35	307.99	319.07	329.66

Figure 127 - Adjusted estimates of top-down marine fuels for period 2012-2017 (million tonnes)



2.9 Consensus estimates of shipping emissions

Consistent with earlier GHG Studies, the consortium has selected a single estimate for presentation of results being the bottom-up method estimation, calculated using the voyage-based allocation between international and domestic emissions. The justification for this selection is:

- Consistent with the Third IMO GHG Study 2014; the quality assurance and control analysis of the top-down estimate (Section 2.8.2) show that the underlying data have a systemic bias towards underestimation. This includes the exclusion of all emissions associated with LNG use, where LNG carried as a cargo is consumed (e.g. in many liquefied gas carriers).
- The extensive quality analysis of the bottom-up estimation results using a range of measured and modelled data sources, evidenced the high quality and reliability of this method. This quality analysis included a detailed comparison against the measured fuel consumption data reported in the 11,000-ship EU MRV database for the year 2018, with a discrepancy from the bottom up consensus estimate of less than 5% on an annualized basis.
- The bottom-up method replicates exactly the IPCC definition of international shipping in order to derive the estimated inventory. The bottom-up method therefore is likely to be most accurate in reducing risks of double counting and aligning with other accounting frameworks (e.g. national inventory reporting under UNFCCC in accordance with IPCC guideline). The top-down method is unable to differentiate between the portion of an individual fuel sale to an individual vessel which is used for international shipping, it can only allocate an individual fuel sale to either international or domestic activity.
- With assessing two statistic sources (IEA and UNSD) for Top-down approach indicated that slight difference of fuel consumption for individual country/region, which may represent the potential uncertainties related to other sources such as data collection methods, data processing methods.

The consensus estimates and results are therefore those results presented in Section 2.5. Where the top-down results are included in tables and plots, these have been included for illustration purposes only.

3 Estimates of carbon intensity

3.1 Introduction

In accordance with the Initial IMO Strategy on Reduction of GHG Emissions from Ships (IMO, 2018), CO_2 emissions per transport work, as an average across international shipping, are to be reduced by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008. Under this background, potential metrics for carbon intensity of international shipping should be able to indicate “CO_2 emissions per transport work” in essence. Given various understandings on “transport work” under different circumstances and for different ship types, several potential metrics have been proposed as candidates for use in IMO policy making. However, no metric has been generally accepted as the best choice for the time being.

To provide comprehensive insights into carbon intensity as possible, the following four metrics are mainly used to estimate the carbon intensity of international shipping:

- Energy Efficiency Operational Indicator (EEOI): CO_2 emissions per factual cargo tonne miles or passenger miles (sum of the product of payload and the corresponding distance travelled), in g_{CO_2}/tonne/nautical mile;
- Annual Efficiency Ratio (AER): CO_2 emissions per unit of nominal transport work (product of a ship’s capacity and total distance travelled), in g_{CO_2}/dwt/nautical mile;
- DIST: CO_2 emissions per distance travelled, in kg_{CO_2}/nautical mile; and
- TIME: CO_2 emissions per hour underway, in $tonne_{CO_2}$/hour.

EEOI was put forward in 2009 by the IMO (2009). As an integrated indicator, EEOI is able to capture almost all technical and operational influencing factors. However, the key component in EEOI calculation, i.e. the amount of cargo/passenger carried on board a ship, has been excluded from the IMO data collection system (IMO DCS) for fuel oil consumption of ships (IMO, 2016) due to commercial sensitivity.

The latter three metrics are derived from the proposals submitted by IMO member states (IMO, 2014, 2013a, 2013b), but have been revised at some point from their original versions to have more general and typical implications. As requested by the IMO DCS, a ship’s capacity together with the aggregated values for fuel oil consumption (which can be converted to CO_2 emissions), distance travelled and hours underway for each calendar year as from 2019 shall be collected and reported compulsorily. This will make their calculation for individual ships of 5,000 GT and above quite straight forward. Therefore, these metrics can be regarded as consistent with the IMO DCS.

In addition to the four typical metrics, other variants of AER, including cDIST which uses different capacity units (such as twenty-foot equivalent unit, gross tonnage and cubic meter) defined by this study, and Energy Efficiency Performance Indicator (EEPI) which uses laden distance instead of total distance at sea (IMO, 2019a), are also estimated where applicable for reference purposes.

As per inventory estimation in Chapter 2, two approaches to distinguish between domestic and international shipping have been applied to estimate carbon intensity in this chapter accordingly. One is the method used in the Third IMO GHG Study 2014 (Smith, et al., 2015a), which differentiated domestic and international shipping according to ship type and size only. The other assumes that all ships may be engaged in both international and domestic voyages and whether a voyage should be defined as international or domestic depends on its port calls. These two approaches are referred to as “Option 1” and “Option 2” respectively, and are denoted as “OP1” and “OP2” in relevant tables and figures.

This chapter provides estimates on the carbon intensity of international shipping between 2012 and 2018, as well as in 2008, through both Option 1 and Option 2. The features, trends, drivers of the carbon intensity performance, as well as the uncertainties in the estimated results are also discussed.

3.2 Methodology

3.2.1 Carbon intensity metrics of individual ships

In line with the Initial IMO Strategy, the candidate carbon intensity indicators (CII) discussed by this study all follow the same concept formula, i.e. CII = CO_2/transport work. Since CO_2 emissions have been taken as the numerator in all candidate metrics under discussion, the differences merely lie in the denominator which represents “transport work”. In calculating EEOI, transport work is measured by factual cargo tonne miles or passenger miles undertaken by a ship; while in AER, DIST and TIME formulas, various proxies have been applied. The annual average carbon intensity metric values of individual ships are calculated as follows:

$$EEOI = \frac{\sum m_{co_2}}{\sum \left(m_{payload} \times D_{payload} \right)} \quad (1)$$

$$AER = \frac{\sum m_{co_2}}{dwt \times \sum D_{total}} \quad (2)$$

$$DIST = \frac{\sum m_{co_2}}{\sum D_{total}} \quad (3)$$

$$TIME = \frac{\sum m_{co_2}}{\sum T_{underway}} \quad (4)$$

– where $\sum m_{co_2}$ stands for the annually aggregated CO_2 emissions of a ship, $\sum \left(m_{payload} \times D_{payload} \right)$ stands for the annually aggregated transport work in tonne-miles, dwt stands for a ship’s deadweight tonnage, $\sum D_{total}$ and $\sum T_{underway}$ respectively stands for the annually aggregated distance and hours at sea.

In calculating EEOI and AER, the transport work and ship capacity are identically measured in tonnes in this study for the sake of comparability. To explore other potential metrics, a series of alternative units of a ship’s capacity are taken to replace the dwt in AER. Such variants of AER are generally referred to as cDIST in this study, which can be calculated as follows:

$$cDIST = \frac{\sum m_{co_2}}{capacity \times \sum D_{total}} \quad (5)$$

where, $capacity$ stands for a ship’s capacity rather than deadweight, such as TEUs for container ships, cubic meters for liquified gas carriers, and gross tonnage for cruise ships and vehicle carriers. Note that both AER and cDIST can be deemed as simplified versions of EEOI, where actual cargo/passenger carried on board is replaced by the ship's capacity.

— Another approximation of EEOI is a metric named Energy Efficiency Performance Indicator (EEPI). It shares the same numerator with EEOI and AER, yet using the product of dwt and laden distance as the proxy of transport work in the denominator. For bulk carriers, tankers and other ship types which have typical ballast voyages, such a proxy is a better approximation to the factual cargo tonne-miles undertaken. For ship types which are always fully or partly loaded, such as container ships, EEPI is equivalent to AER. The annual average EEPI is calculated as follows (Zhang et al., 2019):

$$EEPI = \frac{\sum m_{co_2}}{dwt \times \sum D_{laden}} \quad (6)$$

— where $\sum D_{laden}$ stands for the annually aggregated laden distance travelled at sea, whilst others share the same meaning as in AER.

Except for those mentioned above, there are some other metrics proposed for non-cargo ships. For instance, the product of available lower berth (ALB) capacity and total distance travelled has been proposed to be taken as a transport work proxy for cruise passenger ships (IMO, 2019b) while the product of installed rated engine power and engine running hours has been proposed for use by offshore and marine contracting vessels (IMO, 2019c). Due to limited time and data available, these metrics have not been discussed by this study. For a specific ship, however, these metrics can be transformed from AER or TIME simply through introducing a constant correction factor. Hence. features of such metrics are expected to be quite similar to AER or TIME.

Having consistently taken CO_2 emissions as the numerators, a smaller metric value of all these metrics mentioned above always indicates a better performance. For a specific ship type, however, values of EEOI and AER of individual ships generally decrease with ship size, while values of DIST and TIME increase. This is because the former two metrics have in the meanwhile incorporated the ship capacity or cargo carried on board into their denominator which are highly correlated with ship size, while the latter two metrics have not. Except for EEOI, all other metrics have excluded the factual cargo mass from their formulas. Therefore, an increase in payload utilization of a ship, which will cause a deeper draught and then a consequent increase in fuel consumptions, will merely lead to a higher value of CO_2 emissions in the numerators of these metrics whilst leaving the denominators unchanged. As a result, an improvement in a ship's payload utilization will generally lead to an inferior value of these metrics. However, the biasness is not identical between metrics due to their unequal sensitivity to draughts. Similarly, a reduction in ship speed will result in different improvement in carbon intensity performance when measured in differ metrics. Given various practical implications and dominant drivers, values of different carbon intensity metrics of the same ship cannot be comparable to each other.

3.2.2 Methods to estimate carbon intensity of international shipping, 2012-2018

In calculating the typical carbon intensity metric values for individual ships in year 2012-2018, annually aggregated CO_2 emissions are directly derived from the results of Chapter 2, while the data sets of various transport activities are identical with those used for inventory estimation. The mass of cargo carried on board a ship is estimated mainly based on operational draughts and the ship's particulars through the approach as per Smith et al.(2015). A certain modifications have been made to this method, taking into account the work of Olmer et al.(2017) and some others. The process applied to estimate voyage draughts based on operational draughts reported in AIS data and cargo mass used for the subsequent calculations of EEOI is outlined in Annex D.

Based on the results of Chapter 2, the overall carbon intensity per ship type and size category, as well as the international shipping as a whole, can be estimated through dividing the annually aggregated CO_2 emissions by the associated transport work or proxies (expressed in cargo tonne-miles, dwt-miles, miles or hours). Such results are equivalent to the transport work weighted average metric values, which can capture all drivers of carbon intensity of international shipping, including a shift in the ship size composition of a fleet and consequently a shift in the proportion of transport work from each size category.

— Since two options have been applied to estimate CO_2 emissions and transport activities in Chapter 2, the results of carbon intensity estimation on international shipping are also presented in two groups accordingly, i.e. results derived from Option 1 and Option 2. The calculation methods, however, are completely identical.

3.2.3 Methods to estimate carbon intensity of international shipping, 2008

Method to estimate carbon intensity in year 2008 based on Option 1

Methods to estimate carbon intensity of international shipping in year 2008, indicated by cDIST, DIST and TIME, are quite straightforward when Option 1 is followed. For ships of type i and size category k , which have been categorized as always serving international shipping, the overall carbon intensity of this type and size bin can be calculated as follows:

$$AER_{i,k} = \frac{m_{co_2,i,k}}{d\bar{w}t_{i,k} \times (24 \times d\bar{a}y_{i,k}) \times sp\bar{e}ed_{i,k} \times n_{i,k}} \quad \textbf{(7)}$$

$$DIST_{i,k} = \frac{m_{co_2,i,k}}{24 \times d\bar{a}y_{i,k} \times sp\bar{e}ed_{i,k} \times n_{i,k}} \quad \textbf{(8)}$$

$$TIME_{i,k} = \frac{m_{co_2,i,k}}{24 \times d\bar{a}y_{i,k} \times n_{i,k}} \quad \textbf{(9)}$$

where $AER_{i,k}$, $DIST_{i,k}$ and $TIME_{i,k}$ respectively stands for the overall carbon intensity metric values of ships covered by size category k of type i, $m_{co_2,i,k}$ stands for the total mass of CO_2 emissions, $n_{i,k}$ is the total number of ships observed, while $d\bar{w}t_{i,k}$, $d\bar{a}y_{i,k}$ and $sp\bar{e}ed_{i,k}$ respectively stands for the average deadweight tonnage, average days at sea and average sea speed of ships covered by this bin. All of these have readily been provided in the Third IMO GHG Study.

Since the cargo tonne-miles undertaken by ships in year 2008 are unknown, metric values of EEOI cannot be calculated directly based on the results in the Third IMO GHG Study. To denote the average operational productivity (average cargo tonne-miles done per dwt) of ships covered by size bin k of ship type i as $p_{i,k}$, the overall EEOI of this bin can be calculated as follows:

$$EEOI_{i,k} = \frac{m_{co_2,i,k}}{p_{i,k} \times d\bar{w}t_{i,k} \times n_{i,k}} \quad \textbf{(10)}$$

where all other parameters share identical meanings as in AER.

The parameter $p_{i,k}$ can be estimated through a random forest regression model (Liaw and Wiener, 2002) trained on the estimated results from the year 2012-2018, using deadweight tonnage, speed at sea, average CO_2 emissions per dwt, average distance at sea per dwt, and average hours at sea per dwt as the regressors. For each ship type, a random forest consisting 300 trees is constructed, while the ten-fold cross validation is applied to decide the optimized number of variables (denoted as "mtry") randomly sampled as candidates at each split to minimize the mean square errors. In order to ensure the comparability of the estimates of year 2008 with the results over 2012-2018, as well as to capture the unique seaborne trade features in 2008, a series of correction factors are applied to the regression results where applicable. The corrections factors are calculated as $C_i = (1 - k_{i,ref}) / (1 - k_{i,avg})$, where $k_{i,ref}$ is the deviation rate of the estimated tonne-miles of cargo type i in year 2008 from the published data in UNCTAD's Review of Maritime Transport (2018) (UNCTAD, 2018), $k_{i,avg}$ is the average deviation rate of the estimated tonne-miles of cargo type i over year 2012-2018 from the published data. Estimates on average operational productivity of each ship type and size bin regarding both Option 1 and Option 2 can be found in Table 57.

For ships of type i as a whole, the overall carbon intensity metric values can be calculated through dividing the aggregated CO_2 emissions of its all size categories by the corresponding aggregated transport work or proxies. The overall carbon intensity metric values for the whole world fleet can be calculated similarly.

Table 57 – Estimates on average operational productivity of each ship type and size bin

Ship type	Size category	Units	Number of ships	Average dwt	Productivity (kt.nm/dwt)	Correction factor		Corrected productivity (kt.nm/dwt)	
						OP1	OP2	OP1	OP2
Bulk carrier	0-9999	dwt	1151	3100	26.0	1.22	1.25	31.7	32.5
	10000-34999	dwt	2177	25515	28.9	1.22	1.25	35.2	36.0
	35000-59999	dwt	2030	48249	28.8	1.22	1.25	35.2	36.0
	60000-99999	dwt	1616	75867	29.0	1.22	1.25	35.3	36.2
	100000-199999	dwt	724	165582	32.4	1.22	1.25	39.4	40.4
	200000-+	dwt	129	252904	35.0	1.22	1.25	42.7	43.7
Chemical tanker	0-4999	dwt	1514	2163	32.6	0.99	1.01	32.3	32.8
	5000-9999	dwt	728	8164	37.4	0.99	1.01	37.0	37.6
	10000-19999	dwt	770	16737	38.6	0.99	1.01	38.2	38.8
	20000-+	dwt	1177	43482	37.5	0.99	1.01	37.2	37.7
Container	0-999	TEU	1200	9284	40.0	1.03	1.05	41.3	42.0
	1000-1999	TEU	1275	21824	44.7	1.03	1.05	46.3	47.0
	2000-2999	TEU	745	37556	61.1	1.03	1.05	63.2	64.2
	3000-4999	TEU	797	56036	60.1	1.03	1.05	62.1	63.2
	5000-7999	TEU	484	80503	64.3	1.03	1.05	66.5	67.6
	8000-11999	TEU	172	117315	64.2	1.03	1.05	66.4	67.5
	12000-14500	TEU	8	163136	64.3	1.03	1.05	66.5	67.6
Cruise	0-1999	GT	194	241	25.5	1.00	1.00	25.5	25.5
	2000-9999	GT	78	1174	35.1	1.00	1.00	35.1	35.1
	10000-59999	GT	129	4687	69.9	1.00	1.00	69.9	69.9
	60000-99999	GT	77	8810	89.6	1.00	1.00	89.6	89.6
	100000-+	GT	31	11088	91.1	1.00	1.00	91.1	91.1
Ferry-pax only	0-1999	GT	2988	162	29.3	–	1.00	–	29.3
	2000-+	GT	80	1643	58.1	1.00	1.00	58.1	58.1
Ferry-RoPax	0-1999	GT	1633	1000	32.7	–	1.00	–	32.7
	2000-+	GT	1263	3400	33.2	1.00	1.00	33.2	33.2
General cargo	0-4999	dwt	12990	1904	25.7	1.22	1.25	31.4	32.1
	5000-9999	dwt	2763	7321	29.0	1.22	1.25	35.3	36.2
	10000-+	dwt	2006	21444	31.3	1.22	1.25	38.2	39.1
Liquefied gas tanker	0-49999	cbm	1021	6544	30.5	0.95	0.96	29.1	29.1
	50000-199999	cbm	415	69872	52.8	0.95	0.96	50.4	50.5
	200000-+	cbm	21	188232	54.4	0.95	0.96	52.0	52.0
Miscellaneous - fishing	0-+	GT	23622	149	24.7	–	1.00	–	24.7
Miscellaneous - other	0-+	GT	3902	101	16.4	–	1.00	–	16.4
Offshore	0-+	GT	5140	1666	7.6	–	1.00	–	7.6
Oil tanker	0-4999	dwt	3722	1909	20.9	1.13	1.14	23.6	23.8
	5000-9999	dwt	527	6857	19.0	1.13	1.14	21.4	21.6
	10000-19999	dwt	227	16073	18.7	1.13	1.14	21.1	21.3
	20000-59999	dwt	714	44502	20.3	1.13	1.14	22.9	23.1
	60000-79999	dwt	358	74030	22.6	1.13	1.14	25.5	25.8
	80000-119999	dwt	773	109452	24.2	1.13	1.14	27.3	27.6
	120000-199999	dwt	369	156778	24.8	1.13	1.14	27.9	28.2
	200000-+	dwt	526	312723	32.9	1.13	1.14	37.1	37.5
Other liquids tankers	0-+	dwt	165	775	55.7	1.00	1.00	55.7	55.7
Refrigerated bulk	0-9999	dwt	1243	5681	30.4	1.22	1.25	37.1	38.0
Ro-Ro	0-4999	dwt	1224	1310	23.1	1.00	1.00	23.1	23.1
	5000-+	dwt	472	11399	48.1	1.00	1.00	48.1	48.1
Service - other	0-+	GT	3014	1941	13.5	–	1.00	–	13.5
Service - tug	0-+	GT	12618	243	11.8	–	1.00	–	11.8
Vehicle	0-3999	vehicle	347	9315	27.2	1.00	1.00	27.2	27.2
	4000-+	vehicle	468	20306	29.3	1.00	1.00	29.3	29.3
Yacht	0-+	GT	1263	461	14.7	–	1.00	–	14.7

Method to estimate carbon intensity in year 2008 based on Option 2

Option 2 applies a new strategy to distinguish between international and domestic shipping, which is different from the one used in the Third IMO GHG Study. In order to generate comparable carbon intensity estimates of year 2008 using the same approach, appropriate correction factors representing the international shares from the world total should be allocated to the given results of each type and size category. To denote the plausible share of international CO_2 emissions, distance travelled, days at sea and cargo tonne-miles as r_1, r_2, r_3, and r_4, the annual average carbon intensity metrics for size category k of ship type i can be calculated as follows:

$$AER_{i,k} = \frac{r_{1,i,k} \times m_{co_2,i,k}}{r_{2,i,k} \times \overline{dwt}_{i,k} \times (24 \times \overline{day}_{i,k}) \times \overline{speed}_{i,k} \times n_{i,k}} \quad \textbf{(11)}$$

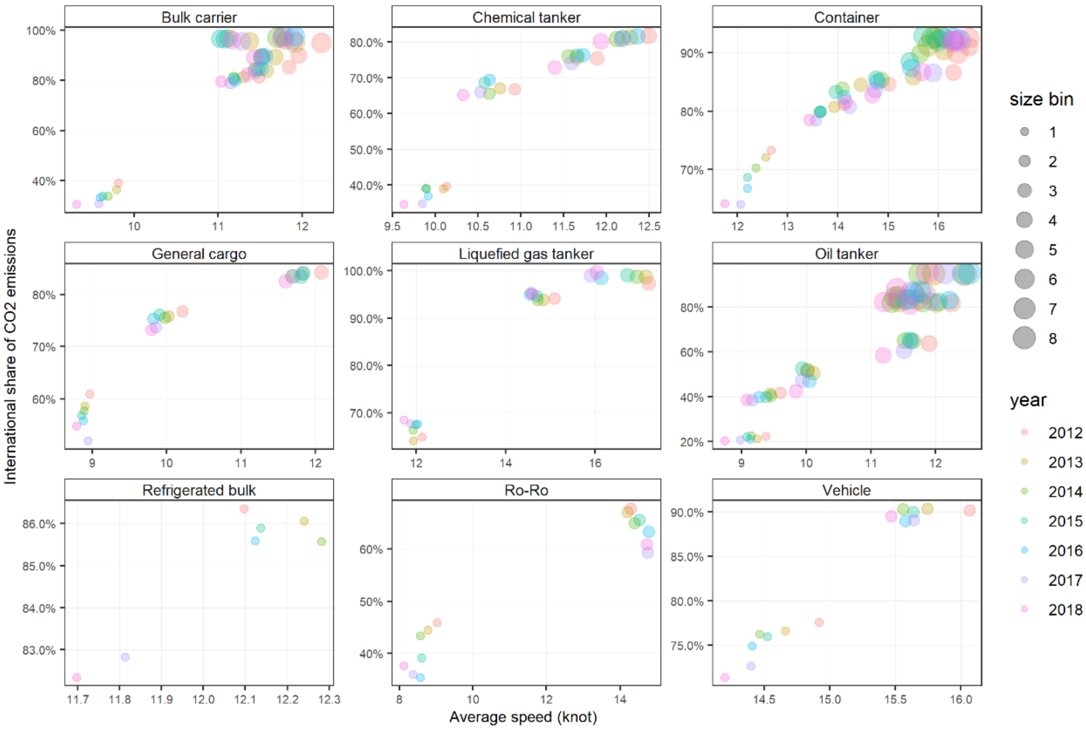
$$DIST_{i,k} = \frac{r_{1,i,k} \times m_{co_2,i,k}}{r_{2,i,k} \times (24 \times \overline{day}_{i,k}) \times \overline{speed}_{i,k} \times n_{i,k}} \quad \textbf{(12)}$$

$$TIME_{i,k} = \frac{r_{1,i,k} \times m_{co_2,i,k}}{r_{3,i,k} \times (24 \times \overline{day}_{i,k}) \times n_{i,k}} \quad \textbf{(13)}$$

$$EEOI_{i,k} = \frac{r_{1,i,k} \times m_{co_2,i,k}}{r_{4,i,k} \times p_{i,k} \times \overline{dwt}_{i,k} \times n_{i,k}} \quad \textbf{(14)}$$

where all other parameters share identical meanings as in formulas introduced in Section 3.2.3. Parameters r_1, r_2, r_3 and r_4 can be estimated through k-nearest neighbours (KNN) regression models informed by the estimates from year 2012-2018. Since the Third IMO GHG Study used slightly different ship size categories, results derived from this study for year 2012-2018 are reaggregated before modelling to coincide with the former categorizations. The international share of CO_2 emissions and transport activities of a ship of a specific type is dominantly determined by her capacity. It may be additionally affected by the changing market situation, especially for a smaller ship which is more flexible in switching between domestic and international trades. Under a depression, ships tend to slow down to cater for the shrinking international shipping requirement and to undertake a relatively smaller share of international transport work than normal period. Therefore, the average speed at sea of ships covered by a specific type and size bin can be taken as a proxy of the influence of the market situation. The correlation between average speed and the international share of CO_2 emissions of each ship type and size bins are presented in Figure 128. It is observed that the speed of typical cargo ship types has been generally decreased between 2012 and 2018, for both larger and smaller size bins. However, the shifts in international share of CO_2 emissions are not as significant for larger size bins as for smaller ones, likely due to their difficulties in switching trading patterns. Similar features can be also found in allocating the international share of transport work to ships.

Figure 128 - Correlation between average speed and international share of CO_2 emissions



To estimate the international share of CO_2 emissions in year 2008, for instance, three KNN model settings have been explored, as follows:

A. $r_1 = f(\bar{dwt}) + \varepsilon$

B. $r_1 = f(\bar{dwt}, \bar{speed}) + \varepsilon$

C. $r_1 = f(\bar{dwt}, \bar{speed}, C_{size}) + \varepsilon$

Where, $\bar{dwt}$ is the average deadweight tonnage of ships of a specific sizes category, $\bar{speed}$ is the average sea speed, and C_{size} is a classification variable indicating different size categories. Model A is taken as the starting point, while Model B incorporates the influence of speed (a proxy of market situation). Since the influence of shipping market may be not identical to different size bins, the dummy variable C_{size} incorporated into Model C is expected to catch this factor. The best kernel (triangular, rectangular, epanechnikov, or optimal) and the most appropriate number of neighbours in the model setting are decided on their contributions in minimizing the mean absolute error (MAE) (Samworth, 2012). Having compared the total performance of the three model settings, Model A stood out at the best choice. The international shares of transport work are estimated following the same method, all of which shared the best model setting similar to Model A, i.e. using merely average deadweight tonnage as the regressor. Detailed model settings, results and fitting quality can be found in Table 58. In this table, “TR”, “RE”, “EP” and “OP” respectively stands for the kernel “triangular”, “rectangular”, “epanechnikov” and “optimal” for short. Figure 129 through Figure 132 illustrate the estimated international shares of international CO_2 emissions, distance travelled, hours at sea and cargo tonne-miles (marked in red “*” symbols), where the colourful tiny circles represent their counterparts during year 2012 to 2018.

Table 58 - Detailed KNN model settings, results and fitting quality

Ship type	Size category	Units	International share of CO_2				International share of distance				International share of hour				International share of cargo			
			share	MAE	ker-nel	neigh-bors	share	MAE	ker-nel	neigh-bors	share	MAE	ker-nel	neigh-bors	share	MAE	ker-nel	neigh-bors
Bulk carrier	0-9999	dwt	0.31	0.007	TR	2	0.31	0.007	TR	2	0.33	0.007	TR	2	0.35	0.008	TR	3
	10000-34999	dwt	0.81	0.007	TR	2	0.81	0.007	TR	2	0.80	0.007	TR	2	0.86	0.008	TR	3
	35000-59999	dwt	0.85	0.007	TR	2	0.85	0.007	TR	2	0.85	0.007	TR	2	0.89	0.008	TR	3
	60000-99999	dwt	0.89	0.007	TR	2	0.90	0.007	TR	2	0.90	0.007	TR	2	0.92	0.008	TR	3
	100000-199999	dwt	0.96	0.007	TR	2	0.96	0.007	TR	2	0.96	0.007	TR	2	0.97	0.008	TR	3
	200000-+	dwt	0.95	0.007	TR	2	0.95	0.007	TR	2	0.95	0.007	TR	2	0.96	0.008	TR	3
Chemical tanker	0-4999	dwt	0.35	0.010	TR	4	0.36	0.011	TR	3	0.36	0.012	TR	3	0.44	0.011	TR	3
	5000-9999	dwt	0.67	0.010	TR	4	0.70	0.011	TR	3	0.68	0.012	TR	3	0.72	0.011	TR	3
	10000-19999	dwt	0.75	0.010	TR	4	0.79	0.011	TR	3	0.78	0.012	TR	3	0.81	0.011	TR	3
	20000-+	dwt	0.81	0.010	TR	4	0.85	0.011	TR	3	0.85	0.012	TR	3	0.87	0.011	TR	3
Container	0-999	TEU	0.73	0.009	OP	2	0.71	0.011	OP	2	0.68	0.013	OP	2	0.74	0.010	OP	2
	1000-1999	TEU	0.81	0.009	OP	2	0.82	0.011	OP	2	0.81	0.013	OP	2	0.83	0.010	OP	2
	2000-2999	TEU	0.85	0.009	OP	2	0.86	0.011	OP	2	0.86	0.013	OP	2	0.87	0.010	OP	2
	3000-4999	TEU	0.87	0.009	OP	2	0.87	0.011	OP	2	0.87	0.013	OP	2	0.88	0.010	OP	2
	5000-7999	TEU	0.89	0.009	OP	2	0.89	0.011	OP	2	0.87	0.013	OP	2	0.90	0.010	OP	2
	8000-11999	TEU	0.92	0.009	OP	2	0.92	0.011	OP	2	0.90	0.013	OP	2	0.93	0.010	OP	2
	12000-14500	TEU	0.90	0.009	OP	2	0.90	0.011	OP	2	0.89	0.013	OP	2	0.92	0.010	OP	2
Cruise	0-1999	GT	0.27	0.019	EP	5	0.28	0.017	TR	5	0.28	0.018	TR	5	0.28	0.016	RE	1
	2000-9999	GT	0.40	0.019	EP	5	0.42	0.017	TR	5	0.40	0.018	TR	5	0.55	0.016	RE	1
	10000-59999	GT	0.66	0.019	EP	5	0.67	0.017	TR	5	0.66	0.018	TR	5	0.68	0.016	RE	1
	60000-99999	GT	0.76	0.019	EP	5	0.77	0.017	TR	5	0.77	0.018	TR	5	0.77	0.016	RE	1
	100000-+	GT	0.82	0.019	EP	5	0.83	0.017	TR	5	0.83	0.018	TR	5	0.84	0.016	RE	1
Ferry-pax only	0-1999	GT	0.21	0.027	RE	5	0.18	0.019	RE	5	0.15	0.013	RE	5	0.15	0.031	RE	5
	2000-+	GT	0.13	0.027	RE	5	0.15	0.019	RE	5	0.16	0.013	RE	5	0.08	0.031	RE	5
Ferry-RoPax	0-1999	GT	0.22	0.015	EP	5	0.20	0.014	EP	5	0.20	0.013	EP	5	0.21	0.018	RE	2
	2000-+	GT	0.30	0.015	EP	5	0.28	0.014	EP	5	0.28	0.013	EP	5	0.29	0.018	RE	2
General cargo	0-4999	dwt	0.54	0.010	OP	3	0.50	0.009	OP	2	0.51	0.009	OP	2	0.60	0.009	OP	3
	5000-9999	dwt	0.76	0.010	OP	3	0.76	0.009	OP	2	0.74	0.009	OP	2	0.79	0.009	OP	3
	10000-+	dwt	0.84	0.010	OP	3	0.85	0.009	OP	2	0.84	0.009	OP	2	0.90	0.009	OP	3
Liquefied gas tanker	0-49999	cbm	0.65	0.007	TR	4	0.61	0.011	OP	2	0.59	0.011	OP	2	0.80	0.008	TR	4
	50000-199999	cbm	0.95	0.007	TR	4	0.96	0.011	OP	2	0.95	0.011	OP	2	0.96	0.008	TR	4
	200000-+	cbm	0.99	0.007	TR	4	1.00	0.011	OP	2	0.99	0.011	OP	2	1.00	0.008	TR	4
Miscellaneous - fishing	0-+	GT	0.31	0.008	RE	2	0.33	0.009	RE	4	0.31	0.007	EP	5	0.44	0.018	TR	5
	0-+	GT	0.48	0.039	TR	1	0.51	0.022	RE	5	0.49	0.025	RE	5	0.54	0.032	TR	2
Offshore	0-+	GT	0.30	0.009	OP	2	0.24	0.004	OP	2	0.23	0.003	OP	2	0.47	0.042	OP	2
Oil tanker	0-4999	dwt	0.21	0.010	RE	2	0.20	0.009	EP	2	0.21	0.009	EP	2	0.21	0.010	TR	2
	5000-9999	dwt	0.39	0.010	RE	2	0.41	0.009	EP	2	0.41	0.009	EP	2	0.45	0.010	TR	2
	10000-19999	dwt	0.45	0.010	RE	2	0.50	0.009	EP	2	0.49	0.009	EP	2	0.53	0.010	TR	2
	20000-59999	dwt	0.59	0.010	RE	2	0.68	0.009	EP	2	0.66	0.009	EP	2	0.72	0.010	TR	2
	60000-79999	dwt	0.82	0.010	RE	2	0.87	0.009	EP	2	0.86	0.009	EP	2	0.91	0.010	TR	2
	80000-119999	dwt	0.83	0.010	RE	2	0.89	0.009	EP	2	0.88	0.009	EP	2	0.92	0.010	TR	2
	120000-199999	dwt	0.87	0.010	RE	2	0.93	0.009	EP	2	0.92	0.009	EP	2	0.95	0.010	TR	2
	200000-+	dwt	0.95	0.010	RE	2	0.97	0.009	EP	2	0.97	0.009	EP	2	0.98	0.010	TR	2
Other liquids	0-+	dwt	0.62	0.027	RE	3	0.62	0.025	RE	5	0.49	0.026	RE	3	0.95	0.008	TR	4
Refrigerated bulk	0-9999	dwt	0.84	0.016	RE	4	0.84	0.014	EP	4	0.82	0.017	EP	4	0.89	0.012	EP	4
Ro-Ro	0-4999	dwt	0.37	0.019	TR	3	0.36	0.016	TR	1	0.37	0.012	TR	1	0.39	0.018	EP	2
	5000-+	dwt	0.67	0.019	TR	3	0.68	0.016	TR	1	0.69	0.012	TR	1	0.70	0.018	EP	2
Service - other	0-+	GT	0.31	0.012	OP	3	0.27	0.012	RE	5	0.27	0.014	EP	5	0.41	0.020	RE	2
Service - tug	0-+	GT	0.20	0.008	EP	1	0.19	0.008	RE	1	0.20	0.008	RE	1	0.27	0.011	TR	1
Vehicle	0-3999	vehicle	0.71	0.005	EP	1	0.71	0.006	TR	1	0.70	0.006	TR	1	0.78	0.006	TR	2
	4000-+	vehicle	0.90	0.005	EP	1	0.90	0.006	TR	1	0.89	0.006	TR	1	0.90	0.006	TR	2
Yacht	0-+	GT	0.61	0.016	EP	3	0.55	0.018	TR	4	0.54	0.019	TR	5	0.63	0.021	RE	5

Figure 129 - The estimated international share of international CO_2 emissions

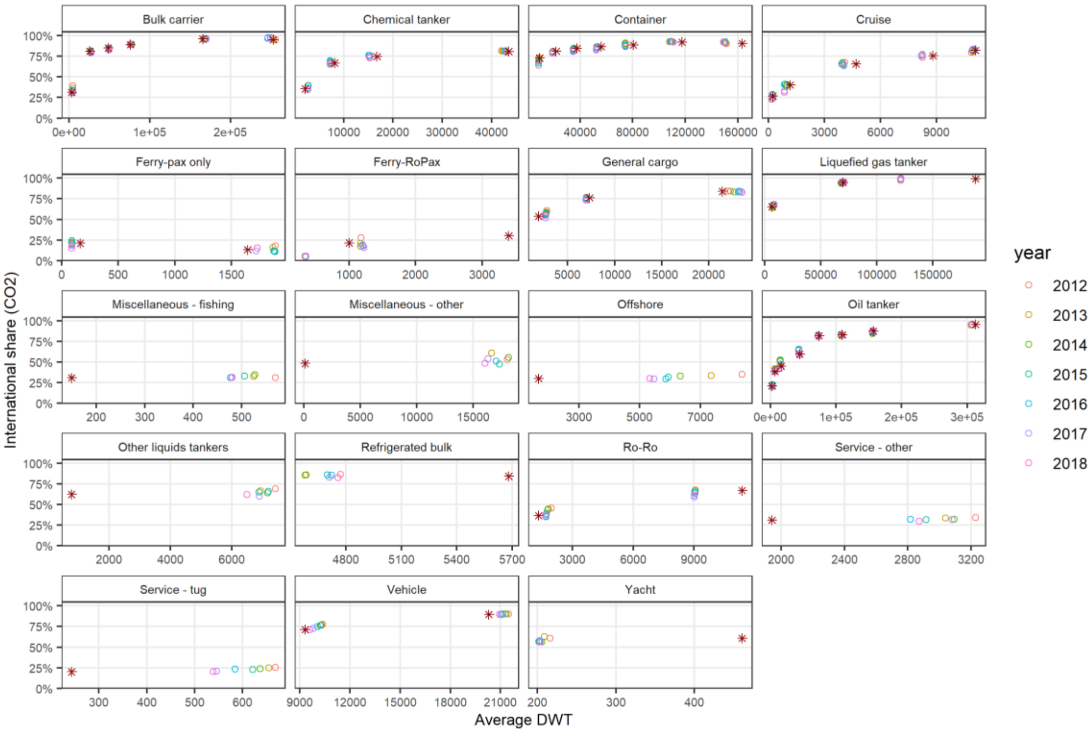


Figure 130 - The estimated international share of distance at sea

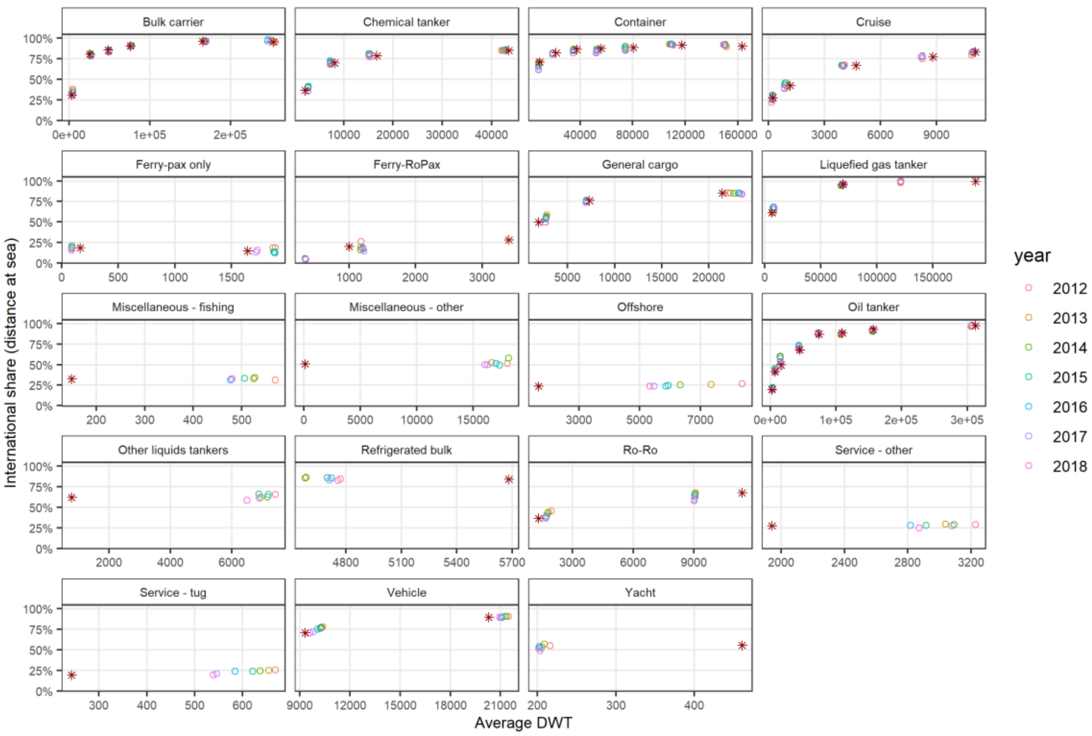


Figure 131 - The estimated international share of hours at sea

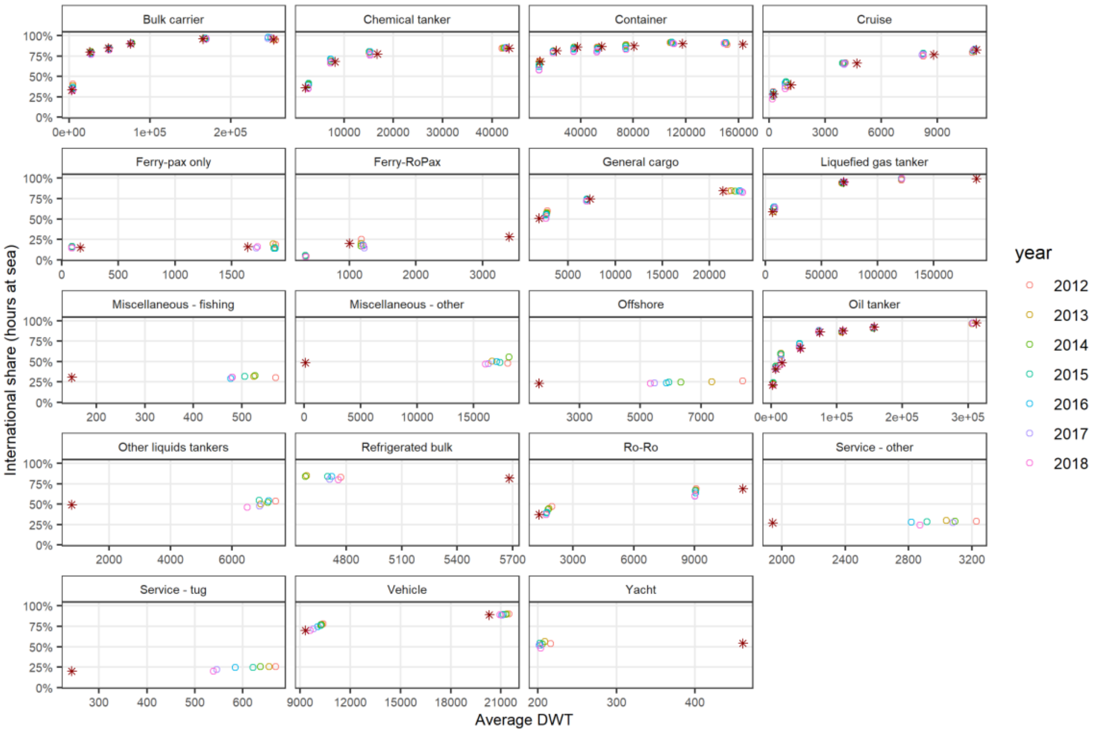
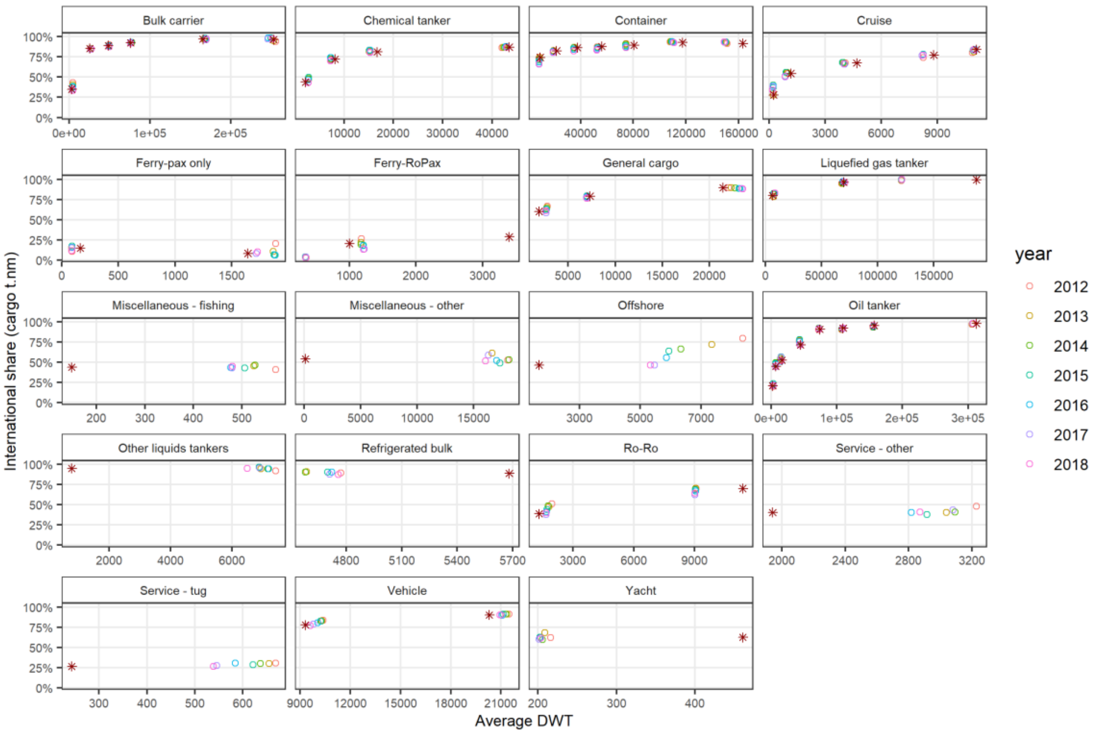


Figure 132 - The estimated international share of cargo tonne-miles



3.2.4 Method to quantify the trends of carbon intensity

The most straightforward way to quantify the carbon intensity trend in international shipping is to calculate the percentage change of a metric value in a given calendar year compared to the reference year value. To denote the carbon intensity metric value in the reference year and year y as CII_{ref} and CII_y, the percentage change in overall carbon intensity is calculated as $(CII_y - CII_{ref}) / CII_{ref} \times 100\%$. Such a comparison can capture the impacts of all drivers of carbon intensity performance, including a shift in the ship size composition of a fleet and consequently a shift in the proportion of transport work from each size category.

Single term power law functions in form of $CII = \alpha \cdot dwt^{\beta}$ can be additionally used to explore the effects of scale economy on changes in carbon intensity of international shipping. Such an approach borrows the philosophy of EEDI base-line functions (IMO, 2013c), which can generate a like-to-like comparison result based on individual performance. Following this approach, a shift in the ship size composition alone, e.g. bigger ships entered into the fleet whilst smaller ones scrapped, will not trigger a variation in the carbon intensity performance of a fleet. Such an analysis can provide an insight into the trends of carbon intensity of international shipping carbon intensity decoupled from the shift in ship size composition of a fleet, which is quite useful in IMO decision making.

Through a logarithmic transformation, a linear formula in form $\ln(CII) = \ln\alpha + \beta\ln(dwt)$ can be obtained. By introducing a dummy variable representing calendar years under observation (Wooldridge, 2015), the regression model for carbon intensity performance of a specific ship type i can be expressed as follows:

$$\ln(CII_y) = \ln\alpha_i + \beta_i \ln(dwt) + \delta_{i,y} year + \varepsilon \quad (15)$$

where CII_y generally represents a carbon intensity metric value of an individual ship in year y, dwt stands for a ship’s deadweight tonnage, $year$ is a binary variable equal to 1 or 0, representing a specific calendar year, for instance year 2013, 2014, … , and 2018, given the year 2012 as a reference; α_i, β_i, and $\delta_{i,y}$ are parameters to be estimated, and ε is the error term. Since the year 2012 has been taken as reference, the parameter $\delta_{i,y}$ can be interpreted as the carbon intensity variation of a ship type compared with its average performance in year 2012. For a small value of $\hat{\delta}_{i,y}$, for instance less than 5%, $\hat{\delta}_{i,y}$ can be an acceptable approximation of the factual percentage change. For a relatively large value of $\hat{\delta}_{i,y}$, the factual percentage change can be calculated through $\exp(\hat{\delta}_{i,y}) - 1$. The median estimator, instead of ordinary least squares estimator (OLS), is applied to estimate this function due to numerous outliers (Koenker, 2005).

The percentage change in individual based carbon intensity of the international shipping as a whole in year y, compared to the reference year, can be estimated through calculating the transport work weighted average percentage change of all ship types concerned, as per $\Delta_y = \sum_i \rho_{i,y} \cdot \left[\exp(\hat{\delta}_{i,y}) - 1\right]$, where Δ_y stands for the individual based percentage change of the whole fleet, $\rho_{i,y}$ is the transport work proportion of ship type i in year y.

Similarly, the trend in carbon intensity of international shipping, taking year 2008 as the reference, can be further estimated. Due to a lack in statistics of individual ships, the power law regression models of each ship type estimated on data in year 2012-2018 are taken as the basis. Taking the fitted regression model for ship type i in year 2012-2018,

$\ln(CII) = \ln\hat{\alpha}_i + \hat{\beta}_i \ln(DWT) + \hat{\delta}_{i,y} year$, as an example, the regression curve in year 2008 can be estimated as follows:

$$\ln(CII) = \ln\phi_i + \hat{\beta}_i \ln(DWT) + \varepsilon \qquad \textbf{(16)}$$

In this model, only the intercept $\ln\phi_i$ needs to be estimated, while the slope $\hat{\beta}_i$ can be inherited from the basic model as a given parameter. The rationale behind this model setting is that the carbon intensity level of a specific ship type (represented by the intercept of the regression curve) may vary, but the partial effect of a ship's capacity on her carbon intensity performance (represented by the slope of the regression curve) holds consistent over years. Then, the percentage change in carbon intensity performance of ship type i in year y , when compared to year 2008 (noted as $\Delta_{i,j}$), can be calculated as $\Delta_{i,j} = \exp(\ln\hat{\alpha}_i + \hat{\delta}_{i,y} - \ln\hat{\phi}_i) - 1$. Specifically, the percentage change in individual based carbon intensity of international shipping as a whole in year y , compared to year 2008, can be estimated through calculating the transport work weighted average percentage change of all ship types concerned, as per $\Delta_y = \sum_i \rho_{i,y} \cdot \left[\exp(\ln\hat{\alpha}_i + \hat{\delta}_{i,y} - \ln\hat{\phi}_i) - 1\right]$.

3.3 Estimates of carbon intensity, 2008 and 2012-2018

3.3.1 Carbon intensity per ship type and size category

The estimates on carbon intensity per ship type and size category in year 2008 and 2018, obtained through Option 1 and Option 2, are shown in Table 59, Table 60 and Table 61, while results of other years are provided in Annex E. Underlying data for carbon intensity calculation are additionally proved as an appendix to Annex E (as spreadsheets) for reference. Figure 133, as an instance, shows the carbon intensity ranges per size bin of bulk carriers over years, derived from both Option 1 and Option 2. Similar figures for other ship types can be found in Annex F. Since figures derived from the two options are quite similar to each other, only outputs based on Option 2 are presented in this annex.

Table 59 - Carbon intensity per ship type and size category in year 2008

Ship type	Size range	Units	EEOI (g-CO2/t/nm)		AER (g-CO2/DWT/nm)		DIST (kg CO2/nm)		TIME (t CO2/h)	
			OP1	OP2	OP1	OP2	OP1	OP2	OP1	OP2
Bulk carrier	0-9999	dwt	55,89	48,67	41,47	41,81	128,56	129,61	1,32	1,25
	10000-34999	dwt	20,66	19,16	9,89	9,96	252,37	254,19	3,08	3,13
	35000-59999	dwt	14,07	13,10	6,52	6,49	314,66	313,12	4,00	4,01
	60000-99999	dwt	12,58	11,82	5,33	5,25	404,53	398,08	5,30	5,24
	100000-199999	dwt	8,03	7,75	3,66	3,66	606,60	605,29	8,01	8,00
	200000-+	dwt	4,61	4,44	2,45	2,44	619,19	616,99	7,74	7,71
Chemical tanker	0-4999	dwt	56,93	45,28	43,97	42,93	95,10	92,85	1,00	0,98
	5000-9999	dwt	35,46	32,32	20,42	19,54	166,73	159,56	1,97	1,93
	10000-19999	dwt	25,02	22,63	13,35	12,66	223,42	211,91	2,86	2,75
	20000-+	dwt	18,58	16,97	8,78	8,32	381,63	361,87	5,19	4,95
Container	0-999	TEU	31,62	30,48	23,18	23,84	215,23	221,34	2,84	3,03
	1000-1999	TEU	24,93	24,07	17,67	17,41	385,53	380,00	5,86	5,83
	2000-2999	TEU	16,61	15,97	14,71	14,40	552,44	540,82	9,23	9,06
	3000-4999	TEU	21,66	20,95	12,24	12,13	686,15	679,65	12,42	12,41
	5000-7999	TEU	20,59	20,05	11,77	11,79	947,62	949,33	18,67	18,98
	8000-11999	TEU	17,06	16,65	9,30	9,34	1090,86	1095,97	22,14	22,63
	12000-14500	TEU	14,26	13,83	8,26	8,28	1347,62	1351,17	25,87	26,15
Cruise	0-1999	GT	876,46	832,56	606,90	583,13	146,26	140,54	1,36	1,28
	2000-9999	GT	286,13	210,25	179,12	169,14	210,29	198,57	2,40	2,43
	10000-59999	GT	186,33	181,11	172,13	169,04	806,78	792,30	11,94	11,86
	60000-99999	GT	211,16	206,62	210,27	205,99	1852,44	1814,77	30,19	29,79
	100000-+	GT	215,75	210,11	180,67	178,33	2003,30	1977,37	34,26	34,03
Ferry-pax only	0-1999	GT	–	1825,16	–	458,41	–	74,26	–	1,69
	2000-+	GT	150,93	241,20	134,67	120,62	221,26	198,19	2,90	2,42
Ferry-RoPax	0-1999	GT	–	167,74	–	105,09	–	105,09	–	1,23
	2000-+	GT	278,56	292,46	111,55	119,45	379,28	406,13	6,52	6,95
General cargo	0-4999	dwt	38,27	33,39	32,16	34,79	61,24	66,24	0,56	0,60
	5000-9999	dwt	38,77	36,44	19,58	19,64	143,32	143,81	1,62	1,66
	10000-+	dwt	26,72	24,45	13,13	12,96	281,65	277,85	3,63	3,62
Liquefied gas tanker	0-49999	cbm	58,72	48,04	33,56	35,89	219,60	234,85	2,68	2,98
	50000-199999	cbm	15,76	15,48	8,94	8,84	624,44	617,81	9,37	9,31
	200000-+	cbm	5,90	5,87	3,24	3,23	610,73	607,78	10,69	10,64
Miscellaneous - fishing	0-+	GT	–	654,84	–	443,88	–	66,14	–	0,66
Miscellaneous - other	0-+	GT	–	1988,19	–	1299,98	–	131,30	–	1,13
Offshore	0-+	GT	–	390,64	–	124,82	–	207,94	–	2,04
Oil tanker	0-4999	dwt	102,76	101,45	66,54	70,55	127,03	134,68	1,22	1,19
	5000-9999	dwt	52,88	44,87	28,13	26,13	192,87	179,19	1,95	1,83
	10000-19999	dwt	38,47	32,45	19,21	17,39	308,74	279,57	3,33	3,08
	20000-59999	dwt	25,31	20,82	8,37	7,31	372,62	325,48	4,73	4,24
	60000-79999	dwt	18,97	16,91	6,73	6,31	497,91	467,12	6,67	6,33
	80000-119999	dwt	14,53	12,94	5,13	4,81	561,48	526,23	7,41	7,01
	120000-199999	dwt	13,76	12,47	4,56	4,30	715,13	673,73	9,73	9,21
	200000-+	dwt	7,95	7,67	3,21	3,15	1005,29	983,55	14,68	14,39
Other liquids tankers	0-+	dwt	121,48	79,63	482,19	484,40	373,70	375,41	2,88	3,64
Refrigerated bulk	0-9999	dwt	79,71	73,85	58,07	58,29	329,89	331,17	4,52	4,66
Ro-Ro	0-4999	dwt	375,54	354,52	222,49	223,93	291,46	293,34	2,89	2,84
	5000-+	dwt	61,93	59,06	40,07	39,76	456,81	453,22	6,58	6,40
Service - other	0-+	GT	–	127,29	–	85,95	–	166,82	–	1,53
Service - tug	0-+	GT	–	863,40	–	409,45	–	99,50	–	0,82
Vehicle	0-3999	vehicle	107,00	98,30	30,89	31,12	287,73	289,91	4,29	4,37
	4000-+	vehicle	67,17	66,75	17,42	17,36	353,64	352,42	5,91	5,94
Yacht	0-+	GT	–	432,45	–	247,87	–	114,27	–	1,49

Table 60 - Carbon intensity per ship type and size category in year 2018 (Option 1)

Ship type	Size category	Units	EEOI (g-CO2/t/nm)					AER (g-CO2/DWT/nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	37,9	44,9	30,8	69,7	0,87	22,8	25,5	18,1	40,3	0,87	111,6	110,0	88,2	139,5	0,47	1,0	1,0	0,8	1,4	0,59
	10000-34999	dwt	12,7	12,8	10,8	16,8	0,47	7,6	7,4	6,7	8,7	0,26	212,0	208,5	187,4	232,7	0,22	2,3	2,3	2,0	2,7	0,30
	35000-59999	dwt	9,4	9,5	8,2	11,4	0,34	5,4	5,4	4,9	6,1	0,22	268,6	269,9	242,1	297,6	0,21	3,1	3,0	2,7	3,4	0,24
	60000-99999	dwt	7,9	7,8	6,8	9,2	0,30	4,1	4,1	3,7	4,6	0,20	315,0	306,6	284,1	341,5	0,19	3,6	3,5	3,2	4,0	0,22
	100000-199999	dwt	5,3	5,3	4,7	6,1	0,26	2,7	2,7	2,5	3,0	0,19	465,5	459,9	416,6	508,2	0,20	5,2	5,1	4,5	5,8	0,25
	200000-+	dwt	4,7	4,8	4,2	5,4	0,26	2,3	2,3	2,1	2,5	0,19	584,9	544,7	480,0	652,1	0,32	6,9	6,5	5,5	7,9	0,38
Chemical tanker	0-4999	dwt	68,5	82,7	47,4	163,0	1,40	52,6	62,2	36,6	116,2	1,28	152,0	148,6	120,7	218,0	0,65	1,5	1,5	1,2	2,0	0,51
	5000-9999	dwt	39,2	39,9	32,7	51,5	0,47	28,5	29,2	23,6	37,5	0,48	209,9	208,7	179,4	253,3	0,35	2,2	2,2	1,8	2,6	0,38
	10000-19999	dwt	25,2	27,2	21,4	34,1	0,47	17,4	18,1	14,7	22,3	0,42	270,3	268,8	229,5	324,6	0,35	3,1	3,1	2,6	3,7	0,35
	20000-39999	dwt	16,6	16,8	14,2	20,0	0,35	11,5	11,3	10,0	13,6	0,32	367,8	370,0	318,8	432,1	0,31	4,4	4,5	3,9	5,2	0,29
	40000-+	dwt	12,9	12,9	11,1	15,1	0,31	7,8	7,8	6,9	9,0	0,27	382,4	380,6	341,1	425,2	0,22	4,5	4,6	4,0	5,1	0,25
Container	0-999	teu	35,3	36,7	29,7	48,5	0,52	23,4	24,1	20,0	30,8	0,45	208,1	205,4	174,4	244,4	0,34	2,5	2,4	1,8	3,1	0,55
	1000-1999	teu	26,9	27,4	23,7	31,9	0,30	17,0	17,3	15,1	20,5	0,31	326,1	320,7	281,8	364,6	0,26	4,4	4,3	3,6	5,0	0,33
	2000-2999	teu	19,9	19,5	17,3	22,4	0,26	12,0	11,5	10,3	13,4	0,27	417,4	396,7	360,4	448,2	0,22	5,9	5,5	4,8	6,6	0,33
	3000-4999	teu	17,1	17,1	14,8	19,2	0,26	10,5	10,3	9,2	11,5	0,23	556,9	525,7	472,8	601,6	0,25	8,2	7,7	6,6	9,3	0,34
	5000-7999	teu	16,3	16,3	14,5	18,1	0,22	9,9	9,8	8,8	11,0	0,22	746,3	748,3	646,9	830,4	0,25	11,7	11,7	9,8	13,6	0,32
	8000-11999	teu	13,4	13,6	12,0	15,2	0,24	8,2	8,3	7,6	9,0	0,17	908,6	909,8	843,6	976,8	0,15	14,8	14,8	13,4	16,3	0,20
	12000-14499	teu	10,8	10,7	9,7	12,2	0,23	6,8	6,8	6,1	7,4	0,19	1010,3	1026,5	900,2	1125,6	0,22	16,5	16,7	14,3	18,7	0,26
	14500-19999	teu	8,1	8,5	6,8	8,9	0,25	5,4	5,5	4,5	5,8	0,24	972,4	1059,5	787,3	1107,0	0,30	16,1	17,1	13,2	18,4	0,30
	20000-+	teu	7,9	8,0	6,7	9,5	0,34	4,9	5,2	4,1	6,2	0,40	960,3	1041,5	791,2	1188,3	0,38	15,6	17,8	12,6	20,7	0,46
General cargo	0-4999	dwt	36,5	38,9	29,7	53,7	0,62	25,3	25,3	19,5	39,1	0,78	71,6	69,3	58,3	81,4	0,33	0,6	0,6	0,5	0,8	0,50
	5000-9999	dwt	30,8	31,8	25,9	40,5	0,46	19,4	19,4	16,4	23,4	0,36	138,7	132,8	115,8	159,8	0,33	1,4	1,3	1,0	1,6	0,44
	10000-19999	dwt	28,9	28,4	24,3	36,4	0,43	17,1	17,0	14,9	19,3	0,26	230,9	216,6	193,0	261,4	0,32	2,6	2,4	2,1	3,1	0,42
	20000-+	dwt	14,1	14,6	11,8	19,2	0,51	8,3	8,6	6,8	10,9	0,48	309,2	295,7	257,7	336,9	0,27	3,7	3,5	3,0	4,2	0,35
Liquefied gas tanker	0-49999	cbm	46,0	67,1	45,6	115,6	1,04	23,4	38,5	21,5	72,6	1,33	224,3	214,5	167,5	294,5	0,59	2,6	2,5	1,9	3,8	0,77
	50000-99999	cbm	20,4	20,8	18,1	25,1	0,34	9,5	9,3	8,5	10,6	0,22	508,6	501,9	466,9	546,9	0,16	7,2	7,2	6,6	7,9	0,18
	100000-199999	cbm	16,3	16,4	13,5	19,3	0,36	10,6	10,3	8,9	12,3	0,33	884,4	855,1	753,7	1008,4	0,30	13,2	12,7	10,7	15,9	0,40
	200000-+	cbm	18,0	16,9	14,9	24,7	0,57	10,6	10,3	9,6	11,7	0,20	1281,6	1262,8	1191,5	1332,7	0,11	20,5	20,4	19,2	21,5	0,11
Oil tanker	0-4999	dwt	83,4	114,6	62,1	262,5	1,75	59,3	71,3	43,4	177,0	1,87	176,8	183,2	127,9	386,1	1,41	1,6	1,7	1,2	2,7	0,91
	5000-9999	dwt	57,8	64,6	44,9	137,9	1,44	35,6	37,0	27,1	65,0	1,03	242,1	240,5	183,2	452,6	1,12	2,2	2,3	1,7	3,5	0,77
	10000-19999	dwt	44,0	52,2	36,8	92,9	1,07	23,9	24,3	18,9	37,9	0,79	353,7	340,1	267,0	562,2	0,87	3,5	3,5	2,8	5,2	0,70
	20000-59999	dwt	26,3	26,6	20,7	37,6	0,64	11,1	10,6	8,8	14,3	0,52	494,4	467,7	405,6	568,7	0,35	5,6	5,4	4,7	6,4	0,32
	60000-79999	dwt	15,5	15,4	12,6	20,1	0,49	7,1	6,8	6,0	8,3	0,34	516,9	498,2	445,0	593,6	0,30	6,0	5,8	5,2	6,9	0,30
	80000-119999	dwt	12,0	12,0	9,6	16,3	0,56	5,2	5,0	4,5	6,0	0,30	566,4	551,3	492,5	640,7	0,27	6,4	6,2	5,5	7,3	0,29
	120000-199999	dwt	9,3	8,9	7,6	11,5	0,44	4,4	4,2	3,8	4,9	0,26	681,4	654,6	597,9	761,7	0,25	7,8	7,5	6,8	8,7	0,25
	200000-+	dwt	5,7	5,6	4,9	6,7	0,33	2,7	2,6	2,4	2,9	0,20	828,1	811,2	727,2	902,6	0,22	9,9	9,6	8,4	11,1	0,28

Add.1 Carbon intensity per ship type and size category in year 2018 (Option 1)

Ship type	Size category	Units	EEOI (gCO2/t/nm)					AER (gCO2/dwt/nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids tankers	0-999	dwt	1342,2	1852,6	1633,5	2245,6	0,33	1163,0	1640,0	1152,8	1883,4	0,45	492,6	899,8	522,2	1062,2	0,60	3,5	6,0	3,3	6,7	0,56
	1000-+	dwt	27,4	40,3	21,5	131,4	2,73	17,4	19,6	14,3	87,0	3,72	375,1	304,6	229,0	383,5	0,51	4,8	3,8	2,0	4,9	0,77
Ferry-pax only	2000-+	gt	127,7	133,6	104,2	349,4	1,84	110,7	120,9	95,0	320,7	1,87	231,9	173,5	136,5	306,1	0,98	2,9	2,1	1,5	4,2	1,31
Cruise	0-1999	gt	928,0	1497,1	745,6	1868,7	0,75	810,6	1358,0	666,3	1702,6	0,76	254,8	257,7	204,3	407,1	0,79	2,2	2,2	1,7	3,2	0,68
	2000-9999	gt	316,2	523,9	264,8	1079,8	1,56	290,8	472,6	238,9	1013,6	1,64	257,6	279,8	179,8	447,4	0,96	2,4	2,5	1,8	3,6	0,73
	10000-59999	gt	149,1	159,2	112,3	272,9	1,01	132,9	145,8	103,2	237,9	0,92	582,0	574,9	480,3	671,1	0,33	7,9	7,9	6,5	9,1	0,33
	60000-99999	gt	166,4	171,0	146,0	188,9	0,25	150,4	156,1	132,0	170,5	0,25	1242,9	1248,8	1159,0	1319,0	0,13	19,0	19,3	17,1	21,0	0,20
	100000-149999	gt	143,9	150,7	124,6	167,6	0,29	130,8	140,3	115,4	153,9	0,27	1447,1	1405,3	1334,1	1554,7	0,16	23,2	23,0	20,9	24,7	0,16
	150000-+	gt	119,1	123,1	105,5	143,9	0,31	105,6	108,4	97,2	131,8	0,32	1450,9	1410,9	1328,9	1495,3	0,12	23,8	23,4	21,4	25,9	0,19
Ferry-RoPax	2000-4999	gt	270,7	355,7	217,1	693,9	1,34	211,3	259,5	171,5	422,3	0,97	193,0	185,1	147,1	250,2	0,56	2,2	1,9	1,4	2,8	0,76
	5000-9999	gt	215,2	274,0	153,1	537,3	1,40	159,0	199,7	104,2	368,2	1,32	313,4	308,9	242,9	403,0	0,52	4,1	3,6	2,4	5,8	0,94
	10000-19999	gt	144,2	181,2	112,2	297,1	1,02	109,7	121,9	86,6	201,8	0,95	478,1	473,8	366,0	571,1	0,43	7,2	6,3	4,7	8,7	0,64
	20000-+	gt	139,2	140,6	101,6	203,4	0,72	106,4	105,4	73,4	153,4	0,76	684,8	632,4	520,1	783,6	0,42	11,3	10,2	8,1	13,9	0,56
Refrigerated bulk	0-1999	dwt	190,7	218,1	148,3	445,5	1,36	152,6	180,1	115,5	322,3	1,15	189,3	189,3	146,5	316,1	0,90	1,7	1,7	1,3	2,8	0,88
	2000-5999	dwt	108,6	113,9	88,6	150,0	0,54	72,7	75,0	58,8	100,0	0,55	290,7	297,4	238,2	355,3	0,39	3,3	3,3	2,8	4,1	0,39
	6000-9999	dwt	81,2	85,9	70,3	110,2	0,46	48,2	49,4	42,4	61,7	0,39	366,4	371,6	329,2	427,8	0,27	5,0	5,1	4,3	5,9	0,33
	10000-+	dwt	60,3	63,2	51,0	80,9	0,47	36,4	37,1	32,4	43,4	0,29	463,5	458,3	421,8	510,5	0,19	7,5	7,5	6,6	8,3	0,22
Ro-Ro	0-4999	dwt	147,0	269,0	132,4	615,7	1,80	112,9	193,4	98,6	436,2	1,75	244,3	271,6	181,2	416,7	0,87	2,0	2,0	1,4	3,1	0,88
	5000-9999	dwt	67,6	66,2	54,2	86,0	0,48	51,1	50,8	40,5	63,1	0,44	357,0	356,4	286,0	410,5	0,35	5,1	5,0	3,4	6,6	0,65
	10000-14999	dwt	56,9	55,3	47,3	71,3	0,43	39,3	39,7	31,5	46,6	0,38	476,6	471,1	386,3	561,6	0,37	7,5	7,7	5,5	9,1	0,47
	15000-+	dwt	28,8	27,9	20,9	45,8	0,89	20,5	21,3	13,9	32,6	0,88	568,2	554,4	434,1	650,0	0,39	8,7	8,5	6,4	10,1	0,44
Vehicle	0-29999	gt	135,7	146,7	109,6	186,0	0,52	49,5	54,1	42,3	68,3	0,48	269,8	241,4	203,1	307,2	0,43	3,7	3,2	2,5	4,4	0,61
	30000-49999	gt	73,6	71,5	63,5	85,0	0,30	21,6	21,9	19,3	24,8	0,25	294,1	291,3	272,6	311,2	0,13	4,3	4,2	3,9	4,6	0,16
	50000-+	gt	57,4	57,8	49,2	69,5	0,35	16,4	16,5	15,2	18,2	0,19	344,0	335,6	312,7	363,7	0,15	5,3	5,2	4,8	5,7	0,18

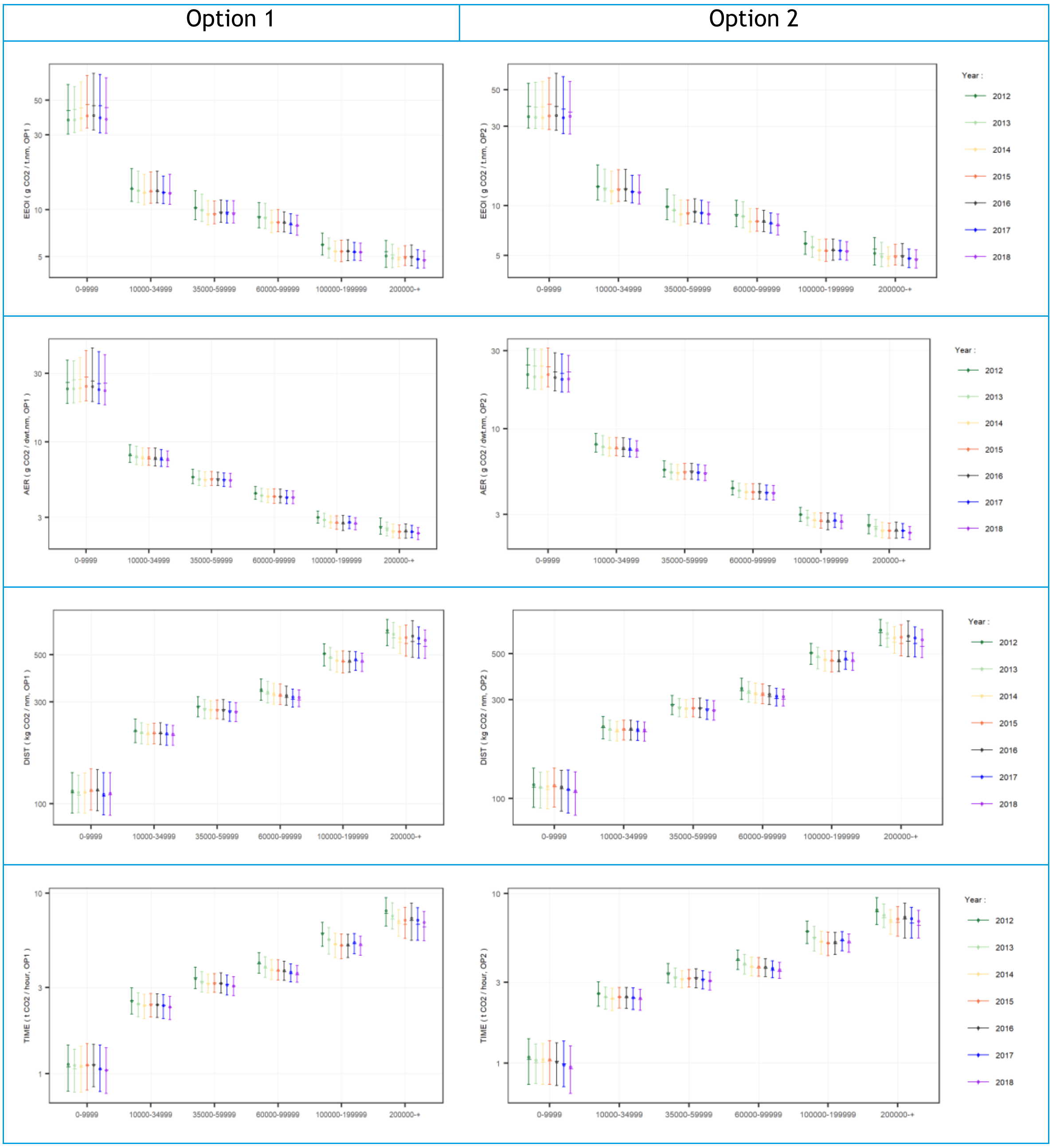
Table 61 - Carbon intensity per ship type and size category in year 2018 (Option 2)

Ship type	Size category	Units	EEOI ($g\text{-}CO_2/t/nm$)					AER ($g\text{-}CO_2/DWT/nm$)					DIST ($kgCO_2/nm$)					TIME (tCO_2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	34,5	36,6	26,9	55,9	0,79	20,2	22,2	16,8	28,1	0,51	108,9	107,1	83,1	134,4	0,48	1,0	0,9	0,7	1,3	0,65
	10000-34999	dwt	11,9	12,1	10,2	15,3	0,42	7,5	7,3	6,7	8,5	0,24	214,7	209,9	189,3	233,6	0,21	2,4	2,4	2,1	2,7	0,29
	35000-59999	dwt	8,9	8,9	7,7	10,5	0,31	5,3	5,4	4,8	6,0	0,22	266,2	267,3	238,3	296,0	0,22	3,1	3,0	2,7	3,5	0,25
	60000-99999	dwt	7,6	7,5	6,6	8,8	0,29	4,0	4,1	3,7	4,5	0,20	309,7	301,2	279,2	336,6	0,19	3,6	3,5	3,2	3,9	0,22
	100000-1999	dwt	5,3	5,3	4,7	6,1	0,26	2,7	2,7	2,5	3,0	0,19	463,5	458,6	415,4	505,2	0,20	5,2	5,1	4,5	5,8	0,25
	200000-+	dwt	4,7	4,7	4,2	5,4	0,25	2,3	2,3	2,1	2,5	0,19	583,6	542,5	478,7	653,8	0,32	6,9	6,5	5,5	7,9	0,38
Chemical tanker	0-4999	dwt	54,9	55,1	41,3	112,4	1,29	42,0	42,7	32,2	68,5	0,85	143,5	138,3	111,3	200,0	0,64	1,4	1,4	1,1	1,8	0,53
	5000-9999	dwt	36,6	37,7	31,2	48,0	0,45	27,1	27,8	22,6	35,2	0,45	200,9	200,8	171,6	238,8	0,33	2,1	2,1	1,8	2,5	0,37
	10000-19999	dwt	22,9	24,9	19,7	31,3	0,47	16,2	17,0	14,0	20,3	0,37	254,6	254,0	217,8	302,0	0,33	2,9	3,0	2,5	3,5	0,32
	20000-39999	dwt	15,4	15,8	13,4	18,6	0,33	10,9	10,9	9,6	13,0	0,31	349,3	351,1	302,6	411,4	0,31	4,3	4,3	3,7	4,9	0,28
	40000-+	dwt	11,9	12,1	10,5	13,8	0,27	7,4	7,5	6,6	8,5	0,26	361,5	364,0	324,6	401,8	0,21	4,3	4,3	3,8	4,9	0,25
Container	0-999	TEU	34,2	35,0	29,0	45,1	0,46	22,7	23,1	19,3	28,5	0,40	215,5	209,1	179,5	245,1	0,31	2,7	2,6	2,1	3,3	0,45
	1000-1999	TEU	26,2	26,8	23,2	30,8	0,28	16,7	17,0	14,7	19,7	0,29	319,0	314,5	274,7	357,6	0,26	4,3	4,2	3,6	5,0	0,33
	2000-2999	TEU	19,7	19,4	17,2	22,1	0,25	12,0	11,5	10,1	13,3	0,28	414,3	395,0	359,1	448,2	0,23	6,0	5,5	4,8	6,7	0,34
	3000-4999	TEU	17,0	16,9	14,8	19,1	0,26	10,6	10,3	9,2	11,6	0,23	562,5	525,9	471,3	608,0	0,26	8,5	7,9	6,7	9,6	0,36
	5000-7999	TEU	16,3	16,2	14,6	18,0	0,21	10,1	10,0	8,9	11,1	0,21	760,6	758,9	654,2	837,7	0,24	12,3	12,1	10,1	14,1	0,33
	8000-11999	TEU	13,3	13,4	11,8	15,1	0,24	8,3	8,3	7,6	9,0	0,17	913,3	911,1	843,5	978,9	0,15	15,2	15,1	13,6	16,6	0,20
	12000-14499	TEU	10,7	10,5	9,6	12,1	0,24	6,8	6,8	6,1	7,3	0,17	1010,3	1023,6	897,1	1126,6	0,22	16,7	16,9	14,5	19,1	0,27
	14500-19999	TEU	8,0	8,3	6,6	8,8	0,27	5,4	5,5	4,5	5,8	0,25	977,9	1068,8	775,0	1115,0	0,32	16,4	17,3	13,3	18,9	0,32
	20000-+	TEU	7,7	7,9	6,6	9,3	0,33	4,9	5,1	3,8	6,1	0,46	949,9	1024,2	736,6	1198,0	0,45	15,7	17,6	11,6	21,1	0,54
General cargo	0-4999	dwt	33,1	34,5	27,6	46,7	0,55	22,8	22,8	18,7	29,6	0,48	74,0	69,9	59,2	82,1	0,33	0,6	0,6	0,5	0,7	0,45
	5000-9999	dwt	29,7	30,4	24,6	38,4	0,45	19,0	18,8	15,9	22,5	0,35	137,5	129,2	111,9	152,5	0,31	1,4	1,3	1,0	1,6	0,45
	10000-19999	dwt	27,4	26,7	23,0	33,3	0,38	16,6	16,3	14,5	18,7	0,26	225,2	208,8	184,9	254,1	0,33	2,6	2,4	2,0	3,1	0,44
	20000-+	dwt	13,3	13,7	10,9	18,0	0,52	8,1	8,3	6,7	10,8	0,49	305,9	291,0	251,7	332,0	0,28	3,7	3,5	2,9	4,2	0,37
Liquefied gas tanker	0-49999	cbm	38,0	56,2	38,6	75,9	0,66	19,0	30,6	16,5	43,8	0,89	228,9	213,3	164,5	282,5	0,55	2,8	2,6	1,8	3,7	0,73
	50000-99999	cbm	20,0	20,4	18,0	24,0	0,29	9,4	9,2	8,5	10,4	0,21	499,0	496,3	460,1	530,2	0,14	7,1	7,1	6,5	7,8	0,17
	100000-1999	cbm	16,2	16,3	13,3	19,2	0,36	10,5	10,2	8,8	12,2	0,33	880,7	849,1	746,9	1005,8	0,30	13,2	12,7	10,6	15,6	0,40
	200000-+	cbm	18,0	16,9	14,9	24,7	0,57	10,6	10,3	9,6	11,7	0,20	1281,4	1262,8	1189,5	1332,7	0,11	20,5	20,4	19,2	21,5	0,11
Oil tanker	0-4999	dwt	73,0	95,8	49,4	238,7	1,98	51,8	59,8	35,2	154,2	1,99	171,3	180,0	116,2	384,8	1,49	1,4	1,5	0,9	2,5	1,07
	5000-9999	dwt	48,9	58,6	40,6	112,0	1,22	31,5	33,7	25,2	57,7	0,97	221,8	228,6	174,3	383,9	0,92	2,1	2,1	1,6	3,2	0,78
	10000-19999	dwt	36,2	41,9	26,2	89,0	1,50	21,3	22,0	16,9	31,1	0,65	312,1	312,1	252,8	393,7	0,45	3,2	3,1	2,7	3,9	0,37
	20000-59999	dwt	21,9	21,9	17,7	29,2	0,53	9,5	9,2	8,2	11,1	0,32	430,5	423,5	375,6	487,9	0,27	5,0	5,0	4,4	5,6	0,25
	60000-79999	dwt	13,9	14,0	11,7	17,0	0,38	6,6	6,4	5,7	7,6	0,29	481,7	466,3	427,2	543,3	0,25	5,7	5,5	5,0	6,5	0,27
	80000-11999	dwt	10,8	11,0	9,0	14,1	0,47	4,8	4,8	4,3	5,5	0,25	532,5	526,8	472,0	596,6	0,24	6,0	5,9	5,3	6,9	0,27
	120000-1999	dwt	8,6	8,4	7,3	10,1	0,34	4,1	4,0	3,7	4,5	0,19	647,1	628,8	581,7	704,2	0,19	7,4	7,3	6,6	8,2	0,22
	200000-+	dwt	5,6	5,5	4,8	6,6	0,33	2,6	2,6	2,3	2,9	0,20	814,5	794,8	716,2	886,9	0,21	9,7	9,5	8,3	10,9	0,27

Add.1 Carbon intensity per ship type and size category in year 2018 (Option 2)

Ship type	Size category	Units	EEOI ($gCO_2/t/nm$)					AER ($gCO_2/t/nm$)					DIST ($kgCO_2/nm$)					TIME (tCO_2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	626,4	1534,4	953,7	1579,3	0,41	526,4	1390,6	849,6	1414,9	0,41	176,0	871,9	482,2	886,4	0,46	1,2	4,6	2,6	4,6	0,43
	1000-+	dwt	25,6	23,4	20,4	100,1	3,41	16,2	17,7	13,2	71,3	3,29	411,0	312,9	283,0	409,9	0,41	5,7	4,4	3,4	5,6	0,50
Ferry-pax only	0-299	GT	800,7	1090,5	825,4	1674,1	0,78	692,4	1004,5	739,6	1540,3	0,80	40,4	43,6	33,0	53,2	0,46	0,6	0,7	0,4	0,8	0,59
	300-999	GT	987,5	1440,6	936,0	2050,1	0,77	767,1	1118,2	763,8	1439,2	0,60	60,6	61,8	44,2	78,2	0,55	1,0	1,0	0,7	1,4	0,74
	1000-1999	GT	290,2	286,1	241,2	328,1	0,30	272,2	268,4	226,3	307,7	0,30	115,5	102,6	81,4	161,2	0,78	1,2	1,2	0,9	2,3	1,22
	2000-+	GT	184,1	290,8	203,7	405,3	0,69	151,4	229,6	155,9	306,9	0,66	220,9	169,1	156,7	199,4	0,25	2,7	1,9	1,7	3,3	0,82
Cruise	0-1999	GT	661,3	712,9	522,3	1364,3	1,18	568,6	605,1	470,4	1064,6	0,98	237,0	183,9	116,9	255,9	0,76	2,1	1,6	1,1	2,3	0,76
	2000-9999	GT	211,9	329,2	188,4	872,5	2,08	195,1	309,2	166,6	819,3	2,11	207,5	195,3	148,9	263,4	0,59	2,1	2,1	1,6	2,5	0,43
	10000-59999	GT	146,3	152,4	110,5	252,2	0,93	129,7	138,9	100,2	205,3	0,76	566,1	540,6	456,3	653,7	0,37	7,7	7,2	6,3	9,3	0,41
	60000-99999	GT	163,2	167,9	143,0	187,1	0,26	147,7	151,0	129,0	167,4	0,25	1218,4	1219,9	1144,9	1284,4	0,11	18,8	19,2	16,9	20,7	0,20
	100000-1499	GT	141,7	146,5	123,5	165,2	0,28	129,0	136,8	114,3	152,3	0,28	1435,6	1400,4	1311,3	1519,6	0,15	23,2	22,5	20,7	24,8	0,18
	150000-+	GT	116,8	121,8	100,3	142,5	0,35	103,7	107,7	90,3	131,4	0,38	1439,9	1394,5	1317,3	1495,3	0,13	23,7	23,2	21,9	25,9	0,17
Ferry-RoPax	0-1999	GT	545,8	730,2	348,9	1395,9	1,43	378,2	470,2	279,9	1078,2	1,70	112,3	119,8	86,5	183,8	0,81	1,2	1,2	0,7	2,2	1,28
	2000-4999	GT	343,8	352,2	218,7	856,6	1,81	270,9	257,9	186,6	518,8	1,29	194,4	177,1	149,6	253,5	0,59	2,1	1,9	1,3	3,0	0,91
	5000-9999	GT	242,3	262,9	142,3	540,3	1,51	170,7	190,1	102,3	396,7	1,55	302,5	318,5	212,7	432,8	0,69	4,1	3,8	2,2	5,6	0,90
	10000-19999	GT	138,3	190,2	112,2	278,4	0,87	102,5	116,2	85,8	175,1	0,77	423,7	414,6	340,1	537,0	0,47	5,6	5,7	4,4	7,3	0,49
	20000-+	GT	141,8	149,0	105,5	210,7	0,71	109,0	113,6	77,8	161,6	0,74	695,1	658,5	542,9	833,2	0,44	11,2	10,6	8,3	14,8	0,61
Refrigerated bulk	0-1999	dwt	181,7	202,6	133,3	391,9	1,28	146,1	161,8	104,2	326,1	1,37	193,6	187,4	141,7	282,5	0,75	1,8	1,7	1,3	2,6	0,79
	2000-5999	dwt	102,3	107,5	83,6	134,7	0,47	68,2	71,1	56,5	93,8	0,52	281,8	282,7	237,3	341,5	0,37	3,2	3,3	2,7	4,0	0,39
	6000-9999	dwt	79,2	82,2	68,8	105,2	0,44	47,1	47,7	41,3	59,7	0,39	358,8	363,0	323,1	418,0	0,26	5,0	5,0	4,1	5,8	0,34
	10000-+	dwt	58,9	62,9	50,4	77,5	0,43	35,8	36,5	32,0	42,9	0,30	456,4	452,9	412,6	503,4	0,20	7,4	7,5	6,5	8,2	0,23
Ro-Ro	0-4999	dwt	137,6	221,5	118,6	550,4	1,95	101,2	164,0	90,4	377,7	1,75	243,6	264,3	171,6	402,5	0,87	2,0	2,0	1,3	3,1	0,92
	5000-9999	dwt	68,2	63,5	53,2	90,3	0,58	47,2	44,2	37,1	61,1	0,54	350,4	350,3	256,6	402,1	0,42	4,6	4,2	2,9	5,7	0,67
	10000-14999	dwt	54,8	53,4	47,0	70,3	0,44	38,5	39,7	31,2	45,3	0,36	474,7	467,7	388,0	561,3	0,37	7,5	7,6	5,4	9,0	0,47
	15000-+	dwt	26,6	27,1	20,1	42,1	0,81	18,8	17,8	13,3	30,6	0,97	532,7	537,4	428,8	645,4	0,40	8,0	8,2	6,4	10,0	0,45
Vehicle	0-29999	GT	139,7	143,6	104,7	196,6	0,64	45,5	49,3	36,9	66,0	0,59	269,5	253,2	210,5	293,2	0,33	3,6	3,4	2,7	4,2	0,47
	30000-49999	GT	72,7	70,4	62,0	83,2	0,30	21,3	21,7	19,1	24,5	0,25	291,5	287,9	270,3	308,2	0,13	4,3	4,2	3,9	4,6	0,17
	50000-+	GT	57,0	57,3	48,9	68,7	0,34	16,4	16,5	15,2	18,3	0,19	343,3	335,2	311,7	363,6	0,15	5,4	5,2	4,8	5,8	0,19
Yacht	0-+	GT	404,1	579,4	389,0	876,8	0,84	341,5	507,0	336,5	750,5	0,82	90,7	68,5	52,4	91,3	0,57	1,0	0,8	0,5	1,1	0,78
Service - tug	0-+	GT	185,6	375,3	157,5	764,1	1,62	147,4	302,3	121,3	611,5	1,62	132,5	119,0	77,0	179,8	0,86	0,8	0,8	0,4	1,3	1,13
Miscellaneous - fishing	0-+	GT	114,4	260,0	133,9	621,0	1,87	94,6	216,7	113,7	513,1	1,84	85,2	79,9	65,0	106,1	0,51	0,7	0,6	0,5	0,9	0,72
Offshore	0-+	GT	73,0	188,8	109,1	463,0	1,87	46,3	113,3	66,8	308,7	2,13	295,3	265,8	169,9	437,3	1,01	2,5	2,1	1,3	3,6	1,09
Service - other	0-+	GT	57,8	157,1	69,6	482,2	2,63	42,7	127,2	50,5	357,1	2,41	205,6	179,5	118,8	286,1	0,93	1,7	1,4	0,9	2,3	1,00
Miscellaneous - other	0-+	GT	37,4	47,0	28,9	66,7	0,80	27,3	33,5	19,7	58,3	1,15	442,5	435,3	307,4	583,0	0,63	5,1	5,0	3,1	7,0	0,77

Figure 133 - Carbon intensity ranges per size category of bulk carriers



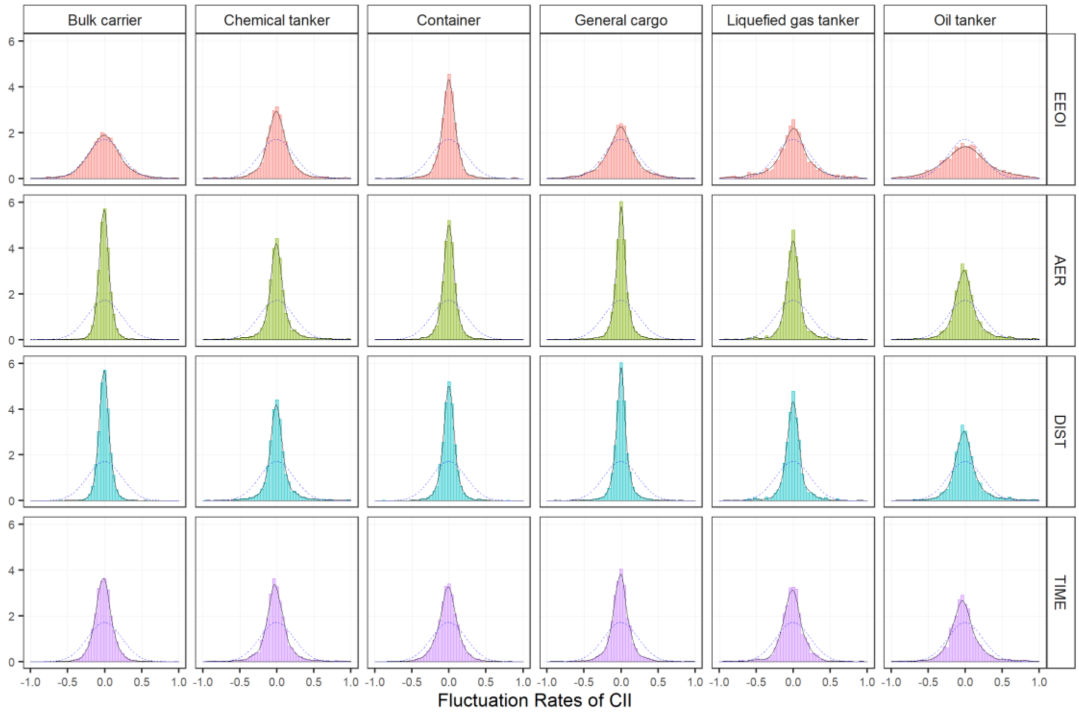
In these figures, values of EEOI and AER of individual ships of a specific type generally decreased with ship size, while values of DIST and TIME increased. This means the differences between operational carbon intensity of ships, no matter which metric has been applied, are first of all determined by ship size, which is a general proxy of design efficiency. Large spread ranges of metric values have been observed across all ship types and size bins, which are mainly caused by the differences in design and operational profiles of individual ships, as well as the various external influencing factors. To quantify such spreads, the carbon intensity spread scale per ship type and size bin is defined as the ratio of interquartile to median. The results are reported in conjunction with the CII metric values in Table 60, **Table 61** and Annex E. It is observed that the spread scales in all metrics are generally larger for smaller ships whist smaller for larger ships across all ship types. As per ship types, the largest spread scales of EEOI, ranging from 0.4 to 2.0, have been observed in oil tankers. This is followed by general cargo ships, bulk carriers, liquefied gas tankers and chemical tankers, with spread scales in EEOI roughly ranging from 0.3 to 0.8. Spread scales in AER are a little bit smaller than in EEOI due to its immunity to variations in payload utilization, yet held similar features with EEOI between ship types.

Further to the differences between ship type and size categories, carbon intensity of a specific individual ship also varies over time, due to the various operational and navigational conditions beyond control. To measure such fluctuation scales, annual fluctuation rate of carbon intensity of a specific ship i in year y is defined as $F_{i,y} = 2(CII_{i,y} - CII_{i,y-1}) / (CII_{i,y} + CII_{i,y-1}) \times 100\%$. **Figure 134** shows the distribution of annual carbon intensity fluctuation rates of typical cargo ship types in year 2013 to 2018. The upper and lower quartiles of fluctuations in EEOI of oil tankers, bulk carriers and container ships were around $\pm$20%, $\pm$15% and $\pm$10% respectively. The fluctuations in EEOI of general cargo ships, liquefied gas tankers and chemical tankers were a little bit smaller than bulk carriers, yet still more significant than container ships. The fluctuation magnitude in other metrics was relatively smaller, where the quartiles still generally reach beyond $\pm$5%.

In estimating CO_2 emissions in Chapter 2, this study applied a constant 9% resistance (and therefore fuel consumption and emissions) penalty to reflect the impacts of hull fouling, and assumed a static 10% or 15% in cease in propulsion requirements of coastal or ocean-going ships. These assumptions may not cause big problems in estimating the aggregated emissions in the absence of additional empirical data, but can significantly smooth the carbon intensity performance of individual ships and consequently narrow down the fluctuation magnitudes. Given the sensitivity of carbon intensity performance of individual ships to hull fouling and weather conditions, the factual fluctuations of all ship types were possibly more scattered than estimated.

Besides, the relatively small EEOI fluctuation magnitudes of container ships were possibly in disguise. Compared with oil tankers and bulk carrier, the variability of loading conditions of container ships is much higher, which should therefore lead to a higher volatile carbon intensity performance. However, such variations may not be fully captured by the manually entered ship draughts into AIS data, because these entries are not compulsory and not always updated timely. Since these draughts have been used for cargo mass estimation and subsequent EEOI calculations, factual fluctuation rates of container ships could be much higher than estimated, even possibly higher than oil tankers.

Figure 134 - Distribution of annual carbon intensity fluctuation rates of typical cargo ships



3.3.2 Carbon intensity and trends per ship type

The carbon intensity level per ship type, in conjunction with the percentage changes based on overall and individual performance, are reported in Table 62 and Table 63. Figure 135 to Figure 138 illustrate the carbon intensity levels of typical cargo ship types from 2012 to 2018, as well as in 2008, derived from Option 1 and Option 2 in parallel, indicated in four carbon intensity metrics. Underlying data for carbon intensity calculation are additionally proved as an appendix to Annex E (as spreadsheets) for reference.

As explained in Section 3.2.4, the percentage changes of overall carbon intensity of ship types in these tables are calculated on aggregated data, while the individual based percentage changes are calculated through power low regression fit. The overall design efficiency of the fleet depends on both individual design efficiency and size composition of the population. If all else is equal, a shift in fleet size composition, i.e. an increase or decrease in average deadweight tonnage of the fleet, will lead to changes in the overall design efficiency of the fleet, and consequently the changes in overall carbon intensity. However, such a shift in fleet size composition will not trigger changes in individual based carbon intensity. Therefore, the decreasing trend in individual based carbon intensity was generally less significant than in overall carbon intensity.

Under different strategies for splitting international and domestic shipping, the estimates on carbon intensity of international shipping are slightly different. Under Option 1, ships covered by certain types have been undifferentiated categorized as international regardless of their sizes and operational features, which therefore counted in a number of small ships merely or mainly serving domestic transportation. As a result, carbon intensity levels estimated through Option 1 were a little bit higher than (i.e. inferior to) those derived from Option 2. Furthermore, shifts in size composition of a ship type also varied when different individual ships have been taken as the population, which yielded different carbon intensity trends. Due to a larger proportion of small ships under Option 1, the population under this option has more potential in carbon intensity reduction. Therefore, the estimated reduction rates were different when different options have been applied. Such differences were around 1 to 5 percentage points higher under Option 1 for main cargo ship types when measured in EEOI, and generally smaller than 2 percentage points higher in AER. For the sake of brevity, results derived from both Option 1 and Option 2 are reported, but discussions on trends and drivers of carbon intensity have mainly focused on Option 2 unless otherwise specified, in line with other chapters of this study.

Table 62 - Carbon intensity per ship type and percentage changes indexed at year 2008 (Option 1)

Ship type	Year	EEOI ($g\text{-}CO_2/t/nm$)			AER ($g\text{-}CO_2/DWT/nm$)			DIST ($kgCO_2/nm$)			TIME (tCO_2/h)		
		value	percentage change		value	percentage change		value	percentage change		value	percentage change	
			overall	individual		overall	individual		overall	individual		overall	individua l
Bulk carrier	2008	12,16	–	–	5,56	–	–	339,90	–	–	4,23	–	–
	2012	8,25	-32,12%	-24,42%	4,28	-23,11%	-14,06%	325,99	-4,09%	-14,06%	3,82	-9,68%	-22,31%
	2013	7,99	-34,25%	-26,48%	4,13	-25,84%	-16,78%	316,73	-6,82%	-16,78%	3,63	-14,23%	-26,64%
	2014	7,56	-37,81%	-30,00%	4,00	-28,08%	-17,98%	314,41	-7,50%	-17,98%	3,55	-15,99%	-28,82%
	2015	7,59	-37,61%	-29,24%	3,97	-28,59%	-17,97%	315,87	-7,07%	-17,97%	3,57	-15,49%	-28,37%
	2016	7,57	-37,69%	-28,94%	3,92	-29,50%	-18,64%	318,02	-6,44%	-18,64%	3,61	-14,58%	-28,86%
	2017	7,40	-39,13%	-30,81%	3,89	-30,14%	-19,54%	316,05	-7,02%	-19,54%	3,59	-15,21%	-29,87%
	2018	7,30	-39,96%	-31,73%	3,83	-31,19%	-20,24%	314,97	-7,34%	-20,24%	3,54	-16,28%	-31,09%
Chemical tanker	2008	22,61	–	–	11,24	–	–	238,42	–	–	2,91	–	–
	2012	19,55	-13,51%	0,64%	12,85	14,30%	26,91%	285,48	19,74%	26,91%	3,32	13,87%	13,03%
	2013	19,44	-14,00%	1,32%	12,78	13,65%	28,40%	288,25	20,90%	28,40%	3,29	13,13%	13,16%
	2014	19,51	-13,70%	2,05%	12,78	13,69%	29,82%	296,18	24,22%	29,83%	3,35	15,02%	13,78%
	2015	19,27	-14,78%	2,53%	12,60	12,07%	31,01%	301,52	26,46%	30,99%	3,43	17,68%	14,87%
	2016	18,94	-16,20%	2,44%	12,41	10,34%	29,74%	304,64	27,77%	29,74%	3,50	20,17%	14,32%
	2017	18,32	-18,98%	0,07%	11,83	5,17%	25,21%	291,31	22,18%	25,21%	3,31	13,76%	9,07%
	2018	18,10	-19,92%	0,62%	11,69	3,93%	25,47%	292,91	22,85%	25,47%	3,27	12,35%	7,28%
Container	2008	20,72	–	–	12,95	–	–	577,46	–	–	9,47	–	–
	2012	18,11	-12,59%	-17,48%	11,11	-14,25%	-11,03%	543,56	-5,87%	-11,01%	8,21	-13,23%	-21,22%
	2013	17,23	-16,85%	-20,30%	10,57	-18,39%	-13,56%	529,35	-8,33%	-13,54%	7,78	-17,79%	-25,81%
	2014	16,22	-21,72%	-22,49%	10,09	-22,06%	-15,55%	528,34	-8,51%	-15,55%	7,60	-19,66%	-29,14%
	2015	16,13	-22,13%	-21,20%	9,77	-24,57%	-16,56%	529,57	-8,29%	-16,56%	7,58	-19,88%	-30,55%
	2016	16,11	-22,22%	-19,16%	9,80	-24,33%	-14,75%	550,99	-4,58%	-14,75%	7,96	-15,92%	-28,25%
	2017	15,79	-23,81%	-20,83%	9,74	-24,79%	-14,79%	562,25	-2,63%	-14,79%	8,16	-13,78%	-28,28%
	2018	15,29	-26,18%	-21,34%	9,49	-26,71%	-15,00%	568,78	-1,50%	-15,00%	8,19	-13,47%	-29,47%
General cargo	2008	32,33	–	–	17,83	–	–	121,47	–	–	1,24	–	–
	2012	25,44	-21,31%	-24,15%	15,59	-12,54%	-7,70%	142,76	17,53%	-7,70%	1,43	15,91%	-16,63%
	2013	25,02	-22,61%	-24,19%	15,27	-14,37%	-7,98%	140,74	15,86%	-7,98%	1,39	12,68%	-17,96%
	2014	24,57	-23,99%	-24,50%	15,07	-15,46%	-7,86%	141,50	16,49%	-7,86%	1,40	12,80%	-18,51%
	2015	25,35	-21,58%	-21,89%	14,90	-16,43%	-7,79%	143,45	18,10%	-7,79%	1,41	14,29%	-18,93%
	2016	25,71	-20,48%	-20,92%	14,82	-16,87%	-7,86%	144,49	18,95%	-7,86%	1,42	15,15%	-18,54%
	2017	24,44	-24,39%	-23,07%	14,55	-18,38%	-9,59%	141,91	16,82%	-9,59%	1,40	13,39%	-20,65%
	2018	23,61	-26,96%	-23,98%	14,37	-19,44%	-8,79%	145,12	19,47%	-8,79%	1,42	14,40%	-20,76%
Liquified gas tanker	2008	19,16	–	–	10,84	–	–	392,48	–	–	5,22	–	–
	2012	20,11	4,99%	14,09%	13,10	20,85%	11,86%	519,97	32,48%	11,86%	7,00	34,14%	9,28%
	2013	20,35	6,23%	18,71%	12,90	19,03%	13,04%	526,14	34,06%	13,04%	6,99	33,94%	9,13%
	2014	20,20	5,45%	19,22%	12,56	15,88%	16,24%	534,84	36,27%	16,40%	7,12	36,50%	11,46%
	2015	20,77	8,43%	20,58%	12,63	16,55%	16,96%	532,15	35,59%	16,96%	7,08	35,70%	10,78%
	2016	20,76	8,36%	17,78%	12,30	13,52%	11,16%	523,07	33,27%	11,16%	6,96	33,36%	6,56%
	2017	20,06	4,72%	13,87%	11,85	9,39%	7,50%	515,80	31,42%	7,50%	6,82	30,77%	1,92%
	2018	19,50	1,79%	12,97%	11,55	6,57%	5,87%	532,52	35,68%	5,87%	7,04	34,88%	-0,47%
Oil tanker	2008	13,59	–	–	5,13	–	–	419,94	–	–	4,84	–	–
	2012	10,36	-23,77%	-13,01%	4,73	-7,66%	3,09%	506,89	20,70%	3,05%	5,72	18,16%	-6,90%
	2013	10,52	-22,65%	-14,42%	4,79	-6,59%	3,41%	503,68	19,94%	3,43%	5,51	13,88%	-9,29%
	2014	10,38	-23,64%	-14,68%	4,80	-6,34%	4,77%	514,68	22,56%	4,77%	5,58	15,33%	-9,19%
	2015	10,53	-22,54%	-11,70%	4,93	-3,82%	10,41%	539,69	28,52%	10,41%	5,94	22,76%	-2,82%
	2016	10,27	-24,45%	-13,18%	4,93	-3,75%	10,62%	552,62	31,59%	10,62%	6,12	26,51%	-2,06%
	2017	9,86	-27,44%	-15,76%	4,68	-8,73%	5,72%	528,03	25,74%	5,72%	5,76	19,00%	-8,21%
	2018	9,66	-28,95%	-17,64%	4,48	-12,59%	3,29%	527,31	25,57%	3,29%	5,67	17,16%	-12,16%

Add.1 Carbon intensity per ship type and percentage changes indexed at year 2008 (Option1)

Ship type	Year	EEOI (gCO2/t/nm)			AER (gCO2/dwt/nm)			DIST (kgCO2/nm)			TIME (tCO2/h)		
		value	percentage change		value	percentage change		value	percentage change		value	percentage change	
			overall	individual		overall	individual		overall	individual		overall	individual
Other liquids tankers	2008	121,48	–	–	482,19	–	–	373,70	–	–	2,88	–	–
	2012	39,63	-67,37%	199,34%	20,52	-95,75%	-50,85%	368,58	-1,37%	-50,85%	4,54	57,78%	-34,90%
	2013	31,61	-73,98%	183,30%	21,01	-95,64%	-50,70%	385,52	3,17%	-48,23%	4,82	67,57%	-32,30%
	2014	31,71	-73,90%	186,25%	18,78	-96,11%	-49,95%	384,76	2,96%	-49,95%	4,93	71,42%	-32,13%
	2015	26,73	-77,99%	117,86%	19,95	-95,86%	-50,95%	388,29	3,91%	-50,95%	4,80	66,65%	-33,93%
	2016	32,05	-73,62%	184,99%	19,92	-95,87%	-48,20%	387,79	3,77%	-46,54%	4,70	63,36%	-31,32%
	2017	30,15	-75,18%	244,40%	19,68	-95,92%	-44,59%	391,60	4,79%	-51,73%	4,66	62,04%	-33,09%
	2018	30,92	-74,54%	226,96%	19,67	-95,92%	-44,21%	385,83	3,25%	-44,21%	4,57	58,81%	-31,02%
Ferry-Pax only	2008	150,93	–	–	134,67	–	–	221,26	–	–	2,90	–	–
	2012	140,17	-7,12%	10,86%	109,61	-18,61%	46,88%	243,73	10,16%	46,88%	3,27	12,83%	-20,58%
	2013	140,18	-7,12%	7,01%	112,45	-16,50%	41,15%	232,64	5,14%	41,31%	2,97	2,54%	-27,84%
	2014	140,19	-7,11%	5,70%	112,40	-16,53%	45,35%	235,83	6,58%	45,35%	3,02	4,08%	-20,33%
	2015	134,16	-11,11%	1,83%	111,47	-17,23%	40,05%	237,26	7,23%	40,05%	3,08	6,23%	-25,44%
	2016	131,54	-12,84%	10,69%	112,34	-16,58%	47,15%	248,40	12,27%	47,15%	3,25	11,96%	-26,20%
	2017	133,34	-11,65%	2,11%	108,15	-19,69%	29,24%	228,95	3,47%	29,24%	2,90	-0,01%	-38,50%
	2018	127,67	-15,41%	-8,72%	110,75	-17,76%	17,95%	231,92	4,81%	17,64%	2,91	0,50%	-50,69%
Cruise	2008	212,09	–	–	194,85	–	–	931,86	–	–	12,09	–	–
	2012	154,63	-27,09%	-9,54%	137,81	-29,27%	0,16%	920,00	-1,27%	0,16%	13,01	7,63%	-3,17%
	2013	153,89	-27,44%	-9,00%	136,31	-30,05%	2,18%	905,77	-2,80%	2,17%	12,46	3,04%	-2,29%
	2014	153,21	-27,76%	-10,07%	136,52	-29,94%	1,36%	913,07	-2,02%	1,02%	12,34	2,03%	-3,40%
	2015	155,78	-26,55%	-5,65%	139,89	-28,21%	5,34%	949,00	1,84%	5,34%	12,90	6,68%	-1,15%
	2016	155,17	-26,84%	-4,67%	140,15	-28,07%	5,70%	959,36	2,95%	5,70%	13,08	8,15%	0,93%
	2017	152,79	-27,96%	-6,76%	137,28	-29,54%	5,06%	966,04	3,67%	5,06%	13,28	9,84%	-0,89%
	2018	153,60	-27,58%	-5,02%	138,48	-28,93%	7,47%	997,62	7,06%	7,47%	13,67	13,05%	-0,46%
Ferry-Ropax	2008	278,56	–	–	111,55	–	–	379,28	–	–	6,52	–	–
	2012	164,99	-40,77%	149,44%	120,64	8,14%	208,67%	505,23	33,21%	208,67%	7,93	21,56%	9,48%
	2013	163,58	-41,28%	148,81%	120,84	8,33%	207,59%	500,40	31,94%	207,59%	7,77	19,16%	10,81%
	2014	165,80	-40,48%	152,37%	123,43	10,65%	207,46%	493,05	30,00%	207,46%	7,61	16,62%	9,19%
	2015	166,28	-40,31%	156,96%	125,72	12,70%	212,79%	502,67	32,53%	212,79%	7,70	18,08%	12,63%
	2016	164,35	-41,00%	149,98%	124,02	11,17%	220,10%	499,79	31,77%	220,10%	7,59	16,29%	11,55%
	2017	157,71	-43,38%	141,08%	119,18	6,84%	196,01%	477,67	25,94%	196,01%	7,08	8,49%	4,24%
	2018	153,19	-45,01%	139,37%	116,78	4,68%	190,37%	464,63	22,50%	190,37%	6,55	0,40%	-3,42%
Refrigerated bulk	2008	79,71	–	–	58,07	–	–	329,89	–	–	4,52	–	–
	2012	72,31	-9,29%	12,07%	43,43	-25,22%	-2,94%	352,79	6,94%	-2,94%	4,84	7,13%	-6,12%
	2013	72,11	-9,53%	13,22%	42,78	-26,33%	-3,67%	352,18	6,76%	-3,67%	4,86	7,54%	-6,65%
	2014	71,66	-10,10%	11,12%	43,10	-25,77%	-3,08%	355,63	7,80%	-3,08%	4,89	8,27%	-6,75%
	2015	70,34	-11,76%	12,30%	43,31	-25,41%	-1,58%	360,74	9,35%	-1,68%	4,95	9,57%	-5,34%
	2016	73,73	-7,51%	20,05%	44,38	-23,58%	3,01%	373,73	13,29%	2,98%	5,14	13,71%	-0,87%
	2017	74,75	-6,23%	18,29%	45,40	-21,82%	3,69%	371,91	12,74%	3,69%	4,98	10,11%	-2,09%
	2018	73,76	-7,47%	17,02%	45,09	-22,35%	2,91%	372,61	12,95%	2,91%	4,94	9,35%	-2,99%
Ro-ro	2008	101,18	–	–	64,73	–	–	361,52	–	–	4,13	–	–
	2012	53,69	-46,94%	-17,31%	36,91	-42,98%	-10,77%	369,06	2,09%	-10,77%	4,54	10,16%	-26,67%
	2013	55,32	-45,33%	-14,68%	38,11	-41,12%	-7,21%	374,55	3,60%	-7,21%	4,52	9,68%	-24,96%
	2014	55,69	-44,96%	-16,90%	39,09	-39,61%	-5,34%	379,34	4,93%	-5,34%	4,53	9,76%	-22,29%
	2015	55,48	-45,17%	-14,70%	38,93	-39,86%	-2,79%	385,30	6,58%	-2,79%	4,61	11,75%	-22,19%
	2016	55,30	-45,35%	-14,99%	38,52	-40,49%	-5,23%	388,13	7,36%	-4,96%	4,73	14,60%	-22,22%
	2017	55,02	-45,62%	-15,92%	39,05	-39,67%	-6,05%	380,27	5,19%	-6,05%	4,57	10,86%	-23,70%
	2018	54,46	-46,18%	-16,32%	39,13	-39,54%	-4,90%	381,52	5,53%	-4,90%	4,54	10,17%	-23,77%
Vehicle	2008	76,72	–	–	20,39	–	–	328,49	–	–	5,24	–	–
	2012	68,18	-11,13%	-11,75%	19,57	-3,99%	-1,73%	326,52	-0,60%	-1,73%	5,07	-3,24%	-6,77%
	2013	67,17	-12,45%	-12,60%	19,28	-5,44%	-2,91%	321,58	-2,10%	-2,91%	4,91	-6,28%	-9,30%
	2014	66,24	-13,66%	-14,02%	19,00	-6,80%	-4,12%	318,63	-3,00%	-4,12%	4,82	-8,14%	-12,25%
	2015	66,50	-13,31%	-12,40%	19,14	-6,11%	-2,54%	323,47	-1,53%	-2,54%	4,91	-6,33%	-10,47%
	2016	67,36	-12,19%	-9,67%	19,14	-6,13%	-2,23%	325,24	-0,99%	-2,23%	4,93	-6,08%	-9,89%
	2017	66,11	-13,82%	-10,24%	18,98	-6,88%	-3,01%	323,93	-1,39%	-2,98%	4,92	-6,25%	-10,38%
	2018	64,66	-15,71%	-12,55%	18,77	-7,91%	-4,23%	322,71	-1,76%	-4,23%	4,84	-7,62%	-12,78%

Table 63 - Carbon intensity per ship type and percentage changes indexed at year 2008 (Option 2)

Ship type	Year	EEOI ($g\text{-}CO_2/t/nm$)			AER ($g\text{-}CO_2/DWT/nm$)			DIST ($kg\text{-}CO_2/nm$)			TIME ($t\text{-}CO_2/h$)		
		value	percentage change overall	percentage change individual	value	percentage change overall	percentage change individual	value	percentage change overall	percentage change individual	value	percentage change overall	percentage change individual
Bulk carrier	2008	11,08	–	–	5,32	–	–	356,98	–	–	4,52	–	–
	2012	7,90	-28,72%	-19,95%	4,13	-22,27%	-14,03%	336,73	-5,67%	-14,02%	3,98	-11,83%	-21,69%
	2013	7,59	-31,45%	-22,61%	3,97	-25,43%	-16,92%	325,83	-8,73%	-16,92%	3,76	-16,83%	-26,34%
	2014	7,18	-35,22%	-26,41%	3,84	-27,86%	-18,29%	323,65	-9,34%	-18,28%	3,68	-18,46%	-28,47%
	2015	7,20	-35,01%	-25,74%	3,81	-28,29%	-18,30%	325,38	-8,85%	-18,30%	3,71	-17,81%	-28,04%
	2016	7,21	-34,93%	-25,44%	3,77	-29,13%	-18,89%	327,88	-8,15%	-18,89%	3,76	-16,79%	-28,50%
	2017	7,03	-36,56%	-27,18%	3,74	-29,77%	-19,75%	326,37	-8,58%	-19,75%	3,74	-17,16%	-29,47%
	2018	6,90	-37,68%	-28,36%	3,67	-31,01%	-20,49%	324,32	-9,15%	-20,49%	3,69	-18,38%	-30,74%
Chemical tanker	2008	19,63	–	–	10,08	–	–	253,39	–	–	3,22	–	–
	2012	17,48	-10,94%	5,93%	11,70	16,01%	27,13%	291,69	15,12%	27,13%	3,47	7,66%	14,62%
	2013	17,23	-12,21%	6,19%	11,50	14,10%	28,31%	292,04	15,26%	28,31%	3,42	6,04%	13,38%
	2014	17,17	-12,52%	5,89%	11,42	13,29%	29,03%	296,64	17,07%	29,03%	3,44	6,63%	13,82%
	2015	17,01	-13,36%	6,35%	11,29	12,01%	30,65%	300,90	18,75%	30,68%	3,50	8,80%	14,76%
	2016	16,70	-14,90%	6,34%	11,12	10,27%	28,99%	305,01	20,38%	28,99%	3,60	11,62%	14,70%
	2017	16,09	-18,00%	4,49%	10,57	4,89%	25,42%	295,18	16,49%	25,42%	3,45	7,13%	9,34%
	2018	15,83	-19,32%	4,06%	10,41	3,26%	24,25%	293,74	15,93%	24,25%	3,38	4,87%	6,98%
Container	2008	19,95	–	–	12,75	–	–	592,63	–	–	9,96	–	–
	2012	17,67	-11,41%	-15,62%	10,95	-14,11%	-9,89%	557,56	-5,92%	-9,89%	8,58	-13,85%	-20,93%
	2013	16,74	-16,09%	-18,92%	10,37	-18,61%	-12,88%	542,22	-8,51%	-12,88%	8,12	-18,47%	-25,49%
	2014	15,71	-21,26%	-21,31%	9,89	-22,40%	-14,89%	543,43	-8,30%	-14,89%	7,99	-19,84%	-29,02%
	2015	15,63	-21,64%	-20,06%	9,57	-24,92%	-15,69%	545,01	-8,03%	-15,69%	7,99	-19,84%	-30,44%
	2016	15,63	-21,62%	-17,72%	9,62	-24,53%	-13,88%	569,65	-3,88%	-13,84%	8,44	-15,23%	-27,88%
	2017	15,31	-23,27%	-19,21%	9,56	-25,03%	-13,85%	587,15	-0,92%	-13,85%	8,79	-11,79%	-27,81%
	2018	14,83	-25,64%	-20,07%	9,33	-26,84%	-14,14%	594,33	0,29%	-14,14%	8,87	-10,98%	-28,64%
General cargo	2008	28,82	–	–	16,89	–	–	142,02	–	–	1,49	–	–
	2012	23,40	-18,81%	-21,07%	14,71	-12,89%	-10,49%	154,53	8,81%	-10,50%	1,58	6,24%	-17,52%
	2013	22,78	-20,95%	-21,74%	14,26	-15,57%	-11,16%	153,02	7,74%	-11,16%	1,54	3,48%	-19,59%
	2014	22,36	-22,43%	-22,06%	14,01	-17,04%	-11,50%	153,86	8,33%	-11,50%	1,54	3,84%	-20,49%
	2015	23,18	-19,60%	-19,38%	13,87	-17,86%	-11,37%	156,75	10,37%	-11,37%	1,58	6,08%	-20,69%
	2016	23,58	-18,21%	-18,41%	13,79	-18,33%	-11,46%	158,99	11,94%	-11,46%	1,60	7,81%	-20,43%
	2017	22,13	-23,23%	-20,65%	13,40	-20,65%	-12,88%	159,24	12,13%	-12,90%	1,61	8,03%	-22,59%
	2018	21,46	-25,54%	-21,47%	13,29	-21,32%	-12,58%	159,05	11,99%	-12,56%	1,59	7,22%	-22,66%
Liquified gas tanker	2008	17,23	–	–	10,01	–	–	441,19	–	–	6,15	–	–
	2012	18,86	9,44%	19,78%	12,39	23,83%	13,14%	595,69	35,02%	13,07%	8,39	36,53%	9,62%
	2013	19,07	10,68%	24,05%	12,14	21,37%	13,10%	595,88	35,06%	12,95%	8,28	34,70%	8,64%
	2014	18,96	10,05%	23,85%	11,85	18,39%	16,28%	588,28	33,34%	16,28%	8,16	32,77%	11,98%
	2015	19,41	12,63%	26,24%	11,88	18,69%	15,69%	579,16	31,27%	15,67%	8,03	30,62%	10,50%
	2016	19,42	12,70%	23,26%	11,56	15,51%	11,42%	565,14	28,10%	11,42%	7,81	27,09%	6,28%
	2017	18,94	9,95%	19,95%	11,22	12,15%	8,01%	568,70	28,90%	8,01%	7,83	27,41%	2,54%
	2018	18,50	7,38%	18,99%	10,99	9,82%	5,57%	579,82	31,42%	5,57%	7,98	29,78%	-0,34%
Oil tanker	2008	11,04	–	–	4,28	–	–	539,75	–	–	6,81	–	–
	2012	8,88	-19,58%	-2,17%	4,12	-3,78%	6,77%	562,37	4,19%	6,85%	6,60	-3,05%	-4,42%
	2013	8,82	-20,14%	-4,33%	4,09	-4,48%	6,42%	557,45	3,28%	6,42%	6,36	-6,66%	-7,05%
	2014	8,64	-21,75%	-5,32%	4,07	-5,01%	6,88%	561,24	3,98%	6,88%	6,32	-7,17%	-7,37%
	2015	8,91	-19,31%	-1,65%	4,24	-1,05%	12,86%	595,39	10,31%	12,86%	6,85	0,65%	-0,74%
	2016	8,70	-21,19%	-2,37%	4,24	-0,87%	13,68%	613,01	13,57%	13,68%	7,14	4,81%	-0,17%
	2017	8,36	-24,33%	-5,05%	4,03	-5,82%	8,59%	590,96	9,49%	8,59%	6,76	-0,71%	-6,06%
	2018	8,18	-25,96%	-8,23%	3,85	-9,96%	5,91%	578,62	7,20%	5,91%	6,52	-4,28%	-10,13%

Add.1 Carbon intensity per ship type and percentage changes indexed at year 2008 (Option 2)

Ship type	Year	EEOI ($g\text{-}CO_2/t/nm$)			AER ($g\text{-}CO_2/DWT/nm$)			DIST ($kg\text{-}CO_2/nm$)			TIME ($t\text{-}CO_2/h$)		
		value	percentage change		value	percentage change		value	percentage change		value	percentage change	
			overall	individual		overall	individual		overall	individual		overall	individual
Other liquids tankers	2008	79,63	–	–	484,40	–	–	375,41	–	–	3,64	–	–
	2012	33,96	-57,36%	406,71%	17,22	-96,45%	-50,17%	395,13	5,25%	-50,17%	5,60	53,91%	-42,68%
	2013	26,07	-67,27%	343,70%	17,23	-96,44%	-46,96%	415,38	10,65%	-44,93%	5,88	61,65%	-42,57%
	2014	26,62	-66,57%	350,60%	15,73	-96,75%	-48,23%	406,74	8,35%	-48,23%	5,72	57,27%	-41,28%
	2015	22,23	-72,08%	269,90%	16,61	-96,57%	-47,28%	400,97	6,81%	-47,28%	5,38	47,75%	-43,50%
	2016	26,96	-66,14%	344,53%	16,73	-96,55%	-46,11%	406,61	8,31%	-44,82%	5,49	50,79%	-43,06%
	2017	24,15	-69,67%	418,58%	15,64	-96,77%	-49,67%	411,64	9,65%	-49,67%	5,64	55,04%	-37,98%
	2018	25,62	-67,83%	425,01%	16,23	-96,65%	-48,57%	410,03	9,22%	-47,35%	5,69	56,23%	-42,41%
Ferry-Pax only	2008	1456,76	–	–	413,79	–	–	76,10	–	–	1,71	–	–
	2012	332,71	-77,16%	-32,72%	284,27	-31,30%	28,93%	85,52	12,39%	28,93%	1,64	-4,09%	-10,75%
	2013	527,24	-63,81%	-39,07%	430,39	4,01%	23,48%	71,42	-6,15%	23,48%	1,40	-17,92%	-21,85%
	2014	677,45	-53,50%	-38,40%	572,57	38,37%	21,68%	73,64	-3,23%	22,05%	1,42	-17,12%	-14,75%
	2015	700,93	-51,88%	-40,40%	597,65	44,43%	17,50%	72,77	-4,37%	17,50%	1,41	-17,76%	-16,38%
	2016	649,14	-55,44%	-35,54%	550,09	32,94%	26,65%	68,96	-9,37%	25,77%	1,33	-22,44%	-17,35%
	2017	569,52	-60,91%	-41,76%	455,38	10,05%	8,52%	59,52	-21,78%	8,52%	1,04	-39,16%	-33,08%
	2018	490,07	-66,36%	-46,83%	401,84	-2,89%	5,47%	61,61	-19,04%	4,21%	0,91	-46,62%	-43,30%
Cruise	2008	202,58	–	–	189,04	–	–	1138,47	–	–	16,28	–	–
	2012	151,17	-25,37%	-24,90%	134,81	-28,69%	-8,87%	992,34	-12,84%	-8,87%	14,83	-8,94%	-5,23%
	2013	147,99	-26,95%	-26,28%	131,11	-30,64%	-10,50%	973,15	-14,52%	-10,50%	14,24	-12,58%	-8,56%
	2014	146,81	-27,53%	-26,66%	131,14	-30,63%	-8,86%	974,72	-14,38%	-9,28%	13,92	-14,54%	-8,18%
	2015	149,32	-26,29%	-24,86%	134,23	-28,99%	-7,31%	1010,32	-11,26%	-7,31%	14,54	-10,74%	-7,74%
	2016	148,96	-26,47%	-25,01%	134,78	-28,70%	-6,67%	1026,39	-9,84%	-6,67%	14,80	-9,10%	-5,80%
	2017	146,73	-27,57%	-24,35%	132,03	-30,16%	-7,34%	1036,32	-8,97%	-7,34%	15,04	-7,65%	-6,04%
	2018	147,56	-27,16%	-24,74%	133,09	-29,60%	-6,28%	1066,01	-6,37%	-6,28%	15,57	-4,39%	-7,01%
Ferry-Ropax	2008	266,15	–	–	117,32	–	–	294,12	–	–	4,30	–	–
	2012	157,76	-40,73%	128,31%	118,74	1,21%	173,49%	567,60	92,99%	173,67%	8,71	102,50%	1,02%
	2013	153,84	-42,20%	129,75%	116,30	-0,87%	179,83%	576,99	96,18%	179,83%	8,74	103,22%	6,15%
	2014	154,10	-42,10%	130,54%	116,34	-0,83%	177,65%	573,49	94,99%	177,65%	8,78	104,19%	2,83%
	2015	158,60	-40,41%	134,89%	121,05	3,18%	178,14%	574,41	95,30%	178,14%	8,64	101,03%	4,81%
	2016	157,08	-40,98%	129,45%	119,97	2,26%	178,81%	571,22	94,22%	178,81%	8,68	101,98%	3,71%
	2017	150,59	-43,42%	121,07%	115,01	-1,97%	165,68%	556,72	89,29%	165,68%	8,36	94,34%	-2,95%
	2018	147,19	-44,70%	116,86%	112,24	-4,33%	160,57%	542,98	84,62%	160,57%	7,80	81,46%	-10,01%
Refrigerated bulk	2008	73,85	–	–	58,29	–	–	331,17	–	–	4,66	–	–
	2012	69,90	-5,36%	18,68%	41,91	-28,11%	-5,39%	358,23	8,17%	-5,39%	5,05	8,25%	-9,39%
	2013	69,22	-6,27%	17,36%	41,14	-29,42%	-6,22%	353,24	6,67%	-6,22%	4,99	7,02%	-11,90%
	2014	68,82	-6,81%	16,63%	41,40	-28,98%	-5,81%	356,82	7,74%	-5,81%	5,04	8,03%	-11,99%
	2015	67,45	-8,67%	17,73%	41,50	-28,82%	-4,66%	361,76	9,24%	-4,66%	5,09	9,24%	-9,96%
	2016	70,54	-4,49%	24,09%	42,43	-27,22%	-1,09%	374,67	13,14%	-1,09%	5,28	13,29%	-6,31%
	2017	70,68	-4,30%	23,63%	43,12	-26,04%	-0,33%	373,29	12,72%	-0,33%	5,15	10,36%	-7,65%
	2018	70,00	-5,22%	24,13%	42,88	-26,44%	-0,31%	375,99	13,53%	-0,31%	5,17	10,83%	-8,79%
Ro-ro	2008	80,71	–	–	54,07	–	–	385,58	–	–	4,56	–	–
	2012	47,37	-41,31%	-13,67%	31,97	-40,88%	-17,44%	384,68	-0,23%	-17,44%	4,88	6,92%	-33,35%
	2013	48,46	-39,95%	-10,21%	32,99	-38,98%	-12,82%	392,93	1,91%	-12,82%	4,96	8,72%	-29,16%
	2014	48,43	-39,99%	-13,25%	33,41	-38,22%	-8,45%	396,64	2,87%	-8,45%	4,94	8,33%	-26,77%
	2015	47,69	-40,90%	-11,49%	32,85	-39,25%	-10,09%	406,78	5,50%	-10,09%	5,15	12,79%	-27,96%
	2016	46,38	-42,54%	-13,22%	31,82	-41,15%	-11,82%	403,94	4,76%	-11,80%	5,16	13,03%	-29,18%
	2017	45,77	-43,28%	-13,68%	32,34	-40,20%	-12,18%	408,47	5,94%	-12,18%	5,17	13,28%	-31,18%
	2018	46,17	-42,79%	-13,51%	32,50	-39,89%	-10,24%	409,77	6,27%	-10,24%	5,23	14,67%	-28,47%

Add.2 Carbon intensity per ship type and percentage changes indexed at year 2008 (Option 2)

Ship type	Year	EEOI ($g-CO_2/t/nm$)			AER ($g-CO_2/DWT/nm$)			DIST ($kgCO_2/nm$)			TIME (tCO_2/h)		
		value	percentage change		value	percentage change		value	percentage change		value	percentage change	
			overall	individual		overall	individual		overall	individual		overall	individual
Vehicle	2008	73,49	–	–	19,87	–	–	331,97	–	–	5,39	–	–
	2012	65,60	-10,73%	-5,88%	18,83	-5,21%	-2,98%	327,32	-1,40%	-2,98%	5,11	-5,14%	-6,70%
	2013	64,55	-12,17%	-7,37%	18,51	-6,81%	-4,68%	322,40	-2,88%	-4,68%	4,96	-8,02%	-9,57%
	2014	63,50	-13,59%	-8,68%	18,23	-8,24%	-5,62%	319,43	-3,78%	-5,62%	4,87	-9,68%	-12,33%
	2015	63,90	-13,05%	-6,87%	18,43	-7,25%	-4,28%	324,41	-2,28%	-4,28%	4,97	-7,76%	-10,39%
	2016	64,97	-11,60%	-4,09%	18,43	-7,22%	-4,02%	326,85	-1,54%	-3,95%	5,00	-7,14%	-10,06%
	2017	63,63	-13,42%	-4,14%	18,23	-8,22%	-4,18%	326,80	-1,56%	-4,18%	5,01	-6,95%	-10,68%
	2018	62,19	-15,38%	-6,88%	18,03	-9,26%	-5,49%	325,63	-1,91%	-5,49%	4,95	-8,06%	-12,27%
Yacht	2008	432,45	–	–	247,87	–	–	114,27	–	–	1,49	–	–
	2012	421,99	-2,42%	-33,96%	361,45	45,82%	-1,81%	94,08	-17,67%	-1,84%	1,14	-23,55%	-2,48%
	2013	406,85	-5,92%	-34,50%	346,93	39,97%	-4,58%	90,75	-20,58%	-4,54%	1,08	-27,56%	-5,95%
	2014	442,89	2,41%	-34,64%	367,77	48,37%	-3,01%	87,86	-23,11%	-2,95%	1,05	-29,61%	-3,56%
	2015	428,30	-0,96%	-34,49%	369,46	49,05%	-1,42%	92,23	-19,29%	-1,42%	1,08	-27,47%	-1,81%
	2016	426,31	-1,42%	-34,64%	378,25	52,60%	-3,05%	95,15	-16,73%	-3,05%	1,13	-24,20%	-3,25%
	2017	426,75	-1,32%	-37,70%	370,37	49,42%	-7,43%	89,04	-22,08%	-7,43%	1,02	-31,17%	-9,73%
	2018	404,13	-6,55%	-38,90%	341,54	37,79%	-8,32%	90,69	-20,63%	-8,32%	1,03	-30,57%	-13,46%
Service - tug	2008	863,40	–	–	409,45	–	–	99,50	–	–	0,82	–	–
	2012	190,52	-77,93%	-39,45%	144,07	-64,81%	3,93%	137,21	37,90%	4,09%	1,01	23,89%	-13,18%
	2013	187,39	-78,30%	-38,61%	148,17	-63,81%	7,38%	139,25	39,96%	7,38%	1,00	22,40%	-12,01%
	2014	185,28	-78,54%	-38,37%	145,71	-64,41%	7,31%	136,46	37,15%	7,31%	0,96	17,22%	-12,75%
	2015	187,58	-78,27%	-38,22%	148,01	-63,85%	7,03%	137,88	38,58%	7,03%	0,95	15,99%	-14,55%
	2016	186,88	-78,36%	-37,82%	146,65	-64,18%	8,62%	139,60	40,31%	8,62%	0,96	16,88%	-13,57%
	2017	194,54	-77,47%	-38,84%	153,33	-62,55%	7,06%	132,02	32,69%	7,06%	0,88	7,06%	-15,77%
	2018	185,60	-78,50%	-39,10%	147,42	-64,00%	5,97%	132,49	33,16%	5,97%	0,85	3,92%	-17,63%
Miscellaneous - fishing	2008	654,84	–	–	443,88	–	–	66,14	–	–	0,66	–	–
	2012	124,93	-80,92%	-17,19%	102,61	-76,88%	10,55%	85,27	28,93%	10,58%	0,69	3,93%	-15,25%
	2013	127,84	-80,48%	-16,52%	105,77	-76,17%	10,43%	84,44	27,67%	10,43%	0,67	1,29%	-16,07%
	2014	126,38	-80,70%	-15,87%	104,40	-76,48%	11,90%	87,25	31,92%	11,90%	0,71	6,87%	-13,48%
	2015	130,77	-80,03%	-17,58%	110,16	-75,18%	11,61%	86,58	30,90%	11,61%	0,69	4,84%	-14,08%
	2016	128,29	-80,41%	-17,74%	108,58	-75,54%	10,24%	85,24	28,88%	10,26%	0,68	3,04%	-14,02%
	2017	118,44	-81,91%	-15,40%	97,93	-77,94%	7,76%	84,13	27,21%	7,76%	0,67	0,97%	-19,65%
	2018	114,37	-82,53%	-16,16%	94,63	-78,68%	6,77%	85,25	28,89%	6,78%	0,67	1,57%	-21,00%
Offshore	2008	390,64	–	–	124,82	–	–	207,94	–	–	2,04	–	–
	2012	16,62	-95,75%	-45,72%	8,71	-93,02%	11,26%	326,98	57,24%	11,17%	2,95	44,30%	0,00%
	2013	23,43	-94,00%	-45,10%	11,32	-90,93%	12,17%	314,85	51,41%	12,15%	2,78	36,00%	-2,36%
	2014	32,86	-91,59%	-44,79%	15,70	-87,42%	14,82%	341,04	64,00%	14,82%	2,97	45,46%	1,18%
	2015	35,83	-90,83%	-42,35%	19,48	-84,39%	21,03%	317,24	52,56%	21,03%	2,76	35,04%	4,29%
	2016	52,54	-86,55%	-40,30%	26,05	-79,13%	28,54%	311,03	49,57%	28,54%	2,68	31,40%	10,68%
	2017	73,16	-81,27%	-41,43%	43,79	-64,92%	21,49%	303,19	45,80%	21,49%	2,56	25,62%	2,95%
	2018	73,00	-81,31%	-41,99%	46,30	-62,91%	18,88%	295,26	41,99%	18,88%	2,53	24,15%	-0,73%
Service - other	2008	127,29	–	–	85,95	–	–	166,82	–	–	1,53	–	–
	2012	45,29	-64,42%	-9,03%	30,60	-64,40%	-0,04%	196,18	17,60%	-0,03%	1,61	5,18%	-4,96%
	2013	61,79	-51,46%	-3,45%	42,05	-51,07%	4,00%	192,33	15,29%	4,00%	1,55	1,49%	-0,23%
	2014	58,05	-54,39%	-3,31%	42,33	-50,74%	9,27%	197,89	18,62%	9,27%	1,61	4,95%	2,88%
	2015	69,47	-45,43%	-0,55%	50,53	-41,20%	11,50%	200,70	20,30%	11,50%	1,66	8,63%	1,73%
	2016	70,85	-44,34%	1,13%	51,64	-39,92%	14,57%	206,28	23,65%	14,57%	1,76	15,01%	5,91%
	2017	56,92	-55,28%	1,05%	41,78	-51,39%	12,92%	207,28	24,25%	12,92%	1,68	9,87%	2,91%
	2018	57,82	-54,58%	0,81%	42,65	-50,37%	13,18%	205,64	23,27%	13,18%	1,69	10,16%	0,86%
Miscellaneous - other	2008	1988,19	–	–	1299,98	–	–	131,30	–	–	1,13	–	–
	2012	39,68	-98,00%	-49,30%	28,02	-97,84%	-28,14%	495,68	277,52%	-28,14%	6,24	450,46%	5,83%
	2013	39,79	-98,00%	-45,10%	30,26	-97,67%	-18,88%	612,40	366,42%	-18,88%	7,37	550,74%	21,88%
	2014	41,88	-97,89%	-47,11%	30,81	-97,63%	-25,87%	550,31	319,13%	-26,70%	6,74	494,77%	7,91%
	2015	37,88	-98,09%	-40,57%	28,16	-97,83%	-23,73%	506,24	285,57%	-23,73%	6,12	440,24%	11,96%
	2016	40,51	-97,96%	-45,66%	30,01	-97,69%	-25,13%	474,43	261,34%	-25,13%	5,64	398,07%	14,94%
	2017	37,79	-98,10%	-46,54%	24,41	-98,12%	-21,94%	466,31	255,16%	-21,94%	5,67	400,15%	15,74%
	2018	37,44	-98,12%	-44,48%	27,29	-97,90%	-28,34%	442,54	237,05%	-28,34%	5,06	346,43%	4,99%

Figure 135 - Carbon intensity levels of typical cargo ships over years (in EEOI)

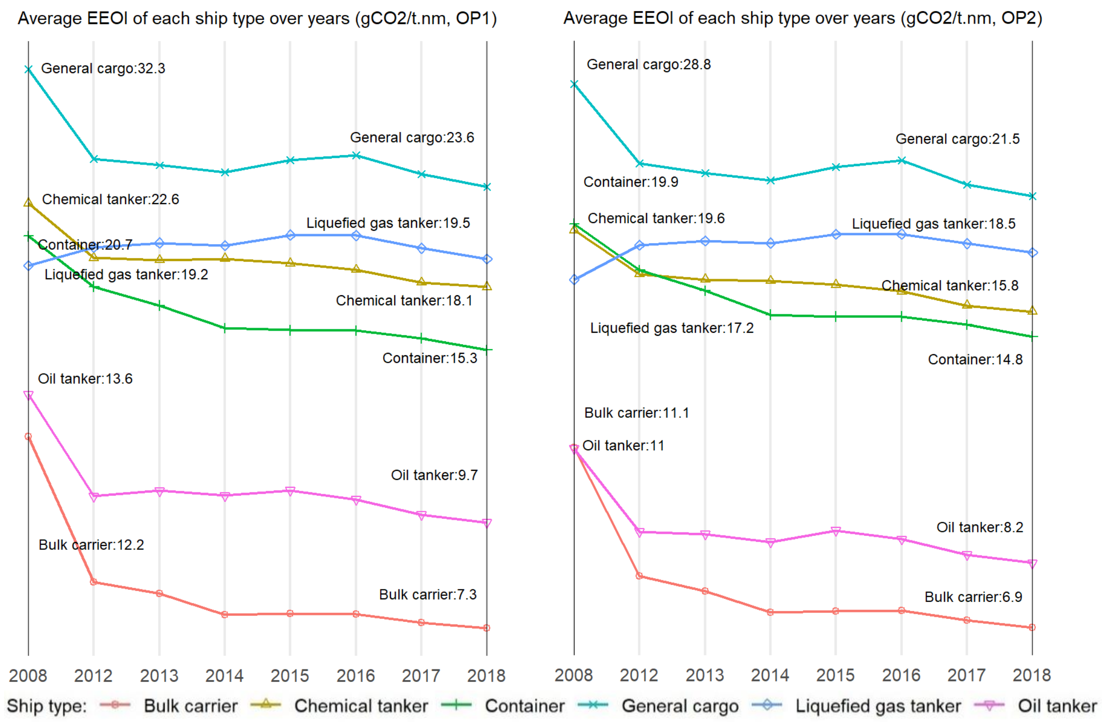
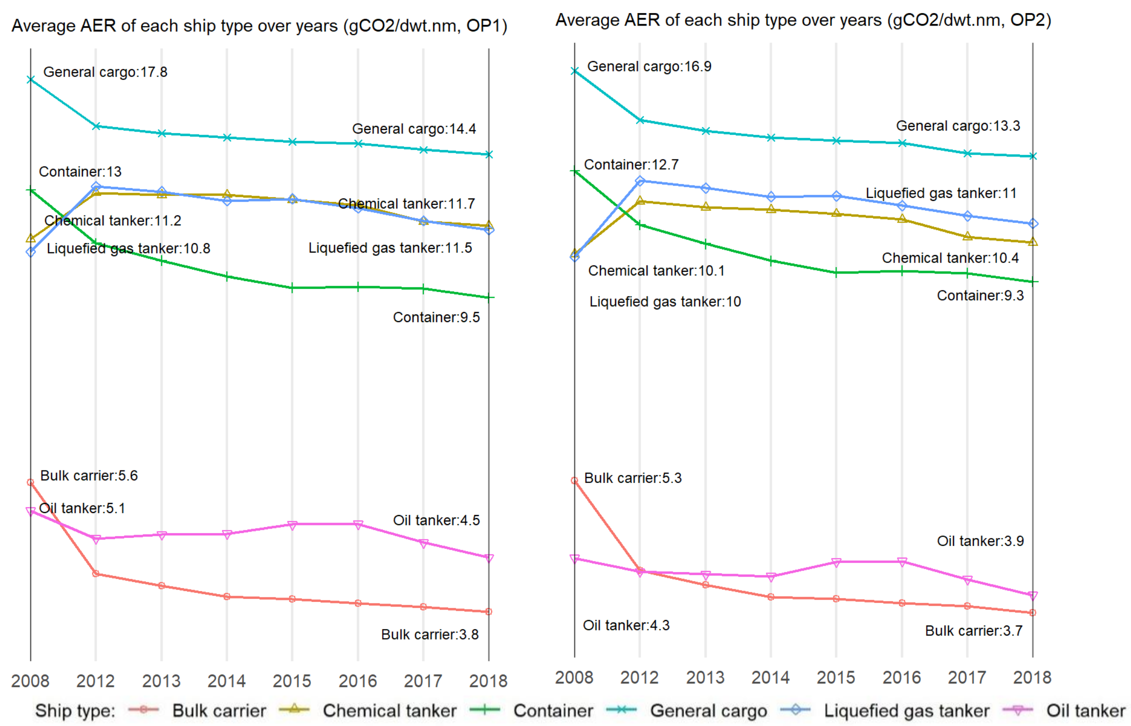


Figure 136 - Carbon intensity levels of typical cargo ships over years (in AER)



1.

Figure 137 - Carbon intensity levels of typical cargo ships over years (in DIST)

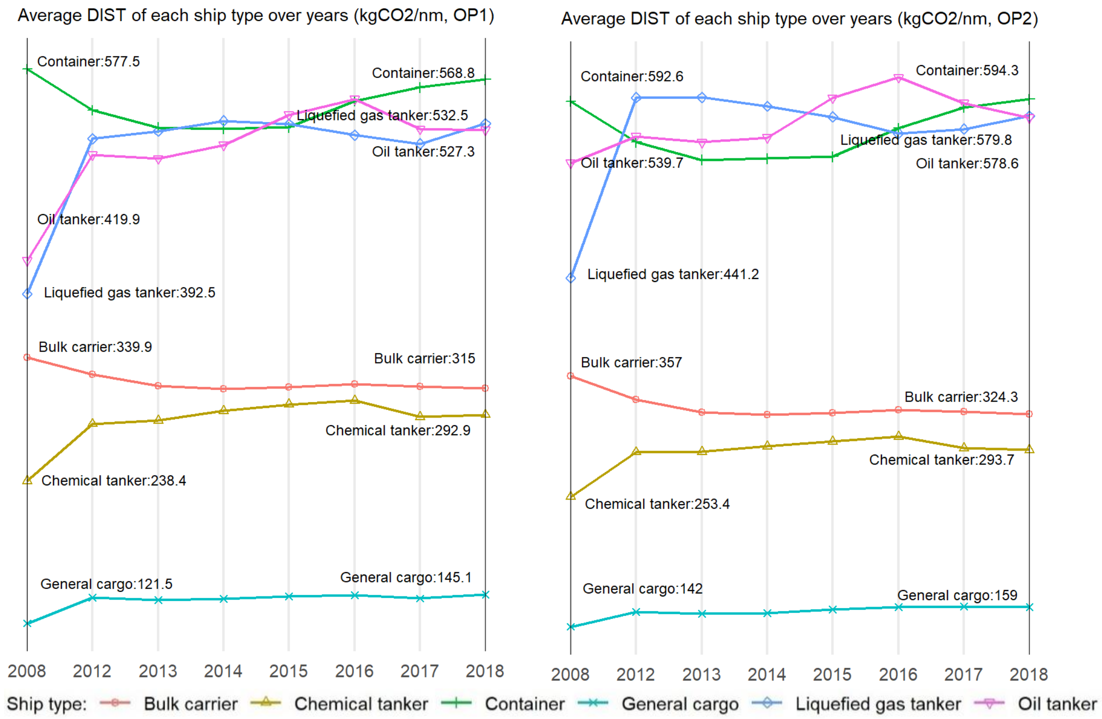
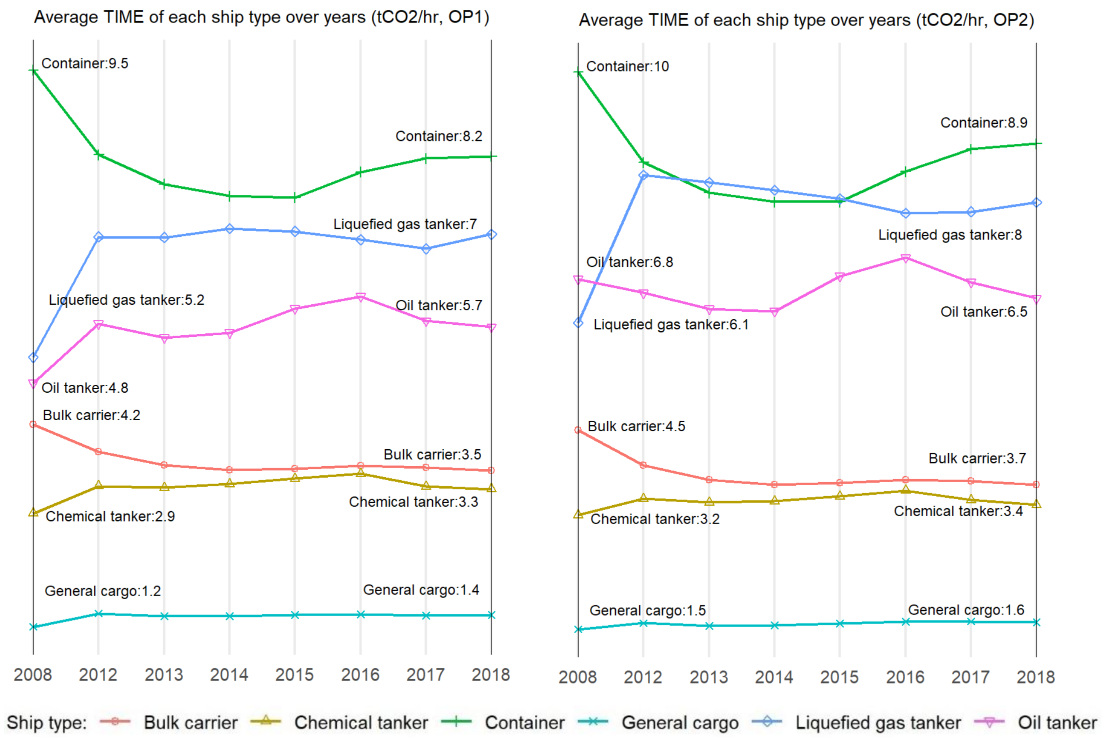


Figure 138 - Carbon intensity levels of typical cargo ships over years (in TIME)



Throughout the period under observation, lowest carbon intensity levels, measured in EEOI or AER, were achieved by bulk carriers and oil tankers, followed by container ships, chemical tankers and liquefied gas tankers. Among the major cargo ship types, general cargo ships hold the highest carbon intensity levels. Although carbon intensity performance per ship type varied from each other, most ship types have shared a decreasing trend between 2012 and 2018. Taking the year 2008 as a reference, the most significant carbon intensity reduction was achieved by bulk carriers, where the overall EEOI and AER in 2018 was around 38% and 31% lower. The trends in overall EEOI of oil tankers, container ships and general cargo ships were roughly identical, all of which decreased by 25-26% in 2018.

Drivers for carbon intensity reduction of ships mainly include design efficiency improvement, speed reduction and payload optimization. In this analysis, average installed engine power per dwt is taken as a rough proxy of design efficiency in lack of accurate EEDI or its estimated index value (IMO, 2013d), payload utilization is calculated through dividing the total cargo tonne-miles by the aggregated nominal transport work (product of dwt and total distance travelled), and sea speed is the distance weighted average speed of individual ships. Changes in these drivers over years and trends in the overall carbon intensity of ship types, indexed at year 2008 and 2012, are jointly presented in Figure 139 to Figure 142. In these figures, trends in total CO_2 emissions as well as transport work in cargo tonne-miles are also provided for reference.

Figure 139 – Percentage changes in overall carbon intensity per ship type indexed at 2008 (Option 1)

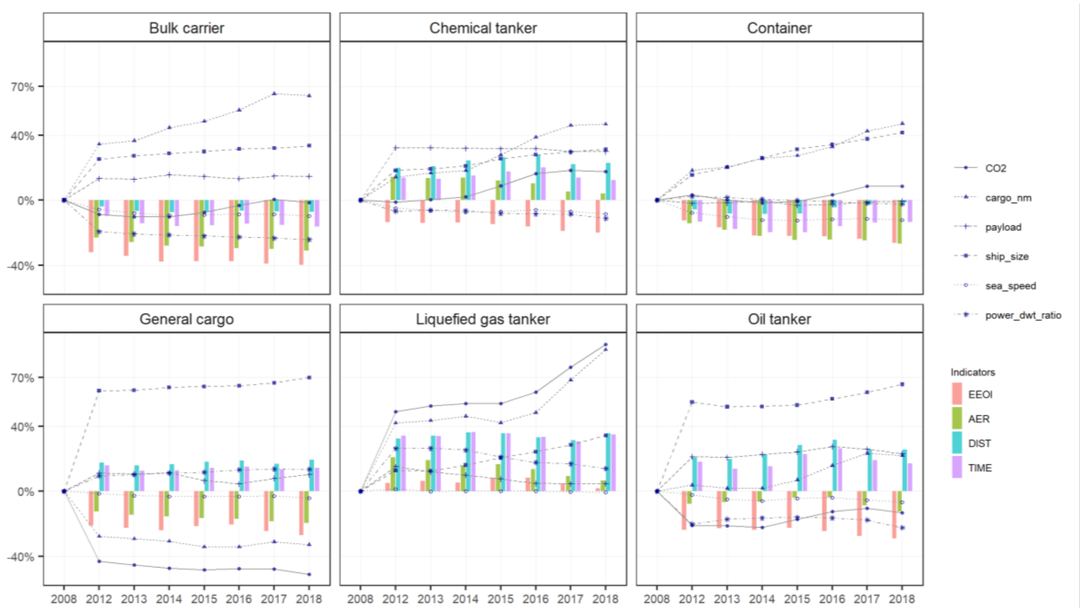


Figure 140 – Percentage changes in overall carbon intensity per ship type indexed at 2012 (Option 1)

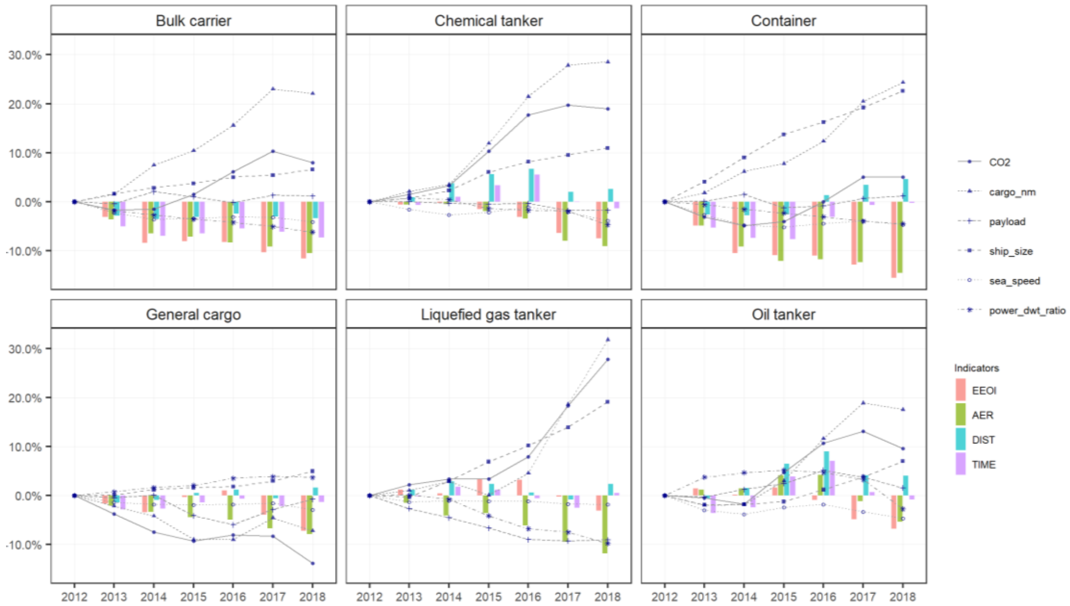


Figure 141 -Percentage changes in overall carbon intensity per ship type indexed at 2008 (Option 2)

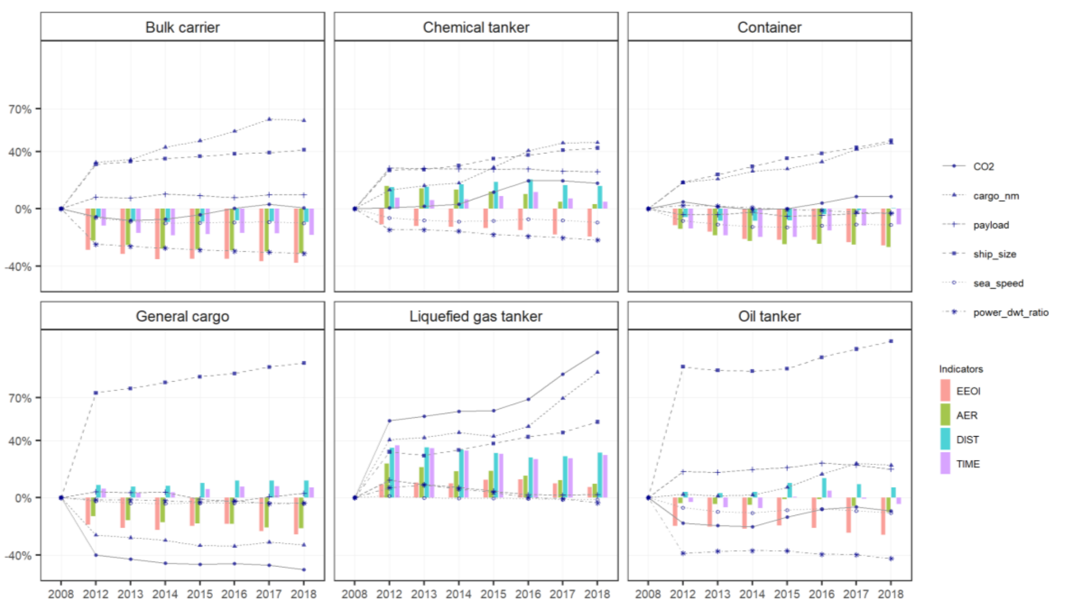
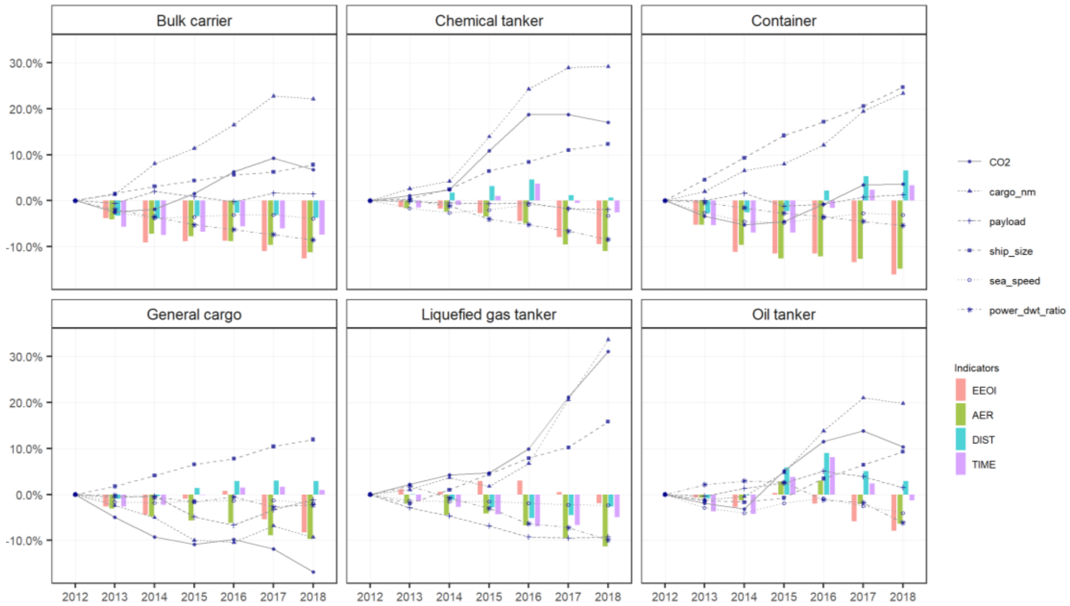


Figure 142 – Percentage changes in overall carbon intensity per ship type indexed at 2012 (Option 2)



As shown in these figures, dominant drivers for carbon intensity changes varied with ship types. The increasing average ship size had taken a dominant role in carbon intensity reduction in all typical ship types when compared with year 2008, yet got less significant when compared with 2012, except for container ships and liquefied gas tankers. In the meanwhile, large improvement in overall design efficiency has been observed in most segments, especially in oil tankers, bulk carriers and chemical tankers. Given year 2012 as a reference, however, only a 5% - 10% improvement in design efficiency has been observed in bulk carriers, chemical tankers, container ships and liquefied gas tankers. Note that such improvements have stemmed partly from real improvement in design efficiency of individual ships triggered by the enforcement of EEDI requirements (IMO, 2011) and partly from scale economy of the segment. The improvement in design efficiency of oil tankers even showed certain drawback during 2012 to 2015, mainly due to a temporary decrease in average ship size. Speed reduction has been another key driver especially for bulk carriers, chemical tankers, container ships and oil tankers since 2008. However, most ship type ceased slowing down further from year 2015, due to the improving market situation, decreasing fuel oil price as well as certain technical limitations or concerns. Similarly, payload utilization has been improved more or less for most ship types compared with year 2008, but went downwards or fluctuated during 2012-2018. Such volatile trends in speed and payload utilization were largely the lagging consequences of the sluggish recovery from global financial crisis which started from mid-2008. Trends in carbon intensity of liquified gas tankers seem questionable when the year 2008 is taken as a reference. This may be caused by inconsistent ship type categorization between the Third IMO GHG Study and this study, as informed by the quite large average size of ships of 200,000 dwt and above in year 2008. Another noteworthy finding is that changes in payload utilization showed opposite impacts on the trends in EEOI and AER. An increase in payload utilization generally triggers a reduction in EEOI, but will trigger an increase in AER or compromise its expected reduction magnitude.

Trends in individual based carbon intensity per ship type over years are calculated through fitting a series of power law regression curves, as shown in **Figure 143**, which takes the segment of bulk carriers as an example. The estimated parameters of the regress curves for all ship types are presented in **Table 64** and Table 65.

Figure 143 - Carbon intensity regress curves (bulk carriers)

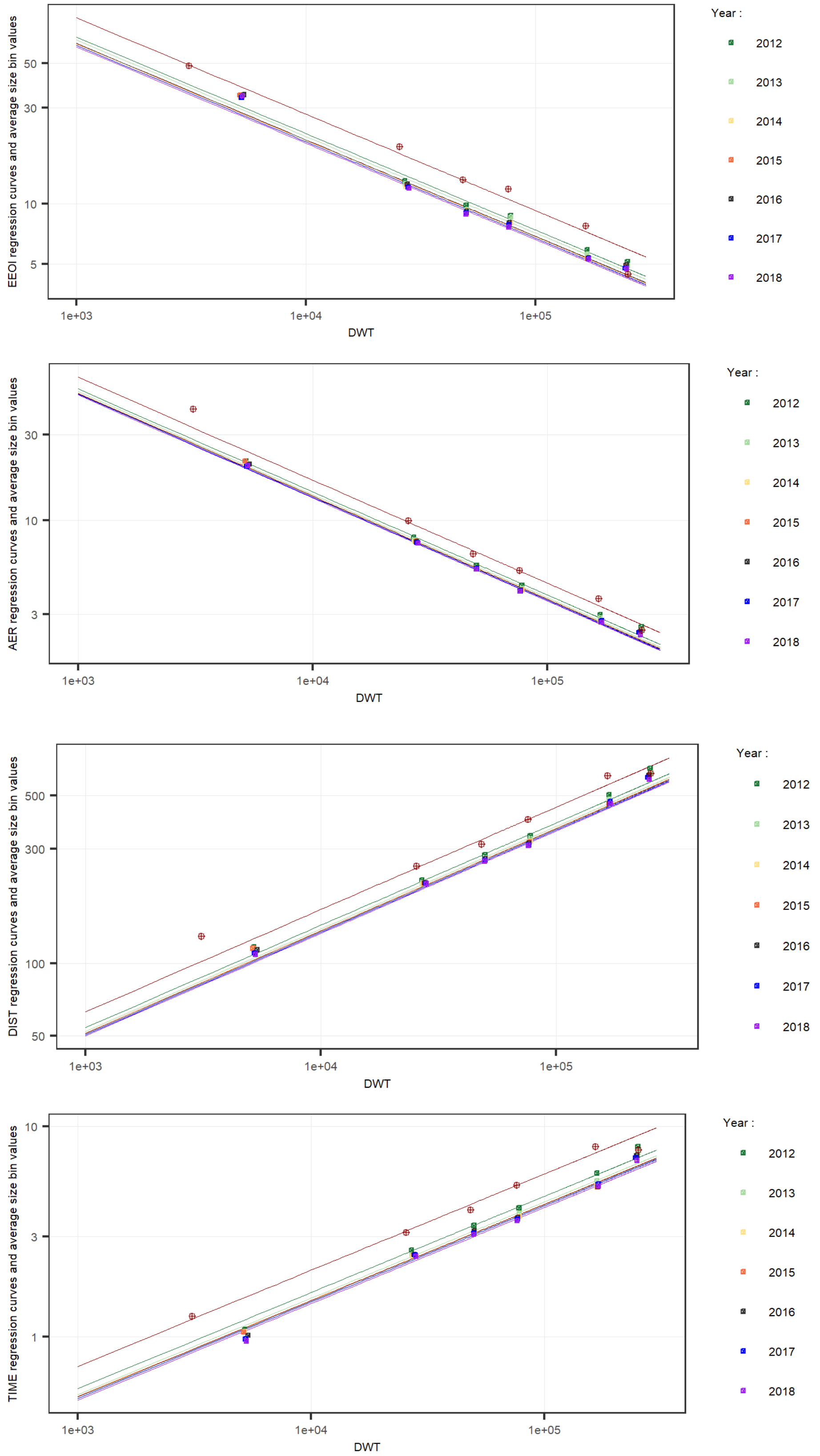


Table 64 - Estimated parameters of the individual based carbon intensity regress curves (Option 1)

Ship type	Indicaor	β	α						
			2012	2013	2014	2015	2016	2017	2018
Bulk carrier	EEOI	-0.498	2322.40	2259.15	2150.98	2174.27	2183.57	2125.97	2097.92
	AER	-0.576	2949.86	2856.56	2815.17	2815.76	2792.75	2761.79	2737.68
	DIST	0.424	2.95	2.86	2.82	2.82	2.79	2.76	2.74
	TIME	0.456	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Chemical tanker	EEOI	-0.564	5718.39	5756.82	5798.30	5825.37	5820.32	5686.12	5717.29
	AER	-0.643	8478.81	8577.94	8673.12	8752.54	8667.84	8364.95	8382.42
	DIST	0.357	8.48	8.58	8.67	8.75	8.67	8.36	8.38
	TIME	0.432	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Container	EEOI	-0.420	1770.43	1709.82	1662.86	1690.53	1734.36	1698.50	1687.69
	AER	-0.446	1429.86	1389.16	1357.15	1340.97	1370.02	1369.49	1366.08
	DIST	0.554	1.43	1.39	1.36	1.34	1.37	1.37	1.37
	TIME	0.649	0.01	0.01	0.01	0.01	0.01	0.01	0.01
General cargo	EEOI	-0.330	543.61	543.34	541.12	559.82	566.78	551.38	544.88
	AER	-0.397	616.94	615.05	615.86	616.37	615.86	604.33	609.69
	DIST	0.603	0.62	0.62	0.62	0.62	0.62	0.60	0.61
	TIME	0.753	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liquified gas tank	EEOI	-0.510	5316.74	5531.79	5555.82	5619.21	5488.59	5306.14	5264.37
	AER	-0.521	3327.55	3362.79	3458.01	3479.37	3306.89	3197.99	3149.49
	DIST	0.479	3.33	3.36	3.46	3.48	3.31	3.20	3.15
	TIME	0.545	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Oil tanker	EEOI	-0.656	24596.25	24196.59	24124.12	24965.18	24547.05	23817.23	23286.24
	AER	-0.695	16536.85	16587.27	16806.79	17710.91	17745.11	16958.16	16567.94
	DIST	0.305	16.53	16.59	16.81	17.71	17.74	16.96	16.57
	TIME	0.373	0.09	0.09	0.09	0.09	0.10	0.09	0.09
Other liquids tank	EEOI	-0.745	51687.33	48918.84	49427.44	37618.69	49210.76	59468.94	56457.69
	AER	-0.816	54000.97	54160.04	54985.59	53881.76	56908.17	60876.29	61285.53
	DIST	0.184	54.00	56.88	54.99	53.88	58.74	53.02	61.29
	TIME	0.281	0.29	0.30	0.30	0.29	0.31	0.30	0.31
Ferry-pax only	EEOI	-0.630	17702.19	17087.42	16878.47	16259.81	17674.45	16305.38	14575.88
	AER	-0.659	16756.07	16102.27	16581.94	15977.26	16787.71	14744.22	13456.24
	DIST	0.341	16.76	16.12	16.58	15.98	16.79	14.74	13.42
	TIME	0.179	0.61	0.56	0.61	0.57	0.57	0.47	0.38
Cruise	EEOI	-0.471	10520.74	10583.74	10459.10	10973.67	11087.11	10843.54	11046.81
	AER	-0.456	8120.32	8283.76	8217.50	8539.93	8569.00	8517.68	8712.78
	DIST	0.544	8.12	8.28	8.19	8.54	8.57	8.52	8.71
	TIME	0.681	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ferry-Ropax	EEOI	-0.591	23570.74	23511.05	23847.47	24280.83	23621.62	22780.44	22618.80
	AER	-0.610	20544.37	20472.43	20463.94	20818.69	21305.08	19701.39	19326.09
	DIST	0.390	20.54	20.47	20.46	20.82	21.31	19.70	19.33
	TIME	0.532	0.09	0.10	0.09	0.10	0.10	0.09	0.08
Refrigerated bulk	EEOI	-0.512	7465.55	7542.58	7402.77	7481.22	7997.28	7880.30	7795.57
	AER	-0.638	13959.98	13855.69	13939.84	14155.77	14815.50	14913.51	14801.40
	DIST	0.362	13.96	13.86	13.94	14.14	14.81	14.91	14.80
	TIME	0.607	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ro-ro	EEOI	-0.779	74264.85	76622.51	74632.19	76607.05	76349.32	75512.21	75152.22
	AER	-0.815	68833.43	71581.51	73024.24	74994.85	73108.13	72472.59	73364.51
	DIST	0.185	68.83	71.58	73.02	74.99	73.31	72.47	73.36
	TIME	0.421	0.10	0.11	0.11	0.11	0.11	0.11	0.11
Vehicle	EEOI	-0.582	19000.20	18815.40	18511.11	18858.72	19446.45	19323.81	18826.29
	AER	-0.756	30346.05	29981.55	29605.98	30094.41	30190.71	29948.17	29571.94
	DIST	0.244	30.35	29.98	29.61	30.09	30.19	29.96	29.57
	TIME	0.350	0.17	0.17	0.16	0.16	0.17	0.16	0.16

Table 65 - Estimated parameters of the individual based carbon intensity regress curves (Option 2)

Ship type	Indicaor	β	α						
			2012	2013	2014	2015	2016	2017	2018
Bulk carrier	EEOI	-0.481	1867.95	1805.91	1717.36	1732.87	1739.99	1699.23	1671.87
	AER	-0.574	2840.02	2744.73	2699.54	2699.03	2679.61	2651.08	2626.75
	DIST	0.426	2.84	2.74	2.70	2.70	2.68	2.65	2.63
	TIME	0.457	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Chemical tanker	EEOI	-0.563	5451.37	5464.79	5449.57	5473.13	5472.74	5377.68	5355.47
	AER	-0.636	7665.92	7736.99	7780.47	7877.81	7778.20	7562.70	7491.83
	DIST	0.364	7.67	7.74	7.78	7.88	7.78	7.56	7.49
	TIME	0.437	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Container	EEOI	-0.418	1701.40	1634.82	1586.65	1611.81	1659.10	1628.99	1611.67
	AER	-0.438	1310.20	1266.67	1237.50	1225.89	1252.20	1252.67	1248.37
	DIST	0.562	1.31	1.27	1.24	1.23	1.25	1.25	1.25
	TIME	0.660	0.01	0.01	0.01	0.01	0.01	0.01	0.01
General cargo	EEOI	-0.343	589.95	584.96	582.55	602.57	609.86	593.14	586.97
	AER	-0.405	655.73	650.86	648.39	649.31	648.67	638.24	640.43
	DIST	0.595	0.66	0.65	0.65	0.65	0.65	0.64	0.64
	TIME	0.746	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liquified gas tank	EEOI	-0.494	4425.61	4583.28	4575.90	4664.04	4554.21	4431.78	4396.49
	AER	-0.509	2931.43	2930.49	3012.93	2997.64	2886.79	2798.57	2735.27
	DIST	0.491	2.93	2.93	3.01	3.00	2.89	2.80	2.74
	TIME	0.558	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Oil tanker	EEOI	-0.630	17222.59	16842.70	16669.13	17314.42	17187.28	16715.83	16155.72
	AER	-0.677	13048.59	13006.27	13062.26	13793.55	13893.14	13271.25	12943.88
	DIST	0.323	13.06	13.01	13.06	13.79	13.89	13.27	12.94
	TIME	0.389	0.07	0.07	0.07	0.08	0.08	0.07	0.07
Other liquids tank	EEOI	-0.758	62439.58	54675.74	55525.40	45581.56	54777.34	63902.89	64695.20
	AER	-0.829	59772.73	63619.44	62092.67	63241.83	64637.73	60374.27	61686.47
	DIST	0.171	59.77	66.06	62.09	63.24	66.19	60.37	63.15
	TIME	0.254	0.38	0.39	0.39	0.38	0.38	0.42	0.39
Ferry-pax only	EEOI	-0.645	19238.02	17423.29	17614.21	17041.40	18432.31	16652.75	15203.72
	AER	-0.668	17664.28	16917.22	16670.77	16098.45	17351.99	14868.23	14450.14
	DIST	0.332	17.66	16.92	16.72	16.10	17.23	14.87	14.28
	TIME	0.166	0.65	0.57	0.62	0.61	0.60	0.49	0.41
Cruise	EEOI	-0.402	5660.72	5556.51	5527.44	5663.54	5652.26	5701.92	5672.80
	AER	-0.390	4520.34	4439.43	4520.46	4597.27	4629.20	4596.10	4648.39
	DIST	0.610	4.52	4.44	4.50	4.60	4.63	4.60	4.65
	TIME	0.756	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ferry-Ropax	EEOI	-0.564	18857.08	18976.33	19041.00	19400.36	18950.85	18259.03	17911.34
	AER	-0.583	16113.26	16486.68	16358.73	16387.41	16427.07	15653.31	15352.40
	DIST	0.417	16.12	16.49	16.36	16.39	16.43	15.65	15.35
	TIME	0.550	0.08	0.08	0.08	0.08	0.08	0.08	0.07
Refrigerated bulk	EEOI	-0.499	6543.15	6470.16	6430.24	6490.68	6841.07	6815.76	6843.58
	AER	-0.630	12816.19	12702.66	12758.21	12913.92	13398.47	13500.56	13503.66
	DIST	0.370	12.82	12.70	12.76	12.91	13.40	13.50	13.50
	TIME	0.619	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ro-ro	EEOI	-0.745	53872.25	56032.28	54137.06	55232.29	54155.23	53865.21	53975.12
	AER	-0.783	49512.03	52277.84	54902.95	53917.80	52880.60	52666.98	53828.25
	DIST	0.217	49.51	52.28	54.90	53.92	52.89	52.67	53.83
	TIME	0.457	0.07	0.08	0.08	0.08	0.08	0.07	0.08
Vehicle	EEOI	-0.580	18516.16	18224.73	17965.67	18322.20	18869.48	18859.72	18320.76
	AER	-0.749	28482.32	27983.47	27707.11	28099.12	28175.38	28130.89	27744.44
	DIST	0.251	28.48	27.98	27.71	28.10	28.20	28.13	27.74
	TIME	0.359	0.16	0.15	0.15	0.15	0.15	0.15	0.15
Yacht	EEOI	-0.644	14872.21	14749.33	14718.15	14752.11	14718.40	14029.94	13759.13
	AER	-0.659	13817.91	13428.32	13649.01	13872.85	13643.16	13026.75	12902.17
	DIST	0.341	13.81	13.43	13.66	13.87	13.64	13.03	12.90
	TIME	0.415	0.11	0.11	0.11	0.11	0.11	0.11	0.10
Service - tug	EEOI	-0.736	29752.87	30163.58	30283.81	30357.33	30553.77	30051.69	29926.90
	AER	-0.759	27537.82	28452.25	28434.09	28360.54	28779.92	28369.06	28078.93
	DIST	0.241	27.58	28.45	28.43	28.36	28.78	28.37	28.08
	TIME	0.297	0.14	0.14	0.14	0.14	0.14	0.13	0.13
Miscellaneous - fishing	EEOI	-0.835	35419.82	35706.41	35984.22	35253.45	35184.52	36185.41	35857.73
	AER	-0.861	36513.22	36472.15	36959.88	36863.91	36410.87	35592.39	35264.52
	DIST	0.139	36.52	36.47	36.96	36.86	36.42	35.59	35.27
	TIME	0.233	0.17	0.17	0.18	0.18	0.18	0.17	0.16
Offshore	EEOI	-0.616	20500.28	20734.57	20849.72	21771.23	22546.62	22119.46	21907.22
	AER	-0.692	23539.83	23731.82	24293.54	25607.88	27196.55	25703.29	25152.64
	DIST	0.308	23.52	23.73	24.29	25.61	27.20	25.70	25.15
	TIME	0.328	0.18	0.17	0.18	0.19	0.20	0.18	0.18
Service - other	EEOI	-0.715	26055.61	27653.93	27694.52	28482.93	28966.37	28941.51	28874.65
	AER	-0.777	30845.21	32092.65	33719.37	34408.27	35354.84	34846.41	34924.55
	DIST	0.223	30.85	32.09	33.72	34.41	35.35	34.85	34.92
	TIME	0.246	0.23	0.24	0.24	0.24	0.25	0.24	0.24
Miscellaneous - other	EEOI	-0.657	20907.06	22636.23	21810.02	24503.86	22407.33	22044.45	22894.85
	AER	-0.695	23081.01	26056.73	23812.79	24499.16	24050.37	25072.69	23016.85
	DIST	0.305	23.08	26.06	23.55	24.50	24.05	25.07	23.02
	TIME	0.294	0.31	0.36	0.31	0.33	0.34	0.34	0.31

Since a logarithmic transformation has been applied to both x- any y- axis, the regression curves appear as straight lines. These regression lines were fitted on individual carbon intensity values (individual data points not shown), where the colorful square dots mark the individual based carbon intensity level of each size bin over years, the red line and round dots with cross show the 2008 performance level and average metric values per size bin. The position (intercept) of regression lines indicate the individual based carbon intensity level over years. Like EEDI reference lines (IMO, 2013c), such power law regression lines might not behave equally well for all ship types and might be biased for extremely small or large ships, but can still yield a robust estimate on the carbon intensity performance across a ship type in spite of a substantial number of outliers. Given a consistent slope over years, the changes in position (intercept) of a regression line can reflect the carbon intensity changes triggered by all factors except for a shift in size composition of the ship type segment. When the interest of policy makers or stakeholders is on the carbon intensity performance of ships already in operation, meaning the ship size is no longer changeable, such measurements are particularly useful.

As shown in Figure 144 to Figure 147, having been excluded from the impacts of scale economies, the individual based carbon intensity reductions in most ship types narrowed down when measured in EEOI or AER. The differences are quite significant in bulk carriers (from 38% to 28% in year 2018 indexed to year 2008), chemical tankers (from 19% reduction to 4% increase) and oil tankers (from 26% to 8%), yet modest in container ships (from 26% to 20%) and general cargo ships (from 26% to 21%). This implies that the sharp reductions in carbon intensity of the former group of ships were largely led by the increasing ship size, while were mainly achieved by individual design and operational improvement for the latter group. In this like-to-like comparison, identical trends of AER and DIST can be clearly identified. This is because the only difference between AER and DIST for an individual ship is that AER additionally incorporates the ship's constant capacity (dwt) into the metric calculation whilst DIST not. Like DIST, the metric TIME also generally goes up with ship size. Having been jointly influenced by increasing ship size and decreasing sea speed, changes in the overall TIME were determined by the one which dominant, thus showed divergent trends between ship types. Having decoupled from the size factor, however, TIME has showed a decreasing trend in most ship types, with reduction rates even larger than in EEOI. This implies that TIME is much more sensitive to speed reduction than other metrics.

Figure 144 – Percentage changes in individual based carbon intensity per ship type indexed at 2008 (Option 1)

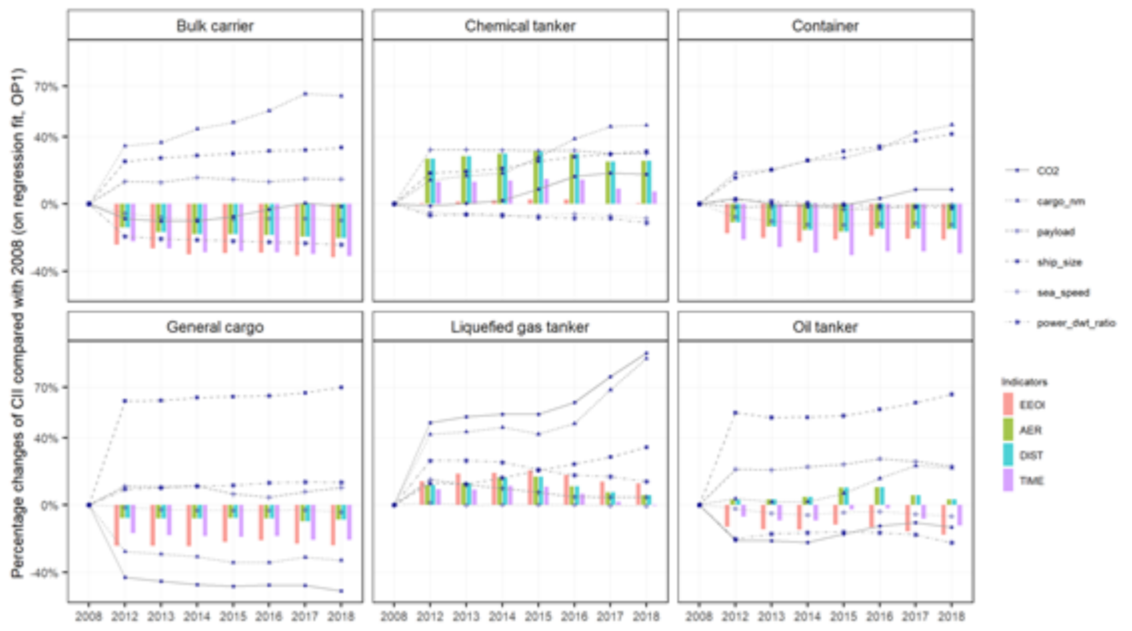


Figure 145 – Percentage changes in individual based carbon intensity per ship type indexed at 2012 (Option 1)

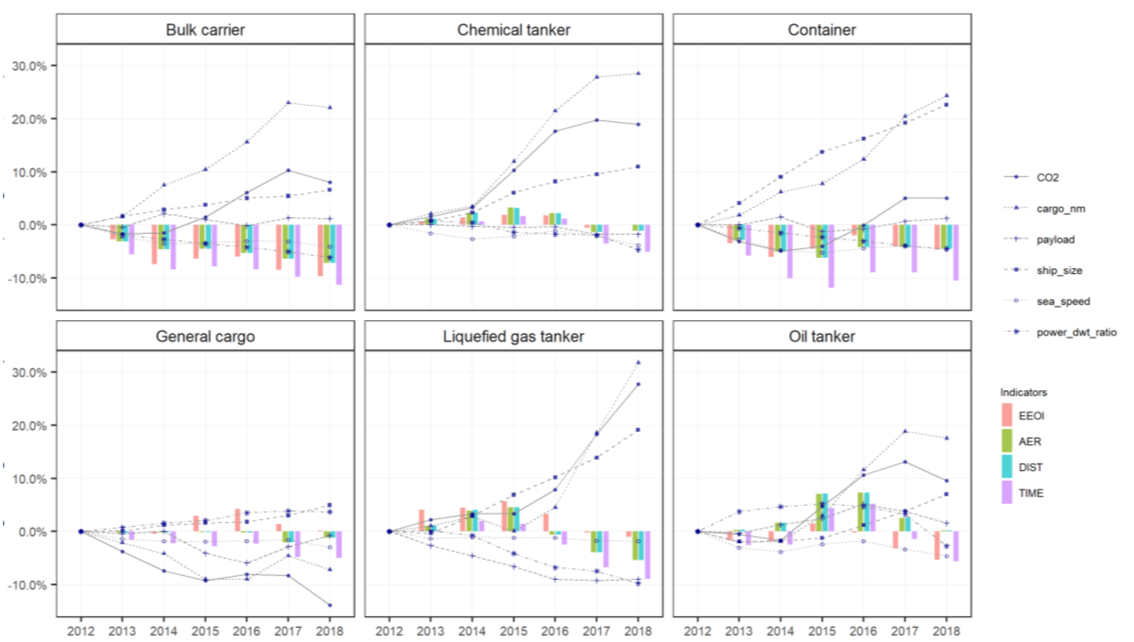


Figure 146 – Percentage changes in individual based carbon intensity per ship type indexed at 2008 (Option 2)

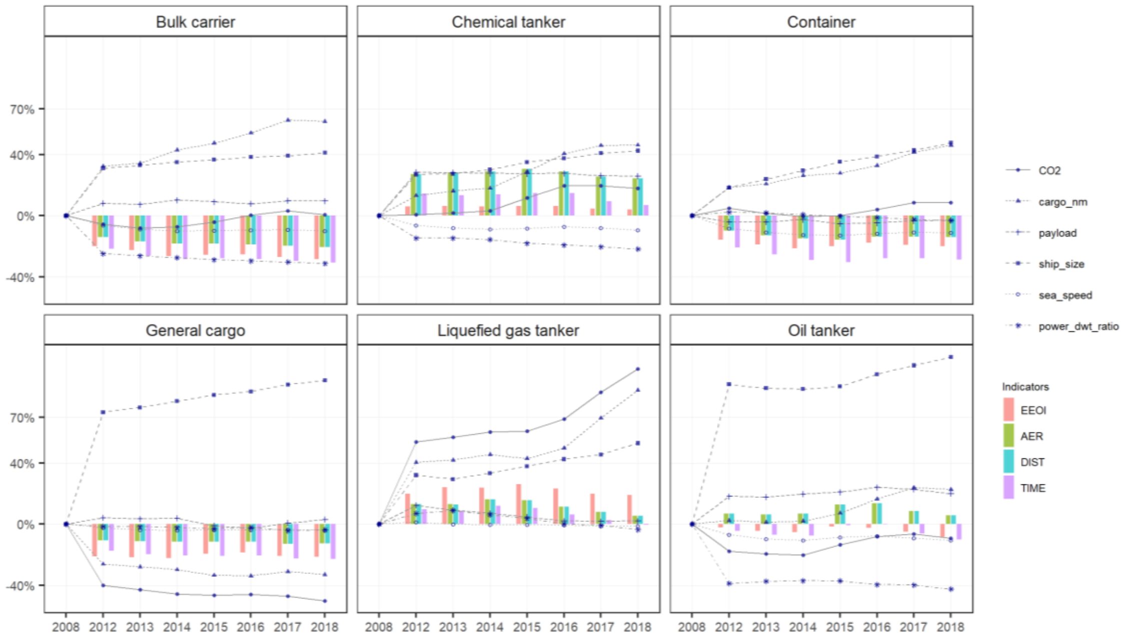
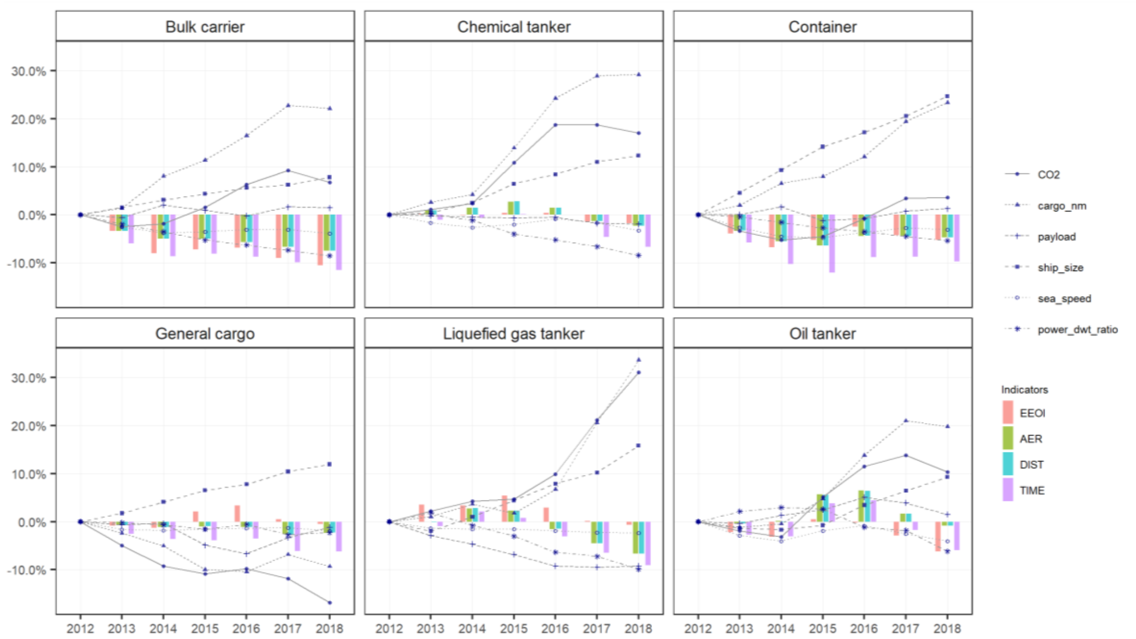


Figure 147 – Percentage changes in individual based carbon intensity per ship type indexed at 2012(Option 2)



3.3.3 Carbon intensity and trends of world fleet

Table 66 and Table 67 report the carbon intensity levels of world fleet between 2012 and 2018, as well as in 2008, derived from both Option 1 and Option 2. The percentage changes in overall and individual based carbon intensity are jointly provided in these tables, taking year 2008 and 2012 as a reference respectively. Since models run for estimating CO_2 emissions and transport activities cannot be equally good for all ship types, seven typical ship types have been chosen as a representative of the world fleet, namely bulk carrier, oil tankers, container ships, chemical tankers, liquefied gas tankers, general cargo ships and refrigerated bulk carriers. As illustrated in Figure 148, these ships accounted for around 88% CO_2 emissions from international shipping, and around 98% of total transport work in cargo tonne-miles throughout the period under observation.

Figure 148 - Representativeness on CO_2 emissions and transport work of typical cargo ships

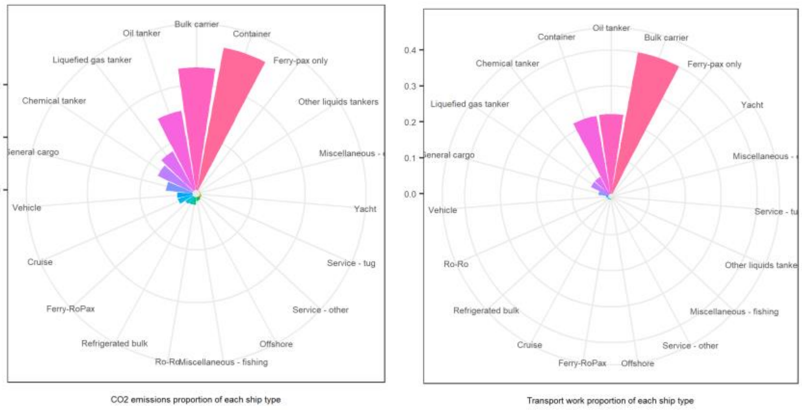


Table 66 - Carbon intensity levels and percentage changes of international shipping（Option 1）

Year	EEOI (gCO2/t.nm)					AER(gCO2/dwt.nm)					DIST(kgCO2/nm)					TIME(tCO2/hr)				
	Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012	
		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual
2008	17.10	–	–	–	–	8.08	–	–	–	–	306.46	–	–	–	–	3.64	–	–	–	–
2012	13.16	-23.1%	-16.8%	–	–	7.06	-12.7%	-5.6%	–	–	362.65	18.3%	-5.6%	–	–	4.32	18.57%	-14.7%	–	–
2013	12.87	-24.7%	-18.3%	-2.2%	-2.0%	6.89	-14.8%	-7.1%	-2.4%	-1.7%	357.73	16.7%	-7.1%	-1.4%	-1.7%	4.18	14.61%	-18.1%	-3.3%	-4.2%
2014	12.34	-27.9%	-20.4%	-6.3%	-4.6%	6.71	-16.9%	-7.8%	-4.9%	-2.4%	360.44	17.6%	-7.7%	-0.6%	-2.4%	4.17	14.36%	-19.9%	-3.6%	-6.2%
2015	12.33	-27.9%	-19.0%	-6.3%	-2.8%	6.64	-17.8%	-6.5%	-5.9%	-1.3%	366.56	19.6%	-6.5%	1.1%	-1.3%	4.25	16.62%	-18.5%	-1.6%	-4.9%
2016	12.22	-28.6%	-18.7%	-7.2%	-2.5%	6.58	-18.6%	-6.4%	-6.8%	-1.4%	373.46	21.9%	-6.4%	3.0%	-1.4%	4.35	19.32%	-18.0%	0.6%	-4.4%
2017	11.87	-30.6%	-20.8%	-9.8%	-5.0%	6.43	-20.4%	-8.4%	-8.9%	-3.3%	370.97	21.0%	-8.4%	2.3%	-3.3%	4.31	18.20%	-20.4%	-0.3%	-7.0%
2018	11.67	-31.8%	-21.5%	-11.3%	-6.2%	6.31	-22.0%	-9.3%	-10.6%	-4.2%	376.81	23.0%	-9.3%	3.9%	-4.2%	4.34	19.06%	-22.2%	0.4%	-9.1%

Table 67 - Carbon intensity levels and percentage changes of International shipping（Option 2）

Year	EEOI (gCO2/t.nm)					AER(gCO2/dwt.nm)					DIST(kgCO2/nm)					TIME(tCO2/hr)				
	Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012		Value	Variation vs 2008		Variation vs 2012	
		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual		overall	individual	overall	individual
2008	15.16	–	–	–	–	7.40	–	–	–	–	350.36	–	–	–	–	4.38	–	–	–	–
2012	12.19	-19.6%	-11.4%	–	–	6.61	-10.7%	-4.6%	–	–	387.01	10.5%	-4.6%	–	–	4.74	8.11%	-13.9%	–	–
2013	11.83	-22.0%	-13.6%	-3.0%	-2.6%	6.40	-13.5%	-6.6%	-3.2%	-2.2%	380.68	8.7%	-6.6%	-1.6%	-2.2%	4.57	4.13%	-17.6%	-3.7%	-4.5%
2014	11.29	-25.6%	-16.2%	-7.4%	-5.5%	6.20	-16.1%	-7.6%	-6.1%	-3.1%	382.09	9.1%	-7.6%	-1.3%	-3.1%	4.54	3.49%	-19.4%	-4.3%	-6.6%
2015	11.30	-25.5%	-14.5%	-7.3%	-3.7%	6.15	-16.9%	-6.2%	-6.9%	-2.0%	388.62	10.9%	-6.2%	0.4%	-2.0%	4.64	5.75%	-18.0%	-2.2%	-5.3%
2016	11.21	-26.1%	-14.0%	-8.1%	-3.2%	6.09	-17.7%	-5.9%	-7.8%	-1.8%	397.05	13.3%	-5.9%	2.6%	-1.8%	4.77	8.68%	-17.4%	0.5%	-4.7%
2017	10.88	-28.2%	-15.9%	-10.8%	-5.4%	5.96	-19.5%	-7.7%	-9.8%	-3.7%	399.38	14.0%	-7.7%	3.2%	-3.7%	4.79	9.21%	-19.7%	1.0%	-7.2%
2018	10.70	-29.4%	-17.2%	-12.3%	-7.0%	5.84	-21.0%	-8.9%	-11.5%	-4.8%	401.91	14.7%	-8.9%	3.8%	-4.9%	4.79	9.17%	-21.5%	1.0%	-9.3%

For the same reason explained for estimates on carbon intensity of ship types, carbon intensity levels of world fleet estimated through Option 1 were a little bit higher than (i.e. inferior to) those derived from Option 2, while the percentage changes were a little bit larger (showing a bigger improvement). The differences in carbon intensity improvement were around 2 to 3 percentage points higher under Option 1 when measured in EEOI, and generally smaller than 2 percentage points higher in AER. For the sake of brevity, results derived from both Option 1 and Option 2 are reported, but discussions on trends and drivers of carbon intensity have mainly focused on Option 2 unless otherwise specified, in line with other chapters of this study.

Figure 149 and Figure 150 show the trends of the overall carbon intensity of international shipping, estimated through dividing the aggregated CO_2 emissions by the aggregated transport work. Values of EEOI and AER has generally kept decreasing between 2012 and 2018, and reached a reduction rate around 29% and 21% in 2018 respectively, in comparison with year 2008. Discrepancies between the two metrics were mainly caused by their opposite reflections on payload utilization. Values of DIST and TIME both showed an increasing trend due to the increasing average ship size, whereas the increasing magnitudes have been diminished to a certain extent by sea speed reduction, especially for values of TIME.

Figure 149 – Percentage changes in total carbon intensity of international shipping (Option 1)

Figure 150 -Percentage changes in total carbon intensity of international shipping (Option 2)

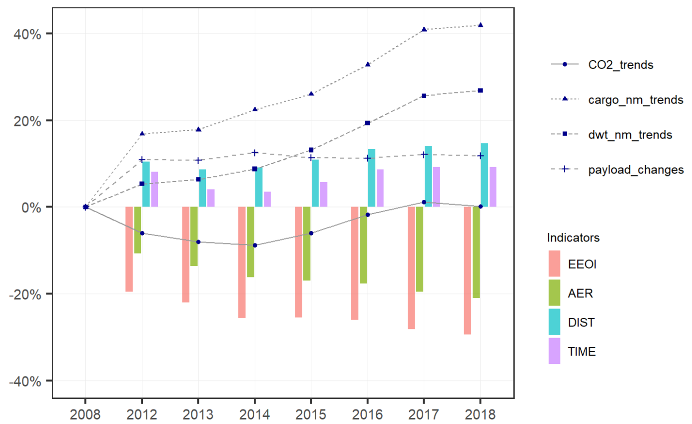
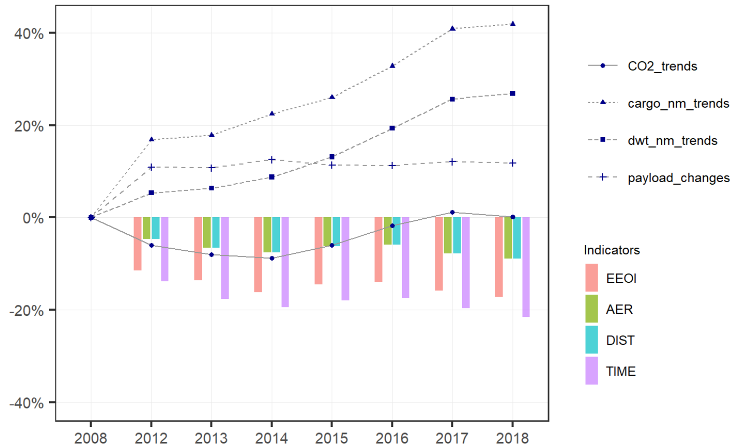


Figure 151 and Figure 152 show the trends of individual based carbon intensity of international shipping, calculated based on the estimates of regression fits of ship types. Having not taken the influence of ship size composition shift into account, the four carbon intensity metrics have generally kept going down between 2012 and 2018, where AERs and DISTs shared identical percentage changes.

Without the contribution of scale economy, reduction magnitudes in EEOI and AER both narrowed down significantly. In comparison with 2008, the reductions in EEOI, AER/DIST and TIME in 2018 were around 17%, 9% and 22% respectively. The relatively smaller improvements in AER/DIST, when compare with in EEOI, were due to their negative response (metric values going up) to the increasing payload utilization, while the relatively larger improvements in TIME were due to their high sensitivity to speed reduction.

Figure 151 - Percentage changes in individual based carbon intensity of international shipping (Option 1)

Figure 152 - Percentage changes in individual based carbon intensity of international shipping (Option 2)

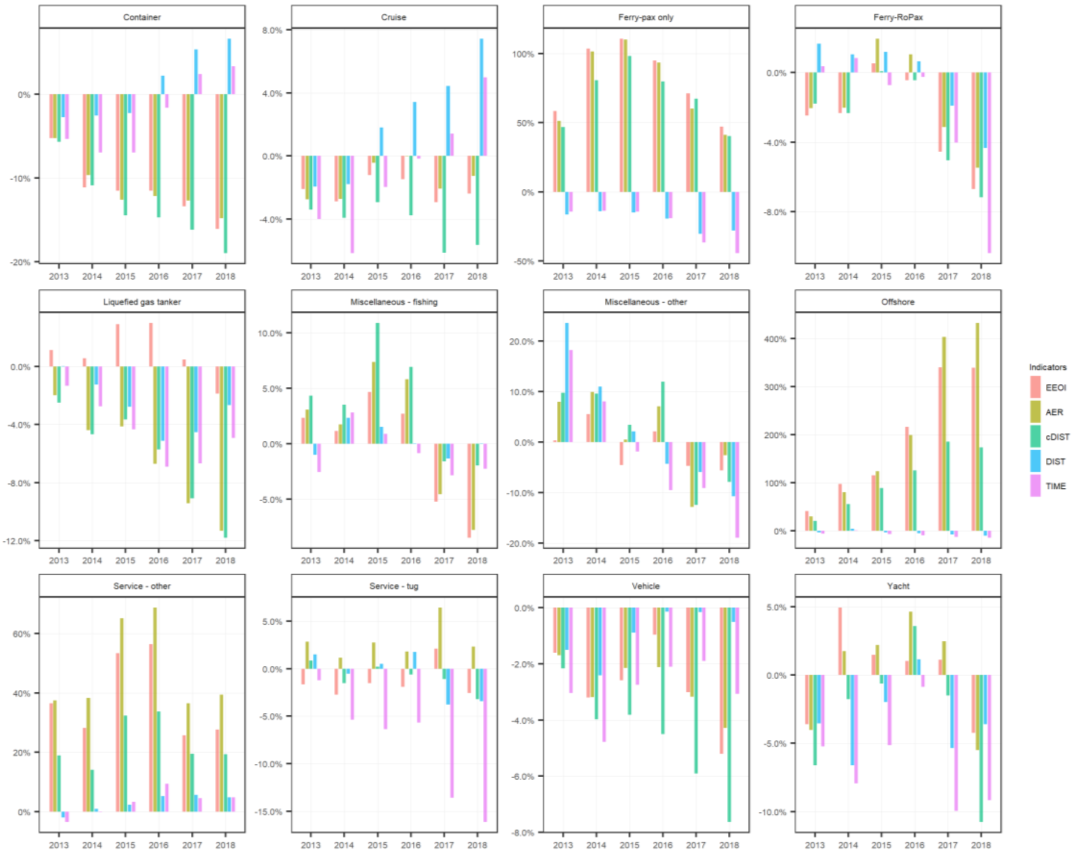


Note that the reduction rates in carbon intensity of international shipping discussed above are all indexed at year 2008, at which time the shipping market was just reaching its peak right before the long-lasting depression. Taking year 2012 as the reference instead, the reductions in overall carbon intensity of international shipping narrowed down from 29% (in EEOI) and 21% (in AER) to around 12% (in both EEOI and AER). The percentage changes in individual based carbon intensity further shrank to 7% (in EEOI), 5% (in AER/DSIT) and 9% (in TIME). This implies that the improvements in carbon intensity of international shipping has not followed a linear pathway, and more than half have been achieved before year 2012. The pace of carbon intensity reduction has been further slowing down since 2015, with average annual percentage changes ranging from 1% to 2%, due to the limit in speed reduction, payload utilization as well as the technical improvements of existing ships.

3.3.4 Comparison between potential carbon intensity metrics

In exploring the suitability of potential carbon intensity metrics, the variants of AER, namely cDIST and EEPI, are additionally calculated where applicable. The metric cDIST applies to a ship type which practically uses a capacity unit rather than dwt, such as container ships (using teu), liquefied gas tankers (using cubic meter), as well as vehicle carriers, cruise ships, ferries, yachts and others (in gross tonnage). As shown in Figure 153, for most ship types, the overall levels of cDIST generally shared similar trends with EEOI and AER, yet with smaller increasing magnitudes and larger decreasing magnitudes. This implies that the carbon intensity improvements of these ship types could be more significant if measured in cDIST instead of AER. Given all else is equal, this can be possibly explained by the alternative units in cDIST used for indicating capacity, which can additionally capture the optimization in ship design, such as more container or gas capacity per given dwt. For working and service ships, such as offshores, tugs and fishing vessels, the metric TIME showed a more sensible behavior.

Figure 153 - Performance of cDIST compared with other metrics



The metric EEPI applies to ship types which typically have ballast voyages, including bulk carriers, oil tankers, general cargo ships and liquified gas tankers. EEPI shares the same numerator with EEOI and cDIST, yet introducing an alternative proxy of transport work in the denominator. Compared with EEOI, EEPI differs by replacing the cargo carried with the ship's capacity (DWT); compared with cDIST, it differs by replacing the total distance travelled under all operational conditions with laden distance. For tankers and other ship categories which operate part of the time loaded and part of the time in ballast, such transport work proxy is roughly in conformity with practice(Zhang et al., 2019). For ship types which are always fully or partly loaded, such as container ships, EEPI is equivalent to AER. As shown in Figure 154, correlation (measured in Spearman's rank correlation coefficient) (Hájek et al., 1999) between EEPI and EEOI for ships of same type and size bin is significantly higher than between AER and EEOI. Figure 155 further shows that, compared with AER, the metric EEPI showed better consistency with EEOI, in terms of both metric values and variation magnitudes.

Figure 154 - Correlation between carbon intesntiy metrics

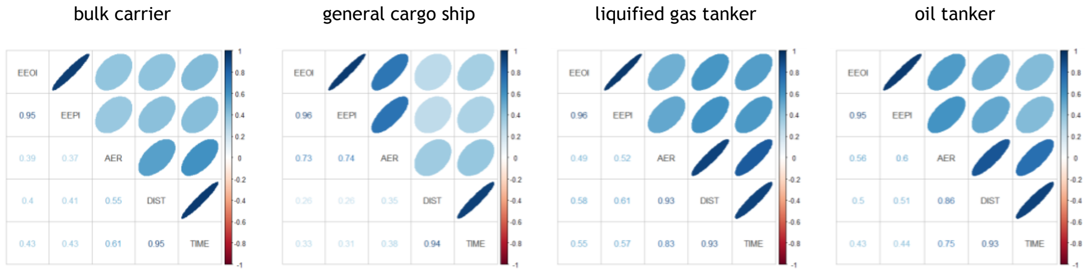
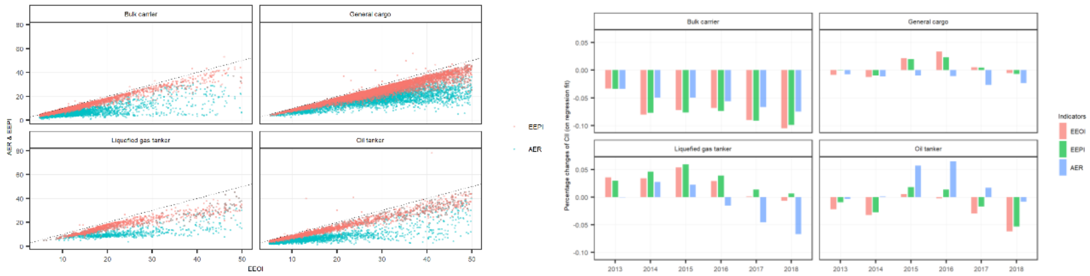


Figure 155 - Performance of EEPI compared with AER



In summary, the suitability of candidate carbon intensity metrics are as follows:

- For typical cargo ships as well as the international shipping as a whole, EEOI, AER, cDIST and EEPI are all potentially applicable, providing data for metric calculation were available.
- Among these metrics above, EEOI can capture almost all technical and operational influencing factors, thus leading to less biasness. However, since data on cargo carried on board are quite commercial sensitive, the application of this metric for individual ships may be impractical.
- AER, cDIST and EEPI are actually designed to approximate of EEOI. Data for calculating these metrics are readily available or potentially available (such as laden distance for EEPI calculation), which makes their application possible. Main drawbacks of these metrics are their distorted reflections on payload utilization, though to a larger or smaller extent.
- Compared with AER and cDIST, EEPI behaves better when applied to ship types which have typical ballast voyages, while equivalent when applied to other ship types such as container ships.
- Metrics, which are generally referred to as cDIST in this study, boast their various units used to measure a ship's capacity in line with shipping practices. These metrics share identical features with AER when used in a like-to-like comparison, but will generate different metrics units for different ship types, thus make the comparison between ship types complicated.
- DIST and TIME both have removed the ship capacity from their metric calculation, which means the mass or volume carried on broad should not be an issue of concern when these metrics are applied. Therefore, these metrics are suitable for ship types which contributions can be practically indicated by distance travelled or hours at sea, such as tugs, offshore and fishing vessels.

3.4 Quality assurance of quality control

3.4.1 Data filtering

In order to eliminate the potential distortion induced by significant outliers whilst ensure the representativeness the data sample, only basic filters are applied to remove ships which did not have any CO_2 emissions counted as international and those with obviously spurious or less representative metric values, including:

- CO_2 emissions counted as international equal to zero;
- year of built earlier than 1970;
- annual average payload utilization of round and laden trips less than 5%;
- annual average proportion of laden distance less than 5%;
- annual average proportion of laden hours less than 5%; and
- annual EEOI metric value larger than 3,000 gCO_2/t.nm or smaller than 3 gCO_2/t.nm.

The excluded ships merely accounted for less than 1% of total CO_2 emissions from international shipping and less than 0.5% of cargo tonne-miles undertaken, under both Option 1 and Option 2. The Wilcoxon's non-parametric rank sum test (Hollander and Wolfe, 1999) is applied to see if the ship size composition of each sample after filtering was significantly different from the original. The results show that the medians of all samples before and after filtering are statistically equivalent to each other (with all p-values significantly above zero).

3.4.2 Results validation

Uncertainties in carbon intensity estimation partly stem from the inventory estimation and partly from the estimates on transport work. The accuracy of carbon intensity estimation, especial for EEOI, heavily relied on the reliability of the estimates on cargo carried on board a ship, which mainly depends on operational draughts reported in AIS as per outlined in Annex D. Besides, models for estimating cargo mass cannot be balanced good for each type.

To validate the estimates on carbon intensity of international shipping, results are compared against the metric values reported in the 11000-ship EU MRV database for the year 2018. The metric values for comparison generated by this study has been recalculated to only include voyages that interacted with EU ports as detailed in Chapter 2, therefore no need to make distinction between Option 1 and Option 2.

To further quantify the differences between the estimated carbon intensity metric values and the EU verified metric values of individual ships, the discrepancy and deviation rate in a carbon intensity metric of the same individual ship yet calculated based on two data sources is respectively defined as $dif_{i,cii} = 2(CII_{i,IMO4} - CII_{i,MRV}) / (CII_{i,IMO4} + CII_{i,MRV})$ and $dev_{i,cii} = (CII_{i,IMO4} - CII_{i,MRV}) / CII_{i,IMO4}$ .The distribution of such discrepancy rates of individual ships covered by each typical cargo ship type, as well as the mean and median values, are presented in Figure 156, Figure 157 and Table 68. It is shown that EEOIs were systematically underestimated by this study, whereas values in AER and DIST seemed to agree well. According to the median discrepancy rates of individual ships, the metric values in EEOI might be underestimated by 10-25% for bulk carriers, container ships, chemical tankers and general cargo ships, whilst by 50% for liquefied gas tankers. The discrepancies in oil tanker was less than 5%. Since CO_2 emissions could have been overestimated, the underestimation on EEOI values was likely caused by a larger overestimation on payload utilization.

Figure 156 - Distribution of deviation rates of indivudal ships

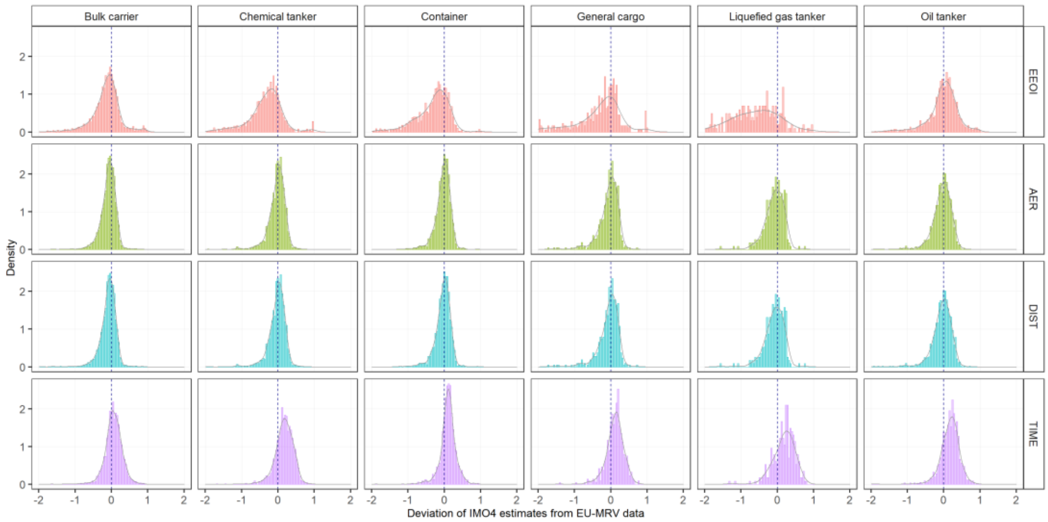


Figure 157 - Deviation of estimated metric values from EU MRV

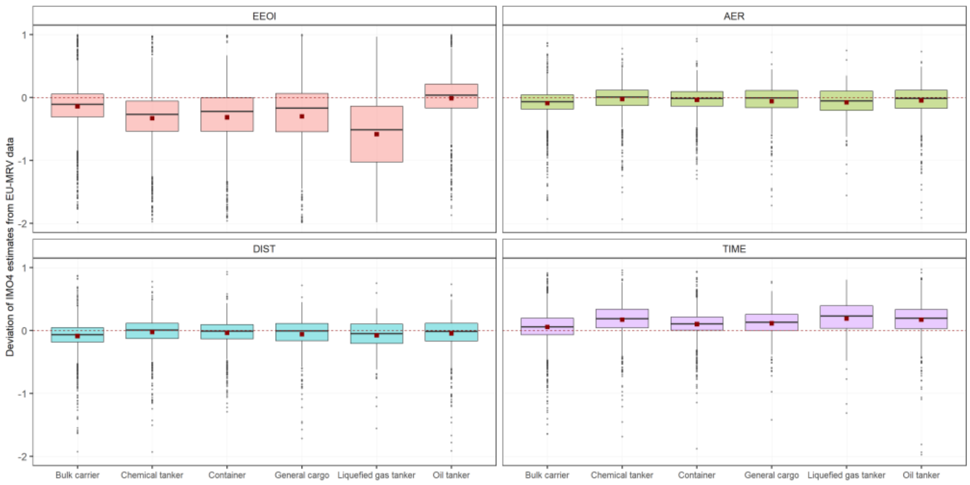


Table 68 - Discrepancy and deviation rates on individual basis

Ship type	Number of ships	Average dwt (t)	Average engine power (kW)	Median discrepancy and deviation rates on individual basis (%)							
				EEOI		AER		DIST		TIME	
				discrepancy	deviation	discrepancy	deviation	discrepancy	deviation	discrepancy	deviation
Bulk carrier	3195	66925	9166	-10.6	-11.2	-6.2	-6.4	-6.2	-6.4	5.9	5.7
Chemical tanker	1637	34767	7652	-24.5	-27.9	0.9	0.9	0.9	0.9	20.8	18.8
Container	1679	71137	36758	-20.6	-23.0	-1.1	-1.1	-1.1	-1.1	11.5	10.8
General cargo	537	19336	6344	-25.5	-29.3	-0.8	-0.8	-0.8	-0.8	14.1	13.2
Liquefied gas tanker	287	26044	8975	-50.5	-67.5	-4.9	-5.1	-4.9	-5.1	26.0	23.0
Oil tanker	1309	121371	14484	3.5	3.4	-1.4	-1.4	-1.4	-1.4	21.9	19.7

These findings echo the validation results on transport work with the cargo tonne-miles published in UNCTAD's Review of Maritime Transport (2018), as presented in Table 69, Table 70, Figure 158 and Figure 159. In order to align the ship type and cargo type categorization of this study and the published data, the main bulks, minor dry bulks and other dry cargo presented in UNCATD report are aggregated into the group of "dry cargo", referring to ship types of bulk carriers, general cargo ships and refrigerated bulk carriers in this study as per previous literature (Smith et al., 2015).

It is shown that the discrepancies in cargo ton-miles for oil tankers, container ships and dry cargo ships (covering bulk, general cargo and refrigerated bulk carriers) were consistently around -2, 30 and -28% over 2012-2018, based on the estimated results through Option 2. The validation results on oil tankers and containers ships were well consistent with the EU MRV comparison findings, while the bias tendency of dry cargo seemed opposite. This was likely caused by the different categorization strategy applied to seaborne trade and to marine transportation. Nevertheless, the discrepancies in total cargo ton-miles between this study and UN published data were limited within ±2%, based on estimated results through Option 2. Since the categorization strategy of Option 1 is more different from the method applied in UNCATD report, the discrepancies were a little bit larger than Option 2. Validation results based on output through Option 1, however, are additionally provided in parallel for reference.

These validations highlight two points: first, the estimates on carbon intensity of international shipping as a whole was more reliable than the results of ship types; second, the estimated trends in carbon intensity performance, which could not be substantially affected by systematically biased estimation in transport work, were more reliable than the absolute metric values. Given the limited data available for validation, subjective rectification such as introducing a series of correction factors to carbon intensity estimates of ship types may incur another uncertainty. Therefore, no corrections have been made to the results presented in Section 3.3. To avoid misleading, however, whenever the estimated carbon intensity levels of ship types are referred to, the possible biasness should be specified jointly.

Table 69 - Deviation of cargo tonne-miles estimates from UNCTAD statistics (Option 1)

Ship type	2008			2012			2013			2014			2015			2016			2017			2018		
	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation
Dry cargo	19357	22810	-17.8%	23941	27518	-14.9%	24216	28859	-19.2%	25441	30510	-19.9%	25956	30811	-18.7%	27051	31574	-16.7%	28728	33111	-15.3%	28464	34193	-20.1%
Chemical tanker	2719	759	72.1%	3105	903	70.9%	3171	925	70.8%	3214	920	71.4%	3475	961	72.3%	3771	993	73.7%	3969	1058	73.3%	3990	1111	72.2%
Container	10307	6431	37.6%	12185	7352	39.7%	12408	7712	37.8%	12940	8157	37.0%	13133	8290	36.9%	13691	8635	36.9%	14681	9117	37.9%	15153	9535	37.1%
Liquefied gas tanker	1862	956	48.7%	2644	1333	49.6%	2672	1337	50.0%	2721	1381	49.2%	2646	1421	46.3%	2765	1462	47.1%	3137	1595	49.1%	3484	1766	49.3%
Oil tanker	11757	11211	4.6%	12202	11831	3.0%	11963	11657	2.6%	11974	11659	2.6%	12571	11993	4.6%	13620	12657	7.1%	14504	13216	8.9%	14343	13809	3.7%
Fleet	46003	42167	8.3%	54077	48937	9.5%	54429	50490	7.2%	56290	52627	6.5%	57782	53476	7.5%	60897	55321	9.2%	65017	58097	10.6%	65435	60414	7.7%

Figure 158 - Deviation of cargo tonne-miles estimates from UNCTAD statistics (Option 1)

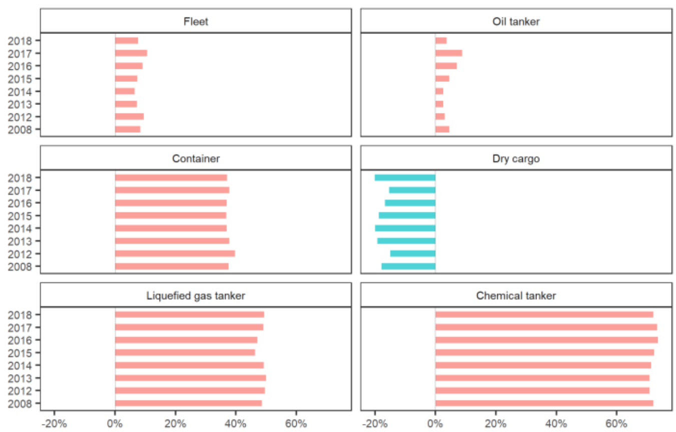
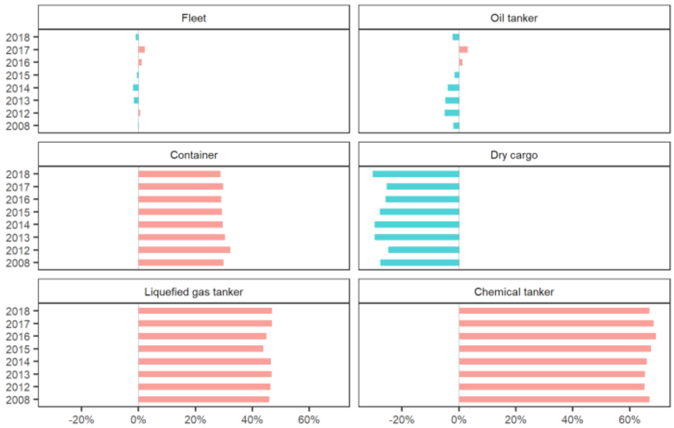


Table 70 - Deviation of cargo tonne-miles estimates from UNCTAD statistics (Option 2)

Ship type	2008			2012			2013			2014			2015			2016			2017			2018		
	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation	IMO4	UN	Deviation
Dry cargo	17878	22810	-27.6%	22050	27518	-24.8%	22274	28859	-29.6%	23546	30510	-29.6%	24117	30811	-27.8%	25106	31574	-25.8%	26420	33111	-25.3%	26234	34193	-30.3%
Chemical tanker	2297	759	67.0%	2598	903	65.2%	2666	925	65.3%	2708	920	66.0%	2960	961	67.5%	3229	993	69.2%	3351	1058	68.4%	3357	1111	66.9%
Container	9175	6431	29.9%	10865	7352	32.3%	11081	7712	30.4%	11579	8157	29.6%	11731	8290	29.3%	12182	8635	29.1%	12977	9117	29.7%	13406	9535	28.9%
Liquefied gas tanker	1772	956	46.0%	2488	1333	46.4%	2514	1337	46.8%	2579	1381	46.5%	2532	1421	43.9%	2655	1462	44.9%	3001	1595	46.9%	3326	1766	46.9%
Oil tanker	11003	11211	-1.9%	11267	11831	-5.0%	11128	11657	-4.8%	11216	11659	-3.9%	11804	11993	-1.6%	12821	12657	1.3%	13634	13216	3.1%	13502	13809	-2.3%
Fleet	42167	42167	0.0%	49268	48937	0.7%	49663	50490	-1.7%	51628	52627	-1.9%	53144	53476	-0.6%	55993	55321	1.2%	59383	58097	2.2%	59824	60414	-1.0%

Figure 159 - Deviation of cargo tonne-miles estimates from UNCTAD statistics (Option 2)



4 Projections of CO_2 emissions of shipping

4.1 Introduction

This chapter presents the projections of CO_2 emissions of shipping until 2050. The emission projections are based on projections of fleet activity which, in turn, are based on projections of transport work using a suite of long-term socio-economic projections in order to account for uncertainty.

Section 4.2 presents the methodology employed to project emissions. Section 4.3 develops the projections of maritime transport work until 2050. Section 4.4 focusses on efficiency improvements of the fleet and presents new Marginal Abatement Cost Curves. Section 4.5 comprises the emission projections.

4.2 Methodology

The method for projecting emissions from shipping in this Study comprises six steps:

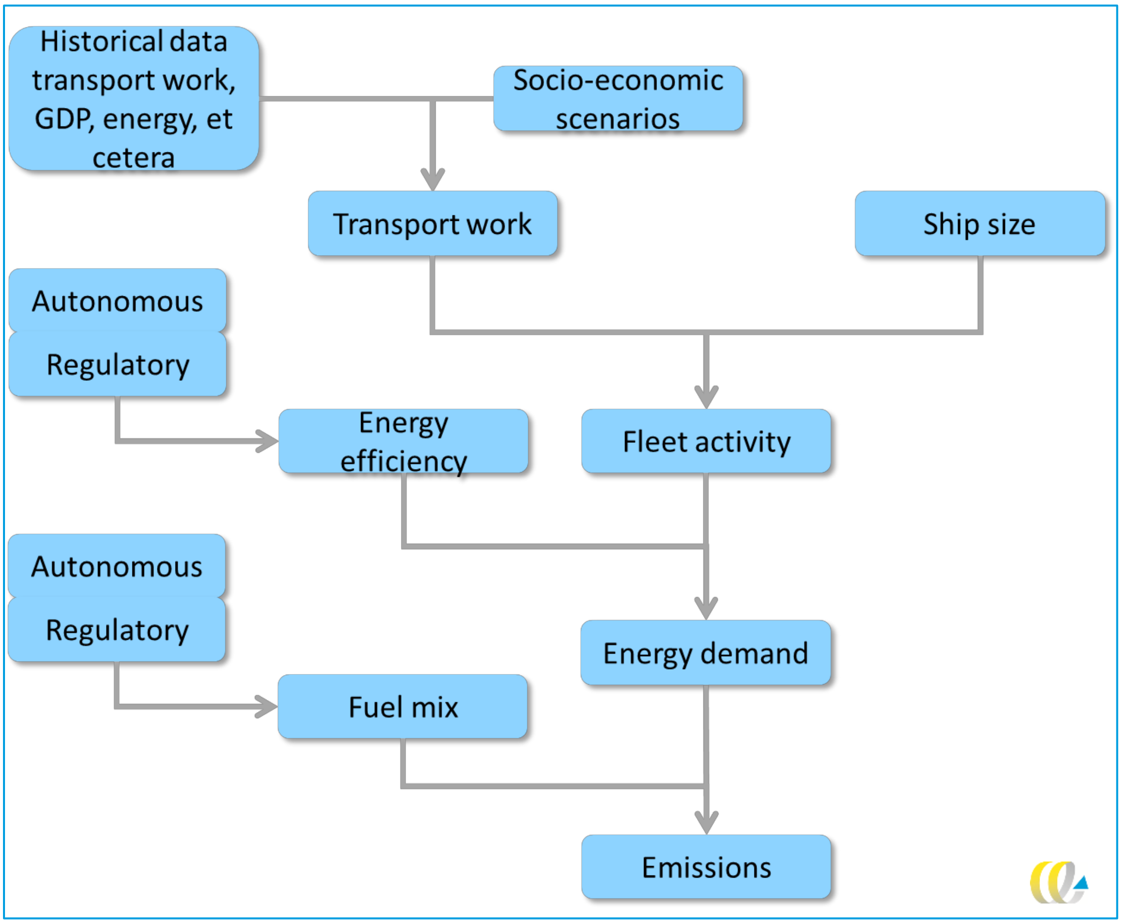
1. Projecting transport work – non-energy products:
   a) Establishing the historical relation between maritime transport work and relevant economic parameters such as world (or country) per capita GDP and population (for transport of non-energy products, such as unitized cargo, chemicals and non-coal dry bulk);
   b) Projecting transport work on the basis of the relations described in (a) and long-term projections of GDP and population (global or by country).
2. Projecting transport work – energy products
   a) Collecting IPCC formal projections of evolution of energy consumption and energy consumption (for transport of energy products like coal, oil and gas).

b) Projecting transport work using the variation of energy consumption projection when considering seaborne transportation of energy products (coal dry bulk, oil tankers and gas tankers).

3. Making a detailed description of the fleet and its activity in the base year 2018. This involves assigning the transport work to ship categories and establishing the average emissions for each ship in each category.
4. Projecting the future fleet composition based on a literature review and a stakeholder consultation.
5. Projecting future energy efficiency of the ships, taking into account regulatory developments and market-driven efficiency changes using a marginal abatement cost curve (MACC).
6. Combining the results of Steps 3, 4 and 5 above to project shipping emissions.

Figure 160 is a graphical representation of the methodology.

Figure 160 - Graphical representation of methodology to develop emission projections



The remainder of this section elaborates on the methods to project transport work (Section 4.2.1); the selection of socio-economic scenarios and energy scenarios (Section 4.2.2); the projections of the structure of the fleet and the size of ships (Section 4.2.3) and efficiency improvements (Section 4.2.5). More details on transport work projections can be found in Annex I. Annex H provides more detail on the selection of long-term scenarios and Annex J provides a detailed analysis of ship sizes.

4.2.1 Methods to project transport work

This study employs two methods to project transport work related to non-energy products transportation. They have in common that they start with analysing the historical relation between transport work on the one hand and a driver of demand on the other, which can be total GDP; per capita GDP and population. They also have in common that they use long-term projections of these drivers developed either by the IPCC or by economic institutions to project transport work in the future.

The differences between the two methods relate to data and mathematics. One of the methods presumes that the relation between transport work and its driver (total GDP) can be described by a logistic curve (sometimes called an S-curve), finds the curve that best resembles historical data and uses the curve to project transport work in the future. We call this the logistic analysis.

The other method presumes that transport work is a function of per capita GDP and population of the trading countries and uses econometric techniques to estimate the elasticity of transport work with respect to its drivers based on panel data of bilateral trade flows. We call this the gravity-model analysis.

The differences in data are that the logistic model uses global data on maritime transport work covering a period of twenty to fifty years, depending on the type of product.[6] The gravity-model analysis uses data on the volume of bilateral trade flows for a five-year period (2014-2018), and estimates the share of maritime transport in that trade flow to generate mode-specific trade volume data (for all non-energy products transported by sea). As the gravity model considers both time and products/ships by pairs of countries dimension (187x187 countries each year), the number of observations is higher than the logistic model.[7]

The models present two different outlooks on how the future resembles the past:
1. Logistic model assumes that the transport work is related to world total GDP with an S-curve, i.e. that transport work goes through a stages of slow initial growth followed by a rapid expansion and finally a mature stage. It can accurately describe the past experience for the different cargo types and captures the specificities of global transport of the different commodities. Because it is based on global data, it does not capture the peculiarities of countries' bilateral trade flows.
2. The gravity model assumes that bilateral sea trade is a function of the income (GDP per capita) and size (population) of the trading countries, as well as of their geographical proximity, and similarities in consumer preferences. It uses panel data techniques to determine the elasticities of trade. It can accurately describe how GDP and population variations impact on sea trade, capturing idiosyncrasies of each trade flow.

When panel data techniques are not applied to estimate elasticities of trade using each bilateral trade flow, it can be demonstrated that the gravity model mimic the logistic model and, therefore, projection results are very similar among models (see Annex I).

However, the two methods yield different results when the gravity model is set up to capture the particularities of bilateral trade flows. This occurs as panel data techniques control for differences in trade between countries (there can be a multitude of observed and unobserved reasons), such as historical linkages, production facilities of multinational corporations, similar languages or legal systems, port infrastructure, et cetera. As a result, elasticities of trade in respect to countries' income and size are lower and, therefore, the aggregated global transport work projections are lower than the logistics model (see section 4.3). Another difference between the models is that the GDP and population projections used are by country, while the socio-economic projections of the logistic model are global.

Because both methods have their strengths and weaknesses, this study presents both as plausible projections of transport work related to non-energy products transportation. The difference between the two can be interpreted as the uncertainty inherent in making projections about future developments.

The method used to project transport work related to the transportation of energy products is based on the change in energy demand projections applied to the total transport work historical measures and data by ship type (for Oil Tankers, Gas Tankers and Bulk Carriers).

[6] Data from Clarksons Shipping Intelligence Network on transport work (tonne-miles) of crude oil, oil products and coal from 1970 to 2019; containers and other unitized cargo from 1983 to 2019; gas, chemicals and non-coal dry bulks from 1999 to 2019.

[7] UN Comtrade data. Appendix I describes all data sources and assumptions.

Throughout this chapter, projections using the logistics model will be denoted '_L' and projections using the gravity model '_G'.

4.2.2 Selecting long-term economic and energy scenarios

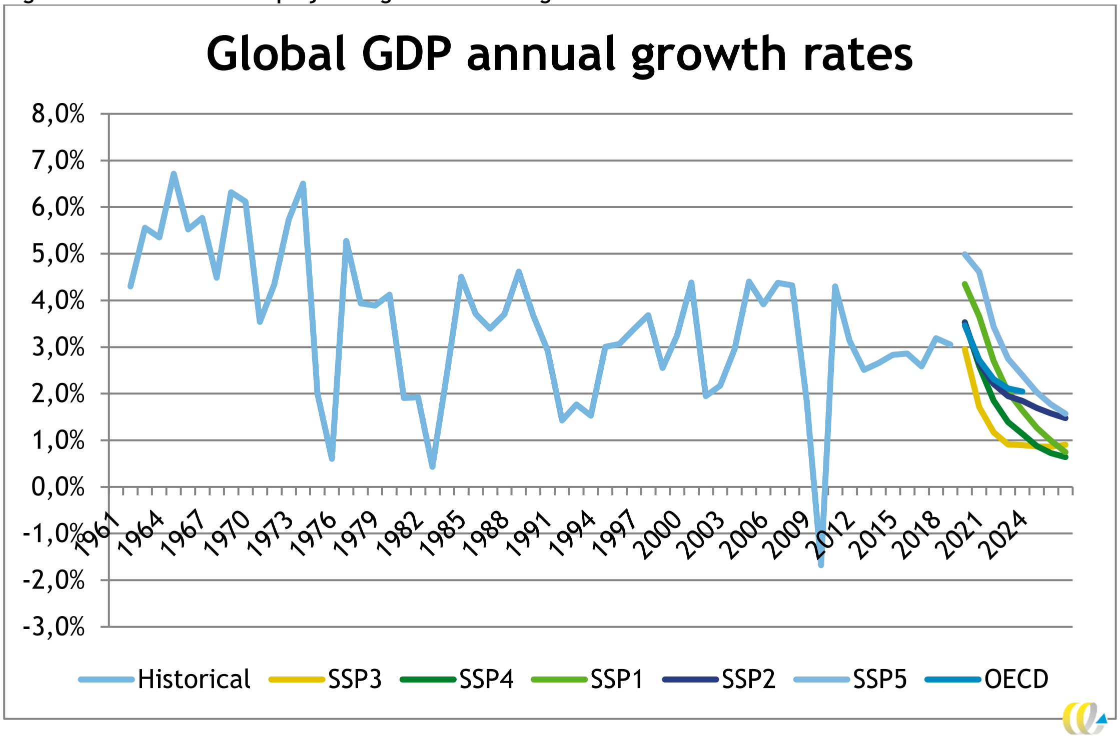
As mentioned, the transport work projections related to non-energy products are based on long-term socio-economic projections (global GDP in the logistic model and country GDP and country population in the gravity model), augmenting the methodology employed in the Third IMO Greenhouse Gas Study 2014. Transport work projections related to energy products are based on energy consumption projections. Hence, the projections are based on GDP and population projections from the so-called Shared Socio-Economic Pathways (SSPs) developed by the IPCC, as well as the OECD long-term baseline projection (OECD 2018). Primary energy consumption projections are from the SSP and Representative Concentration Pathways (RCPs) integrated assessment scenarios, also developed by the IPCC.

The SSPs and RCPs were developed in the 2000s and some scenarios have become less plausible since the entry into force of the Paris Agreement and national policies. According to (Climate Analytics and New Climate (2019), the current policies will result in an increase of global mean temperatures of 2.3°C to 4.1°C with a central estimate of 3.0°C. If pledges are followed up on, the increase will be lower, and this is not taking into account new pledges. All this makes RCP 8.5 and the associated temperature increase of 5°C implausible. Many authors also raise the discussion on possible combinations of SSPs and RCPs by calculating their mitigation costs and carbon prices to achieve the forcing targets based on socio-economic projections (Riahi, et al., 2017; Rogelj, et al., 2018). Based on the plausibility of the scenarios' combinations, the emission projections related to non-energy products are based on the following combinations (see also Appendix H for more details):

1. RCP 1.9 and SSP1 and OECD;
2. RCP 2.6 and SSP1, SSP2, SSP4, and OECD;
3. RCP 3.4 and SSP1, SSP2, SSP3, SSP4; SSP5, and OECD;
4. RCP 4.5 and SSP1, SSP2, SSP3, SSP4; SSP5 and OECD;
5. RCP 6.0 and SSP1, SSP2, SSP3, SSP4; SSP5 and OECD.

While all these combinations are plausible, some have very high GDP growth rates compared to present or historical values. Figure 161 shows historical growth rates alongside projected growth rates of different SSP scenarios and the recent OECD long-term scenario. It can be seen that SSP3 has growth rates that resemble the OECD scenario. SSP1 and especially SSP5 have much more optimistic assumptions about future economic developments. Because the OECD projections are more recent and have incorporated recent experiences, we present the OECD projections and SSP2, SSP3 and SSP4 more prominently than the other SSPs.

Figure 161 - Historical and projected growth rates of global GDP



Regarding transport work projections for energy products, the RCP and SSP combinations utilized were all possible combinations between SSP 1 to 5 and RCP 1.9 to 6.0, according to the marker IAM (integrated assessment model), that is, the same RCP-SSP combinations used to project emissions, except for RCP 6.0-SSP1 and OECD scenarios. Additionally, the transport work projections related to energy products considered SSP1 to SSP5 baseline scenarios and RCP 1.9-SSP2, RCP 1.9-SSP5, RCP 2.6-SSP5 combinations. In turn, to project transport work related to non-energy product transportation, were utilized all SSP scenarios and OECD`s GDP forecast.

4.2.3 Defining the base year for ship emissions

The base year for the ship emissions and ship efficiency is 2018.

In this year, the number of type 1 and type 2 ships and their emissions have been used as a basis. For the following years, the number of ships evolve in line with the projected transport work demand. This development is specific for specific ship types.

The projections are emission projections for total shipping. We expect that the share of international and domestic shipping will not change.

In order to reflect the fact that a share number of chemical tankers is capable of transporting oil products, and there is evidence that they are often engages in transport of oil tankers, we have moved a number of chemical tankers to the oil tankers. More details can be found in Annex K.

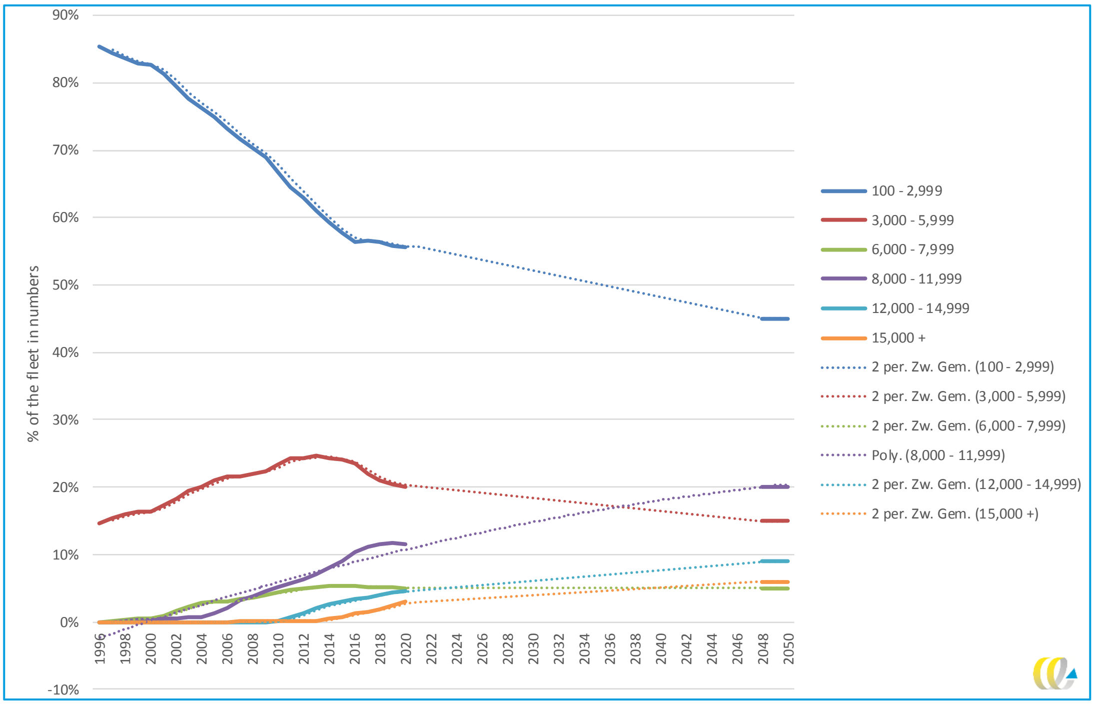
4.2.4 Projecting ship size developments

The model divides the transport work over ships. Ship supply and transport demand are assumed to be in equilibrium each year, and global transport demand for each ship type is distributed over ships of the different size bins.

Several ship types have seen changes in their average size over the past years: bulkers and containers have increased in size, while general cargo ships have decreased (Clarksons Research Portal, 2020). Appendix J analyses the trends in ship size and develops projections. For most ship types, it finds no compelling reason to assume that the size distribution in 2050 will differ significantly from the size distribution in 2018. There are three notable exceptions: containers, bulk carriers and liquefied gas carriers.

Containerships have witnessed a continuing increase in their average size as new classes of large containers have been added repeatedly to the fleet. This is driven by a fast growing market and economies of scale: larger ships have lower costs per TEU. While the growth of the market appears to be tapering off (see Section 4.3), it has not stopped and it can sustain a further increase in size. We do not find the emergence of significantly larger ships very likely (e.g. 30,000 TEU) because the associated investments in terminals would be so large that only a few terminals would make the investment. Consequently, these ships could only be employed on a few routes and would not offer much flexibility. However, an increased number of larger ships is likely. Figure 162 shows the projections graphically.

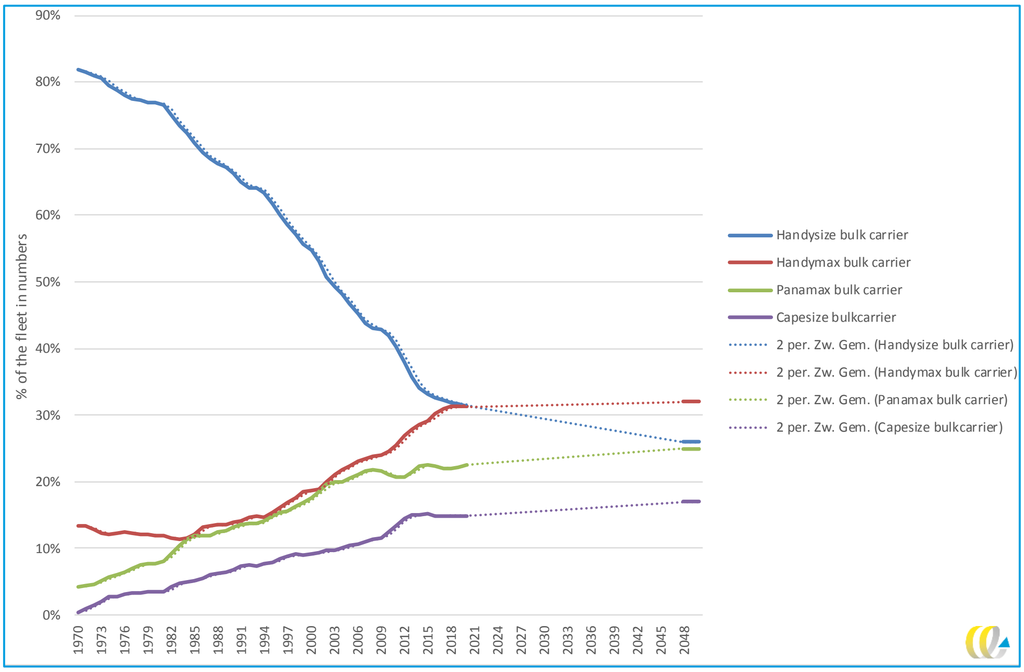
Figure 162 - Size projections of containers



Source: this report, Annex J.

Bulk carriers have also seen a noticeable increase in size in the last decades. The rate of the increase was the largest in the years preceding the opening of the new locks in the Panama Canal. Over the last years, the rate of increase has been lower. We foresee a continued modest increase in the size of bulk carriers, as shown in Figure 163.

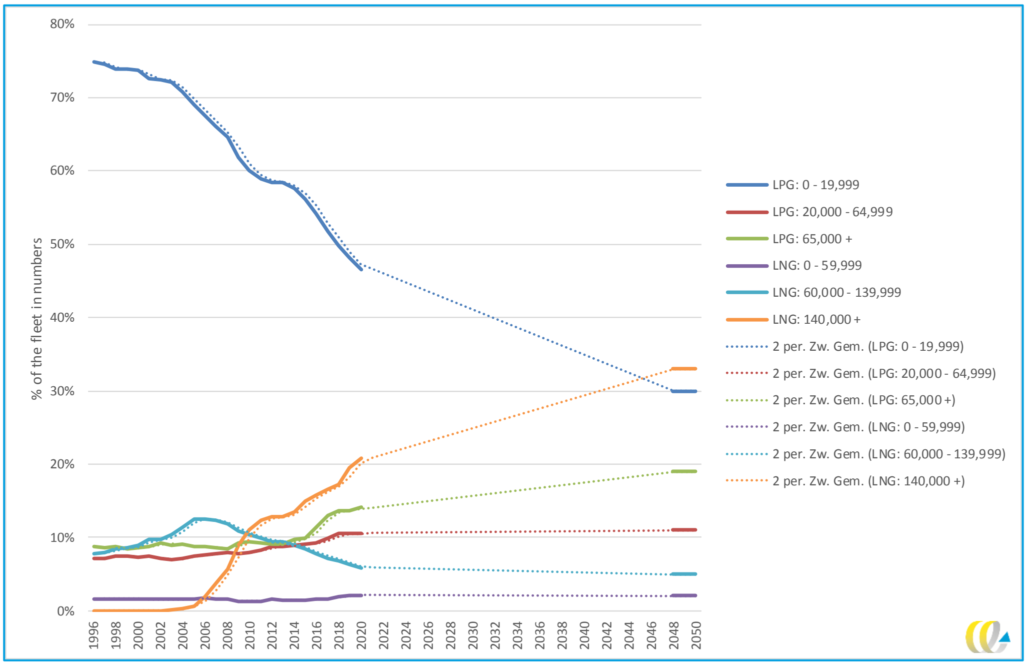
Figure 163 - Size projections of bulk carriers



Source: this report, Annex J.

Finally, the increase in demand for LNG has led to a rapid growth in the share of large LNG carriers in the fleet at the expense of medium sized carriers. We expect this trend to continue as demand for gas is projected to increase. For LPG carriers, large ships are replacing small ones. Figure 164 shows our size projections of gas carriers.

Figure 164 - Size projections of gas carriers



Source: this report, Annex J.

4.2.5 Projecting fleet efficiency developments

Changes in fleet efficiency are the result of three developments:
1. Changes in fleet composition and ship size.
2. Regulatory changes in energy efficiency or fuel mix. And
3. Market-driven changes in energy efficiency or fuel mix.

The changes in fleet composition result from changes in transport work. If, for example, transport work of dry bulk grows faster than transport work of containerized cargoes, the share of bulk carriers in the fleet will increase which will result in an increase in average efficiency because bulk carriers typically have lower emissions per tonne-mile than containers. The emission projection model does not have assumptions about changes in fleet composition.

Regulatory changes in energy efficiency and fuel mix result from EEDI and SEEMP regulations and regulations regarding the sulfur content of fuel oil.

The EEDI will result in more efficient ship designs and consequently in ships that have better operational efficiency. In estimating the impact of the EEDI on operational efficiency, this study takes two counteracting factors into account. First, the current normal distribution of efficiency (i.e. there are as many ships below as above the average efficiency, and the larger the deviation from the mean, the fewer ships there are) is assumed to change to a skewed distribution (i.e. most ships have efficiencies at or just below the limit, and the average efficiency will be a little below the limit value). As a result, the average efficiency improvement will exceed the imposed stringency limit. Second, the fact that most new-build ships install engines with a better specific fuel consumption than has been assumed in defining the EEDI reference lines is also taken into account. The result of these two factors is that operational improvements in efficiency of new ships will exceed the EEDI requirements in the first three phases but will lag behind in the third. These assumptions are the same as in the Third IMO GHG Study 2014.

As all ships were required to have a SEEMP in 2018 and no changes to the SEEMP have been agreed, this report does not assume that the SEEMP will cause changes in operational efficiency over the next decades in the business as usual scenarios.

As of 1 January 2020, the sulfur content of fuel oil consumed outside ECAs has to be lower than 0.50% m/m, down from a previous value of 3.50% m/m. This results in some ships using MGO, others Very Low Sulfur Fuel Oil, other LNG, and yet others conventional HFO in combination with a scrubber. Some of these choices would result in higher CO_2 emissions per unit of propulsion power, others in lower emissions. The difference is typically a few percent at most (IVL, 2019). In view of the other uncertainties in the projections, which are larger, we have assumed that this regulation has not net impact on CO_2 emissions.

Market-driven efficiency changes are projected using a Marginal Abatement Cost Curve (MACC). The MACC is presented in Section 4.4.

4.3 Projections of maritime transport work, 2018-2050

This section presents the transport work projections between 2018 and 2050. As explained in Section 4.2, projections are characterised by three factors:

1. The socio-economic scenario projecting future income (GDP per capita) and population, which is assumed to be related to the maritime transport demand for non-energy products, such as non-coal dry bulks, chemicals, containerized and other unitized cargoes.
2. The energy scenario projecting the future use of fossil and non-fossil primary energy sources, which is assumed to be related to the maritime transport demand for fossil energy products: coal, oil and oil products, and gas. And
3. The method to determine the relation between transport works on the one hand and GDP per capita and population on the other, for projecting non-energy products 'transport work.

Socio-economic scenarios can be one of the so-called Shared Socio-economic Pathways (SSPs) developed by Riahi, et al, (2017) or the OECD long-term baseline projections. Energy-scenarios can be one of the so-called Representative Concentration Pathways as developed by (Van Vuuren, et al., 2011b). The method to determine the relation between non-energy products' transport works on the one hand and GDP per capita and population on the other can be either Logistics analysis or Gravity-model analysis. Thus a projection can, for example, be identified as SSP1_RCP1.9_G, meaning that it is based on GDP and population projections of SSP1 (comparatively high economic growth), results in a temperature increase of about 1.5 degrees in 2100 (i.e. assumes a sharp reduction in emissions of greenhouse gases from all sectors) and has used a gravity model to analyze the relation between GDP per capita, population, and transport work. It is noteworthy that, in the gravity model, seaborne transport demand for non-energy products were projected using GDP per capita growth and population forecasts by country (Table 66). When it comes to maritime transport work demand from energy products, the energy projections come from IIASA (all possible combinations between SSPs 1 to 5 and RCPs 1.9 to 6.0 and SSP1 to SSP5 baseline scenarios).

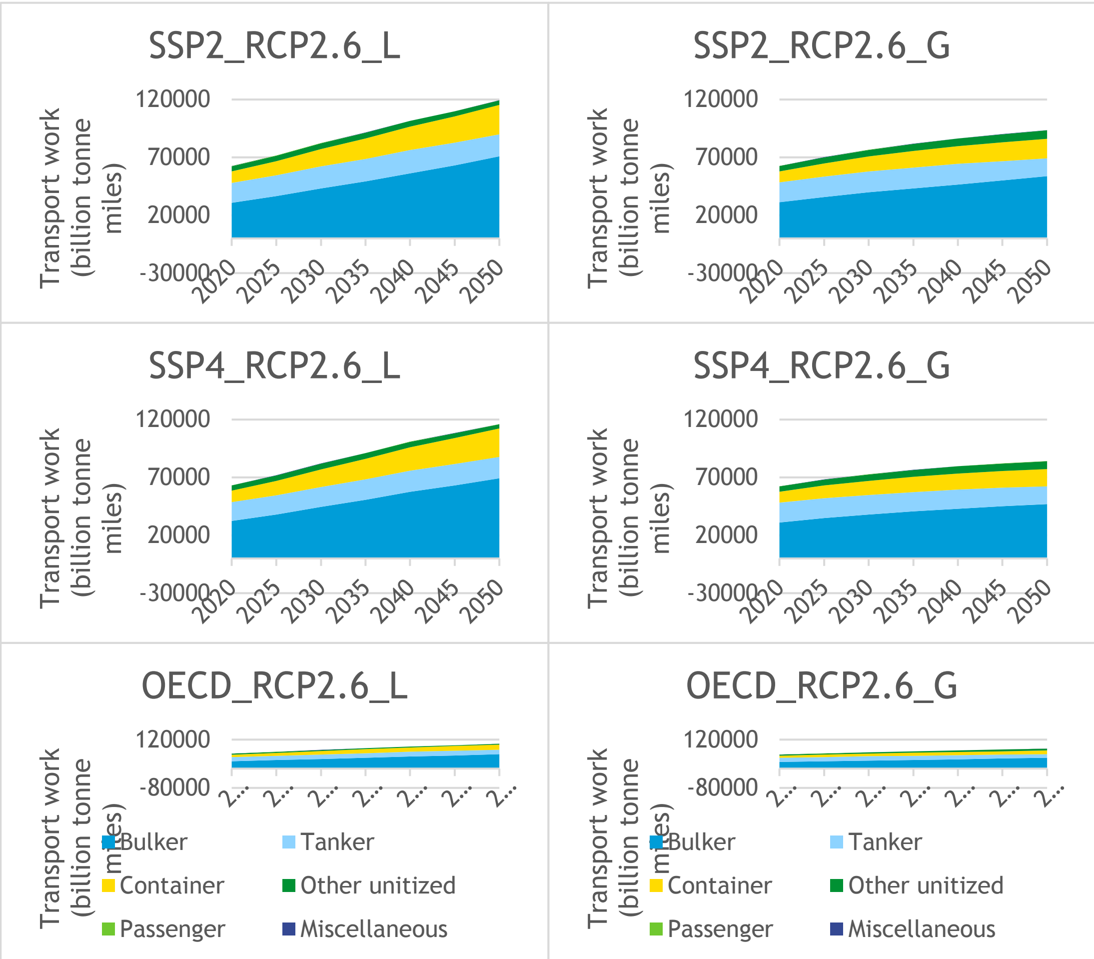
Table 71 - Characteristics of transport demand projections

Non-coal dry bulk, containers, other unitized cargo, and chemicals (Relation between transport work and relevant drivers: Logistics, denoted by _L; Gravitation model, denoted by _G)	**Coal dry bulk,-oil tankers and gas tankers**
Long-term socio-economic scenarios	**Long-term energy scenarios**
SSP1 (Sustainability – Taking the Green Road)	RCP1.9 (1.5°C) in combination with SSP1, SSP2 and SSP5
SSP2 (Middle of the Road)	RCP2.6 (2°C, very low GHG emissions) in combination with SSP1, SSP2, SSP4 and SSP5
SSP3 (Regional Rivalry – A Rocky Road)	RCP3.4 (extensive carbon removal) in combination with SSP1, SS2, SSP3, SSP4 and SSP5
SSP4 (Inequality – A Road Divided)	RCP4.5 (2.4°C, medium-low mitigation or very low baseline) in combination with SSP1, SS2, SSP3, SSP4 and SSP5
SSP5 (Fossil-fueled Development – Taking the Highway)	RCP6.0 (2.8°Cmedium baseline, high mitigation in combination with SSP1, SS2, SSP3, SSP4 and SSP5
OECD long-term baseline projections	

As discussed in Section 4.2.2, while this report contains projections of transport work based on all plausible combinations of socio-economic and energy scenarios, it presents scenarios that are in line with recent long-term projections and with efforts of land-based sectors to limit the global temperature increase to well below 2 degrees centigrade than the other scenarios.

Figure 165 shows the projections of transport work for three long-term scenarios in which the energy mix of land-based sectors would limit the global temperature increase to well below 2 degrees centigrade (Van Vuuren, et al., 2011a) and which have GDP growth projections from the OECD or SSPs that are in line with recent projections from the OECD. In these scenarios, total transport work increases with 40-100%. In general, projections using a logistics analysis exhibit higher growth rates (75-100%) than projections using a gravitation model approach (40-60%)[8]. Scenarios that have higher aggregate economic growth see a larger increase in transport work.

Figure 165 - Projections of total transport work, energy and non-energy products (billion tonne-miles per year)



Source: (Van Vuuren, et al., 2011b), (Riahi, et al., 2017), Making sense of climate change scenarios: Senses Toolkit

[8] It is noteworthy that the models were used to project transport demand for non-energy products. The projections of energy products is based on the future consumption evolution for energy products.

Table 72 presents transport work projections for coal, oil and gas in SSP1 scenarios (i.e. a relatively high economic growth and emphasis on sustainability). As is to be expected, scenarios that result in a larger temperature increase have a higher demand for fossil fuels and thus more transport work. Note that the trend is not always uniform as different scenarios have different assumptions about the use of carbon capure and storage, which allows the continued use of fossil fuels without increasing emissions of CO_2.

Table 72 - Transport work projections for coal, oil and gas in SSP1 scenarios with different RCPs (billion tonne-miles per year)

		2019	2020	2030	2040	2050
Coal	RCP19_L	5600	4000	2000	1100	900
	RCP19*	5600	5500	2600	1300	1100
	RCP26_L	5600	4900	4600	3400	2400
	RCP26*	5600	5600	4900	3600	2400
	RCP34_L	5600	5100	5600	5200	4300
	RCP34*	5600	5600	5700	5200	4200
	RCP45_L	5600	5100	5800	6200	6100
	RCP45*	5600	5600	6000	6200	6000
	RCP60_L	5600	5200	5500	5100	4900
	RCP60*	5600	5600	6000	6400	6400
Oil	RCP19_L	13700	10500	5900	3000	2300
	RCP19*	13700	13600	7600	3900	3000
	RCP26_L	13700	11600	10200	8400	7600
	RCP26*	13700	13700	11900	9700	8800
	RCP34_L	13700	11900	10800	9400	9000
	RCP34*	13700	13700	12400	10800	10400
	RCP45_L	13700	11900	10900	9700	9600
	RCP45*	13700	13700	12500	11100	10900
	RCP60_L	13700	11500	10200	8400	7600
	RCP60*	13700	13700	12500	11200	11100
Gas	RCP19_L	1900	1700	2400	2900	3100
	RCP19*	1900	2000	2100	2300	2200
	RCP26_L	1900	2000	3200	3900	4000
	RCP26*	1900	2000	2500	2700	2600
	RCP34_L	1900	2100	3400	4600	5100
	RCP34*	1900	2000	2600	3100	3300
	RCP45_L	1900	2100	3500	4800	5500
	RCP45*	1900	2000	2700	3200	3500
	RCP60_L	1900	1700	2600	3400	4000
	RCP60*	1900	2000	2700	3300	3600

*** Projections based on future energy consumption (IIASA projections: all possible combinations between SSPs 1 to 5 and RCPs 1.9 to 6.0 and SSP1 to SSP5 baseline scenarios).**

Table 73 presents transport work projections in RCP4.5 scenarios with different long-term socio-economic scenarios. RCP4.5 was chosen because this RCP can be combined with all SSPs. As is to be expected, scenarios with higher aggregate GDP growth have higher transport work projections. The difference depends on the type of cargo and on the projections method, but is around 50% for projections based on logistics analysis and 30-40% for projections based on gravity models. The difference between both methods is larger for economic scenarios with higher GDP growth rates and can be up to 50-60%.

Table 73 - Transport work projections in RCP4.5 scenarios with different long-term socio-economic scenarios (billion tonne-miles per year)

		2019	2020	2030	2040	2050
Coal	SSP1_45_L	5600	5100	5800	6200	6100
	SSP1_45*	5600	5600	6000	6200	6000
	SSP2_45_L	5600	4500	4800	4300	4000
	SSP2_45*	5600	5600	5600	4900	4500
	SSP3_45_L	5600	5300	6400	4900	4600
	SSP3_45*	5600	5700	6500	4800	4500
	SSP4_45_L	5600	6000	6600	6300	4900
	SSP4_45*	5600	5700	5900	5400	4100
	SSP5_45_L	5600	3800	2700	2100	3200
	SSP5_45*	5600	5500	3700	2800	4100
Non-coal dry bulk	SSP1_L	24000	26400	43600	64900	86200
	SSP1_G	24400	25700	37400	46500	53900
	SSP2_L	24000	26500	40400	54400	68900
	SSP2_G	24300	25600	36400	44500	51500
	SSP3_L	24000	26500	38200	47000	53800
	SSP3_G	24000	24900	31800	36900	41400
	SSP4_L	24000	26400	40400	54100	66200
	SSP4_G	24200	25400	34200	39900	44200
	SSP5_L	24000	26500	46500	75800	108100
	SSP5_G	24500	25900	39500	51200	61200
	OECD_L	24000	26000	37000	47800	57800
	OECD_G	21100	22100	29700	36300	42500
Oil	SSP1_45_L	13700	11900	10900	9700	9600
	SSP1_45*	13700	13700	12500	11100	10900
	SSP2_45_L	13700	14100	15300	16100	15900
	SSP2_45*	13700	13900	15000	15700	15600
	SSP3_45_L	13700	14500	16300	16600	16000
	SSP3_45*	13700	14000	15600	15900	15300
	SSP4_45_L	13700	12900	13200	13200	13000
	SSP4_45*	13700	13800	13900	13900	13700
	SSP5_45_L	13700	16000	21700	23600	23300
	SSP5_45*	13700	14200	19000	20600	20400
Chemicals	SSP1_L	1300	1400	2400	4000	6000
	SSP1_G	1300	1300	1800	2200	2500
	SSP2_L	1300	1400	2300	3400	4800
	SSP2_G	1300	1300	1800	2100	2400
	SSP3_L	1300	1400	2100	2900	3700
	SSP3_G	1300	1300	1600	1900	2000
	SSP4_L	1300	1400	2300	3300	4600
	SSP4_G	1300	1300	1700	1900	2100
	SSP5_L	1300	1400	2600	4700	7500
	SSP5_G	1300	1300	1900	2400	2800
	OECD_L	1300	1400	2100	3000	4000
	OECD_G	1100	1100	1500	1800	2100
Gas	SSP1_45_L	1900	2100	3500	4800	5500
	SSP1_45*	1900	2000	2700	3200	3500
	SSP2_45_L	1900	1700	2700	4000	5100
	SSP2_45*	1900	2000	2500	3300	3900

		2019	2020	2030	2040	2050
	SSP3_45_L	1900	1800	2600	3100	3300
	SSP3_45*	1900	2000	2400	2400	2400
	SSP4_45_L	1900	1900	3200	4200	4600
	SSP4_45*	1900	2000	2600	3000	3100
	SSP5_45_L	1900	2300	4100	5900	7200
	SSP5_45*	1900	2000	2900	3600	4100
container	SSP1_L	9000	9900	16400	24200	31900
	SSP1_G	9000	9500	13200	15600	17500
	SSP2_L	9000	10000	15200	20300	25600
	SSP2_G	9000	9400	12900	15200	16900
	SSP3_L	9000	10000	14400	17600	19900
	SSP3_G	8900	9200	11600	13200	14300
	SSP4_L	9000	9900	15200	20200	24500
	SSP4_G	9000	9400	12200	13900	14900
	SSP5_L	9000	10000	17500	28300	40100
	SSP5_G	9100	9500	13700	16900	19500
	OECD_L	9000	9800	13900	17800	21400
	OECD_G	8000	8300	10900	13000	14800
other unitized cargo	SSP1_L	4400	4400	5400	5600	4700
	SSP1_G	4400	4600	5800	6900	7800
	SSP2_L	4400	4400	5000	4700	3700
	SSP2_G	4400	4500	5700	6600	7400
	SSP3_L	4400	4400	4700	4100	2900
	SSP3_G	4400	4400	5100	5600	5900
	SSP4_L	4400	4400	5000	4700	3600
	SSP4_G	4400	4500	5500	6200	6700
	SSP5_L	4400	4400	5700	6600	5900
	SSP5_G	4400	4600	6100	7600	9000
	OECD_L	4400	4400	4500	4100	3100
	OECD_G	4200	4400	5500	6600	7600

*** Projections based on future energy consumption (IIASA projections: all possible combinations between SSPs 1 to 5 and RCPs 1.9 to 6.0 and SSP1 to SSP5 baseline scenarios).**

4.4 Marginal abatement cost curves

Marginal Abatement Cost Curves (MACCs) of GHG reduction represent the relationship between the total reduction of GHG emissions and the cost efficiency for individual abatement measures. MACC shows how much the marginal cost increases with additional abatement measures for GHG emissions in a given year.

This section presents the MACCs developed for this study. It starts with a review of the available technologies in Section 4.4.1, presents a grouping of technologies in Section 4.4.2 and presents the MACCs in Section 4.4.3.

4.4.1 Methodology for screening technologies

In the 2nd IMO GHG Study, MAC Curves of 25 abatement technologies in 2020 were provided. In the 3rd IMO GHG study, although the MAC Curve was not shown in the report, the MACs of 22 abatement technologies were calculated for establishing the future scenario. This project

updated the MAC Curves for 2030 and 2050, with more energy-saving technologies, possible use of alternative fuels and speed reduction.
We screened new abatement technologies by reviewing scientific and engineering literatures. In addition, we took into account the possible use of alternative fuels in maritime sectors. Table 74 shows 44 technologies in total. The 44 technologies consisted of four types: (1) 23 of energy-saving technologies, (2) 4 of use of renewable energy (e.g. wind engine, solar panels), (3) 16 of use of alternative fuels (e.g. LNG, hydrogen and ammonia) and (4) speed reduction.

Because of insufficient information when used onboard, we could not include some potential technologies, such as motor ships with rechargeable batteries, carbon capture onboard from exhaust gas, and powered by gas-turbine engines. The CO_2 reduction potential of these technologies depends on how electricity is generated on-land and how the captured CO_2 emission are used. Regarding use of gas-turbine engines, the current thermal efficiency of these engines is worse than that of diesel engines and fuel cells, unless combined-cycle would be implemented onboard. It should be noted that the omission of these technologies from the MACC does not imply a judgement on their applicability on ships.

Table 74 - Groups of 28 abatement technologies and use of alternative fuel

	Gr. No.	Abatement technologies and use of alternative fuels and renewable energy
(1) Energy-saving technologies	**Group 1** Main engine improvements	Main Engine Tuning Common-rail Electronic engine control
	Group 2 Auxiliary systems	Frequency converters Speed control of pumps and fans
	Group 3 Steam plant improvements	Steam plant operation improvements
	Group 4 Waste heat recovery	Waste heat recovery Exhaust gas boilers on auxiliary engines
	Group 5 Propeller improvements	Propeller-rudder upgrade Propeller upgrade (nozzle, tip winglet) Propeller boss cap fins Contra-rotating propeller
	Group 6 Propeller maintenance	Propeller performance monitoring Propeller polishing
	Group 7 Air lubrication	Air lubrication
	Group 8 Hull coating	Low-friction hull coating
	Group 9 Hull maintenance	Hull performance monitoring Hull brushing Hull hydro-blasting Dry-dock full blast
	Group 10 Optimization of water flow hull openings	Optimization water flow hull openings
	Group 11 Super light ship	Super light ship
(2) Use of renewable energy	**Group 12** Reduced auxiliary power demand	Reduced auxiliary power demand (low energy lighting etc.)
	Group 13 Wind power	Towing kite Wind power (fixed sails or wings) Wind engine (Flettner rotor)
	Group 14 Solar panels	Solar panels
	Group 15A Use of alternative fuel with carbons	LNG+ICE or FC

	Gr. No.	Abatement technologies and use of alternative fuels and renewable energy
(3) Use of alternative fuels		Methanol + ICE Ethanol + ICE
	Group 15B Use of alternative fuel without carbons	Hydrogen + ICE or FC Ammonia + ICE or FC Synthetic methane + ICE or FC Biomass methane + ICE or FC Synthetic methanol + ICE Biomass methanol + ICE Synthetic ethanol + ICE Biomass ethanol + ICE
(4) Speed reduction	**Group 16** Speed reduction	Speed reduction by 10%

4.4.2 Assumptions of grouping, current and future penetrations and future scenario

MAC calculation needs reasonable and realistic assumptions. To calculate MACs, we allocated the 44 abatement technologies to 16 groups by similar characteristics. If more than one technique belongs to the same group, then only one of them can be installed on a ship because the technologies exclude each other. We split the use of alternative fuel (Group15) to two subgroups; Group 15A as alternative fuel contains carbon (conversion factor, Cf is not to be zero) and Group 15B as alternative fuel contains no carbon or may be regarded as carbon neutral fuel. For example, synthesized methane made from carbons from DAC (Direct Air Capture) and hydrogen from electrolysis of water may be considered as carbon neutral fuel.

Fuel cells can be used in combination with electrical motors to provide propulsion power. However, since it is difficult to estimate the incremental cost compared to conventional driven system, we calculated the CAPEX of using fuel cell by applying a median of CAPEX from various types of propulsion systems, including motor-driven system.

For individual technologies and use of alternative fuels, GHG reduction potentials, applicability, CAPEX/OPEX and current/future penetration were estimated for all ship type and size bins, taking into account recent developments and actual implementation in the market. The results are shown as the factsheets in Annex for the external review.

The penetration rate is newly implemented in this update. It is defined as the percentages of the ships which will implement each technology. The amount of CO_2 reduction is considerably affected by the penetration rate of abatement technologies. CO_2 reduction capacity of each technology is related to the difference between the expected penetration rate in 2030/2050 and that in 2018. The method to calculate MACs with the penetration rate is used also in other literature as noted in section Q.3.3 of Annex Q.

Some cost-effective technologies, which have been already spread to the market by 2018, we assumed 100% penetration rate by 2030. On the other hand, it is quite difficult to estimate penetration rates for the technologies and the use of the alternative fuels, which are not widely spread by 2018 because of higher cost and/or their technical immaturity. Thus, we set two scenarios assuming different penetration for 2030 and 2050, as shown in Table 75.

Scenario 1, as a basis, the amount of CO_2 emission reduction is maximized in theory. Each abatement technology is expected to be fully adopted by all newly built ships after 2019. As a result, regardless of its penetration in 2018, the number of ships adopting the technology after 2019 was assumed to account for 54% of the total number of ships in 2030 (45% for scrap and built and 9% for increased fleet) and 100% of the total number of ships in 2050. For use of alternative fuel, either Group 15A or 15B will be installed. First of all, use of LNG in Group 15A is being adopted and spread, and then the fuel will be changed to zero-carbon fuels in Group 15B.

Scenario 2 is assumed to have comparatively high barriers for implementation, therefore, lower penetration rates than those in Scenario 1 were assumed.

Table 75 - Penetration rates of technologies

Group		Penetration rates (% of ships applying a technology)				
		2018	Scenario 1		Scenario 2	
			2030	2050	2030	2050
Group 1 Main engine improvements	Main Engine Tuning	75.0%	100%	100%	80.0%	100%
	Common-rail	2.0%	56.0%		7.0%	32.0%
	Electronic engine control	1.0%	55.0%		6.0%	31.0%
Group 2 Auxiliary systems	Frequency converters	12.5%	66.5%	100%	17.5%	42.5%
	Speed control of pumps and fans	50.0%	100%		55.0%	80.0%
Group 3 Steam plant improvements	Steam plant operation improvements	(75.0%)	(100%)	(100%)	(80.0%)	(100%)
Group 4 Waste heat recovery	Waste heat recovery	12.5%	66.5%	100%	17.5%	42.5%
	Exhaust gas boilers on auxiliary engines	12.5%	66.5%	100%	17.5%	42.5%
Group 5 Propeller improvements	Propeller-rudder upgrade	12.5%	66.5%	100%	17.5%	42.5%
	Propeller upgrade (nozzle, tip winglet)					
	Propeller boss cap fins	10.0%	64.0%		15.0%	40.0%
	Contra-rotating propeller	12.5%	66.5%		17.5%	42.5%
Group 6 Propeller maintenance	Propeller performance monitoring	12.5%	66.5%	100%	17.5%	42.5%
	Propeller polishing	75.0%	100%		80.0%	100%
Group 7 Air lubrication	Air lubrication	(0.0%)	(100%)	(100%)	(5.0%)	(30%)
Group 8 Hull coating	Low-friction hull coating	12.5%	66.5%	100%	17.5%	42.5%
Group 9 Hull maintenance	Hull performance monitoring	12.5%	66.5%	100%	17.5%	42.5%
	Hull brushing					
	Hull hydro-blasting					
	Dry-dock full blast (old ships)	50.0%	100%	100%	55.0%	80.0%
Group 10 Optimization water flow hull openings	Optimization water flow hull openings	12.5%	66.5%	100%	17.5%	42.5%
Group 11 Super light ship	Super light ship	(0.0%)	(100%)	(100%)	(5.0%)	(30%)

Group		Penetration rates (% of ships applying a technology)				
		2018	Scenario 1		Scenario 2	
			2030	2050	2030	2050
Group 12 Reduced auxiliary power demand	Reduced auxiliary power demand (low energy lighting etc.)	50.0%	100%	100%	55.0%	80%
Group 13 Wind power	Towing kite	(0.0%)	(100%)	(100%)	(5.0%)	(30%)
	Wind power (fixed sails or wings)					
	Wind engine (Flettner rotor)					
Group 14 Solar panels	Solar panels	(0.0%)	(100%)	(100%)	(5.0%)	(30%)
Group 15A Use of alternative fuel with carbons	LNG+ICE	1.0%	55.0%	0.0%	1.5%	20.0%
	LNG+FC, Methanol + ICE, Ethanol + ICE	0.0%	54.0%		0.05%	
Group 15B Use of alternative fuel without carbons	Use of alternative fuel: i.e. Hydrogen, Ammonia and etc.	0.0%	0.1%	100%	0.05%	20.0%
Group 16 Speed reduction	Speed reduction by 10%	(0.0%)	(100%)	(100%)	(100%)	(100%)

* Numerical value with brackets means penetration ratio to applicable ships.

* For example, Speed reduction by 10% is not applied to ships other than Ferry-pax only, Cruise, Ferry-RoPax, Ro-Ro and Vehicle.

For the future fuel costs, we set the costs as indicated in Table 76. Note that the MACCs presented in this section assume constant fuel prices in order to highlight the changes between 2030 and 2050 in terms of availability of options and innovation. In the emissions modelling, fuel prices from the World Bank have been used (see Annex K). With regard to alternative fuel such as LNG, the cost was estimated to be higher than its delivery price for land use, because we include additional cost caused by logistics and bunkering to marine sectors.

The annual investment cost of each abatement technology is calculated as an annuity, and the redemption is fixed as 25 years. Therefore, CAPEX remains constant and is not affected by the year of implementation. However, the penetration rate changes every year, and the future cost may be discounted as for the current values. This can be estimated by applying the net present value (NPV). More detailed Methodology is provided in Annex Q.

Table 76 - Future costs fuel at 2030 and 2050

Fuels	Year	
	2030	2050
HFO (VLSFO)	375	375 (9USD/GJ)
LNG	590	590 (12USD/GJ)
Hydrogen	3,300	3,300 (28USD/GJ)
Ammonia	660	660 (32USD/GJ)
Methanol	400	400 (20USD/GJ)
Ethanol	670	670 (25USD/GJ)
Synthetic methane	-	4,500 (90USD/GJ)
Biomass methane	-	2,250 (45USD/GJ)
Synthetic methanol	-	1,500 (75USD/GJ)
Biomass methanol	-	800 (40USD/GJ)

Fuels	Year	
	2030	2050
Synthetic ethanol	-	2,600 (97USD/GJ)
Biomass ethanol	-	1,300 (27USD/GJ)
Unit: Unit: USD/tonne, and the cost per Low Calorimetrice values are shown in the brackets		

4.4.3 Calculation results of MACC and conclusion

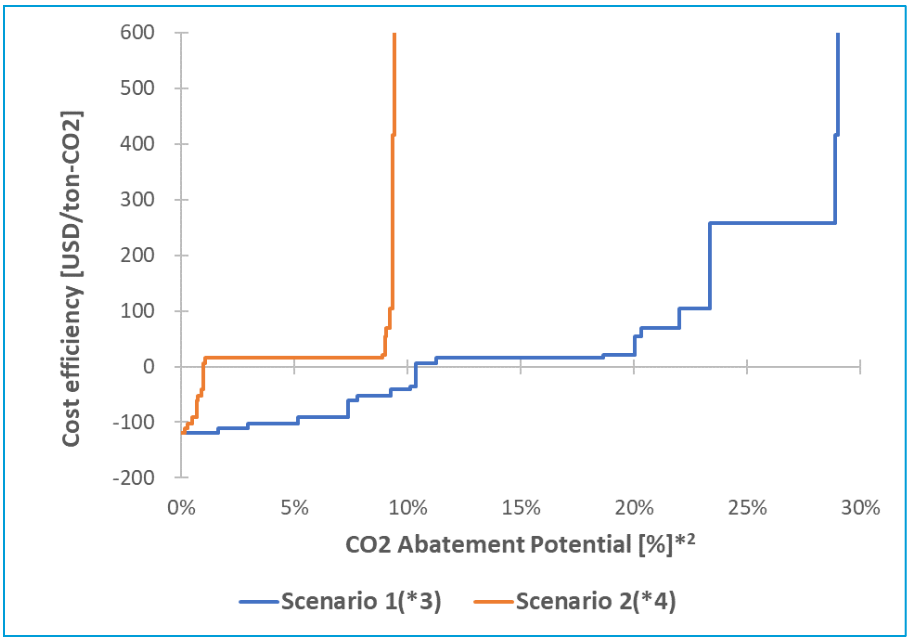
The marginal abatement cost curves for CO_2 of 2030 and 2050 are shown in Figure 166 and Table 77. The horizontal axis represents the ratio of CO_2 abatement potential in the given year, and the vertical axis represents MAC of each group of technologies. The groups are sorted by ascending order of MAC. Table 77 shows MAC and CO_2 reduction rate for every 16 groups.

Since fuel cost is greatly affected by social situations, fuel cost has large uncertainty, and it is difficult to quantify the change of the cost. As an example, a sensitivity analysis of the future price of VLSFO is shown in Figure 167. For more details, refer to Q.4.1 of Annex Q.

In considering these curves, the following issues should be concluded.

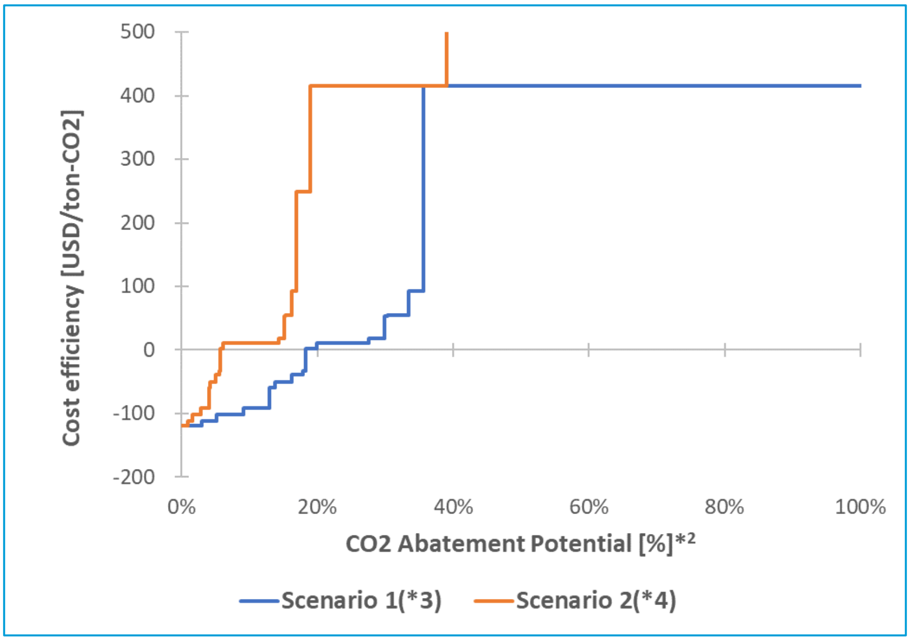
1. Applying all the potential mitigation measures selected to all newly built ships from 2025, CO_2 emissions reduction in 2050 can achieve both IMO's mid-term and long-term reduction targets. The expected value of costs per year to achieve the maximum reduction is 257 USD/tonne-CO_2 towards 2050.
2. In 2050, about 64% of the total amount of CO_2 reduction is contributed to by use of alternative fuel. This result confirms that it is difficult to achieve IMO's mid-term target by energy-saving technologies and speed reduction of ships only.
3. In all scenarios, a few groups have a negative value of MAC (i.e. eight groups in 2030 and 2050), meaning that these technologies are profitable to install, at least from a social perspective. However, the amount of CO_2 reduction by these groups is relatively small (i.e. less than 10% from baseline in 2030 and 18% of the baseline in 2050).
4. Use of alternative fuel with carbon contents has a higher positive value of MAC of >250 USD/tonne-CO_2. Intending to use zero-carbon fuels, the MAC will increase to >410 USD/tonne-CO_2, which is caused by the higher fuel price from synthesis process. [Therefore, it is crucial to receive sufficient alternative fuel with reasonable price.]
5. CO_2 abatement potential of Speed reduction indicates higher values than other technologies. The saving cost of the "original" fleet has to be offset against the extra CAPEX to build the additional vessels. In addition, part of CO_2 reduction has to be offset. Sensitivity analysis shown in Figure 167 and Table 79 implies that the MACC varied significantly with the ratio of vessels should be added to maintain the total transportation capacity.

Figure 166 – Marginal abatement cost curve (interest rate: 4% *5, lifetime: 25 years, price of fuel oil: 375 USD/tonne) *1 - (a) Calculated results for 2030



Source: this report, Annex Q.

(b) Calculated results for 2050



Source: this report, Annex Q.

*1 Calculation result of Group 14 “Solar panels” is out of graph.

*2 Ratio of CO_2 abatement potential to baseline CO_2 emissions at 2030 (a) and 2050 (b).

*3 Scenario 1, as a basis, the amount of CO_2 emission reduction is maximized in theory.

*4 In Scenario 2, penetration rates at 2030 and 2050 of abatement technologies are assumed as BAU due to various implementation barriers such as technological barriers, institutional barriers, and financial barriers.

*5 MACs are expressed as nominal monetary values, without applying any discount rate.

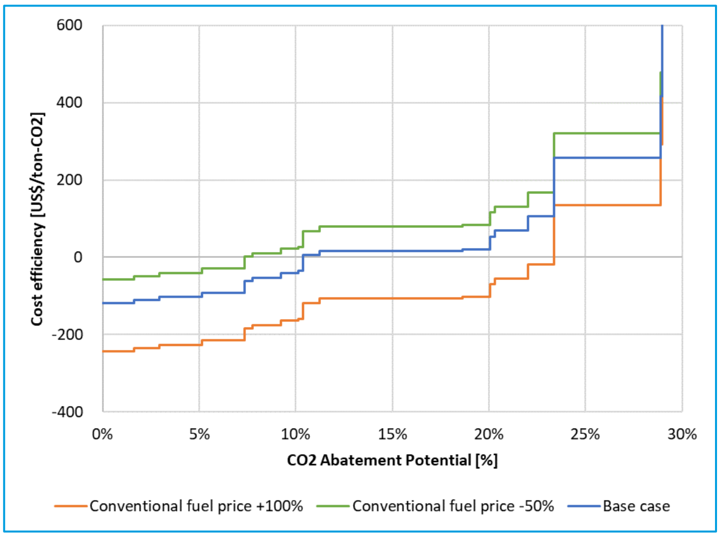
Table 77 - 4 Cost efficiency and abatement potential (interest rate: 4%, lifetime: 25 years, price of fuel oil: 375 USD/tonne) - (a) Calculated results for 2030

Code	Technology group	Scenario 1		Scenario 2	
		MAC (USD/tonne -CO_2)	CO_2 abatement potential (%)	MAC (USD/tonne -CO_2)	CO_2 abatement potential (%)
Group 10	Optimization water flow hull openings	-119	1.64%	-119	0.15%
Group 3	Steam plant improvements	-111	1.30%	-111	0.12%
Group 6	Propeller maintenance	-102	2.20%	-102	0.21%
Group 9	Hull maintenance	-92	2.22%	-92	0.22%
Group 12	Reduced auxiliary power usage	-61	0.40%	-61	0.04%
Group 8	Hull coating	-53	1.48%	-53	0.15%
Group 2	Auxiliary systems	-41	0.87%	-41	0.08%
Group 1	Main engine improvements	-35	0.25%	-35	0.02%
Group 13	Wind power	6	0.89%	6	0.08%
Group 16	Speed reduction	17	7.38%	17	7.81%
Group 5	Propeller improvements	21	1.40%	21	0.14%
Group 11	Super light ship	54	0.28%	54	0.03%
Group 4	Waste heat recovery	69	1.68%	69	0.16%
Group 7	Air lubrication	105	1.35%	105	0.14%
Group 15A	Use of alternative fuel with carbons	258	5.54%	258	0.01%
Group 15B	Use of alternative fuel without carbons	416	0.10%	416	0.05%
Group 14	Solar panels	1,186	0.18%	1,186	0.02%

Table 78 - (b) Calculated results for 2050

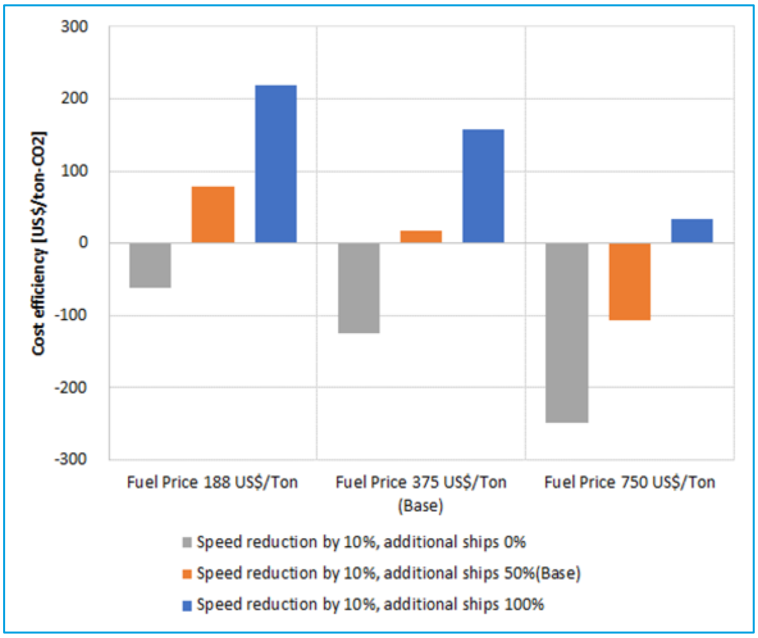
Code	Technology group	Scenario 1		Scenario 2	
		MAC (USD/tonne -CO_2)	CO_2 abatement potential (%)	MAC (USD/tonne -CO_2)	CO_2 abatement potential (%)
Group 10	Optimization water flow hull openings	-119	3.00%	-119	0.90%
Group 3	Steam plant improvements	-111	2.13%	-111	0.64%
Group 6	Propeller maintenance	-102	3.95%	-102	1.22%
Group 9	Hull maintenance	-91	3.90%	-91	1.24%
Group 12	Reduced auxiliary power usage	-59	0.71%	-59	0.21%
Group 8	Hull coating	-50	2.55%	-50	0.83%
Group 2	Auxiliary systems	-39	1.59%	-39	0.48%
Group 1	Main engine improvements	-34	0.45%	-34	0.14%
Group 13	Wind power	2	1.66%	2	0.50%
Group 16	Speed reduction	10	7.54%	10	8.18%
Group 5	Propeller improvements	18	2.40%	18	0.80%
Group 11	Super light ship	54	0.39%	54	0.12%
Group 4	Waste heat recovery	54	3.09%	54	0.93%
Group 7	Air lubrication	93	2.26%	93	0.77%
Group 15A	Use of alternative fuel with carbons	-	-	249	2.03%
Group 15B	Use of alternative fuel without carbons	416	64.08%	416	20.00%
Group 14	Solar panels	1,048	0.30%	1,048	0.09%

Figure 167 - Sensitivity analysis of conventional fuel price in 2030 (Scenario 1)



Source: this report, Annex Q.

Figure 168 - Sensitivity analysis of speed reduction by 10% in 2030 (Scenario 1)



Source: this report, Annex Q.

* The percentage which additional ships account for means the ratio between the number of newly built ships and the number of additional ships to keep the total freight transport volume.

* Change of transport volume is not taken into account.

Table 79 - Cost efficiency and abatement potential of Speed reduction by 10% in 2030 (Additional ships: 0~100%)

CO_2 reduction potential	MAC (USD/tonne)		
	Fuel Price 188 USD/Tonne	Fuel Price 375 USD/Tonne (Base)	Fuel Price 750 USD/Tonne
Additional ship 0%	-62	-124	-248
Additional ship 50% (Base case)	79	17	-107
Additional ship 100%	219	157	33

4.5 Emission projections, 2018-2050

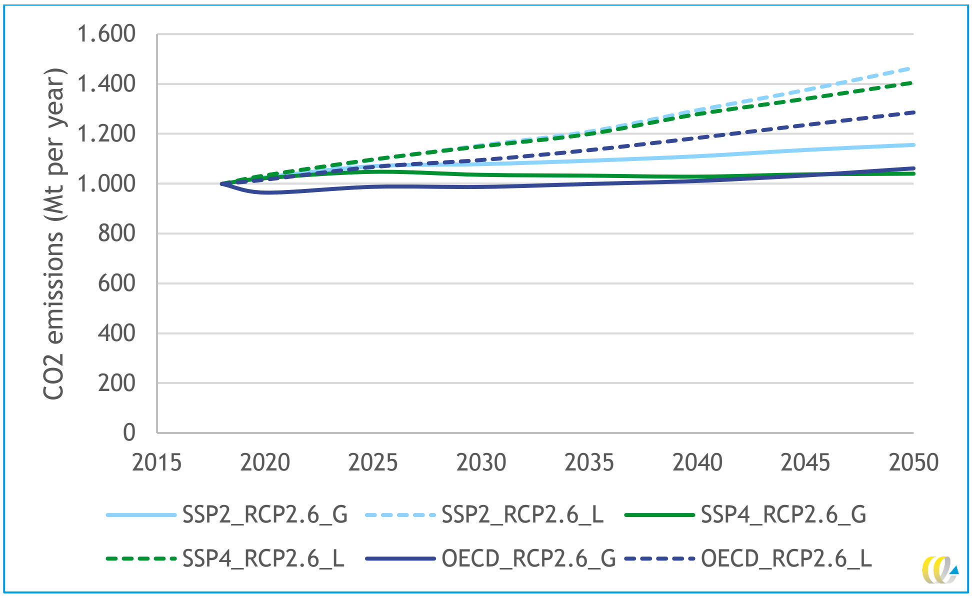
This section presents the projections of CO_2 emissions of shipping up to 2050 in business-as-usual (BAU) scenarios. In the context of this study, BAU refers to the shipping sector. The definition of BAU is that no new regulation will be adopted for shipping that has an impact on emissions or energy efficiency. The projections are based on long-term socio-economic pathways and representative concentration pathways of the IPCC. Some of these pathways assume that non-shipping sectors undergo transitions that require policies like carbon prices or energy-efficiency regulations. Since the definition of BAU refers to the shipping sector, we still consider these scenarios to be BAU scenarios.

One way to interpret the BAU scenarios is that they show how the emissions of shipping would develop when other sectors follow a certain economic and climate pathway and shipping does not. In this interpretation, the scenarios show the effort required to meet a certain emissions target for the shipping sector.

Figure 169 shows the BAU scenarios for three long-term scenarios in which the energy mix of land-based sectors would limit the global temperature increase to well below 2 degrees centigrade (Van Vuuren, et al., 2011a) and which have GDP growth projections from the OECD or from the IPCC that are in line with recent projections from the OECD (other IPCC shared socio-economic pathways are characterised by higher GDP growth, as shown in Section 4.2.2). In these BAU scenarios, the emissions of shipping are projected to increase from 1,000 Mt CO_2 in 2018 to 1,000 to 1,500 Mt CO_2 in 2050. This represents an increase of 0 to 50% over 2018 levels and is equal to 90-130% of 2008 levels.[9]

[9] 2008 emissions of total shipping were 1135 Mt CO_2 (IMO, 2015).

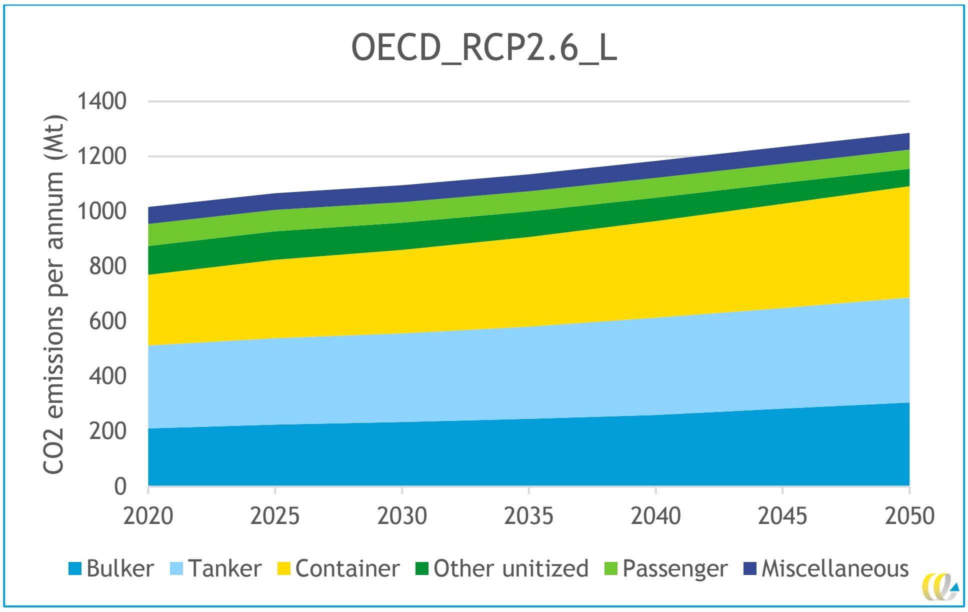
Figure 169 - BAU scenarios GDP growth in line with recent projections, energy transition in line with 2 degrees target



The variation in the projections is caused by two factors: different projections of transport work and different GDP projections. As explained in Section 4.2.1, this study has projected transport work using two different models with different underlying assumptions. Transport work projections that have been made with a gravity model typically have a lower elasticity with regards to GDP than projections made with a logistics model. Following the argument from Section 4.2.1, this study considers both to be plausible future projections and the difference between them is considered to reflect the uncertainty inherent in making projections of the future. In this example, the gravity-model projections are some 20-30% lower in 2050 than the corresponding logistics-model projections. The lowest GDP projection (from the OECD) in this set of scenarios is about 15% lower in 2050 than the highest (SSP2).

Figure 170 shows how the emissions of different ship types evolve in a scenario of relatively modest economic growth and an energy scenario for non-shipping sectors would limit the temperature increase to below 2 degrees centigrade. In this scenario, emissions of bulkers increase by 10-50% (depending on the method applied for transport work projections), as the reduction in coal transport is offset by an increase by an increase in other dry bulk transport work. Emissions from tankers decrease by 10% or increase by 30% because the transport of chemicals and gas increases, even when crude oil transport work decreases. Emissions from containers are projected to increase by almost 20-70%, driven by an increase in transport work of 70-140% and increases in efficiency because of an increase in sizes of ships.

Figure 170 - Emission projections per ship type



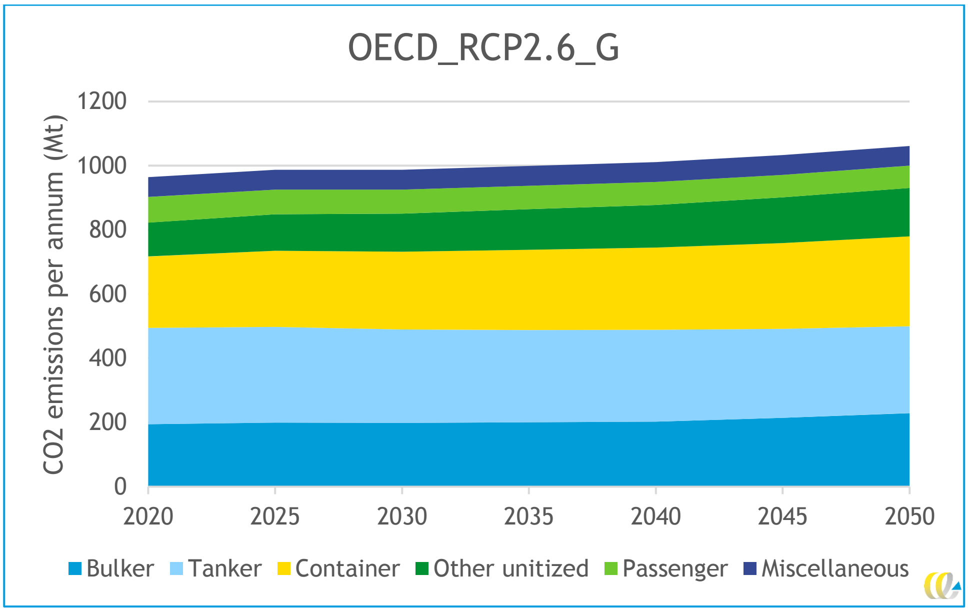
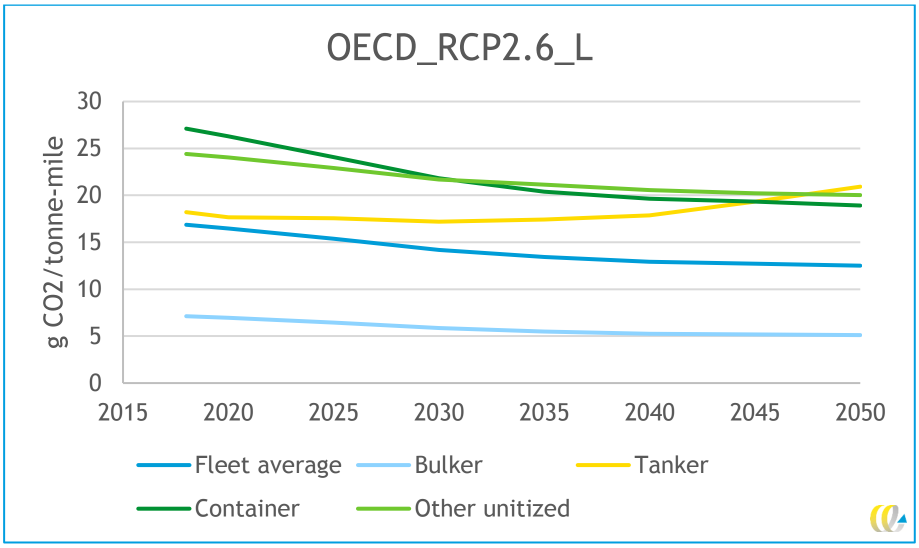
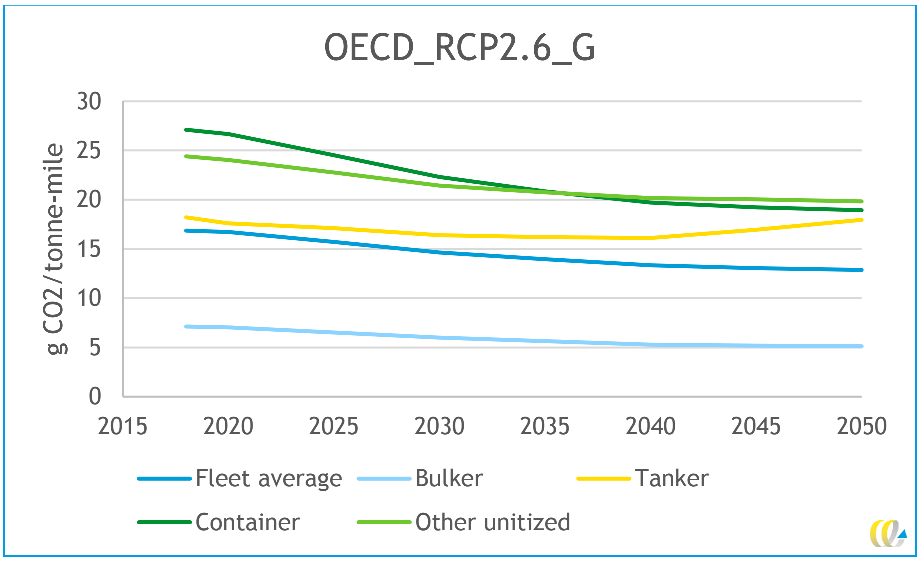


Figure 171 shows how the operational of different ship types is projected to develop over time in a scenario of relatively modest economic growth and an energy scenario for non-shipping sectors that would limit the global temperature increase to less than 2 degrees centigrade. As a fleet average, efficiency is projected to improve by about 25% between 2018 and 2050 as a result of changes in fleet composition (e.g. the replacement of smaller ships by larger, higher demand growth for containers than for dry bulk and tankers), regulatory efficiency improvements (e.g. the replacement of pre-EEDI ships with EEDI Phase 1, 2 and 3 ships) and market-driven efficiency improvements (see Section 4.4).

The efficiency improvements are larger for cargo ships than for passenger and other ships. Bulk carriers and containers are projected to see operational efficiency improvements of around 30% as a result of the replacement of older ships by ships that comply with Phases 1, 2 and 3 of the EEDI and an increase in their average size (see Section 4.2.3). Other unitized ships, a category that includes general cargo ships and Ro-Ro ships, is projected to improve the operational efficiency by a little less than 20%. Tankers either have a constant efficiency or a deterioration of the efficiency. This is due to the fact that this is an aggregate category of oil tankers, gas tankers and chemical tankers. Although the efficiency of all ship types improves over time as a result of fleet renewal and retrofits, a scenario in which transport of oil reduces while the transport of chemicals increases results in a relatively higher share of chemical tankers in this category, which tend to be smaller and relatively less efficient than oil tankers. The different trends between the two projection models can be explained by their different outlook on containers: the gravity model finds that a share of demand growth is picked up by general cargo and Ro-Ro ships, whereas the logistics model finds that the latter sectors decline and containerization continues to increase.

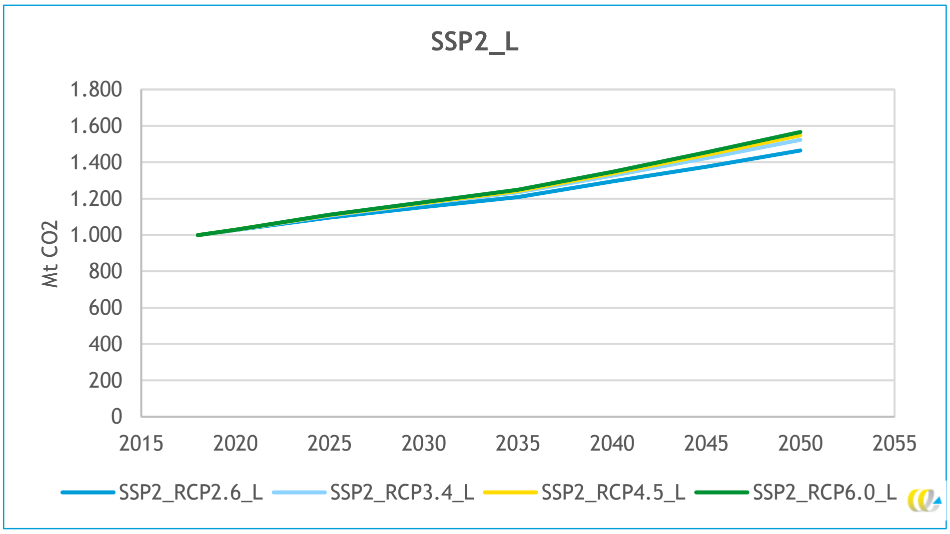
Figure 171 - Projected operational efficiency of ship types

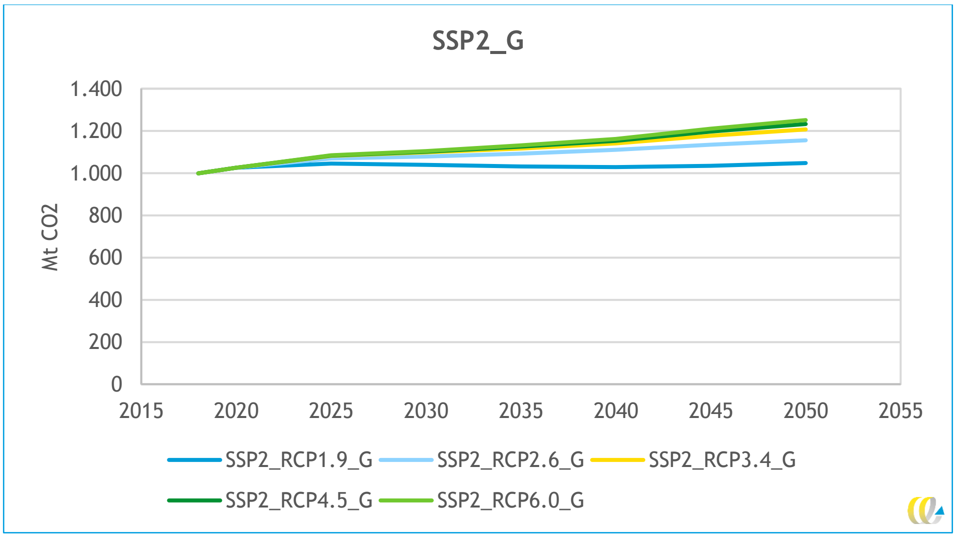




Long-term energy scenarios have an impact on emission projections because, for example, scenarios in which fossil fuels are phased out result in less transport work for oil tankers, bulk carriers carrying coal and gas tankers. Figure 172 shows the impact of long-term energy scenarios on shipping emissions. All emission projections are in the same family of so-called shared socio-economic pathways (in this case SSP2) and therefore have almost the same assumptions about GDP and population growth. The main difference between the projections is energy: RCP 1.9, which would result in a global average mean temperature of 1.5 degrees by the end of this century, sees large shares of renewables and carbon capture and storage (CCS), whereas RCP 6.0, which would result in a temperature increase of about 3 degrees by the end of this century, projects increasing use of fossil fuels without CCS. In this case, the difference in shipping emissions between the scenarios is 6-17%: because of more transport of fossil fuels, RCP6.0 has 17% more CO_2 emissions in 2050 than RCP 1.9. Similar analyses of other SSPs or with the logistics model transport work projections lead to similar results.

Figure 172 - Impact of long-term energy scenarios on shipping emissions

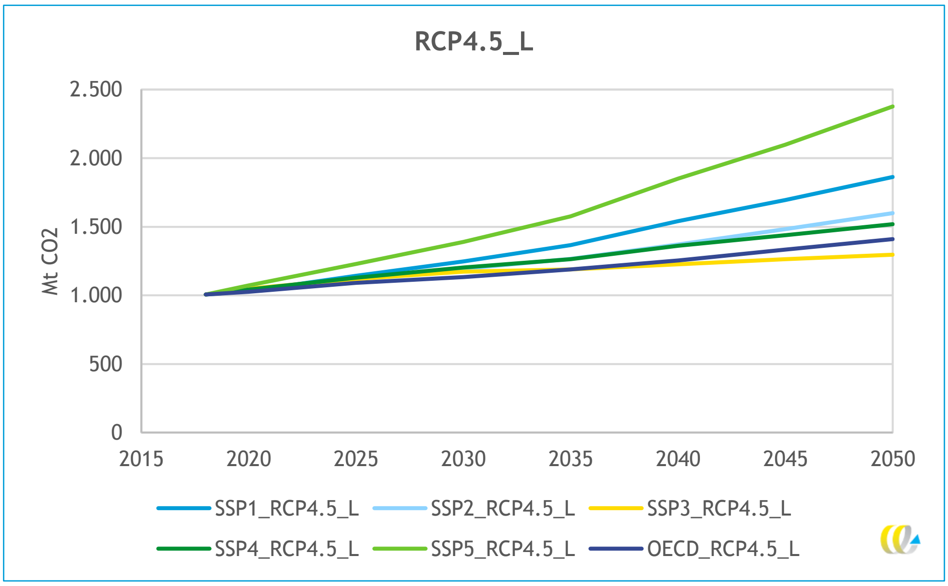


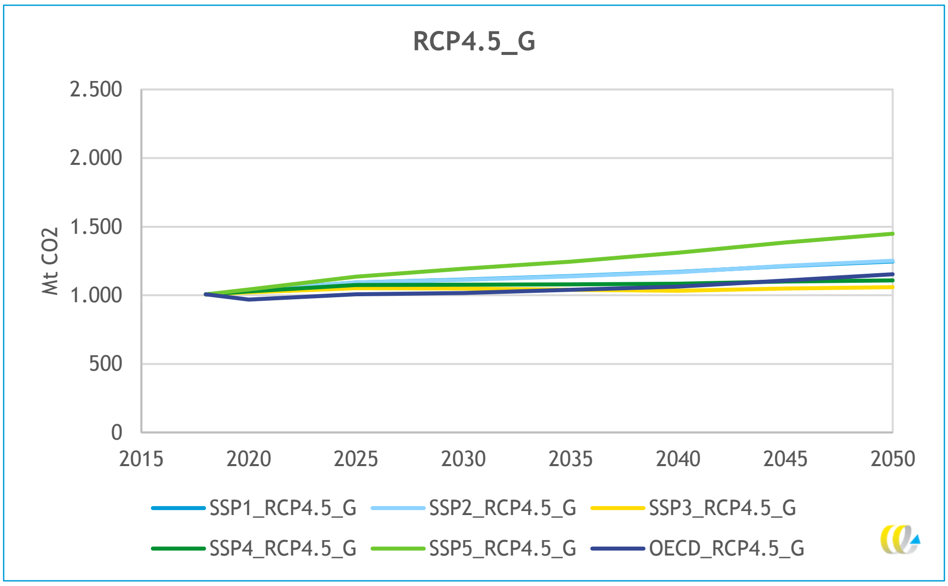


There is a clear relation between trade and economic growth and therefore also between economic growth and maritime transport work and shipping emissions. Figure 173 shows the impact of long-term economic scenarios on shipping emissions. All emission projections are in the same family of so-called representative concentration pathways, which determine to an extent demand for fossil fuels, in this case RCP 4.5 which would result in a temperature increase of about 2.5 degrees by the end of this century (for this RCP, the largest set of matched long-term economic scenarios is available).

Because transport demand is more sensitive to economic growth in the logistics model than in the gravity model, the upper panel in Figure 173 shows significantly higher emissions than the lower panel (the maximum increase in emissions in the upper panel is 130% over 2018 levels in 2050; the maximum increase in the lower panel is 40% over 2018 levels). Consequently, the difference in emissions between the SSP with the highest economic growth (SSP5) and the one with the lowest economic growth (SSP3) is 80% in the upper panel and 40% in the lower panel. Amongst the SSPs that this study deems the most relevant (see Section 4.2.2), differences in GDP growth result in a 11-13% change in emission projections in 2050.

Figure 173 - Impact of long-term economic scenarios on shipping emissions





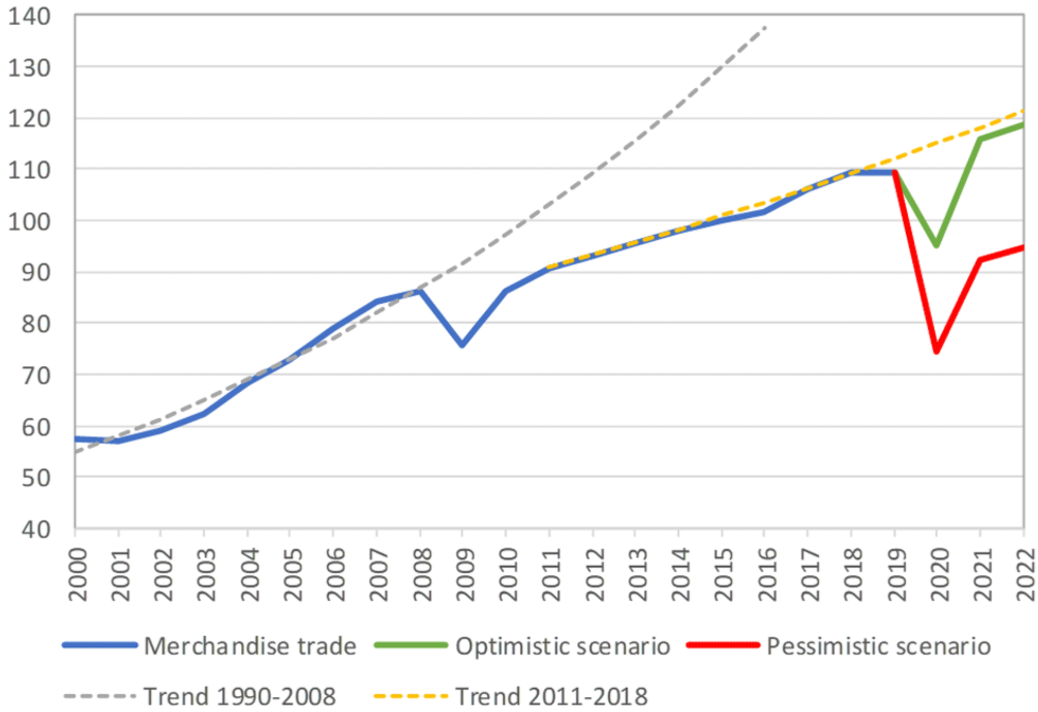
Source: this report

4.5.1 Potential caveats of COVID-19 on emission projections

COVID-19 is changing the socioeconomic development all over the world and might also influence international shipping significantly. As the pandemic has not ended until the finalization of this report and, therefore, a complete assessment would demand extra modelling procedures and data update, we present here a qualitative assessment stating the potential changes of predictions due to the COVID-19 pandemic.

COVID-19 will have a relevant impact on countries' GDP, one of the leading indicators we use to project transport demand. Therefore, the emissions projections are likely to be lower in the short term. The size of the bias, however, is unclear. The World Trade Organization (WTO) projects a decrease in global trade between 13 and 32% in 2020 due to the COVID-19 pandemic. According to WTO, "the recovery in trade is expected from 2021, but it will dependent on the duration of the outbreak and the effectiveness of the policy responses." Other organisations have similar projections. The OECD projects a delay in growth of at least two years: it will take until the end of 2021 before world GDP is at the same level as at the end of 2019 (OECD, 2020). It also has a more pessimistic scenario that takes a second wave of the pandemic into account. The IMF projects a sharp decline in 2020 and a rebound in 2021 but global GDP will be 6.5% lower than anticipated before the pandemic (IMF, 2020). Depending on the policy responses and the duration of the crisis, the economic damage could be temporary or permanent.

Figure 174 - Global trade volume (2015=100), 2000-2022



Source: WTO secretariat. Chart 1. World merchandise trade volume, 2000-2022

Figure 174 presents the WTO projections to global trade volume annual variation (%), in relation to 2015, considering all transportation modes using historical data until 2018.The optimistic scenario corresponds to the lower bound of WTO's projected decrease in global merchandise trade to 2020 (13%) and the pessimistic scenario corresponds to the upper bound decrease (32%). From 2021 on, the optimistic scenario considers that global trade will catch up with the original trend (yellow line).

Many experts also project socioeconomic transformation after COVID-19 pandemic (such as changes in urban transportation, labour markets and consumption) that might influence trade. Digital and technological advancements, as well possible substitution between different transportation modes (air, ground, and sea transportation) will also impact maritime transportation forecast in post-coronavirus years. These transformations are still very uncertain and can only be modelled after the pandemic with updated and specific data that are out of the scope of the Fourth IMO GHG Study.
So while it is all but certain that maritime transport wok will be depressed in the next few years, the impacts of Covid-19 in the longer term depend on how the world economy recovers from the crisis. This depends, in turn, on the policy response and on whether or not a second wave occurs and how severe that wave will be. The impacts after a few years depend on whether or not the current recession does permanent damage to the economy. If it does, GDP in 2030 and 2050 may be a few percent below the projected level, or, in other words, the GDP level previously foreseen for 2050 may only be reached in 2051 or 2052. If it does not, the GDP in 2030 or 2050 will not be affected.

In addition to the impacts on GDP there may also be an impact on ship efficiency. In our model, ship efficiency is a result of the cost-effectiveness of efficiency improvements, which in turn depends on the oil price, and of the share of new ships that enter the fleet. The IMF projects a significantly lower oil price in 2020 and 2021, which results in less efficiency improvement in that period (IMF, 2020). When transport work is depressed permanently, the share of new ships in the fleet is will be smaller than projected. This would also have a negative impact on the efficiency of the fleet.

Overall, the emissions will be significantly lower in 2020 and possibly 2021 as a result of lower transport demand. In the years thereafter, emissions may be still a little lower depending on how fast the economy recovers. In the next decades, there may be no impact on emissions if there is a fast economic recovery, or a small reduction in emissions of there is a permanent impact on GDP because the lower efficiency improvement will not offset lower transport demand.

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Fourth IMO GHG Study

Annexes

Fourth IMO GHG Study

Annexes

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Publications of CE Delft are available from www.cedelft.eu

Further information on this study can be obtained from the contact person Jasper Faber (CE Delft)

Content

A Inventory - methodological review

A.1 Introduction

This is a draft bottom-up methodology for the Fourth IMO GHG Study for the IMO Steering Committee to consider. This report is an outcome of Task 1.1 (review of inventory methodology of Third IMO GHG Study) and Task 1.2 (emission factors). In our offer, we included this deliverable as Task 1.1.2, but we recognize that the recommended changes to emission factors are an important component of refining the bottom-up methodology. Therefore, we include recommended emission factors in this report.

This work was coordinated by Bryan Comer (ICCT) and contributed to by, Dan Rutherford (ICCT), Jasper Faber (CE Delft), Tristan Smith (UCL/UMAS), Xiaoli Mao (ICCT), Elena Hauerhof (UMAS), Shinichi Hanayama (Class NK), Wendela Schim van der Loeff (UCL), and Shuang Zhang (DMU).

A.2 Task 1.1 Review of inventory methodology of Third IMO GHG Study

Task 1.1 is to review the bottom-up inventory methodology of the Third IMO GHG Study 2014 and to make suggestions for improvement. Section 1.3 of the Terms of Reference for the Fourth IMO GHG Study states:

"…The emission estimate should include a thorough review of the methodology and assumptions used in the inventory forming part of the Third IMO GHG Study 2014, including all data set out in Table 14 [tabular data for 2012 describing the fleet (international domestic and fishing) analysed using the bottom-up method] and Annex 2 [details for Section 1.3: inventory results], taking into account work undertaken since publication of the Third IMO GHG Study 2014…"
In our offer, we proposed to take the following steps to complete Task 1.1:
1. Collate any further published studies, made available between now and contract start.
2. Extract all the key method developments contained within the literature published since the Third IMO GHG Study.
3. Building on the four areas already identified here (missing technical specifications for ships; interpolating between missing AIS data points; environmental effects on power requirements; auxiliary and boiler power requirements by ship type, operation, and geography), produce a short summary of the main findings.
4. Share this proposal with the Fourth IMO GHG Study Steering Committee and invite any additional comments to the review.
5. React to comments and implement the method developments where feasible in extensions to the method described in Chapter 4 [Methodological Offer].

A.3 Studies published between the proposal and the contract start date

In the offer, we committed to identify any additional key studies that have been published between the time we submitted the offer and today. We gave the example of the Mediterranean ECA study.
There are two Med ECA feasibility studies. The first of which is Ineris et al. (2019), titled *ECAMED: A Technical Feasibility Study for the Implementation of an Emission Control Area (ECA) in the Mediterranean Sea*, published on January 11th, 2019. It was published before the

offer but was not able to be reviewed in detail prior to our offer. Ineris et al. estimate ship emissions from AIS and IHS data according to the methods laid out in the EMEP/EEA air pollutant emission inventory guidebook 2016's section on navigation (shipping). It is, essentially, a simplified version of the method applied in the Third IMO GHG Study 2014.
We found no key method developments compared to the Third IMO GHG Study 2014 in this document.

The second is MED ECA feasibility study is the official REMPEC (2019) study, which is titled *Technical and feasibility study to examine the possibility of designating the Mediterranean sea, or parts thereof, as SO_x ECA(s) under MARPOL Annex VI*, published as REMPEC/WG.45/INF.9 on May 31st, 2019. This study uses the Finnish Meteorological Institute's STEAM model, which was also used in the Third IMO GHG Study. Like the Third IMO GHG Study 2014, it also uses AIS operational data paired with IHS ship characteristics data to produce a bottom-up emissions inventory. We found no key method developments compared to the Third IMO GHG Study 2014 in this document.

A.4 Key method developments in literature published since the Third IMO GHG Study

Several regional and local studies have built upon the Third IMO GHG Study 2014's methodology (see (Chen, et al., 2016; Chen, et al., 2017; Ineris, et al., 2019; Kwon, et al., 2019; Li, et al., 2016; REMPEC, 2019; Ricardo, 2017; Zhang, et al., 2019) . Nunes, et al. (2017) provides a useful review of some of these studies published around the time of the Third IMO GHG Study 2014 and they argue that while it is commonly accepted that bottom-up approaches are generally more accurate than top-down, great efforts are required to reduce data gaps and anomalies.

On a global scale, the activity-based methodology raises challenges due to the use of average input parameters, which can cause uncertainties in the estimated emissions (Nunes, et al., 2017; Li, et al., 2016) highlight that further refinement of ship emission inventories should be targeted on introducing local input variables, e.g., local emissions factors. A study focusing on the United Kingdom (UK) attempted to do so with respect to fuel sulphur content (Ricardo, 2017). It used data from the UK Petroleum Industry Association. However, in its discussion, Ricardo et al (2017). highlighted that even the UK's domestic voyages could be undertaken by ships that bought fuel outside the UK, making it difficult to define a 'local' area. For emission factor improvement, Nunes et al. (2017) argue that new on-board measurement studies could be undertaken, while at the same time more precise input data (technical information about ships, engines, load and emission factors) should be obtained.

Zhang et al. (2019) explain that in addition to ships that are observed in the AIS data for which engine parameters are available (*identified vessels*), that ships that are observed in the AIS data but whose engine characteristics cannot be identified in ship registry data can also be important contributors to overall emissions, especially in local areas (the Pearl River Delta region, in this case). The Third IMO GHG Study 2014 and Olmer et al. (2017a; 2017b) estimated global shipping emissions not only for ships that were observed in the AIS data and that could be matched to engine characteristics data from ship registries, but also for ships for which their engine power and other important characteristics (e.g., ship type; maximum speed; etc.) were missing, and for small ships (< 300 GT) that were listed as active in the ship registry data, but not observed in the AIS data.
Since the Third IMO GHG Study 2014, several studies have attempted to update global or regional maritime GHG emissions inventories using AIS-derived operational shipping data. Two studies specifically have produced significant progress on the topic of global bottom-up

modelling: Olmer et al. (2017a; 2017b) and Johansson et al. (Johansson, et al., 2017). These studies advance the Third IMO GHG Study both in terms of extending the analysis into the future and reviewing and improving the method, as well as testing sensitivity of the results to key modelling assumptions. Olmer et al. (2017a; 2017b), published by the ICCT, estimates global shipping emissions for international, domestic, and fishing vessels, similar to the approach that was taken by the Third IMO GHG Study 2014, but it includes additional methodological modifications, including adjustments not only for weather and hull fouling, but also for interpolated speeds and draught. More information is available in the ICCT's detailed methodology document available at: Greenhouse gas emissions from global shipping, 2013-2015.

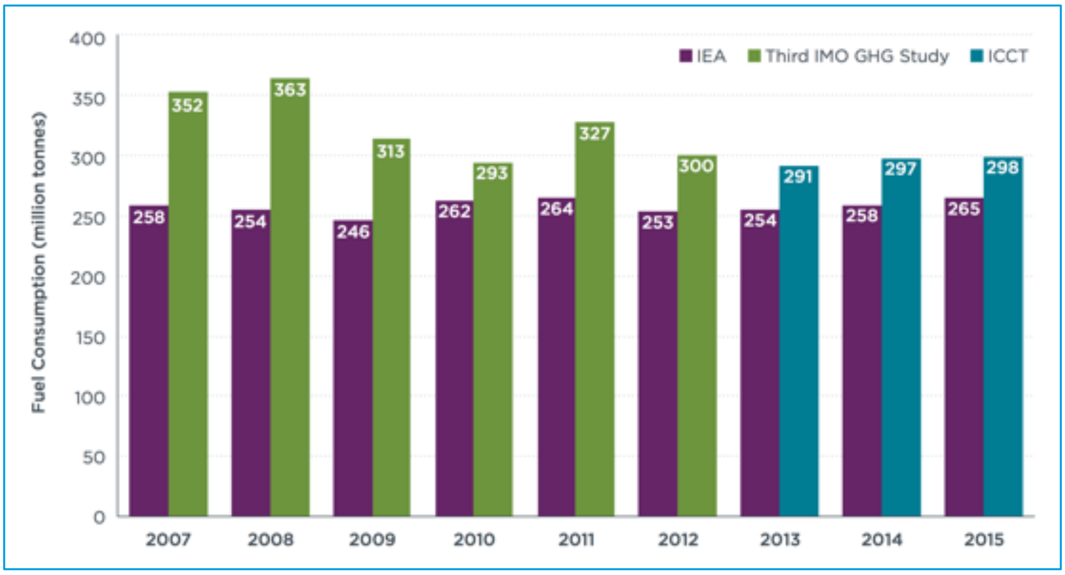
In a published review of different methods for calculating on-board ship's emissions and energy consumption based on operational data, Morena-Gutierrez et al. (2019) find that the most important sources of uncertainty are attributable to incomplete AIS coverage of a ship's activity and the discrepancies between the number of ships observed in the AIS data and the number of ships for which technical specifications are known. Furthermore, their discussion, consistent with Johansson et al. (2017), reflects on the environmental conditions, such as extreme weather, affecting a ship's power requirements and how this could be estimated more accurately. Morena-Gutierrez et al. (2019) find and Johansson et al. (2017) also both indicate that there are improvements that can be made on the way auxiliary and boiler fuel consumption is varied both by ship and in operation.

Importantly, both the Olmer et al. (2017a; 2017b) and Johansson et al. (2017) inventories produced since the Third IMO GHG Study, concluded that they produce results that align well with the results of the Third IMO GHG Study 2014, as indicated by an approximate projection of the 2012 results to compare with the periods studied (2013-15 and 2015 respectively), even if a direct comparison is not possible because there is no overlapping year (see Table 1 and Figure 1 - **Total shipping fuel consumption estimates from IEA, IMO and ICCT, 2007-2015**).

Table 1 - The predicted consumption of fuel for global shipping, reported by the International Energy Agency (IEA) and the Third IMO GHG Study 2014, compared with the values in Johansson et al. (2017)

	IEA 2007	IEA 2011	IMO GHG3 2012	STEAM3 2015
	Statistics	Statistics	Modelled	Modelled
Total fuel consumption [10^9 kg]	249	254	300	276
HFO	195	191	–	195
MDO	54	62	–	81
Processed AIS-messages [10^6]	–	–	3700	7800

Figure 1 - Total shipping fuel consumption estimates from IEA, IMO and ICCT, 2007-2015



Beyond the Third IMO GHG study's QA/QC and uncertainty analysis itself, these independent studies using models and data derived from scratch provide a key indicator that the core method in the Third IMO GHG Study is robust, but that there are features that can now be refined and improved to further increase accuracy.

The key features of the Third IMO GHG Study that, based on a review of key literature (and additional coordination among the consortium members in the case of points 5 and 6 below), deserve to be refined or added include:

1. Evaluation of missing technical specifications of ships.
2. Treatment of shipping activity in the case of sparse satellite AIS data.
3. Reflection of environmental conditions (weather), hull fouling, draught, interpolated speeds, and procedure for main engine load factors > 1.
4. Representation of auxiliary and boiler power requirements as a function of ship type, operation and geography.
5. Accounting for the energy use effects of innovative energy saving technologies and exhaust gas cleaning systems.
6. Update ship size categories (capacity bins).

A.5 Evaluation of missing technical specifications of ships

To deal with discrepancies between AIS ship related data (AIS static and voyage related data, message ID 5) and other technical fleet registers, Johansson et al. (2017) used a data-assimilation technique to assign physically realistic properties to ships, for which the technical information is missing. They argued that the use of vessel type averages can risk leading to unrealistic description in hydrodynamic performance prediction, fuel consumption and emissions. This approach of assigning improvements to individual vessel data is consistent with the approach taken in the Third IMO GHG Study. However, as Morena-Gutierrez et al. (2019) also identifies this as an important source of uncertainty, the details of the method used will be reviewed in light of the approach taken by Johansson et al. (2017) and aligned if necessary.

For AIS records containing an IMO number but missing one or more pieces of ship technical specifications data, Johansson et al. (2017) us a "most similar vessel" (MSV) approach to fill in missing values for main engine power, auxiliary engine power, gross tonnage, and main engine stroke type. To identify the MSV, the ships length over all (LOA) and design speed (v) must be known and are compared candidate vessels' LOA (l_c) and design speed (v_c). To select the MSV, Johansson et al. (2017) calculate a difference measure (s) as follows, where a is an empirical weighting factor equal to 0.35:

$$s = \sqrt{a\left(\frac{v - v_c}{v_c}\right)^2 + \left(\frac{l - l_c}{l_c}\right)^2}$$

The MSV is the candidate vessel with the lowest s. Johansson et al. (2017) claim this approach reduces root mean square error between actual and infilled data compared to using ship-type-average values, which was the approach of the Third IMO GHG Study 2014.

For AIS records that do not contain an IMO number but, instead, only contain an MMSI number, Johansson et al. (2017) developed a web crawler that uses the Bing search engine to search the Internet to find missing technical data associated with a ship AIS transponder's MMSI number.

Olmer et al. (2017a; 2017b) take a different approach from Johansson. They begin with the IHS ship technical specifications database and infill missing values for installed main engine power, maximum speed, fuel capacity (to estimate fuel carriage) and main engine rpm (to differentiate between slow-speed, medium-speed, and high-speed diesel engines). Johansson et al. (2017) needed to infill missing capacity for some ships, but Olmer et al. (2017a; 2017b) did not, because all ships in the IHS dataset had values for capacity. Olmer et al. do not attempt to estimate typical auxiliary engine power because, like the Third IMO GHG Study 2014, they assume that auxiliary engine and boiler power demand (expressed as kW) is a function of ship type, capacity bin, and operating phase (cruise, manoeuvring, anchor, berth). For ships with missing main engine power, maximum speed, or main engine rpm, Olmer et al. (2017a; 2017b) assign the average values for that ship's type and capacity bin from the IHS database. About one quarter (25.4%) of ships in the IHS database were missing values for maximum speed. About one in six ships (16.5%) were missing main engine rpm, and about one in twenty (4.7%) were missing main engine power.

Since the Third IMO GHG Study, the original methodology developed by UCL Energy Institute to infill fleet's missing technical specifications has been updated. The current algorithm implemented by UMAS is based on a multilinear regression created for each ship type and is not simply based on average values by ship class and capacity bin.

The following regressions were used:

Length overall: $loa = b1 + b2 * beam + B3 * draught + B4 * dwt$
Capacity depending on vessel type: $capacity = b1 + b2 * beam + B3 * draught + B4 * loa$
Design Speed: $speed = b1 + b2 * loa + B3 * me\_power + B4 * dwt$
Installed ME power: $me\_power = b1 + b2 * loa + B3 * speed + B4 * dwt$

Additionally, a regression to infill RPM can be added to the methodology.

The fits for LOA and main engine power are shown in Figure 2 and Figure 3. In these figures, a term “fitted” describes the values that exist in technical specification data but have been re-estimated using the obtained regression to ensure its quality (for validation) while the “predicted” values are those that have been infilled.

For ships that still could not be infilled, the median values per type and size were used.

Figure 2 - Regression between length over all and deadweight tonnes in FUSE model

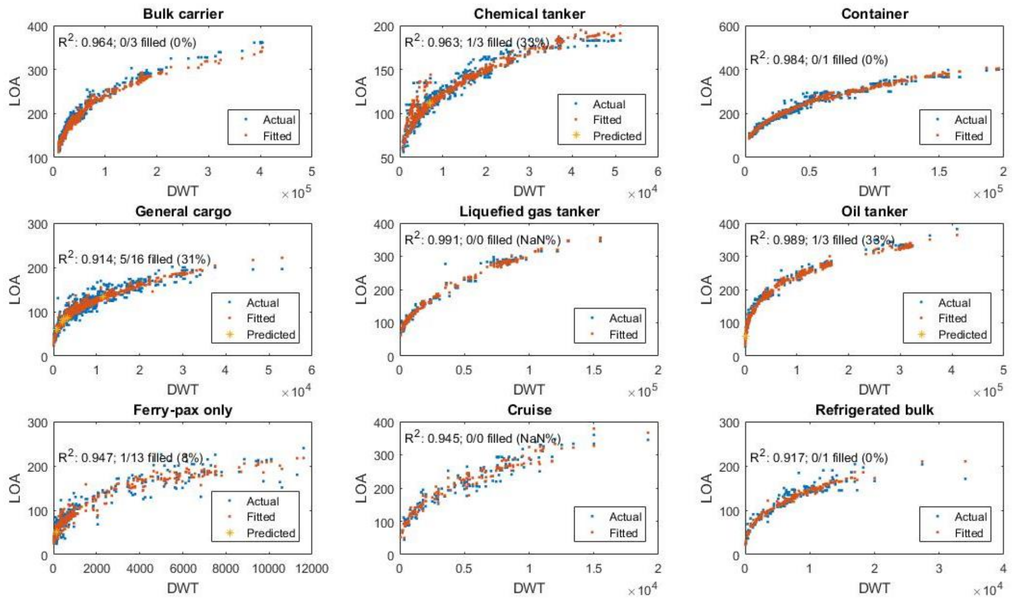
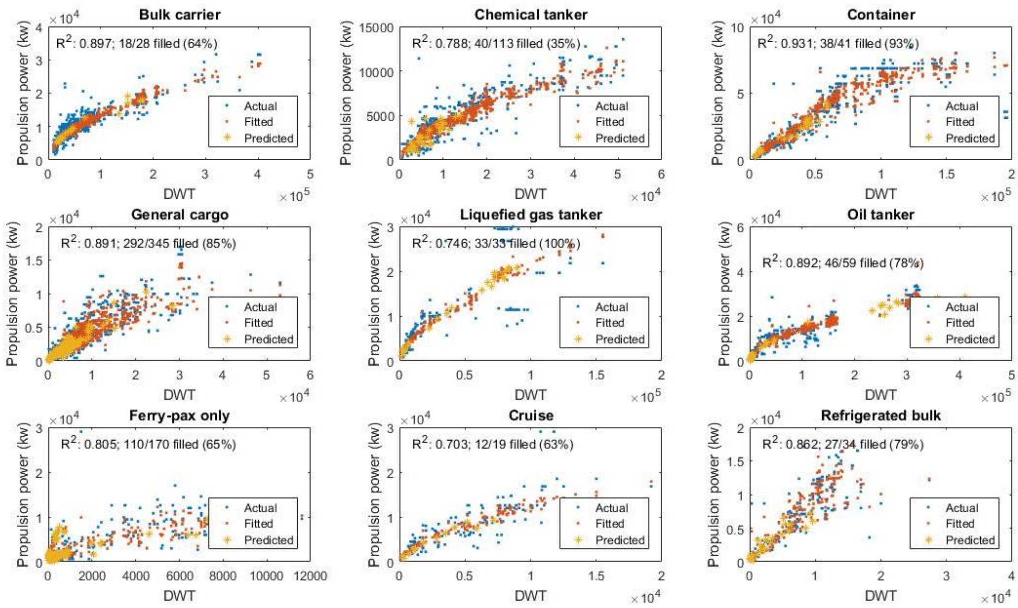


Figure 3 - Regression between propulsion power and deadweight tonnes in FUSE model



Recommendation

On the evidence of the quality of the fits, the experience of Johansson et al. (2017) of the potential to improve on average values, and the method's robustness to various different levels of missing data, we recommend adopting the approach currently used by UMAS.

A.6 Treatment of shipping activity in the case of sparse satellite AIS data

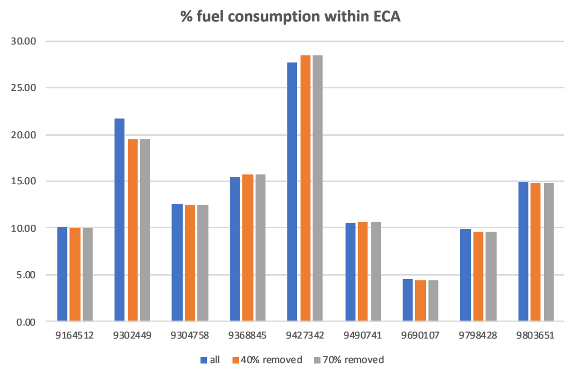
While AIS-acquired operational shipping data has significantly improved over the last years, there is still need for data interpolation to account for activity occurring during missing hours so that all emissions for each ship can be geospatially allocated so that appropriate emission factors can be applied — for example, when ships are within or outside of ECAs. The Third IMO GHG Study estimates activity during time without AIS coverage by extrapolating the distribution of activity when the ship is observed on AIS into the full year. Olmer et al. (2017b) linearly interpolated the ship's position and speed over ground assuming great circle distance travel between valid AIS points. Johansson, et al. (2017) argue that relying on great-circle paths may result in unrealistic situations, in which a route could cross over land areas, and that any two consecutive route points could actually be associated to a much longer travel route across the seas than estimated. Instead, this Johansson et al. (2017) rely on the Dijkstra algorithm to determine the shortest path network, which was also used by Paxian et al. (2010), based on observed ship traffic patterns. Ensuring that ship tracks do not crossland may be important, especially for regional and local emissions inventories. However, for a global ship emissions inventory, what is most important is having reasonable total emissions estimates that align reasonably well with where they were emitted and reflect appropriate emission factors, which are different for some pollutants, such as SO_x, NO_x, and PM, inside and outside of ECAs. The total emissions estimates of Johansson et al. (2017) align well with both the Third IMO GHG Study 2014 and Olmer et al. (2017a). Given the expected computational and human resource intensity of setting up, testing, and implementing a ship lane network, for the sake of ensuring that no ship track crosses land, paired with the fact that AIS data coverage is improving year-over-year, reducing the instances of this occurring, we recommend linearly interpolating ship positions.

We tested whether linearly interpolating ship position and speeds would adversely affect estimates of speed over ground or fuel consumption. We did this by analysing 2018 AIS data for nine ships that travelled inside and outside of ECAs and that travelled globally, including three container ships, three bulk carriers, and three oil tankers. We compared average speed over ground (SOG) and total annual fuel consumption under three scenarios: (1) all observed, hourly aggregated ship positions; (2) artificially removing 40% of hourly ship positions at random and replacing with interpolated ship position, speed, and draught; and (3) artificially removing 70% of hourly ship positions and following the same procedure as scenario 2. We found that linearly interpolating ship position, SOG, and draught resulted in similar average SOG and fuel consumption under all scenarios, even when removing seven-of-ten points. Linear interpolation also did a good job of accurately reflecting the proportion of fuel consumption inside and outside of ECAs, which is important because emission factors for some pollutants are different inside and outside of ECAs. See the tables and graphs below for more information.

Figure 4 - Proportion of fuel consumption within Emission Control Areas from the ICCT SAVE model

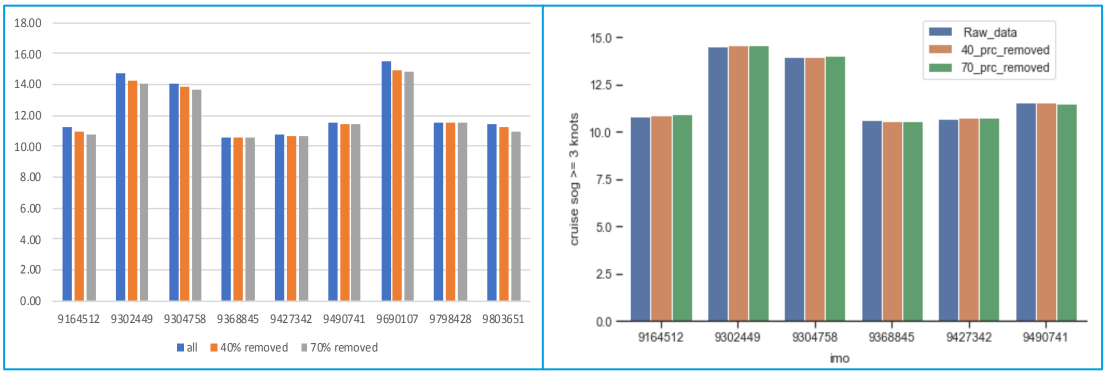
% fuel consumption within ECA

Ship class	IMO	all data	40% removed	70% removed
oil tanker	*9164512*	10.06	10.00	10.00
container	*9302449*	21.73	19.47	19.47
container	*9304758*	12.59	12.40	12.40
bulk carrier	*9368845*	15.44	15.66	15.66
bulk carrier	*9427342*	27.69	28.45	28.45
bulk carrier	*9490741*	10.48	10.63	10.63
container	*9690107*	4.51	4.38	4.38
oil tanker	*9798428*	9.83	9.62	9.62
oil tanker	*9803651*	14.94	14.82	14.82



We also tested whether two different methods of interpolating SOG were similar: (1) linearly interpolating SOG using great circle distance between interpolated points, plus adding in a speed adjustment factor as in Olmer et al. (2017a; 2017b); and (2) infilling with mean cruise-phase (SOG > 3 kts) SOG, as in UMAS's FUSE model. We found that the two approaches produced similar results and that either method would be suitable for infilling SOG for interpolated positions.

Figure 5 - Two methods of interpolating speed over ground: Olmer et al. (2017a; 2017b) **on the left; UMAS FUSE model on the right. Methods produce similar results**



Recommendation

We recommend to first linearly interpolate ship positions between missing AIS signals and then to interpolate missing SOGs with operational phase-specific mean SOG within allowable data gaps. The first should result in more accurate emissions estimates because it would do a better job of applying geography-dependent emission factors (e.g., those that are unique to ECAs) compared to methods that only interpolate speed and draught, which was the approach in the Third IMO GHG Study, while the second would result in a more reliable SOG interpolation than the approach of the Third IMO GHG Study.

A.7 Reflection of environmental conditions (weather), hull fouling, draught, interpolated speeds, and procedure for main engine load factors > 1

Weather

In the Third IMO GHG Study 2014 it was assumed that weather effects alone would be responsible for 15% of additional power margin on top of the theoretical propulsion requirements of ocean-going ships, and a 10% additional power requirement for coastal ships. Johansson et al. (2017)question this method and did not implement such a scaling factor, while Olmer et al. (2017a) followed the lead of the Third IMO GHG Study. In a recent adaption of the Ship Traffic Emission Assessment Model (STEAM), propelling power is determined by wave height and directions, accounting for the environmental conditions in a highly detailed manner. Explicitly resolving wind and wave conditions and then estimating how these increase a ship's resistance introduces both significant computational cost and additional uncertainty (uncertainty both due to the environmental data used and the algorithms to estimate how the weather conditions modify fuel consumption).

Recommendation

Given the resources and timeline available to conduct the Fourth IMO GHG Study, we recommend using the same weather adjustment factors as the Third IMO GHG Study and describing the potential effects of different assumptions in the uncertainty analysis.

Hull fouling

The Third IMO GHG Study 2014 applied a static 9% resistance (and therefore fuel consumption and emissions) penalty to reflect the impacts of hull fouling. Olmer et al. (2017a; 2017b) apply a variable hull fouling factor that is a function of ship length between perpendiculars, the initial roughness of a new ship, ship age (roughness increases with age) and the number of years since drydocking (roughness increases between drydocking due to biofouling). This approach accounts for how hull fouling affects resistance over time on a ship-by-ship level. As explained in Olmer et al. (2017b), the hull fouling factor increased the main engine power demand by 7% on average, ranging from 2-11% depending on each individual ship's age and maintenance schedule.

Recommendation

In the absence of additional empirical data, we recommend using the hull fouling factor from the Third IMO GHG Study 2014.

Draught

Reducing draught reduces the wetted area and reduces a ship's propulsion power requirements. The Third IMO GHG Study 2014 estimated change in resistance due to draught as a function of the instantaneous draught and the ship's reference draught for each hour. For a given hour, instantaneous draught can be highly uncertain and sometimes missing. Rather than calculating the effects of instantaneous draught on resistance every hour, Olmer et al. (2017a; 2017b) calculate an average annual draught adjustment factor, which is unique for each ship, and apply that adjustment factor to each hour. This procedure dampens the effects of erroneous instantaneous draught values, but simplifies the effect of draught at any given hour. They take into account the fact that some ship types routinely sail under ballast conditions (e.g., bulk carriers, general cargo ships, oil tankers, etc.) and others do not (e.g., container ships). For ships that do not typically sail under ballast conditions, the draught adjustment factor is simply the annual average draught divided by the design draught to the 2/3 power. For ships that sail under both ballast and loaded conditions, Olmer et al. (2017b) calculate an annual draught ratio for ballasted voyages and another for loaded voyages. The draught adjustment factor in that case is calculated by the following function:

$$DAF = \left((DR_b)^{\frac{2}{3}} * \frac{\sum t_b}{\sum t}\right) + \left((DR_l)^{\frac{2}{3}} * \frac{\sum t_l}{\sum t}\right)$$

Where DAF is the draught adjustment factor, DR_b is the average annual draught ratio when that ship is operating under ballast conditions, $\sum t_b$ is the time under ballast conditions, $\sum t$ is the total time, DR_l is the average annual draught ratio when that ship is operating under loaded conditions, $\sum t_l$ is the time under loaded conditions, $\sum t$ is the total time. The DAF is unique to each ship. For ships that have fewer than 30 reported draughts in a given year, Olmer et al. (2017a; 2017b) assign average values based on ship type.

Within MEPC 68/INF.24, a set of filters was applied to discard spurious draught data, to mitigate the likelihood of including these in EEOI estimates for ships with sparse or unreliable AIS data. The study relies on the metric *cargo carried* and used a discrete voyage perspective, to subsequently produce an annualised average. The methods used take into account that certain ships operate some of their voyages loaded and some of their voyages in the ballast condition, where at times empty vessels carry ballast water for safety and stability. After measuring the sensitivities of each filter parameter, and the diversity and coverage of the subset of ships was deemed sufficiently diverse and well populated across as many ship types and sizes as possible, the following conditions were followed.

A ship was retained (regardless of its type) in the sample, if the following conditions were met:
- it was active and observed in AIS data;
- at least 62.5% of the ship's messages with draught values were valid and not spurious;
- the sum of the days it spent laden and in ballast was at least 100;
- the ratio of the ship's distance travelled whilst laden to the sum of the distances travelled whilst laden and in ballast was at least 0.05.

While this method is sample based, the study offers extensive justification of its representativeness.

Recommendation

For the purposes of a global inventory, it is more important to minimize uncertainty in the total emissions than hourly emissions. Because instantaneous draught is uncertain and can be frequently missing, not be reported, or incorrectly reported, we suggest applying a voyage-specific draught in this study in order to dampen the effect of erroneous instantaneous draught values, as raised by Olmer et al. (2017a; 2017b), but voyage-by-voyage for each ship instead of annually for each ship, as to be compatible with energy efficiency estimates, similar to MEPC 68/INF.24. The 'draught adjustment factor' for the Fourth IMO GHG study will be calculated as follows: median voyage-level draught divided by design draught, all raised to the 2/3 power, if median voyage-level draught is reported and reliable. This will be multiplied by the used to estimate instantaneous main engine power demand for a given ship by applying a version of the Admiralty formula as follows, and consistent with the Third IMO GHG Study 2014:

In the above equation, P_t is instantaneous main engine power at time t, P_{ref} is installed main engine power, t_t is draught at time t, V_t is vessel speed from AIS at time t, V_{ref} is the ship's maximum speed, n equals 3, and the denominator values are the weather and hull fouling adjustment factors.

$$P_t = \frac{P_{ref}\left(\frac{t_t}{t_{ref}}\right)^{\left(\frac{2}{3}\right)}\left(\frac{V_t}{V_{ref}}\right)^n}{\eta_w \eta_f}$$

If the voyage-level draft is not reported or is considered unreliable, we propose to take a representative draught value for that same ship based on other voyages it has made. If no draught is available for the ship, we will base the draught on similar ships.

A.8 Procedure for main engine load factors > 1

In some cases, the estimated main engine load factor can be greater than 1, implying that a ship is using more than its installed main engine power, which is not possible. To avoid this, the Third IMO GHG Study removes SOG that is > 1.5 times the design speed and then replaces it with max speed. Olmer et al. (2017a, 2017b) remove SOG > 1.5 the maximum speed and replaces it with an interpolated speed, which is simply the estimated distance travelled by the ship in that hour. Additionally, if after applying the hull, weather, draught, and speed adjustment factors the main engine load factor is > 1, Olmer et al. set it to 0.98 and use that load factor to calculate main engine power demand, fuel consumption, and emissions.

Recommendation

We recommend identifying and removing SOGs that are greater than maximum speed and replacing them with an interpolated SOG based on the mean SOG in that phase (cruise or maneuvering; main engines are assumed to be 'off' when at anchor or at berth, so SOG does not need to be interpolated for these operating phases). Then, we suggest following the Third IMO GHG Study approach of estimating the instantaneous power demand using the Admiralty formula based on infilled speed and voyage specific median draught (as described in a section above) and then applying the weather and hull adjustment factors. If, after applying all of the adjustment factors, the main engine load factor is greater than 1, we suggest replacing the main engine load factor to 0.98 (while correcting the power demand) for the purposes of calculating fuel consumption and emissions.

A.9 Representation of auxiliary and boiler power requirements as a function of ship type, operation and geography

The Third IMO GHG Study, as pointed out in Johansson et al. (2017) uses auxiliary and boiler power demands expressed as kW which is then multiplied by hours spent using that machinery to use as a basis for estimating emissions from them. Then auxiliary and boiler power demands are constant as a function of ship type and size, for a given ship speed and mode of operation. This was partly to overcome a shortage of data in the technical specification datasets on the installed power of auxiliary and boiler machinery, and also for the shortcoming of data on the operation of installed machinery. Whilst for some ship types the simplifications applied may be appropriate (for example bulk shipping), there are other ship types where this is a significant simplification. For example: Container ships are increasingly using reefer containers for transporting refrigerated goods and these produce auxiliary machinery power requirements that may vary depending on the route and the year (increasing between 2012 and 2018), or by other factors; cruise ships, some offshore vessels and LNG carriers are increasingly using electric propulsion (or electric augmented propulsion) which means that the auxiliary and boiler power demand are not independent of the installed power but included as part of the overall installed power and total power demand.

As well as there being variations between ship types, there are also different practices of ship design and operation that vary as a function of where the ship is operating geographically.

The consortium has obtained empirical data on auxiliary engine (AE) and boiler (BO) power demand under different circumstances. The data cover major ship types.

We reviewed the empirical ship operations data from ClassNK and also reviewed Port of Los Angeles Vessel Boarding Program (VBP) survey data and compared it with the assumptions in the Third IMO GHG Study 2014. We've updated the auxiliary engine and boiler power demand in some instances and also needed to create assumptions for new ship size category bins (new bins are recommended for some ship types, as explained in point 6 below).

A.10 Updating AE and BO power demand for *unchanged* ship size categories

We averaged the AE and BO power demand for 2012 through 2018 for the VBP .The average numbers then were compared to the Third IMO GHG study. If the numbers were relatively the same, then we used the updated numbers. However, in some instances, the larger vessels were displaying lower power demands than their smaller counterparts.
We considered this to be unrealistic and decided, in those cases, to keep the same proportions between ship sizes as in the Third GHG Study or proportionate to the fuel consumption differences between ship sizes given by ClassNK.

A.11 Updating AE and BO power demand for *new* size categories

In the Fourth IMO GHG Study, there are two ways that we propose new ship size bins are added:

a Split previous capacity bins into multiple size bins.
b Add size bins to represent the new trend of larger ships.

For both cases, where no data were available from VBP or ClassNK, the preference was to keep the same power demand as in the most similar size from the Third IMO GHG Study. While for instances where the data were available from VBP, we used VBP averaged numbers. However, if the numbers were more than 20% lower or higher than the previous (case a. and b.) and forthcoming (only case a.) existing sizes, we reverted to copy the power output of the previous (next smallest) size bin.

A.12 Other aspects

We assumed that almost all ship types will have a waste heat recovery system that will fully cover the heating demand while at sea (hence the power demanded by BO is set to zero).

Peculiar to liquefied gas tankers between 100,000 – 199,999 dwt (Size 3) using steam turbines, normally the electric and heating demand is covered by the steam produced in the main boilers.

Finally, for power outputs above 1,000 kW, we rounded up to the nearest 50 kW, while for power outputs below 1,000 kW, we rounded to the nearest 10 kW.

From previous studies, we found that for some smaller vessels the AE and BO power demand assumptions overestimate AE and BO fuel consumption. We use the following logic to overcome this issue:

- main engine power 0-150 kW – auxiliary engine and boiler are set to zero;
- main engine power 150-500 kW – auxiliary engine is set to 5% of the main engine power while the boiler power is based on the aux AND BOILER look up table;
- main engine power 500 kW + – use look-up tables from the Third IMO GHG Study.

Recommendation

Use the auxiliary engine and boiler power demand assumptions in the tables in the appendix.

A.13 Accounting for the energy use effects of innovative energy saving technologies and exhaust gas cleaning systems

Innovative energy saving technologies

Under the EEDI, ships may use innovative technologies to reduce drag (e.g., hull air lubrication) or to reduce the propulsion power requirements from the main engine (e.g., wind-assist). However, the EEDI database published by IMO Secretariat reveals that few ships have applied these technologies.

A.14 Recommendation: We recommend that the effects of innovative energy saving technologies not be modeled because we understand that few ships have applied them during the period 2012-2018

Exhaust gas cleaning systems

Some ships use EGCS to comply with SECAs and, in the run up to 2020, some ships are installing them to comply with the maximum global 0.50% fuel sulphur standard. Using EGCS reduces sulfur emissions but increases fuel consumption and associated emissions of other pollutants. Between 2012 and 2018, only a very small fraction of the fleet used EGCS (<750 ships had EGCS installed or on order in 2018, according to DNV-GL). Additionally, the use of EGCS is expected to increase fuel consumption by about 2% when they are switched on. For a global analysis, this effect will be negligible.

Recommendation

We recommend that the effects of EGCS on fuel consumption and emissions not be modeled.

Update ship size categories (capacity bins)

The consortium recognized that there is a trend towards larger ship sizes that should be reflected in the
Fourth IMO GHG Study. As such, we have conferred amongst ourselves and determined that it would be appropriate to, as far as possible, keep the ship size categories from the Third IMO GHG Study and to add additional size categories to account for larger ships. One change from the Third IMO GHG Study that we would like to highlight pertains to vehicle carriers. In the Third IMO GHG Study, there was only one size category for vehicle carriers, we've now expanded it to three. Also, whilst the EEDI regulates vehicle carriers according to dwt, we found that dwt correlates poorly with vehicle carrier capacity (e.g., how many cars can be carried by the ship). However, GT correlated well. As such, we also propose to group vehicle carriers by their GT rather than dwt. See the appendix for details.

Recommendation

Use the updated ship size category (capacity bins) found in the tables in the appendix.

B Review of emission factors

B.1 Introduction

Section 1.1 of the Terms of Reference for the Fourth IMO GHG Study states:

"The inventory should include current global emissions of GHGs and other relevant substances emitted from ships of 100 GT and above engaged in international voyages as follows:

1. GHGs should be defined as the six gases initially considered under the UNFCCC process: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), subject to data availability.
2. Other relevant substances that may contribute to climate change include:
   - nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), particulate matter (PM) and sulphur oxides (SO_x), subject to data availability;
   - black carbon (BC), subject to data availability and recognizing the complexity of providing accurate estimates.
3. For the purpose of the emission estimates calculation of substances other than CO_2, the emission factors methodology presented in Section 2.2.7 of the *Third IMO GHG Study 2014* should be updated.
4. The inventory should include total annual GHG emission (IMO, 2018)[1] series from 2012 to 2018, or as far as statistical data are available".

In our offer, we state:
"The aim of this Task is to:
- determine emission factors of CO_2, CH_4, N_2O, NO_x, SO_x, CO, PM, BC, and NMVOC on the basis of fuel use;
- determine emission factors of HFCs, PFC, SF_6, NF_3 and NMVOC (not related to fuel burning; i.e., fugitive emissions)".

We also explain in the offer:

"We propose to carefully review the methodology of the Third IMO GHG Study 2014 and other marine emissions inventories (e.g., (Chen, et al., 2016; Comer, et al., 2017; Johansson, et al., 2017; Li, et al., 2016; Olmer, et al., 2017a; 2017b; Starcrest Consulting Group, 2018; Zhang, et al., 2019; Ricardo, 2017) and to consult with engine manufacturers, research organizations, academic institutions, classification societies, and others to review and update emission factors.

The emission factors will be developed in such a way that they are useful for estimating emissions in bottom-up and top-down inventories as well as future scenarios. Specifically, energy-based emission factors (g/kWh) will be converted to fuel-based emission factors (g/kg-fuel), where necessary, to allow for coherence across inventories (bottom-up and top-down) and scenarios."

[1] Paragraph 3.1.3.

In this section we consider and recommend improvements for:
1. SFOC assumptions.
2. Methodologies for estimating CO_2 and SO_x.
3. Emission factors for other pollutants emitted from combustion (NO_x, PM, CH_4, CO, N_2O, NMVOCs).
4. Black carbon emission factors.
5. Emission factors for fugitive emissions (HFCs, PFCs, SF_6, and NMVOCs).

B.2 SFOC assumptions

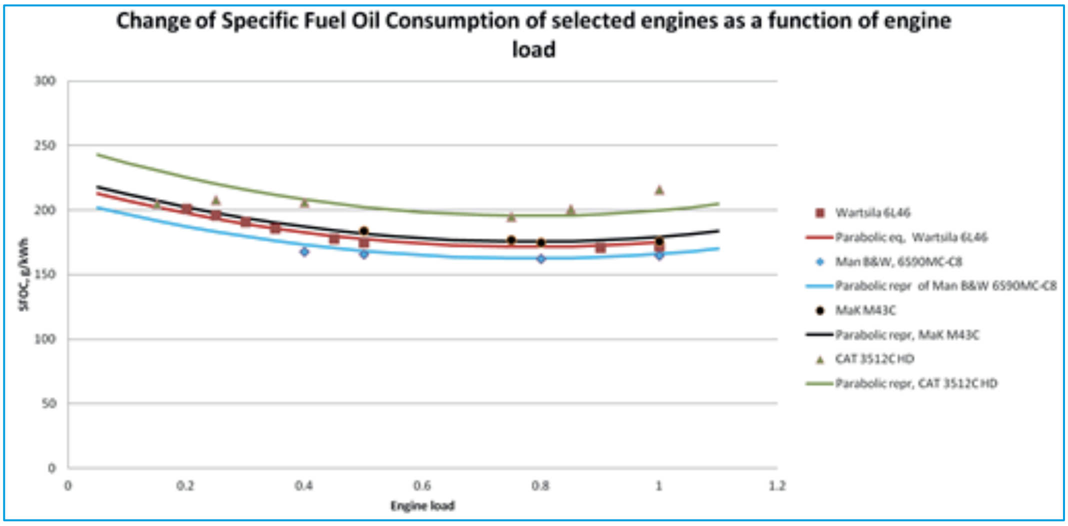
Equation for SFOC as a function of engine load

In the Third IMO GHG Study 2014, fuel consumption was assumed to vary as a function of engine load as shown by the following empirical equation:

$$SFOC_{load} = SFOC_{baseline} * (0.455 * load^2 - 0.71 * load + 1.28)$$

Where $SFOC_{load}$ is the specific fuel oil consumption (SFOC) at a given engine load, $SFOC_{baseline}$ is the lowest SFOC for a given engine. The SFOC curves for marine engines are u-shaped: SFOC is higher at lower loads, gets lower until it reaches a minimum, and begins to increase again at higher loads. The Third IMO GHG Study 2014 showed that this equation satisfactorily described how SFOC changes as a function of engine load when SFOCs are optimized (i.e., lowest) at 80% load (Figure 6).

Figure 6 - SFOC as a function of engine load for select engines



Source: Third IMO GHG Study 2014.

It could be the case that some ships, especially those that are slow steaming and which have electronically controlled engines, have optimized fuel consumption for lower engine loads than approximately 80%. How common this is unknown. We therefore, suggest using this equation to estimate SFOC as a function of engine load. We will discuss the possible effects of the SFOC on the results when discussing uncertainties.

Recommendation

Use the equation for SFOC as a function of engine load optimised at approximately 80% load, which is the same approach as the Third IMO GHG Study.

Baseline SFOC assumptions by engine type and age

The $SFOC_{baseline}$ needs to be assumed and varies based on engine age and engine type (e.g., SSD, MSD, HSD). The baseline SFOC reflects the SFOC at the engine's most efficient load (80% in this case). The Third IMO GHG Study's assumptions for baseline SFOCs for marine diesel main engines are shown in Table 2. For LNG engines (Otto-cycle), the Third IMO GHG Study 2014 assumed a baseline SFOC of 166 g/kWh. Baseline SFOCs for gas turbines, steam boilers, and auxiliary engines are shown in Table 3.

Table 2 - Baseline SFOCs for marine diesel main engines from the Third IMO GHG Study 2014

Engine age	SSD	MSD	HSD
Before 1983	205	215	225
1984-2000	185	195	205
Post 2001	175	185	195

Table 3 - Baseline SFOCs for gas turbines, steam boilers, and auxiliary engines from the Third IMO GHG Study 2014

Engine type	HFO	MDO/MGO
Gas turbine	305	300
Steam boiler	305	300
Auxiliary engine	225	225

We considered if the SFOC assumptions needed to be updated to reflect the current mix of marine engine ages and types, including LNG engines (Otto-cycle, lean-burn spark ignition (LBSI), and Diesel-cycle) as well as to include methanol (MeOH). New research from the ICCT on the climate implications of using LNG as a marine fuel (Pavlenko, et al., 2020) includes an extensive literature review on fuel consumption for LNG-fuelled engines and a review of fuel consumption for late-model SSD and MSD engines. Based on this research, we propose to use the following baseline specific fuel consumption (SFC) values in the Fourth IMO GHG Study (Table 4). These include revised SFCs and new LNG-fuelled engine categories: LNG-Diesel (dual fuel) and LBSI (only uses LNG). For dual-fuel LNG engines, we propose to assume that they always operate on LNG as their primary fuel, rather than fuel oil. Additionally, we assume that the mass of pilot fuel injected, if any, will remain constant across engine loads. Differences from the Third IMO GHG Study 2014 are indicated with an asterisk (*).

Table 4 - Proposed Specific Fuel Consumption (SFC; g/kWh) values for the Fourth IMO GHG Study

Engine Type	Fuel Type	Before 1983	1984-2000	2001+
SSD	HFO	205	185	175
	MDO	190*	175*	165*
	MeOH	N/A	N/A	350*
MSD	HFO	215	195	185
	MDO	200*	185*	175*
	MeOH	N/A	N/A	370*
HSD	HFO	225	205	195
	MDO	210*	190*	185*
LNG-Otto (dual fuel, medium speed)*	LNG	N/A	173*	156*
LNG-Otto (dual fuel, slow speed)*	LNG	N/A	N/A	148 LNG + 0.8 MDO (pilot)*
LNG-Diesel (dual fuel)*	LNG	N/A	N/A	135 LNG + 6 MDO (pilot)*
LBSI*	LNG	N/A	156*	156*
Gas Turbines	HFO	305	305	305
	MDO	300	300	300
	LNG	N/A	N/A	203*
Steam Turbines (and boilers)	HFO	340*	340*	340*
	MDO	320*	320*	320*
	LNG	285*	285*	285*
Auxiliary Engines	HFO	225	205*	195*
	MDO	210*	190*	185*
	LNG	N/A	173*	156*

Energy density assumptions: HFO = 40,200 kJ/kg; MDO = 42,700 kJ/kg; LNG = 48,000 kJ/kg, consistent with Resolution MEPC.308(73); energy density of MeOH is assumed to be 19,900 kj/kg *indicates a difference from the Third IMO GHG Study 2014; source for asterisk (*) values for all engines except steam turbines is ICCT research underlying Pavlenko et al. (2020) but adjusting for 48,000 kJ/kg LNG assumption, whereas Pavlenko et al. assumed 50,000 kJ/kg; Asterisk values for steam turbines are from soon-to-be published analysis from UCL/UMAS; differences in SFC among fuels reflects the different energy densities of the fuels and the efficiency of the engines.

Recommendation

Use the SFC values in Table 4.

B.3 Methodologies for estimating CO_2 and SO_x

Emissions of CO_2 and SO_x are directly proportional to fuel consumption. For a given hour, fuel consumption (g) can be estimated by multiplying $SFOC_{load}$ (g/kWh) by the engine's energy use (kWh).

Carbon conversion factors

Once the fuel consumption is known CO_2 emissions can be estimated based on the conversion factor (C_f) of the fuel, which is 3,114 g CO_2/g fuel for HFO, 3,206 g CO_2/g fuel for MDO, and

2,750 g CO_2/g fuel for LNG as defined in Resolution MEPC.308(73). Note that we use 'MDO' to refer to distillate marine fuels, generally, which would include marine gas oil (MGO). These conversion factors are routinely used in emissions inventories for marine sectors.

Recommendation

Use the same carbon conversion factors for marine fuels as the Third IMO GHG Study 2014.

Equation to convert from fuel S content to SO_x emissions

SO_x emissions vary with fuel sulphur content or with the use of exhaust gas cleaning systems. SO_x emission factors for 2012-2018 will be based on global average fuel sulphur content statistics from IMO, i.e. sulphur monitoring reports in accordance with resolution MEPC.192(61) and resolution MEPC.273(69) and will reflect SECAs and the EU Sulphur Directive. SO_x emission factors used in the Task 2 projections will reflect the 0.50% 2020 global fuel sulphur limit for marine fuels. All estimates will take into account ECAs and projections under Task 2 may reflect expected future ECAs.

SO_x emissions were calculated in the Third IMO GHG Study 2014 and in Olmer et al. (2017a; Olmer, et al., 2017b) as follows:

$$g\,SOx = g\,fuel * 2 * 0.97753 * fuel\,sulphur\,fraction$$

This equation reflects an assumption that 97.753% of the sulphur in the fuel is converted to SO_x (the rest is converted to sulphate/sulphite aerosol and classified as a part of particulate matter) and the two reflects the ratio of the molecular weight of SO_2 to sulphur because, for ship emissions, the vast majority of SO_x is SO_2.

We did not find any suggested alternative approaches to estimate SO_x emissions for ships in the literature. This equation is also directly tied to how PM_{10} is calculated. The sulphur that is not converted to SO_x is assumed to become directly emitted sulphate PM. Any change to this equation will necessitate a change to the equation used to calculate PM_{10}.

Recommendation

Use the same approach as the Third IMO GHG Study 2014 and Olmer et al. (2017b).

B.4 Emission factors for other pollutants emitted from combustion (NO_x, PM, CH_4, CO, N_2O, NMVOCs)

Emissions of NO_x, PM, CH_4, CO, N_2O and NMVOCs vary as a function of engine load.
We propose to assume constant emission factors above 20% main engine load and apply low load adjustment factors for main engine loads below 20%, similar to what has been done in the Third IMO GHG Study 2014 and other researchers (e.g., Olmer et al., 2017b; Comer et al., 2017; Starcrest Consulting Group, 2018). In addition, we propose to distinguish PM_{10} and $PM_{2.5}$. We propose to assume that 92 % (m/m) of PM_{10} is $PM_{2.5}$, which is a typical and accepted assumption in the literature, including U.S. EPA (2016).

NO_x emissions are also a function of engine Tier and, for new ships that have Tier III engines, whether or not they are operating in a NECA. NO_x emission factors are a function of combustion temperature and are also be affected by aftertreatment technologies such as EGR or SCR systems which may be used to comply with IMO MARPOL Annex VI Regulation 13.

We propose to use the emissions limits in Regulation 13 as the emission factor for NO_x (Table 5), which is consistent with the Third IMO GHG Study 2014 and Olmer et al. (2017a; 2017b).

Table 5 - NO_x emission factor assumptions

Tier	Ship construction on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1,999	n >= 2,000
I	1 Jan 2000	17.0	45*n^(-0.2)	9.8
II	1 Jan 2011	14.4	44*n^(-0.23)	7.7
III	1 Jan 2016*	3.4	9*n^(-0.2)	2.0

* For ships operating in the North American and United States Caribbean Sea ECAs; 1 Jan 2021 for ships operating in the Baltic and North Sea ECAs.

PM emissions are a function of fuel sulphur content and are therefore reduced when operating on lower sulphur fuels (e.g., when operating in ECAs) or when using exhaust gas after treatment systems such as scrubbers. Previous IMO GHG studies have assumed the following PM emission factor equations:

For HFO:

$$PM\left(\frac{g}{kWh}\right) = 1.35 + SFOC\left(\frac{g}{kWh}\right) * 7 * 0.02247 * (fuel\ sulfur\ fraction - 0.0246)$$

For MDO/MDO:

$$PM\left(\frac{g}{kWh}\right) = 0.23 + SFOC\left(\frac{g}{kWh}\right) * 7 * 0.02247 * (fuel\ sulfur\ fraction - 0.0024)$$

We suggest continuing to use these equations to estimate PM_{10} and then to estimate $PM_{2.5}$ by assuming that 92% of PM_{10} is $PM_{2.5}$.

For CO, N_2O and NMVOCs emission factors (from fuel combustion), we suggest using those in the Third IMO GHG Study 2014, which is also consistent with Olmer et al. (2017a; 2017b) .

For CH_4, new research has been conducted on emission factors by engine type. In particular, unburned methane from dual fuel and steam turbine engines. Pavlenko et al. (2020) conducted an in-depth assessment of unburned methane from marine engines, which includes an exhaustive review of the literature on methane slip from different engine technologies. We propose to use the CH_4 emission factors in Table 6.

Table 6 - Proposed CH4 emission factors for the Fourth IMO GHG Study

Engine Type	Fuel Type	CH_4 (g/kWh)
SSD	HFO	0.01
	MDO	0.01
	MeOH	0.01
MSD	HFO	0.01
	MDO	0.01
	MeOH	0.01
HSD	HFO	0.01
	MDO	0.01
LNG-Otto (dual fuel, medium speed)*	LNG	5.5*
LNG-Otto (dual fuel, slow speed)*	LNG	2.5*
LNG-Diesel (dual fuel)*	LNG	0.2*
LBSI*	LNG	4.1*
Gas Turbines	HFO	0.002
	MDO	0.002
	LNG	0.06*
Steam Turbines (and boilers)	HFO	0.002
	MDO	0.002
	LNG	0.04*
Auxiliary Engines	HFO	0.01
	MDO	0.01
	LNG	Depends on engine type*

* Indicates a difference from the Third IMO GHG Study 2014; source for asterisk (*) values is Pavlenko et al. (2020).

Emission factors for 2012-2018 will reflect regulations and ECAs that are applicable at the time and future projections under Task 2 will reflect expected fleet characteristics (e.g., to estimate the share of NO_x Tier I, Tier II, and Tier III engines), future fuel sulphur regulations, and future SECAs, NECAs, and ECAs, as appropriate.

Recommendation

Use mostly the same emission factors and approach as the Third IMO GHG Study 2014 and Olmer et al. (2017a; 2017b) but use the updated CH_4 emission (methane slip) factors in Table 6 and differentiate between PM_{10} and $PM_{2.5}$.

B.5 Black carbon emission factors

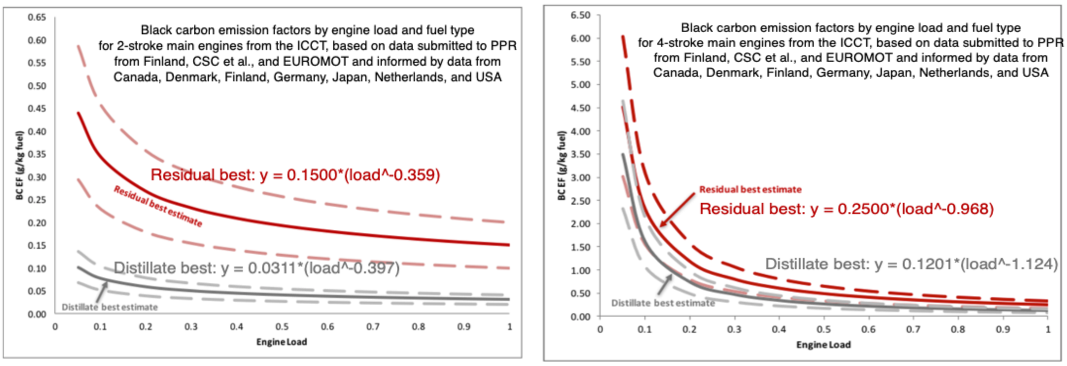
For bottom-up estimates, for ships that use oil-based fuels, we intend to use main engine BC emission factors develop by the ICCT as published in Olmer et al. (2017b) and Comer et al. (2017) and explained in detail in Appendix F of a detailed methodology documen (Olmer, et al., 2017b). The equations for these emission factors were presented by Dr. Bryan Comer, Senior Researcher, ICCT at the Expert Workshop in Preparation of the Fourth IMO GHG Study (GHG-EW) in March 2019; the presentation is available at the link in ISWG-GHG 5/3 para 12. These BC emission factors vary as a function of fuel type (residual or distillate), engine type (2-stroke or 4-stroke), and engine load, as shown in Figure 7
We reviewed additional literature on BC emission factors in recent published research and data submitted to IMO by member states and international organizations, including the following documents: PPR 5/7/2; PPR 5/INF.10; PPR 5/INF.13; PPR 5/INF.14; PPR 6/INF.12;

PPR 6/INF.13; PPR 6/INF.14; PPR 6/INF.15; and PPR 7/8. In reviewing these documents, we did not find any reported values that would change the shape of the emission factor curves in Comer et al. (2017) and Olmer et al. (2017b). We therefore recommend using the BC emission factors for main engines found in Comer et al. (2017) and Olmer et al. (2017b) in the Fourth IMO GHG Study. Black carbon emission factors for steam turbines, gas turbines, auxiliary engines, boilers, and LNG engines will be consistent with those used in Comer et al. (2017) and Olmer et al. (2017a; 2017b).

For top-down estimates, we recommend using representative fuel-consumption-based BC emission factors expressed in terms of mass of BC per mass of fuel consumed. Fuel-consumption-based, ship-class-level emission factors are available in Figure 7 of Comer et al. (2017).For example, container ships, as a class, emit approximately 0.26 grams of BC per kg of fuel consumed. Other ship classes emit more or less than this.

We will explain the complexity of providing accurate estimates of BC in the report.

Figure 7 - Black carbon emission factors from Comer et al. (2017) for 2-stroke (left) and 4-stroke (right) marine diesel engines



Recommendation

Use BC emission factor equations consistent with Comer et al. (2017) and Olmer et al. (2017b) and explain the complexity of providing accurate estimates of BC in the report.

B.6 Emission factors for fugitive emissions (HFCs, PFCs, SF_6, NF_3, and NMVOCs)

HFCs emissions are primarily fugitive emissions from refrigeration systems. The Third IMO GHG Study 2014 estimated fugitive emissions per ship per year, which varied by ship type (Table 7). We propose to estimate the types and amounts of HFCs used for refrigeration on board ships and to estimate fugitive HFCs emissions based on ship activity. We intend to estimate HFCs emissions from reefer containers using available data on the total number of reefer containers. All estimates will reflect regulations that phase out certain HFCs.

Table 7 - HFC emission rates (tonnes per ship per year) from the Third IMO GHG Study 2014

	2012			2030			2050		
	R-22	R-134a	R-404a	R-22	R-134a	R-404a	R-22	R-134a	R-404a
Bulk carrier	0.031	0.031	0.002	0	0.06	0.004	0	0.06	0.004
Chemical tanker	0.024	0.038	0.003	0	0.06	0.004	0	0.06	0.004
Container	0.027	0.035	0.002	0	0.06	0.004	0	0.06	0.004
General cargo	0.037	0.025	0.002	0	0.06	0.004	0	0.06	0.004
Liquefied gas tanker	0.031	0.031	0.002	0	0.06	0.004	0	0.06	0.004
Oil tanker	0.023	0.039	0.003	0	0.06	0.004	0	0.06	0.004
Other liquids tankers	0.023	0.039	0.003	0	0.06	0.004	0	0.06	0.004
Ferry — pax only	0.061	0.041	0.002	0	0.1	0.004	0	0.1	0.004
Cruise	0.76	0.488	0.033	0	1.2	0.08	0	1.2	0.08
Ferry — ro-pax	0.071	0.032	0.001	0	0.1	0.004	0	0.1	0.004
Refrigerated bulk	0.935	0.007	0.118	0	0.06	1	0	0.06	1
Ro-ro	0.075	0.028	0.001	0	0.1	0.004	0	0.1	0.004
Vehicle	0.027	0.034	0.002	0	0.06	0.004	0	0.06	0.004

PFCs have been used on board ships in AFFF fire-fighting foams but manufacturers have been phasing them out under the prohibition to produce them by Montreal Protocol; as such, we propose not to estimate PFCs emissions.

SF_6 gas is sometimes transported by ship but not in large quantities and we expect leakage to be negligible and therefore we propose not to estimate SF_6 emissions.

NF_3 gas was recently added to the list of GHG under UNFCCC framework. However, as with SF_6 gas, we expect any leakage of NF_3 gas either from any activities onboard or any material used onboard to be negligible and therefore we propose not to estimate NF_3 emissions.

NMVOCs fugitive emissions can occur when transporting oil and gas. The Third IMO GHG study 2014 estimated fugitive NMVOCs emissions from crude oil transport based on top-down crude oil transport data from UNCTAD. Given the complexities of estimating bottom-up fugitive emissions (need to account for nature of the cargo, temperature, turbulence in the vapour space, sea conditions, ship design, etc.) we intend to estimate fugitive emissions from transporting oil and gas using a top-down approach by assuming a standard volume of loss.

Recommendation

Estimate fugitive HFC and NMVOC emissions, as far as possible. Do not estimate fugitive PFC, SF_6, or NF_3 emissions.

C Review of projection methodology

This section is divided as follows. Next subsection presents a brief summary of the methodology adopted in the Third IMO GHG Study to project emissions from ships. The subsequent section presents a summary of the recent literature that assess the emissions projections. The final subsection describes the two alternative methodologies that we propose in the Fourth IMO GHG Study to project emissions and concludes with relevant recommendations.

C.1 Brief summary of Third IMO GHG Study 2014

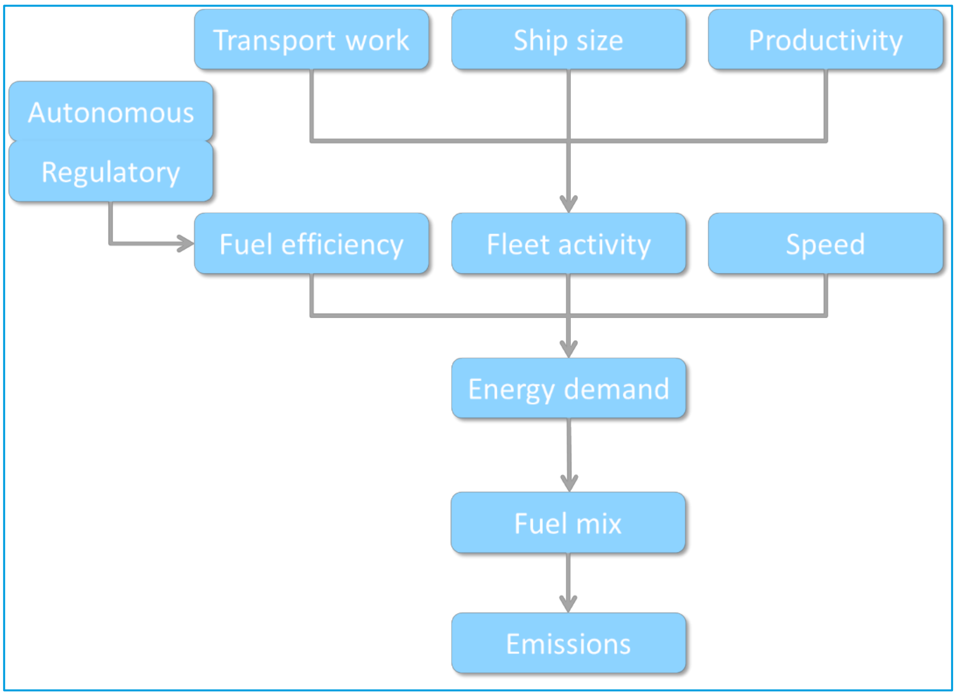
According to the Third IMO GHG Study 2014 and the Update of Maritime Greenhouse Gas Emission Projections 2017 (CE Delft and David S. Lee, 2017, p. 6), the method for projecting maritime emissions from international navigation used in the study considers the following steps (Figure 8):

- Step 1: Establishing the historical non-linear relation between maritime transport work and relevant economic parameters such as: world GDP (for transport for unitized cargo and non-coal dry bulk); and energy consumption (for transport of fossil fuels), using the logistic model.
- Step 2: Projecting transport work on the basis of the relation described above and long-term projections of GDP and energy consumption.
- Step 3: Making a detailed description of the fleet and its activity in the base year 2012 (from the bottom up inventory). This involves assigning the transport work to ship categories.
- Step 4: Projecting the fleet composition and energy efficiency of the ships based on a literature review, the MACC and a stakeholder consultation; projecting the fuel mix based on a literature review, MACC and stakeholder consultation.
- Step 5: Combining the results of Steps 2 and 4 above to project shipping emissions.

In the Third IMO GHG Study, to estimate the historical non-linear relationship between maritime transport work and economic activity (Step 1), data source on seaborne trade for different cargo types used was collected by Fearnleys from 1970-2020 (provided by United Nations Conference on Trade and Development (UNCTAD) as part of their annual 'Review of Maritime Transport'). However, in the Update of Maritime Greenhouse Gas Emission Projections 2017, Clarksons data were used as these provided better discrimination, cargo types and apparently more comprehensive coverage.

The methodology used in the Third IMO GHG Study can be summarized by the following figure:

Figure 8 - Graphical representation of the methodology used in the Third IMO GHG Study



Source: adapted from Third IMO GHG Study.

C.2 Peer reviewed literature

Before revising the literature, it is important to understand the basic approach to project emissions. First, the relationship between transport work and relevant economic variables (such as GDP, population, and energy consumption levels) must be established using historical data. Second, the parameters found in the first step are used to project transport work using GDP and Population projections. After the first and second step, we know how the demand for transport work will vary in the future. Therefore, the next step is to understand how the demand for transport work will be translated to emissions. In this sense, it is important to assess the future efficiency of the fleet in terms of its ship size developments and technological and operational developments.

The main challenge is to obtain consistent estimates of how transport demand evolves over time. Different methods to estimate transport work demand are presented in CE Delft and Lee (2017), CE Delft and Lee (2019) and DNVGL (2019), and transport demand using trade flows is explored in Cristea et al (2013).

CE Delft and Lee (2017 and 2019) are updates of the projections in the Third IMO GHG Study. Apart from the projection of transport work, they are methodologically identical. The differences in transport work projections stem from using more disaggregated data from a different source. In particular, CE Delft and Lee (2019) analyses the influence of GDP and energy on transport work and finds that GDP projections have a larger impact on emission pathways than energy projections because the share of emissions generated by transporting fossil fuels decreases in every scenario.

DNVGL (2019) also projects maritime GHG emissions but develops only one possible future scenario which cannot be considered as a BAU scenario because it assumes an increase in the stringency of design efficiency. DNVGL project a lower growth in maritime transport demand than CE Delft: a compound growth rate in tonnes of 1,1% per year against a compound growth rate of 2.6% in tonne-miles for CE Delft in the OECD-1.6 scenario. The reason for this large difference is not clear. The emissions are projected to increase by a CAGR of 0.4% in CE Delft and decrease by 0.8% per annum on average according to DNVGL (2019). The difference between these projections, apart from differences in transport demand projections, result from the fact that DNVGL (2019) assumes a BAU fuel transition (12 % lower emissions in 2050) and an improvement in logistics (6 % lower emissions in 2050).

The methodology discussed above use linear and non-linear assumptions about the relation between GDP and trade demand. The exception is the work of Cristea et al (2014), published in a prestigious journal of environmental economics. The authors collected a rich data on trade by transportation mode and use this to calculate GHG emissions.

In an ideal world, where all data are available, one would collect historical, bilateral, mode-specific trade-volume data, use a gravity model to establish the relation between bilateral trade volumes and economic parameters, and then use projections of economic parameters to project trade demand in the future. In the real world, only global mode-specific trade-volume data are available as well as bilateral economic trade data (aggregated for all transport modes). Considered the data constraints, there are two ways to estimate the effect of economic activity on transport work demand:

1. Run a logistic model using global mode-specific trade volume data. This approach assumes that the geographical pattern of trade remains constant (or changes predictably) and establishes historical relations between trade demand and economic parameters (i.e. same Third IMO GHG Study approach only updating the data).
2. Run a gravity model using bilateral mode-specific trade data constructed from bilateral trade data, estimates of mode splits of trade and calculating transport work measures by assuming a measure of distance between pairs of countries.

Both approaches have strengths and weaknesses when compared to the ideal way. The first approach (logistic model) uses more accurate data on modal transport work and allows the analysis of more years. It presumes that the relation between transport work and its driver (total GDP) can be described by a logistic curve (sometimes called an S-curve), finds the curve that best resembles historical data and uses the curve to project transport work in the future. The main weakness is that it does not account trade specificities between countries that might be relevant to project future demand. The second approach (gravity model) has the advantage of assessing such trade specificities and considering them when projecting the future demand (it also uses country GDP and population projections into the model). It presumes that transport work is a function of the GDP per capita and population of the trading countries and uses econometric techniques to estimate the elasticity of transport work with respect to its drivers based on panel data of bilateral trade flows. The weaknesses of the second approach are the data limitation (less year than global data) and regarding the assumptions needed to estimate modal share of trade between countries.

Both of the approaches present two different outlooks on how the future resembles the past. In this sense, we recommend supplementing the method to transport work employed in the Third IMO GHG Study with a gravity model approach (trade models). The difference between the two can be interpreted as the uncertainty inherent in making projections about future developments.

C.3 Fourth IMO GHG Study approach

Our approach is divided into the following steps:
- Step 1: Estimate transport work as a function of GDP (global or by country) and population levels.
- Step 2: Project transport work using GDP and Population (for non-energy products) and energy consumption projections (for energy products).
- Step 3: Project the efficiency of the fleet based on projections of ship size development and projections of technological and operational developments.
- Step 4: Project emissions.

For Steps 1 and 2, due to the methodology review in Section C.2, we propose two different methodologies to project transport work related to non-energy products maritime transportation:

First, we will model the transport work for each pair of origin and destination country in terms of each country's GDP and population measures using a gravity model, panel data approach and machine learning techniques (gravity model). Once we establish the relationship between GDP, population and transport work measures, we will use the IPCC (and other institutions) predictions to forecast the future transport work.

Second, we will follow the same methodology previously applied in the Third IMO GHG Study, what we call here as a reduced form time series approach (logistic model). The basic idea in this simpler methodology is to understand a non-linear relationship between global transport work, GDP and energy use over time.

The latter methodology has the advantage of being simple. On the other hand, the bilateral composition of trade is relevant for emissions and the gravity equation gives the ability to distinguish trade growth between China and Europe versus trade growth within Europe. In this sense, the former methodology seems to be more complete. We will compare the results and present both predictions.

The projection of transport work related to energy products' transportation are based on energy consumption projections from IIASA, Clarksons (2020) historical transport work data and Comtrade data by ship type and region (for Oil Tankers, Gas Tankers and Coal Bulk Carriers). Using UN Comtrade data by region is an improvement in relation to the method utilized in the Third IMO GHG Study to project transport work for ships that transport energy products, since it permits to consider heterogeneity by regions related to maritime transportation demand.

C.3.1 Alternative 1 – Project transport work from a gravity equation – ships that transport non-energy products

The transport work demand can be estimated by using trade models. The model estimate (and project) demand in specific markets and countries using regionally disaggregated data (e.g. it is possible to use country's GDP per capita growth and population to project trade flows).

The main reference for trade models is the **gravity model**[2] (Korinek & Sourdin, 2009).

[2] The gravity equation derives from the Newton's law of universal gravitation, under which the attraction force between two masses is proportional to the product of the two masses and inversely proportional to the square

As mentioned by Korinek and Sourdin (2009), Clark et al. (2004) and Limão and Venables (2001) the distance in the traditional gravity models represents a proxy to the transport costs. The improvement of the databases available allowed a deployment in the non-artificial trade barrier component, since the distance has been replaced for a set of elements such as the transport costs and geographical factors. Based on the academic discussion, an **augmented gravity model** can be estimated to project trade flows between an exporter country i and an importer country j concerning the commodity k in year t ($\boldsymbol{TF_{kijt}}$)[3] transported by the sea (m: maritime transport). This variable can represent both export and import values: i) when aggregating trade flows by exporter countries i, we obtain exports value in a given year; and, ii) in the same way, when aggregating the trade flow variable by the importer countries j, we obtain imports value in a specific year.

Korinek and Sourdin (2009) using a panel database for OECD countries, expanded the gravity model including a set of geographical and historical variables and specific effects, such as indicators of early colonial relationship between the countries, or common language between them, as well as variables that describe the existence of regional trade agreement between the trade partners. To simplify the model but still control for those important variables, we follow Kabir et al. (2017) and include origin-destination fixed effects, as well as year fixed effects in the model.

Alternative 2 – Project transport work from a reduced form time series approach

This is the same approach as employed in the Third IMO GHG Study. It has been described above.

C.4 Recommendations

We recommend to supplement the method to transport work employed in the Third IMO GHG Study with a gravity model approach, as described above as Alternative 1.

The results of both methods will be compared and differences analysed. Depending on the differences, the consortium may either decide to have separate projections that represent a band of uncertainty stemming from the method choice, or, when the differences are small, conclude that the projections are robust.

The method to project emissions from transport work will be identical to the Third IMO GHG Study, although the MACC will be updated.

C.5 References

Clark, X.; Dollar, D.; Micco, A. Port efficiency, maritime transport costs, and bilateral trade. **Journal of Development Economics**, 2004.

Korinek, Jane; Sourdin, Patricia. Maritime transport costs and their impact on trade, 2009.

Lee, T.C.; Chang, Y.T.; Lee, P.T.W. Economy-wide impact analysis of a carbon tax on international container shipping. **Transportation Research Part A: Policy and Practice**, v. 58, p. 87-102, 2013.

of the distance between them. Similarly, a country imports from a specific exporter are taken as proportional to the product of the two countries' GDP and inversely proportional to the square of the distance.

[3] It is interesting to analyse the "mode of transport" dimension in this analysis.

Limão, N.; Venables, A. J. Infrastructure, geographical disadvantage, transport costs, and trade. **The World Bank Economic Review**, 2001.

Sheng, Y.; Shi, X.; Su, B. Re-analyzing the Economic Impact of a Global Bunker Emissions Charge. **Energy Economics**, 2018.

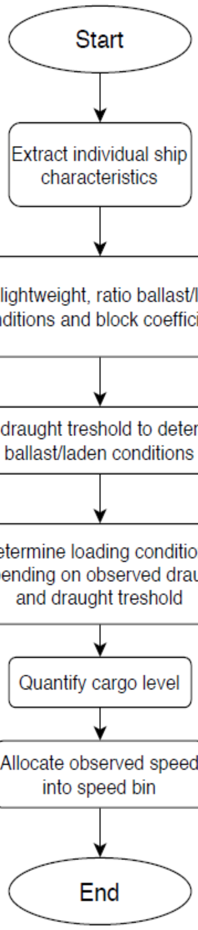
Tavasszy, L.; Harmsen, J.; Ivanova, O.; Bulavskaya, T. Effect of a full internalization of external costs of global supply chains on production, trade and transport. **Transport Research Arena**, Paris, v. 7, 2014.

D Method to estimate cargo tonne-miles

This section provides more detail on the method applied to estimate cargo.

The basis for the methodology for cargo estimation presented in this document were first developed for the IMO 64 MEPC annual meeting in March 2015 by Smith et al. (2015) as requested by the IMO secretariat. From that document, the only changes here included are a detailed description of the equations and a new methodology to estimate fuel capacity in ships. Apart from these, Smith et al. (2015) should still be referred as the core reference for cargo estimation.

The following graph summarises the steps followed by the algorithm for the estimation of cargo.



D.1 Ship mass and buoyancy equilibrium (core equations)

The governing principle to estimate a ship's cargo is the equilibrium between the ship's total mass and water's counteracting buoyancy force, which is described by Equation 1:

$$m_T = \rho * V \qquad \textit{Equation 1}$$

Where m_T is the ship's total mass, ρ is the seawater's density and *V* is the volumetric displacement of the ship. The ship's total mass (m_T) can be estimated as well as the addition of the vessel's lightweight tonnage (lwt) and its variable mass due to the different operational/voyage conditions (m_{var}):

$$m_T = lwt + m_{var} \qquad \textit{Equation 2}$$

Similarly, for the right side of *Equation 1*, the density of seawater ρ is assumed constant at 1025 kg/m^3, while changes in the volumetric displacement of the ship can be estimated from the geometry of the hull and the variation of the operational draught (T_{op}), as defined by the following equation:

$$\rho * V = C_{b,op} * L * B * T_{op} * \rho \qquad \textit{Equation 3}$$

Where T_{op} is the instantaneous draught, $C_{b,op}$ is the instantaneous block coefficient, L is the ship's length (approximated as the length in the loaded condition) and B is for the ship's beam (approximated as the beam in the loaded condition). Therefore, Equation 2 and Equation 3 are combined to calculate m_{var} as follows:

$$mvar = C_{b,op} * L * B * T_{op} * \rho - lwt \qquad \textit{Equation 4}$$

All variable loads (cargo, fuel, ballast water and consumables) are included in m_{var}. So, in order to estimate the ship's cargo (m_{cargo}), m_{var} needs to be decomposed in its parts and rearranged for m_{cargo}:

$$m_{cargo} = m_{var} - m_{ballast} - m_{fuel} \qquad \textit{Equation 5}$$

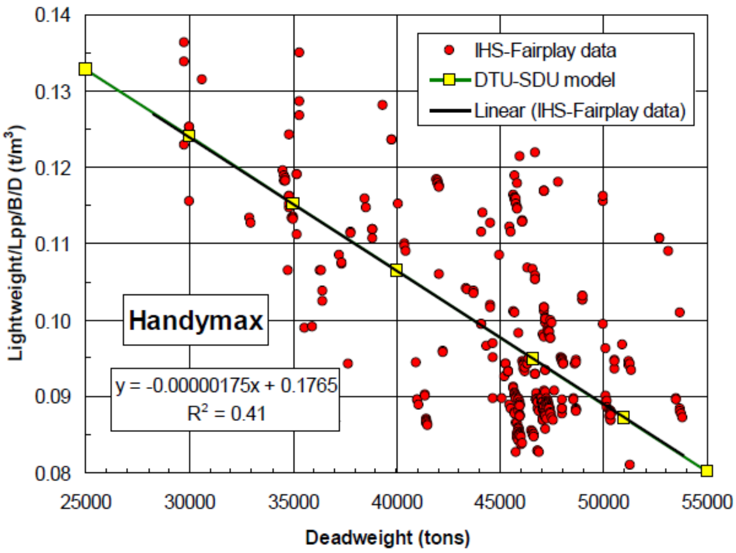
Where $m_{ballast}$ is the ballast mass and m_{fuel} is the mass of fuel being carried by the ship.

The 4th IMO GHG data set on the fleet technical specifications (based on IHS database) and processed AIS data provide some of the variables required to estimate m_{cargo}: voyage specific operational draught (T_{op}), length (*L*) and beam (*B*). However, the instantaneous block coefficient ($C_{b,op}$), lightweight (lwt), ballast mass ($m_{ballast}$) and fuel mass (m_{fuel}) still need to be calculated. In the following subsections, the method to calculate the missing variables will be explained in more detail.

D.2 Lightweight estimation

The work from Kristensen (2012) and Lutzen & Kristensen (2013) was used to estimate the ship's lightweight. In these reports, they demonstrated, through aggregating the IHS database by vessel type and size, that the ship lightweight on tankers and bulk carriers can be inferred based in the ship deadweight (*DWT*), while for containerships the TEU capacity was used. As an example, the figure below shows the regression obtained for a Handymax tanker (25000-50000 *DWT*) with the resulting equation for lightweight is given by Equation 6.

Figure 9 -Lightweight regression as function of DWT for Handymax tankers



Source: (Kristensen, 2012).

$$lwt = L * B * T_{des} * 1.05 * (0.1765 - 0.00000174 * DWT) \qquad \textit{Equation 6}$$

Where T_{des} refers to the ship's design draught at full payload. Similarly, for chemical and LNG tankers the results presented by Anik & Krikke (2011) and Chądzyński (2010) were used respectively. For the remaining ship types, lightweight was estimated by assuming the "at design" state (i.e. m_{var} = *DWT*). This results on Figure 9 adopting the following form to solve for lightweight:

$$lwt = C_{b,des} * L * B * T_{des} - DWT \qquad \textit{Equation 7}$$

Where $C_{b,des}$ is the design block coefficient, calculated directly from the Froude number - explained in more detail in the next subsection*Equation 9*.

D.3 Instantaneous block coefficient estimation

To find the instantaneous bloc coefficient (*Cb,op*) the Riddlesworth's method (MAN Diesel & Turbo 2011) was used assuming that the beam and waterline length stay constant:

$$C_{b,op} = 1 - \left[(1 - C_{b,des}) \left(\frac{T_{des}}{T_{op}} \right)^{\frac{1}{3}} \right] \qquad \textit{Equation 8}$$

The design block coefficient ($C_{b,des}$) is calculated from Equation 7 when lightweight is known. For the cases where lightweight is not available, $C_{b,des}$ can be obtained using the ship's Froude number (*Fn*) as per the Townsin's equation:

$$C_{b,design} = 0.7 + \left(\frac{1}{8} \operatorname{atan} \left(\frac{(23 - 100Fn)}{4} \right) \right) \qquad \textit{Equation 9}$$

The Froude number can be calculated as follow:

$$Fn = \frac{(0.5144 * v_{des})}{\sqrt{9.81 * L}}$$ *Equation 10*

Where v_{des} is the ship design speed given in knots.

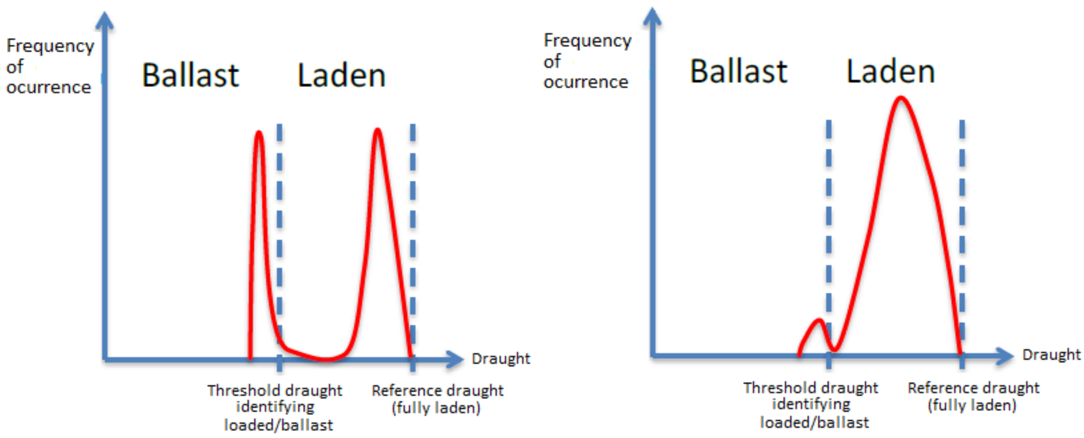
D.4 Estimating ballast mass

Identifying ballast voyages

A first step to estimate the ballast mass is to identify ballast and laden voyages. This was achieved by making use of operational draught to profile the loading level at which vessels are either loaded, partially loaded or in ballast. In order to differentiate between these different loading modes, the methodology defines two main profiles:

1. Ships that operate part of the time loaded and part of the time in ballast (Category 1 in Figure 10.
2. Ships that operate most of the time between part-loaded and fully loaded (Category 2 in Figure 10.

Figure 10 - Representative draught histograms for category 1 (left) and category 2 (right) ship types



As seen in Figure 10, the first category of ships have clearly identifiable peaks in the frequency of occurrence, which can be related to their specific laden and ballast draughts. These are ships that due to the nature of their trade are more likely to load and unload in specific regions, with a resulting inevitable ballast voyage. For the second category of ships these two peaks are not as clear, thus is harder to identify a ballast legs. In some cases, this is because they operate in either loaded or partially loaded mode nearly at all times (e.g. container ships and ferries).

Smith, Prakash, Aldous, & Krammer (2015), suggested a methodology to identify loading modes for these two categories. For category 1 vessels, the frequency of draught histogram is obtained for each vessel. From these, the lower draught peak plus a 10% is assumed as its ballast threshold. For vessels were the lower peak cannot be identified, suitable thresholds per ship type and size are suggested in Table 8. These values were obtained by aggregating the results of vessels with suitable data and taking the median peak for clusters of ships of the same type and size.

Regarding the thresholds assumed for category 2 vessels, Smith et al. (2015) suggested the use of ratios between the mass of ballast water and the ship *DWT* as a percentage. The list of thresholds is also included in Table 8.

Table 8 - List of of default draughts used for Categories 1 and 2 ships for which no ballast draught peak is detected

Type	Size	Draught threshold (decimal % of reference draught)	Variable mass threshold (found from draught/mass relationship and expressed as % of dwt)
Bulk carrier	0-9999	0.6429	-
	10000-34999	0.6179	
	35000-59999	0.5476	
	60000-99999	0.5365	
	100000-199999	0.5201	
	200000-+	0.5247	
Chemical tanker	0-4999	-	0.32
	5000-9999		
	10000-19999		
	20000-+		
Container	0-999	-	0 (assumed always loaded with some TEUs)
	1000-1999		
	2000-2999		
	3000-4999		
	5000-7999		
	8000-11999		
	12000-14500		
	14500-+		
General cargo	0-4999	0.6479	-
	5000-9999	0.6477	
	10000-+	0.6219	
Liquefied gas tanker	0-49999	0.6109	-
	50000-199999	0.6610	
	200000-+	0.6931	
Oil tanker	0-4999	0.6634	-
	5000-9999	0.6604	
	10000-19999	0.6153	
	20000-59999	0.6305	
	60000-79999	0.5844	
	80000-119999	0.5714	
	120000-199999	0.5510	
	200000-+	0.5206	
Refrigerated bulk	0-1999	-	0.33

Estimating fuel mass

In order to estimate the fuel mass per fuel type, the fuel capacity fields within the IHS data set were used. Although not available for all ships, a sample of 65,749 out of 188,220 vessels was used with a main fuel type distribution shown in Table 9.

Table 9 - Number of vessels available in the IHS dataset with reported tank capacity.

Fuel type	Number of vessels
Distillate fuel	25,100
LNG	340
Residual Fuel	40,309
Methanol	0

Only ships with reported fuel type, deadweight and fuel capacity were kept from the original data set. Electric, coal, non-propelled and nuclear-powered vessels were also removed.

s capacity is reported in cubic meters (V_{fuel}), the densities (ρ_{fuel}) shown in Table 10 were used to identify the proportion of fuel capacity mass to deadweight for each vessel (δ):

$$\delta = \frac{V_{fuel} * \rho_{fuel}}{DWT} \qquad \textit{Equation 11}$$

Table 10 - Densities per fuel type used for analysis (Calleya et al. 2016).

Fuel type	Density
HFO (Residual fuel)	1.001 tonne/m^3 (mean)
MDO (Distillate fuel)	0.895 tonne/m^3 (mean)
LNG (Gas Boil off, LNG)	0.450 tonne/m^3
Methanol	0.790 tonne/m^3

Outliers were removed by using a proportion for fuel capacity/dwt below or equal to 15%. This was a conservative threshold based on professional assessment. The resulting dataset included 47,478 ships across types and sizes. A statistics summary of the proportions is given in Table 11 while Figure 11 shows the range of the values for δ in a box plot and Figure 12 gives the distribution of δ for all observations within the 0.15 threshold (i.e. in percentage 15%).

Table 11 - Heuristics of δ per fuel type.

Fuel type	Count (-)	Mean (t/dwt)	Std dev (t/dwt)	Min. (t/dwt)	25% (t/dwt)	50% (t/dwt)	75% (t/dwt)	Max. (t/dwt)	Median (t/dwt)
Distillate Fuel	9,947	0.062	0.035	0.0002	0.035	0.053	0.082	0.149	0.053
LNG	337	0.036	0.013	0.006	0.027	0.036	0.041	0.1028	0.036
Residual Fuel	37,194	0.061	0.030	0.0009	0.037	0.053	0.08	0.149	0.053

Figure 11 - Box plot distribution of δ per fuel type.

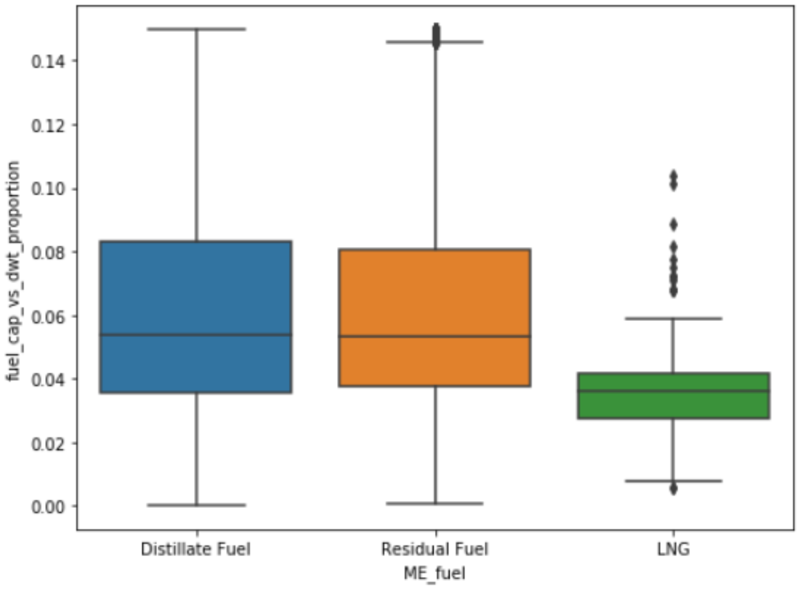
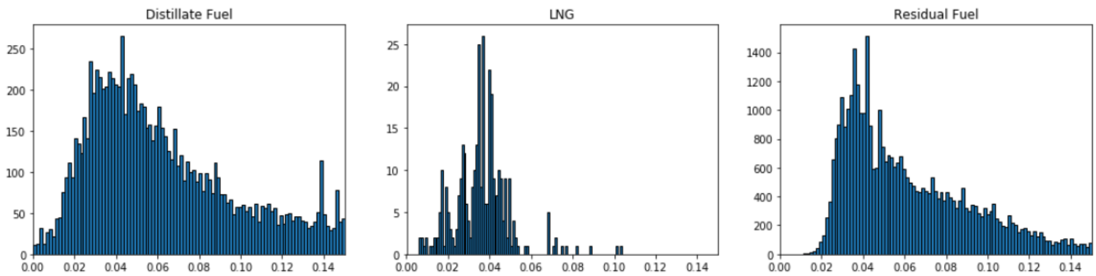


Figure 12 - Histogram of δ per fuel type up to the 0.15 threshold.



Methanol is not included in the study since the tank capacity in the IHS data set is not given for any of the 10 ships reported using this fuel. It was assumed then that δ for methanol ships was similar to that a ship powered by MDO due to their similar densities.

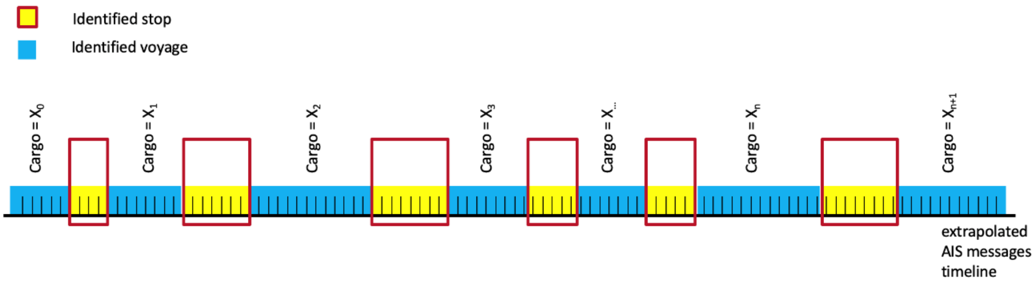
As seen in Table 11, ships carrying residual fuel (HFO) have a median δ of 0.053 and a mean δ of 0.061 with a standard deviation of 0.029. Similarly, ships using LNG have the same median and mean δ value of 0.035 with a standard deviation of 0.013, albeit the results only used a sample of 337 vessels. Finally, with a valid sample of 9,947 observations, distillate fuel vessels (MDO) have a median δ of 0.053 and a mean δ of 0.062 with a standard deviation of 0.035. For methanol the same values as with MDO will be used (i.e. a median δ of 0.053 and a mean δ of 0.062). Finally, for the 4[th] GHG methodology it was decided to use the median value as δ to find the fuel mass:

$$m_{fuel} = \delta * DWT \qquad \textit{Equation 12}$$

D.5 Estimated Cargo for Carbon Intensity Metrics

Once hourly cargo has been estimated for all vessels, it is aggregated on a per-voyage basis to estimate a total annual cargo mass or an average annual cargo mass. As cargo relies on voyage-specific draughts, each voyage has one unique cargo associated with it, while the start and the end of the year are considered individual voyages in this process. Figure 13 visualises the *n* identified voyages, where cargoes X_0 and X_{n+1} are associated with the start and end of the year.

Figure 13 - Methodology to obtain a unique cargo value per voyage



The aggregated voyage-specific cargo mass is then being used in the transport work and EEOI estimations as follows:

- Transport work in tnm

$$WD(tnm) = \sum_i cargo_i(t) * distance\_at\_sea_i(nm) \qquad \text{Equation 13}$$

Where $cargo_i$ - is a voyage specific cargo mass and $distance\_at\_sea_i$ is the distance travelled under laden conditions covering cruising and manoeuvring operations.

- Average payload utilisation in %

$$Payload\ utilisation(\%) = 100 * \frac{cargo_{avg}(t)}{dwt(t)} \qquad \text{Equation 14}$$

Where $cargo_{avg}$ - is an average voyage specific cargo mass based on a vessel's annual performance and dwt is a vessel's reported deadweight.

- Average payload utilisation in %

$$EEOI(\frac{gCO_2}{tnm}) = \frac{CO_2(g)}{WD(tnm)} \qquad \text{Equation 15}$$

Where CO_2 - is a total annual CO_2 emissions in grams emitted by a vessel and WD is work done in tnm as per the definition above.

D.6 Bibliography

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E Estimates on carbon intensity per ship type and size category, 2012-2017

Carbon intensity per ship type and size category in year 2012 (Option 1)

Ship type	Size category	Units	EEOI ($gCO_2/t.nm$)					AER ($gCO_2/dwt.nm$)					DIST ($kgCO_2/nm$)					TIME (tCO_2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	37.5	42.9	30.4	62.9	0.76	23.4	25.8	18.5	36.9	0.71	114.4	112.4	90.3	139.8	0.44	1.1	1.1	0.8	1.4	0.58
	10000-3499	dwt	13.6	13.5	11.3	18.3	0.52	8.2	8.0	7.2	9.5	0.29	219.9	218.2	192.9	248.8	0.26	2.5	2.5	2.1	3.0	0.33
	35000-5999	dwt	10.3	10.3	8.6	13.2	0.45	5.7	5.7	5.1	6.5	0.23	284.3	286.1	255.2	317.0	0.22	3.4	3.4	3.0	3.9	0.27
	60000-9999	dwt	8.9	9.0	7.6	11.1	0.38	4.4	4.4	4.0	4.9	0.21	343.2	336.2	304.5	384.0	0.24	4.1	4.1	3.6	4.7	0.27
	100000-199	dwt	6.0	6.0	5.1	7.1	0.33	3.0	3.0	2.7	3.3	0.20	505.9	505.8	442.7	562.1	0.24	6.0	6.0	5.1	6.9	0.30
	200000-+	dwt	5.1	5.4	4.3	6.3	0.38	2.6	2.6	2.3	3.0	0.26	649.3	631.0	549.3	728.8	0.28	8.0	7.7	6.6	9.4	0.37
Chemical tanker	0-4999	dwt	63.1	68.1	46.2	118.9	1.07	49.4	54.1	35.5	97.1	1.14	143.1	140.9	110.7	201.1	0.64	1.5	1.4	1.2	1.9	0.54
	5000-9999	dwt	38.6	39.4	32.7	50.1	0.44	27.8	28.2	23.4	36.2	0.45	205.9	203.3	176.6	245.9	0.34	2.3	2.2	1.9	2.7	0.35
	10000-1999	dwt	25.0	26.5	21.6	32.5	0.41	17.5	18.1	15.1	21.8	0.37	268.8	268.1	232.3	320.3	0.33	3.2	3.2	2.8	3.8	0.33
	20000-3999	dwt	17.1	17.2	14.9	19.8	0.28	11.8	11.6	10.3	13.9	0.31	379.3	378.0	335.7	434.9	0.26	4.8	4.8	4.2	5.5	0.28
	40000-+	dwt	13.6	13.6	11.9	15.9	0.29	8.3	8.4	7.5	9.4	0.22	401.9	398.0	364.2	440.2	0.19	5.0	5.0	4.5	5.6	0.23
Container	0-999	teu	35.5	36.9	30.7	46.6	0.43	23.6	24.4	20.6	30.1	0.39	217.3	218.1	184.7	254.6	0.32	2.8	2.8	2.1	3.5	0.50
	1000-1999	teu	27.7	28.5	24.3	33.7	0.33	17.3	17.9	15.5	20.8	0.30	341.5	337.6	294.5	390.9	0.29	4.8	4.8	4.0	5.8	0.37
	2000-2999	teu	21.3	20.5	18.0	25.0	0.34	12.5	12.1	10.6	14.1	0.29	441.4	428.0	381.8	485.7	0.24	6.6	6.5	5.4	7.8	0.37
	3000-4999	teu	18.5	18.3	16.5	20.6	0.23	11.6	11.4	10.4	13.1	0.24	618.8	606.0	535.4	692.3	0.26	10.1	9.9	8.3	11.8	0.35
	5000-7999	teu	17.2	17.1	15.4	19.0	0.21	10.6	10.4	9.4	11.5	0.20	784.9	775.0	703.6	845.4	0.18	13.0	12.9	11.3	14.5	0.25
	8000-11999	teu	14.0	13.9	12.7	15.4	0.20	8.3	8.5	7.5	9.3	0.21	901.7	908.8	822.6	987.4	0.18	15.0	15.1	13.2	17.0	0.25
	12000-1449	teu	11.1	11.1	10.0	12.2	0.19	6.8	6.7	6.1	7.7	0.23	1023.6	1026.7	953.1	1142.5	0.18	16.8	16.4	14.7	19.4	0.28
	14500-1999	teu	7.1	7.0	6.8	7.3	0.08	4.4	4.4	4.2	4.5	0.08	687.8	690.4	657.7	706.0	0.07	11.2	10.9	10.2	12.2	0.18
General cargo	0-4999	dwt	36.9	38.2	29.2	52.5	0.61	25.1	24.6	19.8	34.8	0.61	72.4	69.4	58.6	81.5	0.33	0.7	0.6	0.5	0.8	0.49
	5000-9999	dwt	31.2	31.6	25.7	41.0	0.48	19.4	19.4	16.6	23.0	0.33	139.3	132.9	113.6	158.2	0.34	1.4	1.4	1.1	1.7	0.49
	10000-1999	dwt	29.8	29.8	24.4	40.1	0.53	17.2	17.0	15.0	19.8	0.28	236.1	224.5	196.3	276.3	0.36	2.8	2.7	2.2	3.3	0.43
	20000-+	dwt	15.4	15.9	12.5	21.1	0.53	9.3	9.5	7.8	12.0	0.45	317.6	308.0	267.7	357.4	0.29	3.9	3.9	3.2	4.5	0.34
Liquefied gas tanker	0-49999	cbm	52.2	79.2	52.3	130.5	0.99	26.1	42.7	26.2	83.8	1.35	214.3	202.3	155.0	279.5	0.62	2.6	2.4	1.8	3.5	0.69
	50000-9999	cbm	19.5	20.0	16.3	25.3	0.45	10.1	9.9	9.1	11.1	0.20	522.5	517.1	485.9	570.6	0.16	7.5	7.6	7.0	8.1	0.14
	100000-199	cbm	16.9	16.4	14.3	19.8	0.33	12.1	11.7	10.2	13.7	0.30	951.5	929.2	814.7	1067.0	0.27	14.7	14.1	11.8	17.5	0.40
	200000-+	cbm	16.0	16.1	14.0	18.0	0.25	10.9	10.9	10.0	12.3	0.20	1325.0	1341.7	1248.5	1400.4	0.11	22.8	22.9	21.5	24.3	0.12
Oil tanker	0-4999	dwt	78.3	105.9	58.8	267.1	1.97	55.1	69.1	39.5	163.7	1.80	163.5	166.7	117.7	376.4	1.55	1.6	1.6	1.1	2.8	1.04
	5000-9999	dwt	54.6	65.0	40.4	126.2	1.32	33.6	33.8	26.1	65.4	1.16	225.3	225.2	172.4	416.3	1.08	2.2	2.4	1.6	3.3	0.72
	10000-1999	dwt	41.5	50.9	30.0	82.1	1.02	24.0	25.3	18.5	35.6	0.68	351.1	355.8	267.4	482.9	0.61	3.5	3.7	2.8	4.9	0.58
	20000-5999	dwt	25.1	26.1	19.4	40.6	0.81	10.6	10.4	8.7	13.5	0.47	465.6	454.1	398.0	554.4	0.34	5.6	5.5	4.8	6.5	0.31
	60000-7999	dwt	16.5	16.3	13.3	22.6	0.57	7.1	7.0	6.0	8.2	0.31	516.3	505.5	443.1	587.3	0.29	6.3	6.2	5.5	7.4	0.31
	80000-1199	dwt	13.0	13.4	10.4	18.7	0.61	5.2	5.1	4.5	6.0	0.30	561.4	550.4	489.0	637.8	0.27	6.6	6.6	5.7	7.7	0.30
	120000-199	dwt	10.5	10.1	8.3	15.0	0.66	4.3	4.2	3.7	4.9	0.28	675.6	654.8	589.2	763.6	0.27	8.0	7.9	6.8	9.3	0.31
	200000-+	dwt	5.6	5.7	4.7	6.9	0.40	2.8	2.7	2.4	3.1	0.23	850.8	840.3	738.4	941.3	0.24	10.6	10.3	8.8	12.4	0.35

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	1487.2	1598.2	1450.8	1745.5	0.18	1395.0	1499.1	1360.9	1637.3	0.18	979.2	1004.5	960.7	1048.2	0.09	7.6	7.5	7.5	7.6	0.03
	1000-+	dwt	38.4	93.8	34.9	154.5	1.28	19.8	60.1	18.8	128.6	1.83	360.9	297.0	179.9	466.9	0.97	4.5	4.2	2.0	6.2	1.00
Ferry-pax only	2000-+	gt	140.2	165.0	123.3	347.0	1.36	109.6	116.1	99.3	323.0	1.93	243.7	208.7	133.4	360.6	1.09	3.3	2.4	1.5	5.6	1.71
Cruise	0-1999	gt	879.2	1214.3	721.1	1804.9	0.89	795.3	1041.7	614.2	1662.9	1.01	263.7	272.2	188.9	364.3	0.64	2.5	2.5	1.8	3.5	0.67
	2000-9999	gt	223.4	290.1	180.6	568.2	1.34	196.3	250.6	157.3	500.2	1.37	184.4	184.4	137.1	246.5	0.59	1.8	1.9	1.4	2.4	0.50
	10000-5999	gt	142.9	160.1	107.0	229.4	0.76	127.7	145.5	97.9	197.7	0.69	549.8	514.4	464.1	645.7	0.35	7.7	7.4	6.5	9.0	0.33
	60000-9999	gt	163.5	166.0	142.3	190.4	0.29	145.7	151.3	127.0	169.1	0.28	1202.6	1203.6	1117.7	1304.8	0.16	18.9	19.4	16.5	21.6	0.26
	100000-149	gt	147.5	158.1	125.4	170.1	0.28	131.2	143.2	117.3	156.0	0.27	1435.6	1396.8	1318.9	1547.4	0.16	24.0	23.6	22.2	25.5	0.14
	150000-+	gt	115.0	143.1	92.8	156.4	0.44	103.5	131.6	87.1	135.2	0.37	1429.7	1441.3	1438.4	1442.4	0.00	23.3	22.9	22.4	23.2	0.03
Ferry-RoPax	2000-4999	gt	299.8	405.7	245.6	736.0	1.21	211.0	251.9	179.3	436.4	1.02	186.7	185.5	150.4	245.9	0.51	2.3	2.2	1.6	3.1	0.67
	5000-9999	gt	267.2	347.2	199.8	805.3	1.74	185.0	253.6	115.6	507.2	1.54	325.8	339.2	259.3	419.8	0.47	5.1	4.7	3.3	8.6	1.11
	10000-1999	gt	162.3	183.5	113.6	312.2	1.08	117.9	122.3	91.3	212.7	0.99	499.5	457.8	368.7	604.0	0.51	8.1	7.3	5.3	10.1	0.66
	20000-+	gt	149.0	151.0	107.2	218.6	0.74	110.0	111.8	75.1	160.6	0.76	719.2	681.4	551.0	851.0	0.44	12.7	11.8	9.0	16.0	0.59
Refrigerated bulk	0-1999	dwt	167.1	186.5	123.4	308.1	0.99	137.0	152.7	100.6	257.4	1.03	164.7	169.2	131.9	241.0	0.64	1.5	1.6	1.2	2.1	0.55
	2000-5999	dwt	99.6	106.7	81.8	153.5	0.67	68.2	70.2	55.2	102.3	0.67	268.1	275.8	219.0	350.5	0.48	3.1	3.2	2.6	4.1	0.47
	6000-9999	dwt	75.9	76.1	64.7	105.2	0.53	44.2	45.0	38.9	57.4	0.41	337.1	340.6	292.8	401.8	0.32	4.8	4.9	4.1	5.8	0.34
	10000-+	dwt	62.0	62.1	54.0	81.3	0.44	36.4	36.8	32.5	42.1	0.26	453.1	436.9	401.0	495.5	0.22	7.7	7.4	6.6	8.7	0.29
Ro-Ro	0-4999	dwt	128.6	220.4	105.2	464.1	1.63	93.1	151.0	72.9	314.9	1.60	225.8	235.8	167.2	359.7	0.82	2.0	1.9	1.3	3.2	1.01
	5000-9999	dwt	70.0	70.9	54.0	97.6	0.61	49.0	48.7	37.7	65.5	0.57	347.4	337.4	256.4	423.5	0.50	4.8	4.5	3.1	6.3	0.73
	10000-1499	dwt	55.2	54.7	43.8	76.0	0.59	36.5	38.5	29.8	45.7	0.41	447.5	464.0	370.4	521.3	0.33	6.7	6.6	5.2	8.9	0.55
	15000-+	dwt	30.6	29.4	21.9	47.4	0.87	21.2	21.8	15.1	29.8	0.67	557.2	533.3	421.9	643.6	0.42	8.5	8.1	6.3	10.2	0.48
Vehicle	0-29999	gt	137.4	145.1	114.6	193.0	0.54	47.8	54.2	37.8	69.2	0.58	272.1	256.2	203.0	311.5	0.42	3.9	3.6	2.7	4.8	0.59
	30000-4999	gt	71.3	70.0	61.9	83.4	0.31	21.3	21.2	19.2	24.6	0.25	298.1	293.7	270.8	317.7	0.16	4.5	4.5	4.1	5.0	0.20
	50000-+	gt	60.0	61.0	51.7	72.1	0.33	16.7	17.1	15.4	19.2	0.22	358.4	349.4	328.1	379.0	0.15	5.8	5.6	5.2	6.2	0.17

Carbon intensity per ship type and size category in year 2013 (Option 1)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	37.5	43.5	31.1	60.9	0.68	23.4	27.0	18.6	36.6	0.67	112.6	109.6	90.8	135.6	0.41	1.1	1.1	0.8	1.4	0.54
	10000-3499	dwt	13.2	13.2	11.1	17.5	0.49	7.9	7.8	7.0	9.4	0.31	215.2	213.2	190.5	238.9	0.23	2.4	2.4	2.1	2.8	0.30
	35000-5999	dwt	9.9	9.9	8.4	12.5	0.42	5.5	5.5	5.0	6.3	0.24	276.6	279.5	250.4	307.8	0.21	3.2	3.2	2.8	3.7	0.26
	60000-9999	dwt	8.9	8.9	7.6	11.0	0.38	4.3	4.2	3.9	4.8	0.21	333.3	327.0	296.7	374.8	0.24	3.9	3.8	3.4	4.4	0.27
	100000-199	dwt	5.7	5.6	4.9	6.6	0.30	2.9	2.9	2.6	3.2	0.22	484.8	481.7	423.9	540.0	0.24	5.5	5.5	4.6	6.4	0.33
	200000-+	dwt	4.9	5.1	4.2	6.0	0.34	2.5	2.5	2.2	2.8	0.22	624.1	599.5	537.0	706.9	0.28	7.5	7.2	6.3	8.8	0.35
Chemical tanker	0-4999	dwt	65.3	74.0	46.6	130.6	1.13	51.8	59.1	36.2	103.9	1.15	147.3	144.2	114.4	209.4	0.66	1.5	1.5	1.2	2.0	0.56
	5000-9999	dwt	38.9	39.7	33.0	50.4	0.44	28.4	28.8	23.8	36.6	0.44	210.3	207.2	180.5	247.1	0.32	2.3	2.3	1.9	2.8	0.36
	10000-1999	dwt	25.2	27.0	21.7	33.1	0.43	17.9	18.5	15.3	22.3	0.38	274.0	272.5	235.5	324.8	0.33	3.2	3.2	2.7	3.8	0.34
	20000-3999	dwt	17.1	17.1	14.9	20.0	0.30	11.9	11.7	10.4	13.8	0.29	381.1	383.1	340.0	432.2	0.24	4.7	4.8	4.1	5.4	0.26
	40000-+	dwt	13.5	13.5	12.0	15.9	0.29	8.2	8.4	7.4	9.6	0.27	397.5	398.4	360.9	445.1	0.21	4.9	4.9	4.4	5.6	0.25
Container	0-999	teu	35.2	36.7	29.9	46.1	0.44	23.5	24.1	20.3	30.3	0.42	215.3	216.1	182.8	248.3	0.30	2.7	2.7	2.1	3.4	0.48
	1000-1999	teu	27.3	28.0	24.0	32.9	0.32	17.1	17.7	15.0	20.8	0.32	335.9	329.5	291.2	378.4	0.26	4.7	4.6	3.9	5.4	0.34
	2000-2999	teu	20.3	19.5	17.0	22.8	0.30	11.9	11.4	10.0	13.2	0.29	418.9	402.2	354.9	454.6	0.25	6.1	5.8	4.7	7.0	0.39
	3000-4999	teu	17.7	17.6	15.6	20.1	0.25	11.1	11.0	9.8	12.3	0.23	590.0	576.7	508.6	665.5	0.27	9.1	9.1	7.6	10.8	0.36
	5000-7999	teu	16.6	16.6	14.9	18.5	0.21	10.2	10.0	9.1	11.3	0.21	757.9	756.7	680.6	828.0	0.19	12.2	12.3	10.7	13.9	0.26
	8000-11999	teu	13.4	13.4	12.2	14.7	0.19	8.1	8.1	7.5	8.9	0.18	873.3	872.0	807.8	955.8	0.17	14.1	14.0	12.6	15.9	0.24
	12000-1449	teu	10.6	10.4	9.7	11.8	0.20	6.6	6.6	6.0	7.4	0.22	995.0	1011.2	914.4	1129.2	0.21	15.7	15.9	14.0	18.7	0.30
	14500-1999	teu	7.3	7.0	6.9	8.3	0.19	4.1	4.4	4.2	4.6	0.10	694.2	724.9	686.7	782.8	0.13	11.7	11.8	11.4	13.5	0.18
General cargo	0-4999	dwt	36.9	38.6	29.6	53.2	0.61	25.2	24.9	19.7	37.0	0.69	71.4	69.4	58.4	81.3	0.33	0.6	0.6	0.5	0.8	0.47
	5000-9999	dwt	31.3	31.8	26.0	41.2	0.48	19.4	19.4	16.5	23.1	0.34	138.3	133.2	113.2	158.3	0.34	1.4	1.3	1.0	1.7	0.49
	10000-1999	dwt	29.4	29.5	24.5	37.2	0.43	17.1	16.8	15.0	19.5	0.27	233.3	223.1	194.3	272.0	0.35	2.7	2.6	2.2	3.3	0.41
	20000-+	dwt	14.9	15.1	12.2	19.8	0.50	8.9	9.2	7.6	11.6	0.44	312.3	302.3	262.5	348.3	0.28	3.8	3.7	3.1	4.3	0.32
Liquefied gas tanker	0-49999	cbm	55.4	79.5	53.8	132.4	0.99	28.0	43.8	27.6	85.6	1.32	219.5	210.5	163.6	283.4	0.57	2.6	2.5	1.8	3.5	0.68
	50000-9999	cbm	20.6	21.4	17.8	26.7	0.41	10.1	9.9	9.0	11.1	0.22	523.3	508.6	481.8	575.7	0.18	7.4	7.3	6.8	8.2	0.19
	100000-199	cbm	16.8	16.6	13.7	19.8	0.36	11.7	11.4	9.7	13.5	0.33	926.9	905.7	784.5	1059.3	0.30	14.1	13.7	10.6	17.0	0.46
	200000-+	cbm	16.7	16.4	15.0	19.0	0.24	10.8	10.9	9.8	12.2	0.22	1309.5	1316.1	1227.6	1347.6	0.09	22.4	22.7	20.7	23.5	0.12
Oil tanker	0-4999	dwt	81.9	108.6	58.8	263.5	1.88	57.3	70.4	39.9	169.7	1.84	166.6	174.8	120.3	368.0	1.42	1.6	1.6	1.1	2.8	1.04
	5000-9999	dwt	55.4	65.7	42.0	131.7	1.37	34.5	34.9	26.9	59.9	0.95	232.1	229.9	177.5	394.3	0.94	2.2	2.3	1.7	3.3	0.72
	10000-1999	dwt	43.1	49.3	32.6	79.1	0.94	24.3	26.3	19.4	35.2	0.60	352.6	361.5	282.6	519.9	0.66	3.6	3.8	2.8	5.1	0.60
	20000-5999	dwt	25.9	26.3	20.3	39.0	0.71	10.9	10.4	8.8	14.4	0.53	481.5	458.3	407.7	560.3	0.33	5.6	5.5	4.8	6.6	0.33
	60000-7999	dwt	16.8	16.7	13.5	22.0	0.51	7.4	7.2	6.4	8.4	0.28	537.3	517.8	461.6	599.2	0.27	6.5	6.3	5.6	7.3	0.27
	80000-1199	dwt	13.1	13.3	10.6	18.1	0.56	5.2	5.1	4.5	6.1	0.30	568.2	552.7	492.9	648.2	0.28	6.5	6.4	5.6	7.5	0.29
	120000-199	dwt	10.1	9.6	8.0	12.9	0.52	4.4	4.1	3.7	4.9	0.29	683.6	649.2	582.0	749.9	0.26	7.8	7.6	6.5	9.0	0.32
	200000-+	dwt	5.6	5.7	4.7	6.8	0.38	2.7	2.7	2.4	3.0	0.24	837.1	816.7	722.2	921.3	0.24	10.1	9.7	8.2	11.7	0.36

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	446.7	1115.4	613.3	1132.3	0.47	342.3	749.7	417.2	913.8	0.66	179.1	323.4	185.0	442.8	0.80	1.7	2.5	1.5	3.6	0.85
	1000-+	dwt	30.3	92.2	32.7	489.0	4.95	20.2	68.8	18.9	251.3	3.38	406.5	367.2	286.6	736.9	1.23	5.3	4.6	2.8	7.5	1.02
Ferry-pax only	2000-+	gt	140.2	171.8	108.3	405.8	1.73	112.5	119.0	98.6	328.5	1.93	232.6	187.2	139.0	287.6	0.79	3.0	2.0	1.5	3.7	1.12
Cruise	0-1999	gt	889.9	1403.6	728.1	1746.2	0.73	776.3	1316.5	567.9	1613.4	0.79	226.8	203.0	164.1	393.4	1.13	2.1	2.0	1.5	3.2	0.89
	2000-9999	gt	262.9	360.4	191.6	689.9	1.38	232.5	305.7	174.0	596.7	1.38	208.2	211.2	150.7	350.6	0.95	2.0	2.0	1.5	3.4	0.92
	10000-5999	gt	143.6	158.1	105.5	245.2	0.88	126.8	141.4	97.2	207.6	0.78	549.3	518.8	463.6	655.0	0.37	7.6	7.4	6.3	9.1	0.37
	60000-9999	gt	162.6	163.1	144.4	190.2	0.28	144.9	148.4	129.0	167.8	0.26	1196.7	1193.6	1111.4	1273.4	0.14	18.3	18.5	16.0	20.0	0.21
	100000-149	gt	145.7	155.8	126.0	162.2	0.23	127.5	133.5	117.1	148.4	0.23	1398.1	1383.5	1265.7	1531.9	0.19	22.9	22.3	20.2	25.3	0.23
	150000-+	gt	110.0	139.4	91.0	142.5	0.37	100.0	128.6	85.0	129.4	0.35	1384.9	1389.8	1369.5	1392.4	0.02	22.7	22.5	21.8	23.3	0.07
Ferry-RoPax	2000-4999	gt	312.2	422.5	254.7	837.1	1.38	217.8	263.7	187.9	443.7	0.97	199.4	205.7	157.4	254.1	0.47	2.5	2.3	1.8	3.1	0.58
	5000-9999	gt	234.4	335.6	170.4	617.8	1.33	171.3	237.6	115.8	429.8	1.32	320.6	349.8	255.3	429.3	0.50	4.9	4.7	3.0	7.5	0.95
	10000-1999	gt	159.1	173.2	115.1	321.4	1.19	117.4	124.0	90.9	212.5	0.98	492.0	468.3	365.4	613.5	0.53	7.9	7.1	5.3	10.0	0.67
	20000-+	gt	148.4	150.1	106.1	221.1	0.77	110.2	112.1	74.9	161.8	0.78	718.2	682.3	548.6	831.9	0.42	12.5	11.6	9.0	15.3	0.54
Refrigerated bulk	0-1999	dwt	180.1	203.5	142.3	418.4	1.36	140.4	165.2	105.1	272.4	1.01	171.0	173.2	131.5	240.3	0.63	1.6	1.6	1.2	2.2	0.61
	2000-5999	dwt	101.3	110.0	83.3	155.8	0.66	69.6	78.5	55.0	104.4	0.63	277.6	276.7	237.5	344.8	0.39	3.2	3.2	2.7	4.0	0.40
	6000-9999	dwt	73.7	76.6	66.2	91.5	0.33	42.9	44.6	38.0	52.9	0.33	328.3	331.5	293.3	383.8	0.27	4.8	4.8	4.1	5.7	0.33
	10000-+	dwt	62.1	63.2	54.3	77.4	0.36	35.8	36.6	31.8	41.6	0.27	446.7	436.3	401.4	479.4	0.18	7.5	7.3	6.5	8.2	0.23
Ro-Ro	0-4999	dwt	141.6	264.2	117.7	598.5	1.82	104.3	198.3	84.5	401.7	1.60	241.1	266.6	180.8	433.6	0.95	2.1	2.2	1.5	3.6	0.97
	5000-9999	dwt	69.3	66.4	53.4	89.6	0.55	48.2	47.0	36.7	62.4	0.55	340.3	324.0	254.4	416.2	0.50	4.6	4.2	2.8	6.2	0.81
	10000-1499	dwt	55.2	55.4	44.6	71.2	0.48	36.9	38.9	29.8	45.5	0.40	449.9	463.9	363.3	525.1	0.35	6.8	7.3	5.1	8.8	0.51
	15000-+	dwt	32.1	31.9	24.0	51.8	0.87	22.2	22.4	16.8	31.0	0.63	580.6	565.5	464.4	640.2	0.31	8.9	8.4	6.8	10.3	0.41
Vehicle	0-29999	gt	137.5	148.7	114.5	191.7	0.52	47.8	54.7	38.0	69.3	0.57	273.4	247.4	203.0	314.2	0.45	3.9	3.5	2.6	4.8	0.62
	30000-4999	gt	70.0	69.3	61.2	81.1	0.29	21.1	21.4	18.8	24.3	0.26	293.0	288.9	268.6	312.3	0.15	4.4	4.4	3.9	4.8	0.19
	50000-+	gt	59.2	60.5	50.7	71.5	0.34	16.4	17.0	15.2	18.8	0.21	350.1	344.8	321.7	372.8	0.15	5.5	5.5	5.0	6.0	0.18

Carbon intensity per ship type and size category in year 2014 (Option 1)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	38.5	44.5	31.9	65.3	0.75	23.7	27.1	18.9	38.6	0.73	113.3	112.3	90.3	139.0	0.43	1.1	1.1	0.8	1.4	0.58
	10000-3499	dwt	12.8	12.8	10.7	16.8	0.47	7.8	7.7	6.9	9.1	0.29	213.5	210.3	189.5	235.5	0.22	2.4	2.4	2.0	2.8	0.31
	35000-5999	dwt	9.3	9.4	8.0	11.4	0.37	5.5	5.5	4.9	6.2	0.23	274.3	275.6	249.7	303.3	0.19	3.1	3.2	2.8	3.5	0.24
	60000-9999	dwt	8.3	8.2	7.1	9.9	0.34	4.2	4.2	3.8	4.7	0.22	327.5	320.9	293.3	365.7	0.23	3.8	3.7	3.3	4.3	0.25
	100000-199	dwt	5.4	5.4	4.7	6.3	0.30	2.8	2.8	2.5	3.1	0.20	469.1	465.6	412.8	517.8	0.23	5.2	5.2	4.4	6.0	0.31
	200000-+	dwt	4.8	5.0	4.3	5.7	0.27	2.4	2.4	2.2	2.7	0.22	595.9	570.5	504.5	676.6	0.30	7.0	6.8	5.8	8.1	0.34
Chemical tanker	0-4999	dwt	68.3	77.5	48.5	140.2	1.18	54.2	62.4	37.8	113.1	1.21	156.2	152.0	120.1	227.6	0.71	1.6	1.5	1.2	2.1	0.61
	5000-9999	dwt	40.1	40.3	33.9	51.0	0.42	29.2	29.6	24.6	37.9	0.45	216.0	210.4	184.5	255.2	0.34	2.3	2.3	2.0	2.8	0.37
	10000-1999	dwt	25.7	27.2	21.9	33.7	0.44	18.2	18.7	15.5	22.8	0.39	279.2	278.2	240.6	330.4	0.32	3.2	3.3	2.8	3.8	0.31
	20000-3999	dwt	17.2	17.3	14.9	20.1	0.30	12.0	11.7	10.5	14.2	0.32	384.4	385.1	336.8	440.0	0.27	4.7	4.8	4.1	5.4	0.28
	40000-+	dwt	13.6	13.4	11.9	16.1	0.31	8.3	8.4	7.4	9.5	0.24	402.0	399.0	364.3	442.0	0.19	4.9	4.9	4.4	5.5	0.24
Container	0-999	teu	34.9	36.2	29.7	46.0	0.45	23.3	24.4	20.1	30.3	0.42	213.4	215.1	181.3	245.3	0.30	2.6	2.7	2.1	3.3	0.47
	1000-1999	teu	26.9	27.8	23.7	32.6	0.32	17.1	17.8	15.1	20.9	0.33	331.6	327.1	288.1	373.0	0.26	4.5	4.4	3.8	5.2	0.32
	2000-2999	teu	19.9	19.1	16.5	22.3	0.31	11.8	11.0	9.8	13.1	0.30	412.2	394.5	344.5	445.6	0.26	5.8	5.4	4.5	6.7	0.39
	3000-4999	teu	16.8	16.8	15.0	19.0	0.24	10.5	10.4	9.4	11.6	0.21	561.1	543.9	483.0	620.3	0.25	8.4	8.2	6.8	9.8	0.36
	5000-7999	teu	15.8	15.7	14.0	17.8	0.24	9.8	9.6	8.7	10.9	0.23	731.0	720.1	641.5	818.7	0.25	11.4	11.3	9.7	13.2	0.31
	8000-11999	teu	13.0	13.0	11.8	14.2	0.18	8.0	8.0	7.4	8.8	0.17	871.7	871.7	799.1	942.8	0.16	13.9	13.8	12.5	15.6	0.22
	12000-1449	teu	10.2	9.9	9.3	11.0	0.17	6.6	6.5	6.0	7.1	0.18	985.0	988.4	909.7	1046.6	0.14	15.6	15.6	14.2	17.1	0.19
	14500-1999	teu	7.6	7.7	7.1	9.2	0.27	4.7	4.9	4.6	5.2	0.13	828.7	939.1	728.4	1015.9	0.31	13.1	15.0	12.0	16.9	0.33
General cargo	0-4999	dwt	37.1	38.8	29.8	53.4	0.61	25.6	25.4	19.8	37.8	0.71	71.8	69.7	59.1	81.8	0.32	0.6	0.6	0.5	0.8	0.47
	5000-9999	dwt	31.1	31.6	25.8	40.6	0.47	19.4	19.5	16.5	23.3	0.35	138.6	133.4	113.9	159.2	0.34	1.4	1.3	1.0	1.7	0.48
	10000-1999	dwt	29.6	29.7	24.7	37.9	0.44	17.2	17.0	15.2	19.5	0.26	233.0	219.4	197.1	266.3	0.32	2.7	2.6	2.2	3.2	0.38
	20000-+	dwt	14.5	15.1	12.0	19.5	0.50	8.7	9.1	7.4	11.4	0.43	310.6	298.4	262.7	339.1	0.26	3.7	3.6	3.1	4.2	0.31
Liquefied gas tanker	0-49999	cbm	55.3	80.5	54.6	142.7	1.09	28.2	46.9	28.0	96.6	1.46	235.5	224.7	176.4	300.7	0.55	2.8	2.6	2.0	3.7	0.62
	50000-9999	cbm	20.8	21.6	18.3	25.5	0.33	10.1	9.9	9.2	11.3	0.21	525.2	515.4	480.0	583.0	0.20	7.6	7.6	7.1	8.4	0.17
	100000-199	cbm	16.3	16.1	13.4	19.6	0.39	11.2	10.8	9.5	12.6	0.29	894.4	860.7	771.9	1008.6	0.28	13.3	12.8	10.4	15.8	0.42
	200000-+	cbm	17.5	17.0	15.5	21.5	0.36	10.7	10.5	9.8	12.1	0.22	1303.2	1299.4	1222.7	1365.4	0.11	22.1	22.0	20.6	23.9	0.15
Oil tanker	0-4999	dwt	85.4	115.6	63.1	273.6	1.82	60.1	75.2	42.7	185.8	1.90	176.4	183.7	126.8	396.1	1.47	1.6	1.8	1.2	2.9	0.96
	5000-9999	dwt	58.9	67.9	45.7	148.3	1.51	36.9	36.5	28.6	75.2	1.28	247.1	241.2	187.2	479.1	1.21	2.4	2.4	1.7	3.9	0.88
	10000-1999	dwt	42.4	47.0	32.8	77.5	0.95	24.1	25.9	19.4	35.4	0.62	351.7	354.7	280.6	483.7	0.57	3.6	3.7	2.8	5.0	0.59
	20000-5999	dwt	26.5	26.8	20.5	38.5	0.67	11.3	10.7	9.1	14.3	0.48	496.4	468.7	419.3	565.1	0.31	5.8	5.6	4.9	6.5	0.30
	60000-7999	dwt	16.1	16.1	12.9	21.2	0.52	7.5	7.2	6.4	8.6	0.30	543.1	520.5	470.5	611.1	0.27	6.4	6.2	5.5	7.3	0.28
	80000-1199	dwt	13.0	12.8	10.5	17.3	0.53	5.4	5.2	4.6	6.2	0.32	585.4	563.3	498.8	667.5	0.30	6.6	6.4	5.6	7.6	0.31
	120000-199	dwt	9.9	9.3	7.8	12.5	0.51	4.4	4.1	3.7	4.9	0.28	680.9	639.6	581.9	753.9	0.27	7.8	7.4	6.6	8.9	0.31
	200000-+	dwt	5.5	5.6	4.6	6.6	0.35	2.7	2.6	2.3	3.0	0.25	831.7	800.2	714.3	929.8	0.27	9.8	9.5	8.0	11.5	0.37

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	611.2	1656.1	215.6	2179.3	1.19	434.9	965.6	195.6	2023.0	1.89	232.5	697.6	97.8	724.2	0.90	2.1	5.4	0.8	5.6	0.90
	1000-+	dwt	29.6	43.5	24.0	138.7	2.64	17.5	22.1	14.9	105.0	4.07	404.6	350.9	235.2	472.0	0.67	5.5	4.9	2.6	6.4	0.76
Ferry-pax only	2000-+	gt	140.2	144.6	108.0	328.6	1.53	112.4	109.6	96.8	230.2	1.22	235.8	189.1	136.7	303.1	0.88	3.0	2.0	1.6	4.0	1.19
Cruise	0-1999	gt	798.9	1282.9	872.0	1711.6	0.65	675.6	1174.7	531.3	1527.7	0.85	233.8	255.6	159.8	363.9	0.80	2.1	2.2	1.6	2.9	0.62
	2000-9999	gt	271.9	452.2	212.5	899.1	1.52	237.4	382.6	188.4	818.8	1.65	219.1	209.3	166.0	395.2	1.09	2.1	2.0	1.6	3.2	0.80
	10000-5999	gt	147.0	164.1	110.0	272.2	0.99	129.3	143.4	98.1	226.2	0.89	558.0	542.0	461.0	652.4	0.35	7.6	7.5	6.3	9.1	0.38
	60000-9999	gt	161.9	163.2	142.2	186.5	0.27	144.6	149.3	129.5	170.4	0.27	1195.9	1201.8	1121.7	1274.2	0.13	17.9	18.1	15.7	19.6	0.22
	100000-149	gt	141.4	149.5	123.8	158.8	0.23	126.5	131.0	111.8	148.8	0.28	1390.9	1378.1	1249.2	1477.7	0.17	22.3	22.3	20.4	24.5	0.19
	150000-+	gt	117.9	135.9	109.5	146.5	0.27	105.4	126.7	97.1	128.4	0.25	1439.9	1373.4	1346.4	1412.7	0.05	23.7	22.9	22.1	23.7	0.07
Ferry-RoPax	2000-4999	gt	318.3	408.6	255.9	763.7	1.24	233.0	265.0	182.4	431.5	0.94	198.6	201.6	155.1	272.2	0.58	2.4	2.3	1.6	3.3	0.71
	5000-9999	gt	247.6	317.5	184.7	586.1	1.26	173.7	248.9	110.1	405.1	1.19	324.5	326.4	265.0	446.0	0.55	4.9	4.7	3.2	7.8	0.99
	10000-1999	gt	162.3	187.3	119.4	308.8	1.01	121.6	128.2	95.7	213.7	0.92	501.3	473.3	386.0	602.2	0.46	8.1	7.2	5.7	9.9	0.59
	20000-+	gt	147.9	150.4	106.8	214.3	0.71	110.6	111.1	77.8	161.1	0.75	713.1	668.6	542.6	817.9	0.41	12.4	11.3	9.0	15.0	0.53
Refrigerated bulk	0-1999	dwt	199.8	216.7	138.4	503.2	1.68	152.6	170.1	106.3	419.7	1.84	190.8	188.4	148.5	303.7	0.82	1.8	1.7	1.4	2.7	0.77
	2000-5999	dwt	107.2	108.3	85.2	165.1	0.74	71.1	74.8	55.2	104.0	0.65	280.5	282.8	234.3	339.2	0.37	3.2	3.2	2.7	4.1	0.43
	6000-9999	dwt	71.3	74.3	64.2	87.1	0.31	42.7	44.8	38.2	54.7	0.37	328.1	336.1	297.9	384.0	0.26	4.7	4.6	4.1	5.4	0.29
	10000-+	dwt	61.2	65.6	53.0	78.5	0.39	36.0	36.4	32.0	41.8	0.27	447.8	434.2	403.4	470.1	0.15	7.4	7.3	6.4	8.2	0.24
Ro-Ro	0-4999	dwt	151.3	281.6	122.7	581.8	1.63	112.7	210.8	94.1	413.6	1.52	246.7	281.3	188.6	454.6	0.95	2.1	2.2	1.5	3.6	0.99
	5000-9999	dwt	69.2	64.4	55.1	88.7	0.52	49.8	45.4	39.2	62.8	0.52	350.5	327.5	260.5	415.8	0.47	4.9	4.4	2.9	6.3	0.78
	10000-1499	dwt	54.3	53.2	46.2	69.6	0.44	37.2	38.3	31.0	44.4	0.35	452.9	457.1	376.5	520.8	0.32	6.9	7.1	5.2	8.6	0.49
	15000-+	dwt	32.4	33.4	24.0	53.4	0.88	22.6	22.3	16.3	35.1	0.84	584.6	578.3	438.2	659.2	0.38	8.9	9.3	6.4	10.3	0.42
Vehicle	0-29999	gt	135.4	142.3	111.0	198.0	0.61	47.6	55.1	40.2	71.6	0.57	273.4	245.6	206.5	313.3	0.43	3.9	3.3	2.6	4.8	0.65
	30000-4999	gt	70.4	69.5	61.4	78.9	0.25	20.9	21.0	18.9	24.2	0.25	290.1	287.9	268.1	306.3	0.13	4.3	4.3	3.9	4.7	0.19
	50000-+	gt	58.3	58.7	49.9	71.5	0.37	16.3	16.6	15.1	18.6	0.21	344.7	337.6	316.3	363.9	0.14	5.4	5.3	4.8	5.8	0.18

Carbon intensity per ship type and size category in year 2015 (Option 1)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	39.8	46.9	33.1	71.7	0.82	24.4	28.2	19.3	43.1	0.85	115.5	114.1	93.4	145.6	0.46	1.1	1.1	0.8	1.5	0.59
	10000-3499	dwt	13.1	13.0	11.0	17.3	0.49	7.8	7.6	6.9	9.1	0.29	214.5	213.0	190.5	238.0	0.22	2.4	2.4	2.1	2.8	0.30
	35000-5999	dwt	9.4	9.4	8.1	11.3	0.35	5.5	5.6	5.0	6.2	0.22	274.6	275.9	250.0	305.5	0.20	3.2	3.2	2.8	3.6	0.24
	60000-9999	dwt	8.3	8.3	7.2	10.0	0.33	4.2	4.2	3.7	4.7	0.23	324.5	318.5	291.3	363.9	0.23	3.7	3.7	3.3	4.3	0.26
	100000-199	dwt	5.4	5.4	4.6	6.4	0.32	2.8	2.7	2.5	3.1	0.22	465.9	462.3	410.1	518.9	0.24	5.1	5.1	4.3	6.0	0.32
	200000-+	dwt	4.9	5.0	4.4	5.9	0.30	2.4	2.4	2.2	2.6	0.21	601.1	563.5	490.7	687.2	0.35	7.1	6.7	5.6	8.3	0.40
Chemical tanker	0-4999	dwt	67.9	78.5	47.6	141.8	1.20	54.9	63.8	37.9	118.0	1.25	157.7	151.9	122.4	231.0	0.71	1.6	1.5	1.3	2.1	0.55
	5000-9999	dwt	39.1	40.0	33.0	50.4	0.43	29.2	29.5	24.4	36.9	0.42	214.5	208.6	184.6	248.8	0.31	2.3	2.3	1.9	2.7	0.36
	10000-1999	dwt	25.7	26.9	21.9	33.9	0.44	18.4	18.9	15.6	23.2	0.40	282.7	280.0	242.7	336.2	0.33	3.3	3.3	2.8	3.9	0.31
	20000-3999	dwt	17.5	17.5	15.4	20.4	0.29	12.0	12.0	10.7	14.4	0.31	389.7	397.6	345.5	452.9	0.27	4.8	4.9	4.2	5.6	0.29
	40000-+	dwt	13.6	13.4	11.8	15.7	0.29	8.3	8.3	7.5	9.6	0.26	403.0	403.2	366.8	451.4	0.21	4.9	4.9	4.4	5.6	0.24
Container	0-999	teu	35.5	36.6	29.9	47.5	0.48	23.5	24.5	20.3	30.9	0.43	211.4	213.2	179.6	246.2	0.31	2.6	2.6	2.0	3.3	0.48
	1000-1999	teu	27.5	28.3	24.3	33.4	0.32	17.1	17.6	15.0	21.0	0.34	330.8	324.6	287.6	366.1	0.24	4.5	4.4	3.7	5.2	0.32
	2000-2999	teu	20.2	19.7	17.1	22.5	0.27	11.6	11.1	9.7	13.0	0.29	405.4	387.6	345.2	436.4	0.24	5.7	5.4	4.5	6.4	0.35
	3000-4999	teu	16.8	16.9	14.9	18.9	0.24	10.3	10.1	9.1	11.4	0.22	551.5	529.5	472.0	600.9	0.24	8.1	7.8	6.6	9.4	0.35
	5000-7999	teu	16.1	16.0	14.3	18.1	0.24	9.6	9.5	8.5	10.7	0.23	712.5	712.0	628.7	794.0	0.23	11.0	11.0	9.4	12.8	0.31
	8000-11999	teu	13.2	13.4	12.1	14.6	0.19	7.8	7.9	7.2	8.7	0.18	852.8	855.3	790.7	923.5	0.16	13.4	13.5	12.1	15.0	0.21
	12000-1449	teu	10.6	10.3	9.7	11.4	0.17	6.5	6.5	6.1	7.0	0.14	982.0	981.9	921.6	1048.7	0.13	15.7	15.5	14.4	17.1	0.18
	14500-1999	teu	8.2	8.4	7.3	10.1	0.33	5.4	5.6	4.7	6.4	0.29	970.2	1050.6	834.8	1161.0	0.31	16.4	17.0	14.4	20.2	0.34
General cargo	0-4999	dwt	37.8	39.9	30.2	54.5	0.61	25.9	25.7	19.9	39.2	0.75	72.5	70.0	59.7	82.3	0.32	0.6	0.6	0.5	0.8	0.47
	5000-9999	dwt	31.8	32.3	26.5	42.5	0.49	19.5	19.4	16.5	23.2	0.34	138.9	132.3	115.0	158.5	0.33	1.4	1.3	1.0	1.7	0.47
	10000-1999	dwt	31.4	31.3	26.3	40.0	0.44	17.3	17.2	15.3	19.7	0.25	234.8	220.5	197.5	265.9	0.31	2.7	2.6	2.2	3.2	0.39
	20000-+	dwt	15.2	15.4	12.6	20.8	0.53	8.6	8.9	7.1	11.2	0.45	308.9	300.3	258.7	342.6	0.28	3.7	3.7	3.1	4.3	0.34
Liquefied gas tanker	0-49999	cbm	54.2	75.9	52.9	142.2	1.18	27.5	45.4	27.6	87.7	1.33	239.5	224.7	182.1	305.6	0.55	2.9	2.6	2.1	3.9	0.68
	50000-9999	cbm	21.8	22.0	19.1	26.9	0.35	10.0	10.1	9.1	11.2	0.21	525.9	518.1	484.9	583.1	0.19	7.7	7.8	7.1	8.6	0.19
	100000-199	cbm	16.6	16.7	13.7	20.0	0.38	11.4	11.0	9.5	13.6	0.37	914.9	888.2	770.7	1057.6	0.32	13.5	12.8	10.5	16.2	0.45
	200000-+	cbm	17.8	16.9	15.5	23.2	0.46	10.7	10.6	9.9	11.9	0.19	1306.2	1306.9	1208.1	1369.6	0.12	21.8	21.6	20.3	23.0	0.12
Oil tanker	0-4999	dwt	85.2	118.0	63.0	275.8	1.80	62.1	79.3	44.3	188.2	1.82	179.3	183.2	129.3	415.1	1.56	1.7	1.7	1.2	3.1	1.07
	5000-9999	dwt	59.2	66.9	43.9	156.2	1.68	36.8	36.5	27.6	77.1	1.36	244.9	238.9	178.7	523.3	1.44	2.3	2.5	1.7	4.0	0.95
	10000-1999	dwt	43.9	49.9	33.1	90.9	1.16	25.2	26.2	19.7	41.0	0.81	367.4	365.5	289.4	583.0	0.80	3.7	3.8	2.9	5.3	0.63
	20000-5999	dwt	26.1	25.7	20.3	39.2	0.74	11.5	10.9	9.3	14.6	0.49	507.3	481.1	428.3	588.3	0.33	5.9	5.7	5.0	6.9	0.32
	60000-7999	dwt	16.1	15.9	13.3	20.0	0.42	7.6	7.4	6.5	8.5	0.27	550.2	538.7	483.3	607.2	0.23	6.6	6.5	5.9	7.4	0.23
	80000-1199	dwt	12.9	13.0	10.6	16.8	0.48	5.6	5.4	4.8	6.3	0.28	609.3	592.1	526.9	678.6	0.26	7.0	6.9	6.1	7.9	0.27
	120000-199	dwt	10.8	10.2	8.6	13.7	0.50	4.7	4.4	4.0	5.2	0.28	727.0	683.1	630.5	810.5	0.26	8.5	8.1	7.3	9.3	0.25
	200000-+	dwt	5.8	5.9	5.0	6.9	0.33	2.9	2.8	2.6	3.1	0.17	882.4	869.9	795.1	959.9	0.19	11.0	10.8	9.6	12.3	0.25

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	740.5	1461.4	884.2	1870.8	0.68	675.0	1281.9	784.9	1681.7	0.70	340.9	837.5	355.9	919.2	0.67	3.0	6.4	2.7	7.3	0.71
	1000-+	dwt	24.5	79.5	19.5	154.7	1.70	18.2	44.4	14.7	115.7	2.27	393.6	319.1	241.8	423.1	0.57	5.1	4.6	2.5	5.9	0.73
Ferry-pax only	2000-+	gt	134.2	151.2	111.9	321.6	1.39	111.5	110.3	99.1	265.8	1.51	237.3	188.6	142.6	323.2	0.96	3.1	2.2	1.6	4.1	1.17
Cruise	0-1999	gt	768.7	1299.1	602.6	2080.6	1.14	666.1	1218.5	555.4	1788.6	1.01	226.8	222.7	176.9	386.5	0.94	2.0	2.0	1.6	3.1	0.78
	2000-9999	gt	286.0	441.7	230.9	1006.6	1.76	262.3	408.5	208.8	908.1	1.71	236.2	221.8	173.9	418.7	1.10	2.3	2.3	1.7	3.6	0.84
	10000-5999	gt	149.3	164.2	108.4	270.7	0.99	132.2	146.4	99.8	234.6	0.92	565.3	547.3	475.6	668.1	0.35	7.7	7.5	6.3	9.0	0.37
	60000-9999	gt	167.4	171.1	145.8	193.6	0.28	149.5	155.3	134.3	172.4	0.25	1237.2	1235.2	1133.9	1327.1	0.16	18.8	18.7	17.0	20.7	0.20
	100000-149	gt	141.1	148.7	125.4	163.2	0.25	128.5	138.5	114.1	151.3	0.27	1417.6	1405.4	1313.1	1496.8	0.13	22.5	22.5	20.9	24.2	0.15
	150000-+	gt	122.7	137.5	107.3	145.6	0.28	109.2	119.8	97.4	129.3	0.27	1439.5	1411.9	1368.3	1431.6	0.04	23.6	23.1	22.6	25.0	0.11
Ferry-RoPax	2000-4999	gt	293.8	406.7	246.6	796.6	1.35	226.0	282.8	204.2	468.9	0.94	203.6	210.1	170.6	273.7	0.49	2.5	2.4	1.7	3.5	0.71
	5000-9999	gt	266.0	343.5	180.0	598.6	1.22	182.6	244.0	136.4	414.2	1.14	342.1	356.5	278.0	456.8	0.50	5.2	4.8	3.2	7.0	0.78
	10000-1999	gt	161.1	209.5	130.6	316.9	0.89	123.6	137.8	98.4	245.5	1.07	517.6	503.9	413.1	643.5	0.46	8.4	7.8	5.9	10.0	0.53
	20000-+	gt	147.6	152.7	105.7	227.4	0.80	112.1	112.9	77.5	162.1	0.75	722.3	672.6	560.8	846.6	0.42	12.6	11.8	9.0	15.4	0.54
Refrigerated bulk	0-1999	dwt	180.8	204.8	136.0	332.6	0.96	146.7	158.6	107.2	288.2	1.14	174.1	171.8	146.5	238.1	0.53	1.6	1.6	1.3	2.2	0.53
	2000-5999	dwt	107.9	111.0	87.4	150.9	0.57	74.0	76.0	58.9	101.0	0.55	294.0	298.7	248.6	360.1	0.37	3.4	3.4	2.9	4.3	0.42
	6000-9999	dwt	73.4	75.9	65.9	90.9	0.33	43.5	45.4	38.7	55.1	0.36	332.9	339.1	305.8	389.1	0.25	4.8	4.7	4.1	5.5	0.30
	10000-+	dwt	59.0	62.5	51.2	75.3	0.38	36.0	36.7	31.8	41.9	0.27	450.3	432.2	406.6	490.8	0.19	7.5	7.3	6.6	8.0	0.19
Ro-Ro	0-4999	dwt	144.6	289.9	123.5	636.5	1.77	113.6	225.4	99.5	507.0	1.81	252.2	293.3	194.9	465.5	0.92	2.1	2.3	1.5	3.5	0.90
	5000-9999	dwt	71.2	68.3	55.4	93.1	0.55	51.8	47.5	39.7	65.0	0.53	364.6	348.8	256.6	423.4	0.48	5.1	4.7	2.8	6.6	0.81
	10000-1499	dwt	55.5	54.0	46.2	65.2	0.35	37.7	39.4	31.2	45.6	0.37	460.1	455.7	384.7	520.2	0.30	7.0	7.2	5.3	8.9	0.50
	15000-+	dwt	30.8	30.8	22.0	47.4	0.82	21.3	21.3	14.8	31.2	0.77	572.3	558.2	419.5	650.7	0.41	8.7	8.6	6.4	9.9	0.40
Vehicle	0-29999	gt	134.4	143.2	112.3	202.2	0.63	47.5	55.3	38.9	72.7	0.61	273.8	247.2	207.0	313.8	0.43	3.9	3.4	2.7	4.8	0.64
	30000-4999	gt	71.7	70.8	62.5	80.1	0.25	21.4	21.5	19.0	24.7	0.26	293.4	292.5	268.7	309.9	0.14	4.4	4.3	3.9	4.7	0.19
	50000-+	gt	59.0	59.2	50.5	70.7	0.34	16.5	16.7	15.2	18.6	0.20	349.3	342.1	316.2	374.4	0.17	5.5	5.4	4.8	6.0	0.23

Carbon intensity per ship type and size category in year 2016 (Option 1)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	40.0	46.2	32.2	74.1	0.91	24.2	26.5	19.1	44.7	0.97	116.0	114.8	92.6	144.3	0.45	1.1	1.1	0.8	1.5	0.54
	10000-3499	dwt	13.2	13.1	11.0	17.5	0.50	7.7	7.6	6.8	9.1	0.30	214.1	213.0	189.5	239.0	0.23	2.4	2.4	2.1	2.8	0.30
	35000-5999	dwt	9.5	9.6	8.3	11.5	0.33	5.5	5.6	5.0	6.2	0.22	274.0	275.2	247.8	307.5	0.22	3.2	3.2	2.8	3.6	0.26
	60000-9999	dwt	8.3	8.2	7.2	9.7	0.31	4.2	4.2	3.8	4.7	0.22	321.8	314.5	289.2	355.9	0.21	3.7	3.7	3.3	4.2	0.25
	100000-199	dwt	5.4	5.4	4.7	6.4	0.31	2.7	2.7	2.4	3.1	0.24	465.5	460.0	412.2	516.8	0.23	5.2	5.1	4.4	5.9	0.30
	200000-+	dwt	5.0	5.0	4.4	5.9	0.32	2.4	2.4	2.1	2.7	0.24	609.9	574.8	484.5	721.7	0.41	7.3	7.1	5.5	8.8	0.47
Chemical tanker	0-4999	dwt	69.0	81.0	47.3	150.9	1.28	55.4	67.6	37.0	126.5	1.33	160.2	155.7	122.5	246.5	0.80	1.6	1.6	1.2	2.3	0.64
	5000-9999	dwt	39.4	40.2	33.2	51.4	0.45	29.2	29.5	24.2	37.9	0.46	214.9	212.7	184.1	256.0	0.34	2.3	2.3	1.9	2.8	0.36
	10000-1999	dwt	25.9	27.3	21.7	35.2	0.49	18.1	18.7	15.3	23.4	0.43	279.8	277.5	238.4	336.7	0.35	3.3	3.3	2.8	3.9	0.32
	20000-3999	dwt	17.5	17.7	15.1	21.2	0.34	12.1	12.0	10.5	14.6	0.34	391.0	394.7	341.8	469.4	0.32	4.9	5.0	4.3	5.7	0.28
	40000-+	dwt	13.4	13.2	11.6	15.6	0.30	8.3	8.3	7.4	9.5	0.25	403.7	397.8	361.4	447.1	0.22	5.0	4.9	4.4	5.6	0.24
Container	0-999	teu	36.1	37.3	31.1	48.9	0.48	23.8	24.6	20.5	30.8	0.42	213.8	213.1	182.2	248.9	0.31	2.6	2.6	2.1	3.3	0.46
	1000-1999	teu	27.9	28.6	24.7	33.2	0.30	17.2	17.7	15.3	21.0	0.33	331.3	325.8	288.2	371.6	0.26	4.5	4.4	3.7	5.2	0.34
	2000-2999	teu	20.9	20.4	18.0	24.1	0.30	12.0	11.5	10.3	13.5	0.28	416.4	401.5	362.8	450.8	0.22	5.9	5.7	4.9	6.8	0.34
	3000-4999	teu	17.4	17.5	15.4	20.2	0.27	10.6	10.4	9.4	11.8	0.23	561.7	538.2	478.7	620.2	0.26	8.3	8.0	6.8	9.7	0.36
	5000-7999	teu	16.6	16.7	14.8	19.0	0.25	9.7	9.6	8.6	10.9	0.23	722.6	729.4	644.7	816.0	0.23	11.2	11.4	9.8	13.1	0.29
	8000-11999	teu	13.5	13.5	12.3	15.2	0.21	8.1	8.1	7.3	9.0	0.21	886.3	886.9	818.9	949.6	0.15	14.3	14.2	12.9	15.7	0.19
	12000-1449	teu	10.7	10.4	9.6	11.7	0.20	6.9	6.7	6.4	7.2	0.12	1030.8	1018.2	947.0	1105.2	0.16	16.8	16.8	15.1	18.3	0.20
	14500-1999	teu	8.3	8.6	7.1	9.5	0.28	5.5	5.9	4.7	6.3	0.27	1016.5	1084.6	864.7	1178.2	0.29	17.3	17.4	14.9	20.8	0.34
General cargo	0-4999	dwt	38.0	40.8	30.6	55.4	0.61	26.0	25.7	19.9	40.3	0.79	72.7	69.9	59.4	81.8	0.32	0.6	0.6	0.5	0.8	0.49
	5000-9999	dwt	32.3	33.0	26.6	42.9	0.49	19.5	19.4	16.5	23.3	0.35	138.4	132.7	113.6	158.1	0.34	1.4	1.3	1.0	1.7	0.49
	10000-1999	dwt	31.8	31.5	26.0	40.9	0.47	17.3	17.2	15.2	19.5	0.25	235.0	219.4	196.4	264.2	0.31	2.7	2.6	2.2	3.2	0.40
	20000-+	dwt	15.6	15.7	12.6	21.6	0.57	8.6	8.9	7.1	11.3	0.47	312.6	298.7	262.6	345.1	0.28	3.8	3.6	3.1	4.4	0.35
Liquefied gas tanker	0-49999	cbm	51.9	73.3	49.9	132.5	1.13	26.0	43.2	26.1	80.1	1.25	238.6	230.3	178.2	308.9	0.57	2.9	2.7	2.1	4.0	0.70
	50000-9999	cbm	21.2	21.7	18.8	25.7	0.32	9.7	9.8	8.9	10.9	0.21	514.9	515.8	479.5	565.9	0.17	7.5	7.7	6.9	8.3	0.17
	100000-199	cbm	16.7	16.6	13.7	20.0	0.38	11.2	10.8	9.3	13.1	0.36	908.0	878.5	767.9	1025.1	0.29	13.2	12.4	10.1	15.9	0.46
	200000-+	cbm	17.7	17.1	15.3	26.0	0.63	10.7	10.6	10.0	11.9	0.17	1319.0	1294.6	1240.0	1338.1	0.08	21.3	20.9	19.9	22.3	0.11
Oil tanker	0-4999	dwt	86.8	121.3	64.9	289.9	1.86	62.8	82.6	44.8	205.7	1.95	181.8	186.4	131.2	418.1	1.54	1.7	1.7	1.2	3.1	1.04
	5000-9999	dwt	60.1	67.7	45.2	155.7	1.63	36.9	37.0	28.5	69.8	1.12	247.3	245.0	187.6	460.5	1.11	2.3	2.4	1.7	3.8	0.87
	10000-1999	dwt	43.9	48.6	33.9	86.2	1.08	25.0	27.4	19.9	40.1	0.74	365.2	375.0	277.6	569.8	0.78	3.7	3.8	2.9	5.7	0.73
	20000-5999	dwt	26.1	25.8	20.6	38.3	0.69	11.5	10.9	9.2	15.0	0.53	512.2	490.8	430.2	600.6	0.35	6.0	5.8	5.1	7.1	0.34
	60000-7999	dwt	16.2	15.6	13.3	19.9	0.42	7.5	7.2	6.4	8.6	0.30	546.0	529.5	473.1	603.2	0.25	6.7	6.5	5.8	7.5	0.26
	80000-1199	dwt	13.0	13.0	10.7	17.4	0.52	5.6	5.4	4.8	6.4	0.29	608.7	591.6	526.4	682.8	0.26	7.1	6.9	6.1	7.9	0.26
	120000-199	dwt	10.3	9.6	8.2	12.7	0.47	4.7	4.4	4.0	5.2	0.27	741.2	695.3	629.9	822.1	0.28	8.7	8.4	7.4	9.6	0.27
	200000-+	dwt	5.9	5.9	5.0	6.9	0.32	3.0	2.9	2.6	3.2	0.18	912.2	879.9	807.9	975.9	0.19	11.4	11.0	9.8	12.6	0.26

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	878.4	1437.8	994.0	2191.7	0.83	790.1	1348.6	924.6	1736.8	0.60	364.6	916.7	277.8	963.9	0.75	3.0	6.0	2.2	6.6	0.73
	1000-+	dwt	28.8	72.4	23.0	153.0	1.80	17.8	44.3	15.1	124.6	2.47	390.7	316.8	257.3	477.8	0.70	5.0	4.6	2.6	5.8	0.70
Ferry-pax only	2000-+	gt	131.5	139.7	109.5	339.0	1.64	112.3	113.5	97.5	289.7	1.69	248.4	208.2	145.1	332.0	0.90	3.2	2.2	1.6	5.4	1.72
Cruise	0-1999	gt	866.1	1326.8	760.3	1636.1	0.66	792.5	1244.5	694.4	1534.7	0.68	220.8	244.4	158.5	329.3	0.70	1.9	2.0	1.5	2.7	0.63
	2000-9999	gt	303.7	566.0	247.1	1160.4	1.61	273.2	487.8	186.5	961.9	1.59	242.5	275.5	168.1	439.9	0.99	2.3	2.6	1.7	4.1	0.92
	10000-5999	gt	151.3	165.7	113.0	277.9	1.00	135.5	150.7	103.7	240.8	0.91	576.3	567.1	478.0	665.7	0.33	7.9	7.7	6.6	9.3	0.35
	60000-9999	gt	166.4	168.5	148.5	192.1	0.26	149.8	154.7	133.0	168.9	0.23	1234.3	1246.2	1145.0	1327.1	0.15	18.8	18.7	16.8	20.9	0.22
	100000-149	gt	142.4	149.5	126.8	164.7	0.25	129.8	134.1	118.3	152.9	0.26	1433.0	1437.3	1307.2	1535.6	0.16	23.2	23.3	21.1	25.2	0.17
	150000-+	gt	117.7	132.2	105.2	143.2	0.29	106.0	112.5	98.3	131.6	0.30	1436.3	1397.9	1322.1	1454.9	0.10	23.0	23.6	21.5	24.3	0.12
Ferry-RoPax	2000-4999	gt	301.6	382.4	243.9	820.9	1.51	231.5	275.2	191.8	465.7	0.99	208.9	206.0	164.7	266.5	0.49	2.5	2.3	1.7	3.2	0.67
	5000-9999	gt	236.7	289.8	175.2	565.7	1.35	177.3	243.8	134.8	392.4	1.06	343.1	347.0	268.9	442.5	0.50	5.0	4.8	3.0	7.1	0.87
	10000-1999	gt	157.7	191.6	119.2	312.5	1.01	117.4	131.9	90.2	235.2	1.10	500.1	491.2	384.8	609.4	0.46	7.9	7.1	5.5	9.8	0.60
	20000-+	gt	147.7	151.3	108.2	214.2	0.70	112.0	113.4	78.7	158.5	0.70	721.3	669.0	566.9	848.1	0.42	12.6	11.7	9.0	15.3	0.54
Refrigerated bulk	0-1999	dwt	185.9	207.4	145.9	396.8	1.21	151.4	175.6	117.3	367.3	1.42	180.8	195.3	149.0	274.4	0.64	1.7	1.8	1.4	2.6	0.69
	2000-5999	dwt	115.9	114.9	92.2	164.0	0.63	76.6	75.4	62.1	103.2	0.54	305.9	303.7	260.7	364.9	0.34	3.5	3.5	2.9	4.4	0.45
	6000-9999	dwt	81.8	87.4	72.5	111.8	0.45	47.2	50.9	42.3	62.2	0.39	362.2	386.9	320.5	446.9	0.33	5.2	5.3	4.4	6.3	0.37
	10000-+	dwt	60.3	64.9	52.1	78.0	0.40	36.0	36.6	32.3	41.5	0.25	451.3	440.4	409.6	484.3	0.17	7.4	7.3	6.6	7.9	0.17
Ro-Ro	0-4999	dwt	150.3	312.9	138.4	671.1	1.70	116.9	238.8	104.6	524.8	1.76	262.0	304.7	202.5	513.6	1.02	2.2	2.4	1.6	3.7	0.88
	5000-9999	dwt	69.4	66.4	52.7	86.9	0.51	51.4	48.0	38.0	64.3	0.55	362.9	349.1	261.6	428.1	0.48	5.2	5.0	3.0	6.9	0.80
	10000-1499	dwt	57.2	54.9	45.8	69.6	0.43	38.6	39.5	30.4	46.7	0.41	469.5	469.6	390.6	527.7	0.29	7.3	7.3	5.6	9.3	0.51
	15000-+	dwt	29.4	29.8	20.7	47.9	0.91	19.9	17.4	12.8	32.9	1.15	555.4	543.9	413.2	651.9	0.44	8.4	8.7	6.1	10.1	0.46
Vehicle	0-29999	gt	135.3	140.1	113.0	191.0	0.56	47.4	54.0	38.3	69.4	0.58	271.4	247.6	201.8	311.0	0.44	3.8	3.3	2.6	4.7	0.62
	30000-4999	gt	76.5	75.2	65.8	92.3	0.35	21.8	22.3	19.5	25.7	0.28	298.6	298.0	275.1	320.8	0.15	4.4	4.5	4.1	4.9	0.20
	50000-+	gt	59.2	59.6	50.6	73.3	0.38	16.5	16.7	15.4	18.5	0.19	349.1	341.4	319.8	374.5	0.16	5.4	5.3	4.9	5.9	0.18

Carbon intensity per ship type and size category in year 2017 (Option 1)

Ship type	Size category	Units	EEOI ($gCO_2/t.nm$)					AER ($gCO_2/dwt.nm$)					DIST ($kgCO_2/nm$)					TIME (tCO_2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	38.8	46.2	30.9	73.1	0.91	23.1	25.4	18.5	42.3	0.94	110.5	108.5	88.6	139.6	0.47	1.1	1.1	0.8	1.4	0.61
	10000-3499	dwt	12.9	12.8	10.9	16.4	0.43	7.7	7.5	6.8	8.8	0.27	213.0	210.2	188.0	234.2	0.22	2.4	2.4	2.0	2.7	0.31
	35000-5999	dwt	9.5	9.6	8.2	11.4	0.33	5.4	5.5	4.9	6.1	0.22	270.5	272.0	243.0	300.3	0.21	3.1	3.1	2.7	3.5	0.25
	60000-9999	dwt	8.1	8.0	7.0	9.4	0.29	4.1	4.1	3.7	4.6	0.21	316.3	308.6	283.7	344.2	0.20	3.7	3.6	3.2	4.0	0.23
	100000-199	dwt	5.4	5.3	4.7	6.2	0.26	2.8	2.7	2.5	3.0	0.20	472.8	468.2	421.7	516.2	0.20	5.3	5.3	4.6	6.0	0.26
	200000-+	dwt	4.8	4.8	4.2	5.5	0.27	2.4	2.4	2.2	2.6	0.20	596.7	561.0	482.3	673.8	0.34	7.1	6.7	5.5	8.3	0.42
Chemical tanker	0-4999	dwt	67.7	82.0	47.2	162.3	1.41	51.6	61.3	35.4	109.8	1.22	144.7	141.6	113.7	202.0	0.62	1.4	1.4	1.1	1.9	0.54
	5000-9999	dwt	39.2	40.2	33.0	51.8	0.47	28.3	28.8	23.9	36.2	0.42	208.9	206.9	178.8	247.1	0.33	2.2	2.2	1.9	2.7	0.36
	10000-1999	dwt	25.1	26.6	21.5	32.6	0.42	17.3	17.9	14.7	21.9	0.40	268.6	268.2	230.9	318.0	0.32	3.1	3.1	2.7	3.7	0.33
	20000-3999	dwt	17.0	17.0	14.5	20.4	0.34	11.7	11.5	10.1	14.0	0.33	378.0	379.4	327.9	441.8	0.30	4.7	4.7	4.1	5.3	0.27
	40000-+	dwt	13.0	12.9	11.3	15.2	0.30	7.9	7.9	7.0	9.1	0.26	385.8	383.7	343.9	425.3	0.21	4.7	4.6	4.1	5.2	0.24
Container	0-999	teu	35.3	36.3	30.0	50.4	0.56	23.2	24.0	19.9	30.8	0.45	208.3	207.6	175.4	243.8	0.33	2.5	2.5	1.9	3.2	0.52
	1000-1999	teu	27.2	27.8	24.0	32.5	0.31	17.0	17.3	14.9	20.5	0.32	325.8	320.8	282.5	362.4	0.25	4.4	4.3	3.6	5.0	0.33
	2000-2999	teu	20.2	19.9	17.4	22.9	0.28	11.9	11.4	10.3	13.4	0.27	415.0	396.7	360.7	447.2	0.22	5.9	5.6	4.9	6.6	0.31
	3000-4999	teu	17.4	17.4	15.2	20.1	0.28	10.6	10.4	9.3	11.9	0.24	558.3	533.6	475.5	612.5	0.26	8.3	7.9	6.8	9.5	0.34
	5000-7999	teu	16.6	16.7	15.0	18.5	0.21	10.1	10.1	9.0	11.3	0.23	759.2	762.9	660.0	847.5	0.25	12.1	12.1	10.1	14.2	0.33
	8000-11999	teu	13.6	13.8	12.4	15.3	0.20	8.3	8.3	7.5	9.1	0.19	909.8	909.0	841.3	986.6	0.16	14.9	14.8	13.5	16.6	0.21
	12000-1449	teu	10.7	10.6	9.6	11.6	0.19	6.8	6.8	6.4	7.4	0.14	1023.3	1040.7	934.4	1133.5	0.19	16.8	17.1	15.1	19.0	0.23
	14500-1999	teu	8.3	8.4	7.3	9.0	0.21	5.6	5.7	4.8	6.0	0.21	1024.7	1084.5	842.5	1148.5	0.28	17.2	18.3	14.4	19.8	0.30
	20000-+	teu	8.2	9.8	6.5	13.3	0.70	4.3	5.2	3.3	7.4	0.79	828.2	1002.3	642.6	1415.5	0.77	12.6	17.2	10.1	23.3	0.77
General cargo	0-4999	dwt	37.8	40.2	30.2	55.1	0.62	25.9	25.6	19.6	39.8	0.79	71.1	68.7	58.1	80.7	0.33	0.6	0.6	0.5	0.8	0.49
	5000-9999	dwt	31.6	32.5	26.2	42.0	0.49	19.2	19.1	16.3	23.3	0.37	137.1	131.7	112.6	158.0	0.35	1.4	1.3	1.0	1.6	0.48
	10000-1999	dwt	29.5	29.7	24.6	37.4	0.43	16.9	16.8	14.8	19.3	0.27	229.0	214.1	191.6	260.1	0.32	2.6	2.5	2.1	3.1	0.42
	20000-+	dwt	14.6	14.9	11.9	20.0	0.55	8.4	8.7	7.0	11.2	0.48	309.3	296.9	257.0	341.4	0.28	3.7	3.6	3.0	4.3	0.34
Liquefied gas tanker	0-49999	cbm	47.9	67.3	48.0	117.8	1.04	24.3	39.4	23.1	71.7	1.23	222.8	213.4	165.7	290.8	0.59	2.7	2.5	1.9	3.7	0.73
	50000-9999	cbm	20.7	20.9	18.0	26.0	0.38	9.6	9.5	8.6	10.6	0.21	508.6	507.3	471.6	553.0	0.16	7.3	7.4	6.7	8.0	0.17
	100000-199	cbm	16.4	16.5	13.7	19.7	0.36	10.9	10.5	9.2	12.5	0.32	895.7	875.9	759.6	1026.6	0.30	13.2	12.7	10.6	15.9	0.42
	200000-+	cbm	17.9	17.6	14.8	25.1	0.58	10.5	10.1	9.7	11.5	0.18	1279.5	1251.1	1200.3	1310.4	0.09	20.3	19.9	19.0	21.4	0.12
Oil tanker	0-4999	dwt	84.4	118.1	62.7	293.2	1.95	59.2	74.7	43.4	174.0	1.75	169.7	175.7	124.5	360.4	1.34	1.6	1.6	1.2	2.6	0.93
	5000-9999	dwt	57.6	66.0	44.4	123.9	1.21	35.2	36.2	27.7	66.0	1.06	236.3	238.4	183.8	419.5	0.99	2.2	2.2	1.7	3.4	0.75
	10000-1999	dwt	40.5	48.0	32.6	82.4	1.04	23.3	24.8	18.4	36.9	0.75	343.5	341.6	267.2	542.8	0.81	3.5	3.5	2.8	5.4	0.75
	20000-5999	dwt	26.2	27.0	20.9	39.3	0.68	11.0	10.6	8.9	14.2	0.50	488.9	469.2	408.6	568.4	0.34	5.7	5.5	4.8	6.5	0.30
	60000-7999	dwt	16.0	15.7	12.9	21.0	0.51	7.1	6.9	6.2	8.0	0.27	520.1	505.0	453.0	581.6	0.25	6.2	6.1	5.4	6.9	0.25
	80000-1199	dwt	12.6	12.5	10.3	16.5	0.50	5.3	5.1	4.6	6.1	0.29	577.9	559.5	500.9	656.3	0.28	6.6	6.4	5.7	7.5	0.28
	120000-199	dwt	9.7	9.2	7.7	12.1	0.48	4.6	4.3	3.9	5.0	0.26	717.1	672.5	618.3	780.6	0.24	8.4	8.0	7.1	9.2	0.26
	200000-+	dwt	5.7	5.6	4.7	6.8	0.37	2.8	2.7	2.5	3.0	0.20	867.4	844.2	759.2	944.5	0.22	10.6	10.4	9.0	11.8	0.27

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/dwt.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	753.6	1602.7	1031.8	1806.3	0.48	685.9	1448.7	710.6	1648.7	0.65	331.6	838.8	333.6	1001.1	0.80	2.9	5.1	2.2	7.5	1.02
	1000-+	dwt	26.8	46.5	21.2	187.9	3.58	17.4	25.6	14.1	135.5	4.75	401.2	366.4	297.2	508.5	0.58	5.1	4.5	3.1	6.5	0.75
Ferry-pax only	2000-+	gt	133.3	141.5	106.6	338.3	1.64	108.1	117.0	95.2	316.6	1.89	229.0	192.8	139.0	326.1	0.97	2.9	2.0	1.5	4.9	1.65
Cruise	0-1999	gt	895.7	1334.0	698.5	1886.2	0.89	821.5	1123.8	655.2	1769.3	0.99	272.2	289.0	182.1	455.9	0.95	2.4	2.4	1.8	3.9	0.89
	2000-9999	gt	310.6	526.2	248.5	1158.2	1.73	284.1	428.6	225.0	1033.5	1.89	245.2	298.2	170.6	452.0	0.94	2.3	2.7	1.7	3.9	0.84
	10000-5999	gt	152.0	162.4	110.1	281.0	1.05	134.7	151.4	103.2	236.8	0.88	575.9	557.3	472.2	661.4	0.34	7.9	7.7	6.5	9.2	0.35
	60000-9999	gt	165.4	174.0	142.9	191.0	0.28	148.8	152.5	131.0	170.8	0.26	1218.3	1223.4	1136.2	1296.5	0.13	18.6	18.5	16.7	20.8	0.22
	100000-149	gt	141.0	146.7	124.7	162.9	0.26	127.7	134.2	114.8	149.0	0.26	1412.7	1376.3	1307.5	1507.2	0.15	22.8	22.7	20.9	24.7	0.17
	150000-+	gt	111.6	122.0	90.6	142.1	0.42	99.1	109.4	85.1	125.8	0.37	1390.2	1358.9	1282.3	1475.3	0.14	21.8	21.9	20.9	24.2	0.15
Ferry-RoPax	2000-4999	gt	280.0	356.1	227.2	698.4	1.32	213.0	257.4	174.3	412.8	0.93	197.8	195.9	153.3	244.6	0.47	2.3	2.0	1.6	2.9	0.67
	5000-9999	gt	220.6	311.5	169.6	618.2	1.44	160.3	216.8	116.8	360.0	1.12	319.8	306.1	250.6	399.7	0.49	4.6	4.0	2.7	6.2	0.87
	10000-1999	gt	147.8	179.5	114.4	305.6	1.06	113.6	125.4	89.1	205.0	0.92	488.9	462.9	372.4	571.9	0.43	7.6	6.7	4.9	9.3	0.66
	20000-+	gt	143.9	144.9	103.9	203.0	0.68	108.4	104.8	74.6	151.6	0.73	697.7	644.4	528.6	798.7	0.42	11.9	10.6	8.4	14.5	0.57
Refrigerated bulk	0-1999	dwt	194.9	232.4	152.4	399.6	1.06	154.9	189.7	117.9	298.7	0.95	171.3	186.3	137.1	300.2	0.88	1.6	1.7	1.3	2.6	0.78
	2000-5999	dwt	114.7	113.8	91.9	185.9	0.83	74.1	74.8	60.3	105.7	0.61	293.8	300.6	245.6	369.4	0.41	3.3	3.5	2.8	4.3	0.43
	6000-9999	dwt	82.5	87.6	72.2	107.3	0.40	47.9	51.3	42.3	61.8	0.38	366.7	376.9	324.7	450.7	0.33	5.1	5.1	4.4	6.2	0.36
	10000-+	dwt	60.9	64.5	51.5	81.5	0.46	37.0	38.3	33.0	42.7	0.25	463.3	449.9	420.0	514.0	0.21	7.5	7.5	6.8	8.4	0.21
Ro-Ro	0-4999	dwt	148.7	301.1	125.6	668.2	1.80	112.3	218.4	94.8	440.5	1.58	244.9	273.7	179.0	483.9	1.11	2.1	2.1	1.4	3.6	1.06
	5000-9999	dwt	70.1	68.4	55.1	91.6	0.53	51.9	50.3	39.3	65.9	0.53	362.4	359.5	279.3	426.8	0.41	5.2	5.0	3.0	6.7	0.74
	10000-1499	dwt	56.2	53.3	45.0	67.9	0.43	38.7	38.5	30.8	45.9	0.39	470.7	465.4	386.0	527.8	0.30	7.3	7.4	5.4	9.3	0.52
	15000-+	dwt	29.0	28.6	19.0	44.2	0.88	20.4	19.2	13.0	30.2	0.90	557.5	540.8	423.3	655.9	0.43	8.5	8.5	6.5	10.2	0.44
Vehicle	0-29999	gt	135.2	147.5	108.4	186.7	0.53	47.8	52.6	39.5	67.1	0.53	269.2	242.0	198.1	303.2	0.43	3.7	3.3	2.4	4.7	0.70
	30000-4999	gt	73.6	73.4	64.8	83.4	0.25	21.6	21.9	19.5	24.9	0.25	295.1	293.7	269.8	317.1	0.16	4.4	4.4	4.0	4.9	0.20
	50000-+	gt	58.6	60.5	50.9	71.0	0.33	16.5	16.6	15.2	18.7	0.21	347.7	341.4	315.5	371.8	0.17	5.4	5.4	4.9	5.9	0.20

Carbon intensity per ship type and size category in year 2012 (Option 2)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	34.3	39.5	29.2	54.5	0.64	21.4	24.6	17.7	31.0	0.54	117.0	113.5	90.6	140.0	0.43	1.1	1.1	0.7	1.4	0.61
	10000-3499	dwt	13.0	13.0	10.8	17.6	0.52	8.1	8.0	7.2	9.4	0.27	222.3	219.3	194.2	249.1	0.25	2.6	2.6	2.2	3.0	0.33
	35000-5999	dwt	9.8	9.8	8.2	12.5	0.44	5.6	5.6	5.1	6.3	0.23	282.9	284.4	254.5	314.5	0.21	3.4	3.4	3.0	3.9	0.27
	60000-9999	dwt	8.7	8.8	7.4	10.7	0.37	4.3	4.3	3.9	4.8	0.20	339.7	331.8	300.6	380.1	0.24	4.1	4.0	3.6	4.6	0.27
	100000-199	dwt	5.9	5.9	5.1	7.0	0.32	3.0	3.0	2.7	3.3	0.20	505.1	504.9	442.7	561.0	0.23	6.0	6.0	5.1	6.9	0.30
	200000-+	dwt	5.1	5.4	4.4	6.4	0.37	2.6	2.6	2.3	3.0	0.27	649.1	630.4	547.0	729.1	0.29	8.0	7.8	6.6	9.4	0.37
Chemical tanker	0-4999	dwt	52.3	53.7	41.5	85.2	0.81	41.1	40.1	32.2	70.7	0.96	139.3	132.6	107.7	184.2	0.58	1.4	1.4	1.1	1.8	0.56
	5000-9999	dwt	36.0	36.7	31.5	45.5	0.38	26.4	26.7	22.4	33.3	0.41	198.5	193.0	170.6	228.7	0.30	2.2	2.2	1.8	2.6	0.35
	10000-1999	dwt	23.2	25.0	20.1	30.6	0.42	16.6	17.3	14.4	20.4	0.35	256.0	255.4	222.5	300.7	0.31	3.1	3.1	2.7	3.6	0.31
	20000-3999	dwt	16.2	16.5	14.3	18.8	0.27	11.4	11.2	10.0	13.4	0.30	365.7	364.6	328.4	421.2	0.25	4.6	4.7	4.0	5.3	0.28
	40000-+	dwt	12.8	12.9	11.4	15.1	0.29	8.0	8.0	7.3	9.1	0.22	387.9	386.6	354.8	423.0	0.18	4.8	4.8	4.3	5.4	0.22
Container	0-999	TEU	34.9	36.2	30.1	45.0	0.41	23.3	24.0	20.4	29.4	0.38	223.1	218.9	187.2	254.3	0.31	2.9	2.8	2.3	3.6	0.46
	1000-1999	TEU	27.2	28.1	24.0	32.9	0.32	17.1	17.7	15.2	20.5	0.30	337.1	331.8	289.9	386.8	0.29	4.8	4.7	3.9	5.7	0.38
	2000-2999	TEU	20.8	20.2	17.7	24.5	0.34	12.3	12.0	10.6	14.0	0.28	432.2	425.9	379.5	478.8	0.23	6.5	6.5	5.4	7.7	0.36
	3000-4999	TEU	18.3	18.1	16.3	20.4	0.23	11.6	11.3	10.3	13.0	0.24	617.1	605.2	531.0	688.6	0.26	10.1	10.0	8.3	11.8	0.35
	5000-7999	TEU	17.1	16.8	15.2	18.6	0.21	10.6	10.4	9.4	11.5	0.20	791.0	776.2	703.5	847.3	0.19	13.3	13.0	11.4	14.6	0.25
	8000-11999	TEU	13.9	13.8	12.5	15.2	0.20	8.3	8.6	7.5	9.3	0.22	902.8	910.2	820.5	991.7	0.19	15.1	15.3	13.4	17.2	0.25
	12000-1449	TEU	11.0	10.8	9.7	12.1	0.22	6.8	6.8	6.1	7.7	0.23	1028.2	1039.2	960.5	1142.1	0.17	17.0	16.9	14.8	19.6	0.28
	14500-1999	TEU	7.0	6.8	6.7	7.3	0.09	4.5	4.5	4.3	4.6	0.06	701.3	697.3	678.0	716.3	0.05	11.6	11.3	10.7	12.4	0.15
General cargo	0-4999	dwt	33.9	35.3	28.0	47.4	0.55	23.3	23.4	19.3	30.6	0.48	74.5	70.4	59.3	82.5	0.33	0.7	0.6	0.5	0.8	0.46
	5000-9999	dwt	30.1	30.4	24.7	39.7	0.49	19.3	19.1	16.3	22.8	0.34	140.2	132.5	112.7	157.1	0.33	1.5	1.4	1.0	1.7	0.49
	10000-1999	dwt	28.4	28.3	23.2	37.5	0.50	16.8	16.7	14.8	19.2	0.27	231.6	219.5	192.1	272.1	0.36	2.8	2.6	2.2	3.3	0.44
	20000-+	dwt	14.6	14.8	11.8	19.3	0.51	9.1	9.2	7.6	11.7	0.44	313.8	303.2	260.6	350.9	0.30	3.9	3.8	3.2	4.4	0.33
Liquefied gas tanker	0-49999	cbm	43.2	63.4	44.0	93.5	0.78	21.5	34.3	21.6	48.2	0.78	227.9	209.3	160.6	287.0	0.60	2.9	2.6	1.9	3.8	0.74
	50000-9999	cbm	19.2	19.6	16.3	25.1	0.45	10.0	9.7	9.0	10.9	0.20	515.5	509.3	481.1	558.2	0.15	7.4	7.5	6.9	8.1	0.16
	100000-199	cbm	16.8	16.2	14.1	19.8	0.35	12.1	11.7	10.2	13.7	0.30	951.9	921.6	811.1	1060.1	0.27	14.8	14.1	11.7	17.5	0.41
	200000-+	cbm	15.8	15.8	14.0	18.0	0.26	10.8	10.9	10.0	12.3	0.20	1316.0	1326.9	1248.4	1400.4	0.11	22.6	22.5	21.5	24.3	0.12
Oil tanker	0-4999	dwt	80.9	101.2	53.3	252.0	1.96	54.0	63.9	35.3	158.7	1.93	167.5	164.1	110.8	335.8	1.37	1.5	1.5	1.0	2.6	1.15
	5000-9999	dwt	47.2	52.9	36.5	103.0	1.26	30.4	30.1	23.5	53.4	0.99	211.6	203.9	162.4	353.4	0.94	2.1	2.1	1.5	2.9	0.66
	10000-1999	dwt	41.8	48.0	28.2	100.1	1.50	22.8	22.0	17.7	31.9	0.65	323.1	309.0	244.1	396.0	0.49	3.3	3.2	2.5	4.4	0.58
	20000-5999	dwt	21.1	21.9	16.7	32.1	0.70	9.4	9.2	8.2	11.6	0.38	422.8	417.0	376.9	481.5	0.25	5.2	5.2	4.6	5.9	0.26
	60000-7999	dwt	14.9	14.9	12.5	19.5	0.47	6.7	6.7	5.9	7.5	0.25	484.2	480.0	430.2	546.3	0.24	6.0	5.9	5.3	6.9	0.27
	80000-1199	dwt	12.0	12.3	9.7	16.4	0.55	5.0	4.9	4.4	5.6	0.26	539.4	530.6	475.6	603.8	0.24	6.4	6.3	5.6	7.3	0.28
	120000-199	dwt	9.8	9.7	8.0	13.4	0.56	4.1	4.1	3.6	4.6	0.23	643.7	636.1	570.2	707.8	0.22	7.6	7.6	6.7	8.8	0.28
	200000-+	dwt	5.5	5.5	4.6	6.7	0.39	2.7	2.7	2.4	3.0	0.22	837.3	829.6	730.8	924.1	0.23	10.5	10.1	8.7	12.3	0.35

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	1892.9	1892.9	1892.9	1892.9	0.00	1775.5	1775.5	1775.5	1775.5	0.00	1092.0	1092.0	1092.0	1092.0	0.00	7.4	7.4	7.4	7.4	0.00
	1000-+	dwt	33.4	52.5	31.1	114.9	1.59	16.9	20.1	16.6	83.0	3.30	390.9	312.2	235.1	647.5	1.32	5.6	4.5	2.4	6.9	1.00
Ferry-pax only	0-299	GT	1156.5	1337.4	907.5	1937.1	0.77	830.0	1003.0	521.9	1744.2	1.22	44.6	44.5	32.4	67.2	0.78	0.8	0.7	0.4	1.3	1.13
	300-999	GT	1821.1	1820.8	1181.7	2315.7	0.62	1402.3	1632.9	957.9	1982.2	0.63	82.0	77.0	63.5	88.2	0.32	2.0	2.0	1.2	2.4	0.60
	1000-1999	GT	386.0	575.1	315.2	1982.9	2.90	312.1	409.0	295.7	539.5	0.60	114.0	157.0	94.6	179.6	0.54	1.2	1.2	1.0	2.3	1.06
	2000-+	GT	118.2	265.9	130.2	543.5	1.55	103.6	197.5	88.0	319.5	1.17	233.9	224.0	120.8	291.6	0.76	3.1	2.5	1.2	4.2	1.20
Cruise	0-1999	GT	634.3	962.1	502.1	1628.1	1.17	576.2	813.7	471.0	1321.6	1.05	218.5	187.5	130.6	275.4	0.77	2.1	1.7	1.1	2.5	0.79
	2000-9999	GT	157.8	228.4	135.1	495.1	1.58	144.0	190.9	126.1	406.6	1.47	177.4	173.7	134.5	199.4	0.37	1.9	1.8	1.4	2.2	0.41
	10000-5999	GT	143.0	154.8	105.6	245.7	0.91	127.3	142.1	96.3	199.1	0.72	547.3	502.6	458.8	622.3	0.33	7.7	7.2	6.4	8.8	0.34
	60000-9999	GT	162.2	161.6	138.6	187.0	0.30	144.2	148.8	125.3	166.1	0.27	1181.2	1194.6	1111.4	1294.5	0.15	18.7	19.0	16.5	21.3	0.25
	100000-149	GT	146.9	157.1	125.5	170.0	0.28	131.1	139.7	115.8	151.1	0.25	1433.9	1400.4	1310.9	1511.0	0.14	24.1	23.5	21.8	25.5	0.16
	150000-+	GT	111.8	140.3	92.5	154.6	0.44	101.0	129.0	86.8	133.0	0.36	1419.1	1428.8	1412.3	1439.9	0.02	23.3	22.8	22.3	23.2	0.04
Ferry-RoPax	0-1999	GT	793.5	824.4	451.3	1571.0	1.36	577.0	538.4	344.1	944.9	1.12	145.5	118.5	97.3	173.0	0.64	1.6	1.1	0.9	2.1	1.08
	2000-4999	GT	327.5	460.4	247.0	950.5	1.53	260.6	340.4	201.4	595.2	1.16	202.9	198.4	157.6	289.2	0.66	2.5	2.5	1.7	3.8	0.84
	5000-9999	GT	276.5	333.8	161.8	974.6	2.43	203.1	245.0	109.7	629.9	2.12	352.3	342.7	267.3	414.4	0.43	5.4	4.1	3.1	8.3	1.27
	10000-1999	GT	174.1	184.5	111.2	342.6	1.25	125.2	120.6	83.1	220.5	1.14	472.2	435.6	360.5	557.4	0.45	6.6	6.3	4.8	8.5	0.59
	20000-+	GT	144.4	147.3	106.5	201.5	0.65	109.8	110.9	78.7	157.8	0.71	724.7	670.8	548.5	854.5	0.46	12.4	11.5	9.0	16.0	0.60
Refrigerated bulk	0-1999	dwt	154.2	170.9	110.3	269.4	0.93	125.7	146.0	91.8	212.6	0.83	164.4	163.7	136.3	242.0	0.65	1.5	1.6	1.2	2.0	0.50
	2000-5999	dwt	97.9	104.7	78.7	151.5	0.70	66.6	69.2	53.2	100.0	0.68	266.6	264.8	220.4	326.3	0.40	3.1	3.1	2.5	4.0	0.47
	6000-9999	dwt	74.4	75.3	63.3	96.8	0.44	43.4	43.8	38.1	56.1	0.41	332.9	335.7	285.8	386.6	0.30	4.8	4.8	4.1	5.7	0.34
	10000-+	dwt	61.0	61.4	53.3	77.8	0.40	35.9	36.7	31.8	41.5	0.26	447.2	431.8	395.4	487.8	0.21	7.6	7.4	6.6	8.7	0.29
Ro-Ro	0-4999	dwt	117.4	172.3	94.4	384.4	1.68	82.1	117.7	62.9	252.6	1.61	224.2	231.1	156.4	342.5	0.81	2.0	1.9	1.2	3.2	1.06
	5000-9999	dwt	68.5	70.2	54.0	97.6	0.62	45.5	46.2	37.9	60.3	0.49	333.2	327.6	250.5	402.3	0.46	4.4	4.2	2.9	5.8	0.69
	10000-1499	dwt	54.5	53.4	42.8	70.0	0.51	35.6	36.0	28.3	44.2	0.44	443.4	451.4	363.1	519.7	0.35	6.7	6.6	5.1	8.8	0.56
	15000-+	dwt	28.7	28.0	21.5	42.5	0.75	19.8	21.2	15.0	26.8	0.55	524.6	511.9	408.0	618.8	0.41	7.9	7.8	6.2	10.0	0.49
Vehicle	0-29999	GT	130.7	139.8	109.7	201.3	0.65	41.4	48.4	34.7	64.0	0.61	257.8	255.4	197.9	300.8	0.40	3.6	3.6	2.7	4.6	0.55
	30000-4999	GT	71.0	69.4	61.0	81.9	0.30	21.3	21.1	19.1	24.6	0.26	296.5	292.1	269.4	315.8	0.16	4.5	4.5	4.1	5.0	0.20
	50000-+	GT	59.5	60.1	50.9	71.3	0.34	16.7	17.1	15.4	19.2	0.22	357.2	348.6	327.7	378.0	0.14	5.8	5.6	5.2	6.2	0.18
Yacht	0-+	GT	422.0	602.7	399.1	862.8	0.77	361.4	508.1	337.7	744.0	0.80	94.1	71.9	54.7	96.3	0.58	1.1	0.9	0.6	1.2	0.75
Service - tug	0-+	GT	190.5	289.9	138.9	599.4	1.59	144.1	217.9	105.9	480.3	1.72	137.2	124.3	81.5	182.3	0.81	1.0	0.9	0.5	1.4	1.01
Miscellaneous - fishing	0-+	GT	124.9	306.4	144.4	721.7	1.88	102.6	258.6	121.7	633.9	1.98	85.3	80.8	65.9	108.0	0.52	0.7	0.7	0.5	0.9	0.73
Offshore	0-+	GT	16.6	197.7	110.6	440.8	1.67	8.7	124.2	68.9	294.4	1.82	327.0	240.7	156.5	390.0	0.97	2.9	2.0	1.3	3.6	1.13
Service - other	0-+	GT	45.3	136.8	64.7	330.1	1.94	30.6	104.7	45.1	260.6	2.06	196.2	150.9	104.3	235.0	0.87	1.6	1.3	0.8	2.1	0.98
Miscellaneous - other	0-+	GT	39.7	34.4	29.3	48.7	0.56	28.0	27.0	20.9	36.4	0.57	495.7	469.9	293.6	567.4	0.58	6.2	5.7	3.7	7.3	0.63

Carbon intensity per ship type and size category in year 2013 (Option 2)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	34.0	39.1	29.2	55.4	0.67	20.8	24.2	17.4	30.6	0.55	113.5	112.3	89.8	133.7	0.39	1.0	1.0	0.8	1.3	0.54
	10000-3499	dwt	12.6	12.7	10.6	16.6	0.47	7.8	7.7	6.9	9.1	0.28	216.0	213.1	190.4	238.5	0.23	2.5	2.4	2.1	2.8	0.30
	35000-5999	dwt	9.4	9.3	8.0	11.6	0.39	5.4	5.4	4.9	6.1	0.22	273.7	276.1	247.7	304.5	0.21	3.2	3.2	2.8	3.6	0.26
	60000-9999	dwt	8.6	8.6	7.3	10.5	0.37	4.2	4.2	3.8	4.7	0.20	328.6	321.4	291.7	365.8	0.23	3.9	3.8	3.4	4.4	0.27
	100000-199	dwt	5.6	5.6	4.9	6.5	0.29	2.9	2.9	2.6	3.2	0.21	483.0	480.0	421.5	538.1	0.24	5.5	5.5	4.6	6.4	0.33
	200000-+	dwt	4.9	5.1	4.3	6.0	0.33	2.4	2.5	2.2	2.8	0.24	623.0	594.6	536.9	703.0	0.28	7.5	7.2	6.3	8.7	0.33
Chemical tanker	0-4999	dwt	54.2	56.1	41.8	93.9	0.93	42.8	43.0	33.1	77.9	1.04	143.6	136.9	111.7	192.4	0.59	1.5	1.4	1.1	1.8	0.56
	5000-9999	dwt	35.9	37.0	31.2	46.9	0.42	26.8	27.5	22.9	34.2	0.41	201.2	198.4	175.2	234.7	0.30	2.2	2.2	1.9	2.6	0.34
	10000-1999	dwt	23.2	25.5	20.0	31.5	0.45	16.7	17.5	14.6	20.8	0.36	258.2	260.2	223.9	300.8	0.30	3.0	3.1	2.6	3.6	0.32
	20000-3999	dwt	16.0	16.1	14.2	18.7	0.28	11.4	11.2	10.0	13.1	0.27	365.6	368.6	326.2	414.4	0.24	4.6	4.6	4.0	5.2	0.27
	40000-+	dwt	12.6	12.7	11.3	14.9	0.28	7.8	8.0	7.1	9.0	0.24	379.6	383.3	347.9	421.2	0.19	4.6	4.7	4.2	5.3	0.24
Container	0-999	TEU	34.4	35.4	29.4	43.4	0.40	23.0	23.4	19.8	28.7	0.38	220.2	215.0	186.5	246.2	0.28	2.9	2.8	2.2	3.4	0.44
	1000-1999	TEU	26.7	27.4	23.6	32.1	0.31	16.8	17.4	14.8	20.4	0.32	330.0	324.4	285.6	372.3	0.27	4.6	4.5	3.9	5.4	0.33
	2000-2999	TEU	19.9	19.2	16.7	22.7	0.31	11.7	11.3	9.9	13.1	0.29	410.0	398.9	347.3	449.3	0.26	5.9	5.8	4.7	7.0	0.40
	3000-4999	TEU	17.4	17.2	15.4	19.8	0.25	11.0	10.8	9.7	12.2	0.23	585.6	570.9	500.5	655.6	0.27	9.1	9.0	7.5	10.8	0.36
	5000-7999	TEU	16.5	16.4	14.7	18.2	0.22	10.2	10.0	9.2	11.3	0.22	763.2	757.7	684.3	827.7	0.19	12.5	12.4	10.8	14.0	0.26
	8000-11999	TEU	13.2	13.2	12.0	14.6	0.20	8.1	8.2	7.5	9.0	0.17	874.1	877.4	808.9	957.3	0.17	14.3	14.3	12.7	16.1	0.24
	12000-1449	TEU	10.5	10.2	9.5	11.5	0.20	6.6	6.6	6.0	7.4	0.22	996.0	1014.2	920.2	1125.9	0.20	15.9	16.1	14.1	18.8	0.29
	14500-1999	TEU	7.2	7.0	6.9	8.2	0.19	4.1	4.5	4.2	4.7	0.11	692.9	730.7	683.4	785.9	0.14	11.8	12.0	11.5	13.8	0.19
General cargo	0-4999	dwt	33.4	35.2	28.0	47.8	0.56	22.9	23.4	19.1	30.9	0.50	73.3	69.6	58.8	81.7	0.33	0.6	0.6	0.5	0.7	0.45
	5000-9999	dwt	30.0	30.2	25.0	39.6	0.49	19.1	18.9	16.2	22.6	0.34	138.2	131.0	111.8	154.5	0.33	1.4	1.3	1.0	1.7	0.49
	10000-1999	dwt	27.8	27.5	22.8	33.9	0.40	16.7	16.4	14.6	18.8	0.26	228.2	216.9	188.4	263.6	0.35	2.7	2.6	2.1	3.2	0.41
	20000-+	dwt	14.1	14.2	11.5	18.8	0.51	8.7	8.9	7.4	11.3	0.43	308.0	296.8	255.9	340.0	0.28	3.7	3.6	3.1	4.3	0.33
Liquefied gas tanker	0-49999	cbm	45.6	64.5	46.2	91.3	0.70	22.8	36.7	22.7	50.3	0.75	229.7	211.1	163.4	284.8	0.58	2.9	2.5	1.9	3.6	0.70
	50000-9999	cbm	20.4	21.4	17.7	25.6	0.37	9.9	9.7	8.9	10.8	0.20	514.1	502.2	476.1	557.9	0.16	7.4	7.3	6.7	8.0	0.19
	100000-199	cbm	16.7	16.4	13.7	19.7	0.36	11.7	11.2	9.7	13.3	0.32	924.0	901.3	778.9	1056.3	0.31	14.1	13.6	10.6	17.0	0.46
	200000-+	cbm	16.7	16.5	15.0	19.0	0.24	10.8	10.9	9.8	12.1	0.20	1308.5	1318.5	1226.6	1347.6	0.09	22.4	22.7	20.8	23.5	0.12
Oil tanker	0-4999	dwt	77.2	93.8	50.7	203.7	1.63	52.8	61.7	34.8	140.5	1.71	164.1	164.7	110.6	327.2	1.32	1.4	1.4	0.9	2.5	1.11
	5000-9999	dwt	47.3	53.7	37.3	102.4	1.21	30.8	30.3	24.5	50.7	0.87	212.2	206.9	164.5	343.7	0.87	2.1	2.1	1.6	2.9	0.63
	10000-1999	dwt	39.0	42.7	29.5	81.1	1.21	20.8	22.6	17.9	29.9	0.53	296.1	313.4	240.3	418.4	0.57	3.0	3.1	2.5	4.4	0.62
	20000-5999	dwt	21.6	22.2	17.7	30.3	0.57	9.6	9.3	8.3	11.8	0.37	428.4	422.0	383.5	480.9	0.23	5.1	5.1	4.5	5.8	0.25
	60000-7999	dwt	15.0	15.3	12.6	19.7	0.46	6.9	6.8	6.1	7.8	0.26	499.2	492.2	446.6	558.0	0.23	6.0	6.0	5.3	6.8	0.25
	80000-1199	dwt	11.9	12.3	9.9	16.0	0.49	5.0	4.9	4.4	5.6	0.26	539.2	529.6	476.3	602.6	0.24	6.2	6.2	5.4	7.1	0.27
	120000-199	dwt	9.1	8.9	7.6	11.7	0.46	4.1	3.9	3.6	4.5	0.23	637.9	623.0	563.3	702.1	0.22	7.3	7.3	6.3	8.4	0.29
	200000-+	dwt	5.5	5.5	4.6	6.7	0.37	2.7	2.6	2.3	3.0	0.24	825.1	803.3	718.5	906.1	0.23	9.9	9.6	8.0	11.5	0.37

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids tankers	1000-+	dwt	26.1	40.9	23.6	117.7	2.30	17.2	22.1	15.7	84.0	3.09	415.4	332.0	255.2	639.3	1.16	5.9	4.7	3.1	8.1	1.06
Ferry-pax only	0-299	GT	805.8	1429.9	849.2	1877.1	0.72	550.3	1004.5	553.7	1686.0	1.13	45.6	47.6	34.0	60.6	0.56	0.9	0.8	0.6	1.3	0.88
	300-999	GT	1276.4	1684.8	923.6	2117.0	0.71	1064.0	1405.1	633.0	1811.7	0.84	75.9	64.3	50.4	84.2	0.53	1.8	1.6	0.7	2.2	0.91
	1000-1999	GT	408.8	537.0	338.9	796.7	0.85	335.5	315.9	214.2	444.4	0.73	126.2	115.8	99.3	137.7	0.33	1.2	0.9	0.7	1.5	0.86
	2000-+	GT	200.7	256.6	175.7	482.8	1.20	174.1	220.0	132.9	338.8	0.94	191.6	178.5	136.4	225.8	0.50	2.3	2.0	1.4	2.7	0.64
Cruise	0-1999	GT	504.4	742.5	417.0	1664.2	1.68	467.7	611.6	391.2	1328.6	1.53	134.9	125.4	104.3	160.3	0.45	1.3	1.2	0.9	1.7	0.71
	2000-9999	GT	180.4	255.0	152.8	612.1	1.80	165.7	229.2	139.6	446.8	1.34	186.0	174.6	146.4	248.5	0.59	1.9	1.9	1.6	2.5	0.46
	10000-5999(	GT	137.5	151.0	97.2	227.9	0.87	120.9	137.9	89.8	191.1	0.73	524.6	490.1	446.8	599.1	0.31	7.4	7.1	6.1	8.5	0.33
	60000-9999(	GT	160.3	159.4	142.2	187.0	0.28	142.8	145.7	126.7	164.7	0.26	1175.8	1175.6	1095.1	1249.1	0.13	18.1	18.1	15.9	19.9	0.22
	100000-149(	GT	143.7	154.8	124.5	164.1	0.26	125.8	133.9	115.5	146.6	0.23	1382.4	1352.7	1259.8	1509.7	0.18	22.7	22.0	19.9	25.3	0.25
	150000-+	GT	107.0	138.0	90.8	139.5	0.35	97.7	124.9	84.1	127.0	0.34	1371.3	1371.4	1354.4	1390.8	0.03	22.6	22.5	21.9	22.7	0.04
Ferry-RoPax	0-1999	GT	519.2	968.0	356.8	1702.8	1.39	380.9	533.8	264.3	1217.3	1.79	125.7	137.1	96.3	173.7	0.57	1.3	1.6	0.8	2.3	0.88
	2000-4999	GT	338.6	379.1	254.7	603.9	0.92	252.1	260.2	157.4	523.8	1.41	198.6	199.4	146.0	257.2	0.56	2.3	2.2	1.3	3.2	0.87
	5000-9999	GT	202.2	311.2	131.4	693.8	1.81	154.7	203.1	98.0	506.6	2.01	347.4	334.6	243.7	427.1	0.55	4.8	4.3	2.5	9.5	1.63
	10000-1999(	GT	164.6	192.0	113.9	351.3	1.24	118.7	126.5	83.1	224.5	1.12	464.6	452.3	359.2	602.6	0.54	6.4	6.5	5.0	8.8	0.59
	20000-+	GT	145.4	155.5	111.2	218.5	0.69	111.1	118.1	82.2	163.2	0.69	725.5	695.3	562.4	867.1	0.44	12.4	11.8	9.0	16.0	0.59
Refrigerated bulk	0-1999	dwt	168.7	194.8	119.4	299.0	0.92	131.5	137.0	96.6	251.5	1.13	166.9	159.9	128.6	217.0	0.55	1.5	1.5	1.2	1.9	0.52
	2000-5999	dwt	96.7	102.3	78.9	147.3	0.67	66.9	72.5	53.6	97.3	0.60	271.1	267.0	225.2	337.3	0.42	3.1	3.1	2.6	3.8	0.38
	6000-9999	dwt	71.6	74.8	64.5	87.8	0.31	41.8	42.7	37.1	51.3	0.33	321.6	323.2	282.6	376.1	0.29	4.7	4.7	4.0	5.5	0.32
	10000-+	dwt	60.9	61.9	53.4	75.7	0.36	35.3	36.3	31.3	40.5	0.25	440.1	423.9	397.0	473.6	0.18	7.4	7.2	6.3	8.0	0.24
Ro-Ro	0-4999	dwt	134.6	219.5	97.1	520.6	1.93	95.8	157.2	66.8	362.3	1.88	244.2	261.8	170.6	432.9	1.00	2.1	2.2	1.4	3.5	0.93
	5000-9999	dwt	67.6	65.6	52.9	87.9	0.53	44.3	45.0	35.4	58.7	0.52	322.6	319.3	244.8	387.2	0.45	4.1	3.9	2.7	5.3	0.66
	10000-1499(	dwt	53.8	55.1	42.5	69.6	0.49	36.1	37.3	28.9	44.8	0.43	449.5	460.1	363.5	524.1	0.35	6.9	7.1	5.1	8.8	0.53
	15000-+	dwt	29.9	30.3	22.3	45.1	0.75	20.8	22.0	16.3	28.7	0.57	544.7	542.9	453.4	629.6	0.32	8.3	8.3	6.8	10.0	0.38
Vehicle	0-29999	GT	134.2	146.1	106.5	193.3	0.59	42.4	49.8	34.5	66.9	0.65	260.9	237.5	200.2	300.5	0.42	3.6	3.3	2.6	4.7	0.62
	30000-4999(	GT	69.3	68.5	60.0	80.2	0.30	20.9	21.2	18.7	24.1	0.26	291.3	288.6	267.5	310.9	0.15	4.4	4.4	3.9	4.8	0.20
	50000-+	GT	58.8	60.0	50.1	70.2	0.34	16.5	17.0	15.2	18.8	0.21	349.1	344.5	321.2	371.5	0.15	5.5	5.5	5.0	6.0	0.18
Yacht	0-+	GT	406.8	605.9	394.1	908.0	0.85	346.9	488.8	332.9	746.9	0.85	90.8	71.6	53.1	95.1	0.59	1.1	0.8	0.6	1.2	0.77
Service - tug	0-+	GT	187.4	305.4	139.3	647.5	1.66	148.2	237.9	109.5	516.2	1.71	139.3	127.7	86.0	183.7	0.77	1.0	0.9	0.5	1.4	0.97
Miscellaneous - fishing	0-+	GT	127.8	305.5	149.7	699.1	1.80	105.8	259.0	123.5	629.8	1.95	84.4	81.2	65.1	108.3	0.53	0.7	0.6	0.5	0.9	0.75
Offshore	0-+	GT	23.4	203.8	110.9	458.5	1.71	11.3	130.2	66.8	311.8	1.88	314.9	242.7	162.0	369.8	0.86	2.8	2.0	1.3	3.3	1.00
Service - other	0-+	GT	61.8	160.1	67.2	423.0	2.22	42.1	118.4	47.6	324.6	2.34	192.3	152.6	108.5	260.8	1.00	1.6	1.3	0.8	2.2	1.03
Miscellaneous - other	0-+	GT	39.8	42.6	28.4	58.2	0.70	30.3	31.6	22.3	41.1	0.59	612.4	396.0	290.3	665.3	0.95	7.4	4.9	3.3	9.0	1.14

Carbon intensity per ship type and size category in year 2014 (Option 2)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	33.9	39.3	29.0	56.0	0.69	20.8	24.1	17.4	30.6	0.55	114.6	110.5	89.0	134.8	0.42	1.1	1.0	0.8	1.3	0.54
	10000-3499	dwt	12.2	12.3	10.3	16.1	0.48	7.7	7.6	6.8	8.8	0.27	214.0	209.8	189.2	235.7	0.22	2.4	2.4	2.0	2.8	0.30
	35000-5999	dwt	8.8	8.9	7.6	10.8	0.36	5.4	5.4	4.9	6.0	0.22	271.8	272.4	246.7	300.1	0.20	3.1	3.1	2.8	3.5	0.23
	60000-9999	dwt	8.0	8.0	6.9	9.6	0.33	4.1	4.1	3.7	4.6	0.21	322.6	316.1	288.9	360.5	0.23	3.7	3.7	3.3	4.2	0.25
	100000-199	dwt	5.4	5.4	4.7	6.3	0.30	2.8	2.7	2.5	3.1	0.20	467.6	464.3	411.9	516.8	0.23	5.2	5.2	4.4	6.0	0.31
	200000-+	dwt	4.8	4.9	4.3	5.6	0.27	2.4	2.4	2.2	2.7	0.22	595.0	567.2	502.3	674.7	0.30	7.0	6.8	5.8	8.1	0.34
Chemical tanker	0-4999	dwt	55.8	57.3	42.9	102.1	1.03	44.4	45.7	33.6	83.3	1.09	150.6	144.5	114.1	217.4	0.72	1.5	1.4	1.1	2.0	0.59
	5000-9999	dwt	36.3	37.3	31.8	45.7	0.37	26.9	27.5	23.2	33.2	0.36	201.6	197.9	175.8	230.4	0.28	2.2	2.2	1.9	2.6	0.33
	10000-1999	dwt	23.6	25.4	20.4	31.3	0.43	16.9	17.7	14.8	21.1	0.35	261.9	263.8	230.7	304.3	0.28	3.1	3.1	2.7	3.6	0.30
	20000-3999	dwt	16.1	16.2	14.1	18.8	0.29	11.4	11.3	10.1	13.5	0.30	367.4	372.3	320.5	424.9	0.28	4.5	4.6	4.0	5.2	0.28
	40000-+	dwt	12.6	12.7	11.2	15.0	0.30	7.8	8.0	7.1	9.0	0.24	381.4	382.3	350.3	421.7	0.19	4.6	4.7	4.2	5.2	0.22
Container	0-999	TEU	34.0	35.0	29.3	42.7	0.38	22.9	23.6	19.6	28.8	0.39	219.2	215.6	184.8	244.6	0.28	2.8	2.7	2.2	3.4	0.43
	1000-1999	TEU	26.3	27.1	23.3	31.9	0.32	16.8	17.4	14.8	20.5	0.33	325.4	319.8	282.9	367.1	0.26	4.5	4.4	3.8	5.1	0.31
	2000-2999	TEU	19.2	18.7	16.1	21.9	0.31	11.5	10.8	9.6	12.9	0.30	402.2	386.3	339.9	436.8	0.25	5.7	5.3	4.5	6.6	0.40
	3000-4999	TEU	16.6	16.5	14.8	18.6	0.23	10.5	10.4	9.4	11.6	0.21	560.1	541.1	482.3	618.5	0.25	8.4	8.2	6.9	9.8	0.36
	5000-7999	TEU	15.7	15.4	13.9	17.6	0.24	9.8	9.6	8.7	11.0	0.23	735.3	718.6	642.8	819.0	0.25	11.7	11.4	9.9	13.3	0.30
	8000-11999	TEU	12.8	12.8	11.7	14.0	0.18	8.0	8.0	7.4	8.7	0.16	871.1	869.3	796.8	941.6	0.17	14.0	13.9	12.6	15.7	0.23
	12000-1449	TEU	10.1	9.8	9.2	10.9	0.18	6.6	6.5	6.0	7.1	0.18	986.1	990.5	911.7	1048.5	0.14	15.8	15.7	14.3	17.4	0.19
	14500-1999	TEU	7.6	7.8	7.0	9.5	0.32	4.7	4.8	4.6	5.3	0.13	832.3	911.1	734.9	1019.5	0.31	13.2	15.1	12.2	16.9	0.31
General cargo	0-4999	dwt	33.7	35.0	27.8	46.8	0.54	23.1	23.3	19.1	30.2	0.48	73.6	70.0	59.5	82.1	0.32	0.6	0.6	0.5	0.7	0.43
	5000-9999	dwt	30.0	30.3	24.5	38.9	0.47	19.1	19.0	16.2	22.5	0.33	138.1	130.5	112.6	154.2	0.32	1.4	1.3	1.0	1.6	0.48
	10000-1999	dwt	28.1	27.8	23.2	35.9	0.46	16.7	16.6	14.8	18.9	0.25	227.0	213.8	190.0	258.3	0.32	2.7	2.5	2.1	3.1	0.39
	20000-+	dwt	13.7	14.2	11.2	18.0	0.48	8.5	8.9	7.1	11.0	0.44	305.8	292.0	256.3	331.0	0.26	3.7	3.5	3.0	4.1	0.32
Liquefied gas tanker	0-49999	cbm	45.5	66.2	45.5	97.3	0.78	22.9	38.2	23.4	54.7	0.82	239.5	220.8	175.9	302.0	0.57	3.0	2.7	2.0	3.8	0.67
	50000-9999	cbm	20.4	21.0	18.2	25.2	0.33	9.9	9.9	9.0	10.9	0.19	516.8	508.4	476.0	559.4	0.16	7.6	7.5	7.0	8.2	0.17
	100000-199	cbm	16.2	16.1	13.3	19.4	0.38	11.2	10.8	9.4	12.6	0.30	892.8	851.7	758.5	1005.3	0.29	13.3	12.6	10.5	15.8	0.42
	200000-+	cbm	17.4	16.8	15.3	21.6	0.38	10.6	10.5	9.8	12.0	0.22	1294.5	1291.0	1208.5	1364.7	0.12	21.9	21.6	20.4	23.4	0.14
Oil tanker	0-4999	dwt	81.7	103.8	51.1	257.6	1.99	54.7	65.1	35.9	167.1	2.01	173.3	183.3	117.5	376.4	1.41	1.5	1.6	1.0	2.7	1.10
	5000-9999	dwt	49.4	55.5	39.2	113.2	1.33	32.3	32.7	26.2	59.3	1.01	222.9	219.9	174.9	381.1	0.94	2.2	2.1	1.7	3.3	0.78
	10000-1999	dwt	40.1	47.8	29.2	75.9	0.98	21.5	24.0	18.1	34.1	0.67	306.9	328.9	255.4	445.6	0.58	3.1	3.2	2.6	4.6	0.60
	20000-5999	dwt	21.9	22.5	18.0	30.8	0.57	9.7	9.4	8.4	11.8	0.36	436.5	428.0	390.0	486.7	0.23	5.2	5.1	4.6	5.7	0.23
	60000-7999	dwt	14.3	14.5	11.9	18.5	0.45	6.9	6.7	6.1	7.9	0.26	505.2	489.2	450.8	563.3	0.23	6.0	5.9	5.3	6.8	0.25
	80000-1199	dwt	11.7	11.8	9.9	15.3	0.46	5.0	4.9	4.4	5.7	0.25	547.7	535.8	481.4	608.6	0.24	6.2	6.1	5.4	7.1	0.28
	120000-199	dwt	9.1	8.6	7.5	11.3	0.45	4.1	4.0	3.6	4.4	0.20	637.7	620.4	567.0	696.6	0.21	7.3	7.1	6.4	8.2	0.26
	200000-+	dwt	5.4	5.4	4.6	6.4	0.34	2.6	2.6	2.3	2.9	0.24	810.1	786.3	698.2	905.4	0.26	9.5	9.3	7.8	11.1	0.35

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	854.8	661.7	630.4	932.3	0.46	713.5	511.9	491.7	820.1	0.64	414.4	318.9	277.4	512.6	0.74	3.8	3.0	2.5	5.1	0.87
	1000-+	dwt	26.5	32.3	21.6	98.2	2.37	15.7	17.4	14.1	75.2	3.51	406.7	316.0	231.9	406.7	0.55	5.7	4.6	2.3	6.3	0.86
Ferry-pax only	0-299	GT	622.0	1321.8	665.1	1886.4	0.92	500.3	1157.1	616.4	1673.3	0.91	49.3	49.7	39.0	60.3	0.43	0.9	0.9	0.7	1.3	0.69
	300-999	GT	1582.3	1689.3	1249.3	2329.4	0.64	1357.7	1513.6	934.5	1920.3	0.65	84.7	76.9	59.1	93.6	0.45	1.9	1.8	1.0	2.3	0.73
	1000-1999	GT	381.9	555.9	360.9	1012.8	1.17	317.1	338.5	228.3	521.4	0.87	126.9	108.3	91.7	141.6	0.46	1.2	1.1	1.0	1.4	0.37
	2000-+	GT	237.0	295.7	155.5	516.1	1.22	207.6	277.3	142.1	396.5	0.92	166.2	177.0	136.2	218.1	0.46	1.9	1.9	1.7	2.4	0.36
Cruise	0-1999	GT	435.9	685.8	408.4	1327.3	1.34	369.6	611.6	354.9	1069.8	1.17	160.2	140.4	105.9	189.1	0.59	1.5	1.3	1.0	2.0	0.81
	2000-9999	GT	184.6	248.2	159.9	644.4	1.95	158.9	227.3	139.7	581.9	1.95	177.8	175.6	141.2	211.6	0.40	1.8	1.7	1.4	2.1	0.42
	10000-5999	GT	141.6	151.8	105.3	255.1	0.99	124.6	135.5	92.3	218.3	0.93	543.5	516.5	445.8	645.7	0.39	7.5	7.2	6.1	9.1	0.42
	60000-9999	GT	158.9	160.8	140.1	181.6	0.26	142.2	146.3	128.2	167.3	0.27	1175.2	1183.0	1094.4	1243.9	0.13	17.7	17.9	15.4	19.5	0.23
	100000-149	GT	138.7	149.3	121.7	159.3	0.25	124.4	130.0	111.7	147.7	0.28	1370.6	1356.0	1246.6	1464.5	0.16	22.1	21.9	20.4	24.4	0.18
	150000-+	GT	116.1	135.2	107.4	144.8	0.28	104.0	123.5	95.4	128.1	0.27	1434.7	1373.4	1325.4	1417.0	0.07	23.8	22.9	21.9	23.9	0.08
Ferry-RoPax	0-1999	GT	764.4	669.1	367.8	1500.8	1.69	487.0	468.5	276.7	1189.1	1.95	131.9	136.2	105.6	180.8	0.55	1.5	1.5	0.9	2.5	1.06
	2000-4999	GT	347.4	392.5	196.0	698.5	1.28	274.4	257.3	164.6	505.1	1.32	192.9	205.0	138.2	275.4	0.67	2.1	2.0	1.4	3.2	0.94
	5000-9999	GT	210.9	308.1	165.8	785.8	2.01	160.7	232.9	110.9	551.9	1.89	361.5	343.2	277.5	443.2	0.48	5.3	4.4	3.0	7.6	1.06
	10000-1999	GT	168.9	195.2	132.0	334.7	1.04	125.0	146.5	91.7	209.9	0.81	484.2	458.0	370.1	600.7	0.50	7.0	6.7	5.3	9.0	0.55
	20000-+	GT	144.3	146.2	112.3	203.8	0.63	109.4	111.3	81.3	161.1	0.72	710.3	667.5	563.5	842.1	0.42	12.1	11.2	9.0	15.2	0.55
Refrigerated bulk	0-1999	dwt	183.8	184.8	129.9	328.3	1.07	143.0	142.8	101.2	298.9	1.38	185.8	179.8	144.4	274.3	0.72	1.8	1.7	1.3	2.5	0.72
	2000-5999	dwt	101.7	106.1	81.6	140.0	0.55	67.7	71.5	53.8	98.0	0.62	271.9	273.1	229.0	322.9	0.34	3.1	3.1	2.6	3.9	0.43
	6000-9999	dwt	70.0	73.0	63.1	84.7	0.30	41.9	43.1	37.4	53.8	0.38	323.5	326.8	291.2	377.7	0.26	4.7	4.6	4.0	5.3	0.29
	10000-+	dwt	60.2	63.5	52.7	76.6	0.38	35.5	36.0	31.4	41.0	0.27	441.9	429.7	396.5	465.5	0.16	7.3	7.2	6.3	8.1	0.25
Ro-Ro	0-4999	dwt	140.8	260.3	111.2	536.9	1.64	102.3	179.9	81.6	371.1	1.61	247.8	275.1	183.3	431.9	0.90	2.1	2.2	1.4	3.6	1.01
	5000-9999	dwt	68.4	62.5	53.8	80.1	0.42	46.0	42.8	36.5	56.4	0.46	334.4	314.5	246.0	384.8	0.44	4.4	3.8	2.7	5.3	0.70
	10000-1499	dwt	52.6	53.0	44.9	67.4	0.42	36.4	38.0	30.0	44.4	0.38	452.0	454.6	377.5	519.0	0.31	6.9	7.2	5.1	8.7	0.50
	15000-+	dwt	30.2	30.3	23.3	48.1	0.82	20.8	21.4	16.1	30.3	0.66	545.7	571.4	431.5	649.3	0.38	8.2	9.1	6.3	10.1	0.42
Vehicle	0-29999	GT	131.3	133.8	102.6	197.8	0.71	42.3	48.7	35.5	71.2	0.73	261.2	248.7	206.6	296.1	0.36	3.6	3.3	2.7	4.5	0.55
	30000-4999	GT	69.4	68.4	60.5	77.4	0.25	20.8	21.0	18.7	24.0	0.25	288.1	286.0	265.8	304.5	0.14	4.3	4.3	3.9	4.7	0.19
	50000-+	GT	57.7	57.8	49.2	70.4	0.37	16.3	16.5	15.0	18.5	0.21	344.0	337.2	315.5	363.5	0.14	5.4	5.3	4.8	5.8	0.19
Yacht	0-+	GT	442.9	605.9	411.4	936.5	0.87	367.8	514.4	355.1	765.4	0.80	87.9	71.9	56.1	97.0	0.57	1.0	0.9	0.6	1.3	0.79
Service - tug	0-+	GT	185.3	324.6	143.6	679.7	1.65	145.7	253.8	111.5	563.2	1.78	136.5	128.2	86.2	181.2	0.74	1.0	0.9	0.5	1.4	0.96
Miscellaneous - fishing	0-+	GT	126.4	307.1	146.0	720.6	1.87	104.4	257.8	126.5	635.1	1.97	87.3	82.1	66.7	108.2	0.51	0.7	0.6	0.5	1.0	0.77
Offshore	0-+	GT	32.9	184.8	107.9	431.7	1.75	15.7	115.9	67.7	308.3	2.08	341.0	249.2	167.6	389.2	0.89	3.0	2.1	1.3	3.5	1.02
Service - other	0-+	GT	58.1	162.1	74.5	431.4	2.20	42.3	123.2	56.5	344.2	2.33	197.9	163.7	114.6	269.1	0.94	1.6	1.4	0.9	2.3	1.00
Miscellaneous - other	0-+	GT	41.9	43.0	27.3	58.7	0.73	30.8	32.6	21.0	43.3	0.68	550.3	485.9	285.8	640.3	0.73	6.7	5.6	3.3	8.3	0.90

Carbon intensity per ship type and size category in year 2015 (Option 2)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	34.8	40.7	28.7	58.8	0.74	21.4	24.0	18.0	31.1	0.55	115.6	113.7	90.9	140.4	0.44	1.1	1.0	0.7	1.4	0.59
	10000-3499	dwt	12.5	12.6	10.6	16.4	0.47	7.7	7.5	6.8	8.8	0.27	216.0	213.4	191.7	238.6	0.22	2.5	2.4	2.1	2.8	0.28
	35000-5999	dwt	9.0	9.0	7.8	10.8	0.34	5.4	5.5	4.9	6.1	0.22	272.9	273.9	247.9	303.2	0.20	3.2	3.2	2.8	3.6	0.24
	60000-9999	dwt	8.0	8.0	7.0	9.6	0.32	4.1	4.1	3.7	4.6	0.22	320.1	313.8	286.2	356.7	0.22	3.7	3.6	3.3	4.2	0.26
	100000-199	dwt	5.3	5.3	4.6	6.3	0.31	2.7	2.7	2.5	3.1	0.22	463.9	459.7	408.9	515.8	0.23	5.1	5.1	4.3	5.9	0.32
	200000-+	dwt	4.9	5.0	4.4	5.8	0.29	2.4	2.4	2.1	2.6	0.21	600.5	560.1	487.9	689.0	0.36	7.1	6.8	5.6	8.4	0.41
Chemical tanker	0-4999	dwt	54.0	57.2	42.2	94.7	0.92	43.5	45.9	33.7	76.3	0.93	147.7	142.5	114.9	211.2	0.68	1.5	1.4	1.1	1.9	0.52
	5000-9999	dwt	36.1	37.3	31.0	45.3	0.39	27.4	28.3	23.2	33.9	0.38	203.9	199.8	178.1	231.3	0.27	2.2	2.2	1.9	2.6	0.33
	10000-1999	dwt	23.4	25.2	20.2	31.6	0.45	17.1	17.9	14.9	21.4	0.36	265.1	265.6	231.2	306.8	0.28	3.1	3.1	2.7	3.7	0.30
	20000-3999	dwt	16.3	16.6	14.5	18.8	0.26	11.4	11.5	10.3	13.6	0.29	370.7	380.1	328.4	437.5	0.29	4.6	4.8	4.0	5.4	0.29
	40000-+	dwt	12.6	12.6	11.2	14.7	0.28	7.9	8.0	7.2	9.1	0.24	382.4	386.8	350.3	425.3	0.19	4.7	4.7	4.2	5.4	0.24
Container	0-999	TEU	34.6	35.4	29.3	44.4	0.43	22.9	23.5	19.7	28.7	0.38	216.3	214.6	183.9	242.6	0.27	2.8	2.7	2.2	3.3	0.40
	1000-1999	TEU	26.8	27.6	23.8	32.3	0.31	16.7	17.3	14.7	20.6	0.34	323.9	318.6	281.4	360.6	0.25	4.5	4.3	3.7	5.1	0.33
	2000-2999	TEU	19.6	19.4	16.7	22.1	0.28	11.4	10.9	9.6	12.8	0.30	395.6	378.7	338.3	432.9	0.25	5.6	5.3	4.5	6.4	0.36
	3000-4999	TEU	16.6	16.6	14.7	18.6	0.24	10.3	10.1	9.1	11.3	0.21	551.5	527.3	470.4	600.1	0.25	8.3	7.9	6.7	9.4	0.35
	5000-7999	TEU	16.0	15.8	14.2	17.9	0.24	9.6	9.5	8.5	10.7	0.23	718.1	713.4	629.3	795.1	0.23	11.3	11.2	9.5	13.0	0.31
	8000-11999	TEU	13.1	13.2	11.9	14.3	0.19	7.8	7.9	7.2	8.6	0.18	851.9	853.3	791.8	921.6	0.15	13.5	13.5	12.2	15.1	0.22
	12000-1449	TEU	10.4	10.2	9.5	11.2	0.17	6.6	6.5	6.1	7.0	0.13	982.9	987.3	917.8	1052.5	0.14	15.9	15.7	14.4	17.4	0.19
	14500-1999	TEU	8.1	8.3	7.3	10.0	0.33	5.4	5.6	4.8	6.4	0.29	975.0	1057.4	842.3	1181.8	0.32	16.6	17.0	14.7	20.5	0.34
General cargo	0-4999	dwt	34.3	35.9	28.2	49.1	0.58	23.2	23.3	19.0	30.2	0.48	74.9	70.4	60.7	82.8	0.31	0.7	0.6	0.5	0.7	0.42
	5000-9999	dwt	30.6	30.8	25.4	40.6	0.49	19.2	19.0	16.3	22.6	0.33	138.4	130.0	113.5	154.5	0.31	1.4	1.3	1.0	1.6	0.47
	10000-1999	dwt	29.9	29.4	24.5	37.3	0.43	16.9	16.7	14.9	18.9	0.24	228.6	214.2	189.5	258.2	0.32	2.7	2.5	2.1	3.1	0.41
	20000-+	dwt	14.4	14.6	11.9	19.6	0.52	8.4	8.7	7.0	10.9	0.45	305.1	296.1	252.9	338.3	0.29	3.7	3.6	3.0	4.3	0.35
Liquefied gas tanker	0-49999	cbm	44.7	64.8	43.8	90.0	0.71	22.4	36.3	22.2	52.9	0.84	240.4	221.5	176.2	297.7	0.55	3.0	2.7	2.0	4.0	0.72
	50000-9999	cbm	21.4	21.8	19.2	26.0	0.31	9.8	9.8	9.0	11.0	0.21	516.5	512.4	481.8	568.3	0.17	7.6	7.7	7.1	8.5	0.19
	100000-199	cbm	16.3	16.5	13.6	19.6	0.37	11.3	10.8	9.4	13.3	0.36	908.2	874.8	764.0	1043.5	0.32	13.4	12.7	10.3	15.8	0.43
	200000-+	cbm	17.7	16.9	15.5	23.2	0.46	10.6	10.5	9.9	11.9	0.19	1296.8	1299.6	1208.1	1355.3	0.11	21.7	21.3	20.3	22.7	0.11
Oil tanker	0-4999	dwt	76.0	106.5	55.1	255.2	1.88	54.6	70.4	37.0	178.1	2.00	172.7	193.7	120.3	390.6	1.40	1.5	1.6	1.0	2.9	1.20
	5000-9999	dwt	49.2	57.1	39.8	122.5	1.45	31.8	32.5	25.6	58.4	1.01	218.2	216.5	172.5	390.1	1.00	2.1	2.1	1.6	3.3	0.83
	10000-1999	dwt	40.7	47.6	27.9	81.6	1.13	22.8	24.6	17.3	32.9	0.63	325.5	333.2	258.4	456.7	0.60	3.2	3.4	2.6	4.6	0.59
	20000-5999	dwt	21.8	21.7	18.2	32.3	0.65	10.0	9.8	8.6	12.4	0.39	450.4	441.0	401.6	510.8	0.25	5.4	5.3	4.8	6.0	0.24
	60000-7999	dwt	14.5	14.7	12.4	17.8	0.37	7.1	7.1	6.3	7.9	0.22	515.6	512.9	464.4	571.2	0.21	6.3	6.3	5.6	7.0	0.22
	80000-1199	dwt	11.8	11.9	10.0	15.0	0.42	5.3	5.2	4.7	5.9	0.23	578.7	563.8	510.1	633.4	0.22	6.7	6.6	5.9	7.5	0.26
	120000-199	dwt	9.8	9.7	8.1	12.3	0.43	4.4	4.2	3.8	4.8	0.23	683.8	661.1	606.7	746.1	0.21	8.0	7.8	7.0	8.8	0.23
	200000-+	dwt	5.7	5.8	4.9	6.8	0.32	2.8	2.8	2.6	3.0	0.17	865.2	852.1	778.7	936.0	0.18	10.8	10.7	9.3	12.0	0.25

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	1622.2	1571.9	1545.6	1598.1	0.03	1518.5	1412.2	1356.4	1467.9	0.08	762.8	788.7	775.3	802.1	0.03	5.3	5.0	4.8	5.2	0.07
	1000-+	dwt	22.1	23.0	18.8	116.8	4.26	16.5	17.7	13.5	78.6	3.68	400.2	314.9	238.3	394.6	0.50	5.4	4.6	2.5	6.1	0.78
Ferry-pax only	0-299	GT	677.8	1114.8	748.8	1636.1	0.80	550.0	1016.1	656.5	1413.0	0.74	48.5	47.8	39.0	59.7	0.43	0.8	0.9	0.6	1.2	0.68
	300-999	GT	1823.8	1804.9	1243.7	2329.9	0.60	1564.9	1558.7	1022.9	1880.6	0.55	83.9	73.5	58.5	100.7	0.58	2.0	1.7	1.1	2.2	0.61
	1000-1999	GT	229.6	624.2	289.9	952.4	1.06	183.4	338.0	265.3	487.6	0.66	131.5	131.0	90.2	184.0	0.72	1.4	1.5	0.8	2.3	0.95
	2000-+	GT	218.5	240.5	180.9	332.3	0.63	195.0	225.6	150.1	311.7	0.72	182.3	182.6	123.2	237.2	0.62	2.3	2.3	1.6	3.2	0.72
Cruise	0-1999	GT	421.4	645.8	456.6	881.8	0.66	374.2	503.6	384.8	827.1	0.88	159.9	140.3	98.8	181.4	0.59	1.4	1.3	0.9	1.8	0.68
	2000-9999	GT	201.5	256.9	185.6	793.5	2.37	186.5	241.2	169.1	734.5	2.34	199.3	183.4	135.9	230.6	0.52	2.0	1.9	1.4	2.4	0.54
	10000-5999(	GT	142.6	152.2	107.8	235.3	0.84	126.0	140.1	94.5	202.1	0.77	543.1	515.6	458.8	629.1	0.33	7.4	7.1	6.2	8.6	0.34
	60000-9999(	GT	164.0	164.6	141.8	188.5	0.28	146.4	150.0	129.2	168.6	0.26	1208.1	1195.3	1115.6	1299.5	0.15	18.4	18.4	15.8	20.6	0.26
	100000-149(	GT	138.8	147.1	121.5	161.0	0.27	126.7	135.6	112.6	150.0	0.28	1402.1	1394.5	1285.4	1474.5	0.14	22.7	22.6	21.0	24.3	0.15
	150000-+	GT	121.7	137.5	107.1	145.6	0.28	108.4	118.2	96.9	129.1	0.27	1428.1	1416.2	1367.6	1430.8	0.04	23.5	23.1	22.8	25.0	0.09
Ferry-RoPax	0-1999	GT	556.0	682.7	439.0	1064.5	0.92	411.1	553.4	269.1	873.8	1.09	126.0	142.8	102.8	187.8	0.60	1.3	1.4	0.9	2.2	0.97
	2000-4999	GT	339.0	354.6	202.5	804.2	1.70	249.0	254.7	153.5	421.9	1.05	196.8	194.5	150.6	273.3	0.63	2.3	2.0	1.3	3.3	0.98
	5000-9999	GT	237.6	284.3	157.0	597.4	1.55	158.6	189.4	103.7	457.5	1.87	334.3	335.0	267.8	434.5	0.50	4.8	4.2	2.7	6.6	0.92
	10000-1999(	GT	165.0	219.6	134.0	338.3	0.93	125.1	143.5	98.3	226.9	0.90	493.8	501.0	411.7	660.0	0.50	7.1	7.1	5.7	9.3	0.50
	20000-+	GT	149.1	160.6	113.9	231.6	0.73	114.7	121.8	84.6	172.9	0.72	734.6	696.2	585.7	890.4	0.44	12.5	11.9	9.1	16.3	0.60
Refrigerated bulk	0-1999	dwt	175.8	178.3	124.5	257.4	0.75	146.3	141.9	101.8	221.3	0.84	174.3	169.1	143.2	231.8	0.52	1.6	1.7	1.2	2.1	0.49
	2000-5999	dwt	102.8	106.4	82.2	140.2	0.55	70.0	71.4	56.7	95.3	0.54	284.3	284.1	235.1	341.8	0.38	3.3	3.2	2.8	3.9	0.33
	6000-9999	dwt	72.1	75.1	64.3	87.9	0.31	42.7	44.0	38.1	53.9	0.36	327.8	331.8	298.2	379.4	0.24	4.7	4.6	4.0	5.4	0.30
	10000-+	dwt	57.8	61.4	50.3	71.9	0.35	35.3	36.2	31.4	40.8	0.26	442.2	427.0	400.0	479.8	0.19	7.3	7.1	6.4	7.9	0.20
Ro-Ro	0-4999	dwt	130.6	228.8	114.7	654.4	2.36	98.0	175.3	78.7	517.1	2.50	250.2	275.8	185.1	456.2	0.98	2.1	2.2	1.4	3.6	1.00
	5000-9999	dwt	70.4	64.7	55.4	92.7	0.58	48.0	45.4	36.3	61.5	0.55	349.3	324.9	244.7	412.4	0.52	4.6	4.2	2.7	5.7	0.72
	10000-1499(	dwt	54.2	54.2	44.3	63.9	0.36	37.5	38.7	30.6	45.1	0.37	466.9	451.0	388.3	519.9	0.29	7.2	7.2	5.4	8.9	0.50
	15000-+	dwt	28.6	27.4	21.0	42.9	0.80	19.6	17.0	14.1	30.2	0.95	535.6	541.0	413.6	641.1	0.42	8.1	8.3	6.3	9.8	0.42
Vehicle	0-29999	GT	130.8	131.6	104.1	202.2	0.75	42.4	50.2	36.5	66.5	0.60	262.4	249.9	204.0	300.7	0.39	3.6	3.4	2.6	4.4	0.54
	30000-4999(	GT	70.4	69.9	61.5	78.3	0.24	21.2	21.3	18.8	24.6	0.27	291.3	290.9	266.5	306.9	0.14	4.4	4.4	3.9	4.7	0.18
	50000-+	GT	58.4	58.4	49.6	69.4	0.34	16.5	16.6	15.1	18.5	0.20	348.4	341.3	314.9	371.9	0.17	5.5	5.4	4.8	6.1	0.23
Yacht	0-+	GT	428.3	607.1	417.4	926.7	0.84	369.5	516.6	349.7	797.0	0.87	92.2	72.2	54.8	98.1	0.60	1.1	0.9	0.6	1.3	0.79
Service - tug	0-+	GT	187.6	354.8	144.9	710.0	1.59	148.0	277.6	113.2	583.4	1.69	137.9	127.9	86.1	179.2	0.73	0.9	0.9	0.5	1.4	0.98
Miscellaneous - fishing	0-+	GT	130.8	285.6	148.9	683.0	1.87	110.2	249.8	129.3	611.9	1.93	86.6	82.3	66.5	108.2	0.51	0.7	0.7	0.5	0.9	0.73
Offshore	0-+	GT	35.8	196.6	106.6	497.7	1.99	19.5	128.9	68.7	347.4	2.16	317.2	270.0	172.9	427.8	0.94	2.8	2.3	1.3	3.7	1.07
Service - other	0-+	GT	69.5	177.7	76.0	481.0	2.28	50.5	138.3	56.6	360.7	2.20	200.7	168.1	117.4	275.5	0.94	1.7	1.4	0.9	2.3	1.00
Miscellaneous - other	0-+	GT	37.9	45.2	30.6	54.4	0.53	28.2	31.1	21.4	45.7	0.78	506.2	445.4	324.9	645.6	0.72	6.1	5.4	4.1	8.0	0.72

Carbon intensity per ship type and size category in year 2016 (Option 2)

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	34.9	39.5	28.4	62.5	0.86	20.6	22.3	17.0	29.2	0.55	113.8	111.8	87.0	136.6	0.44	1.0	1.0	0.7	1.3	0.56
	10000-3499	dwt	12.6	12.6	10.6	16.5	0.46	7.6	7.5	6.8	8.8	0.27	216.6	213.6	191.7	238.8	0.22	2.5	2.4	2.1	2.8	0.29
	35000-5999	dwt	9.1	9.2	8.0	11.0	0.33	5.4	5.5	4.9	6.1	0.22	272.8	273.8	245.4	305.6	0.22	3.2	3.2	2.8	3.6	0.26
	60000-9999	dwt	8.0	7.9	6.9	9.3	0.30	4.1	4.1	3.7	4.6	0.22	317.5	309.6	284.4	350.5	0.21	3.7	3.6	3.2	4.1	0.25
	100000-199	dwt	5.4	5.3	4.7	6.3	0.30	2.7	2.7	2.4	3.1	0.24	463.7	457.4	410.0	515.0	0.23	5.2	5.1	4.4	5.9	0.30
	200000-+	dwt	4.9	5.0	4.3	5.9	0.31	2.4	2.4	2.1	2.7	0.23	609.1	573.2	485.0	719.4	0.41	7.3	7.1	5.5	8.8	0.47
Chemical tanker	0-4999	dwt	55.1	57.3	42.8	98.3	0.97	44.1	44.9	33.3	81.6	1.08	150.6	143.1	114.8	223.0	0.76	1.5	1.4	1.1	2.0	0.60
	5000-9999	dwt	36.9	37.9	31.4	47.3	0.42	27.8	28.5	23.2	35.1	0.42	206.1	201.5	177.6	241.3	0.32	2.2	2.2	1.9	2.7	0.37
	10000-1999	dwt	23.8	25.4	20.4	32.5	0.48	16.9	17.7	14.6	21.6	0.39	263.8	263.9	229.4	308.2	0.30	3.1	3.2	2.7	3.7	0.31
	20000-3999	dwt	16.4	16.9	14.5	19.9	0.32	11.5	11.6	10.1	13.9	0.32	374.4	375.1	328.4	443.9	0.31	4.7	4.8	4.1	5.4	0.28
	40000-+	dwt	12.4	12.3	11.0	14.3	0.27	7.8	7.8	7.0	8.8	0.24	380.5	378.8	344.4	418.7	0.20	4.7	4.7	4.2	5.3	0.23
Container	0-999	TEU	35.0	35.9	30.2	44.5	0.40	23.1	23.7	19.7	28.4	0.37	218.8	214.1	186.1	246.1	0.28	2.8	2.7	2.2	3.3	0.40
	1000-1999	TEU	27.3	28.1	24.3	32.8	0.30	17.0	17.5	15.1	20.6	0.31	325.1	321.7	281.3	366.1	0.26	4.5	4.4	3.7	5.2	0.34
	2000-2999	TEU	20.4	20.1	17.5	23.7	0.31	11.7	11.3	10.2	13.2	0.27	407.1	393.7	357.2	446.2	0.23	5.8	5.6	4.8	6.8	0.34
	3000-4999	TEU	17.3	17.3	15.3	19.9	0.27	10.6	10.4	9.4	11.8	0.24	562.0	535.9	479.1	622.7	0.27	8.5	8.0	6.8	9.9	0.38
	5000-7999	TEU	16.6	16.5	14.7	18.9	0.25	9.8	9.7	8.8	11.0	0.23	732.9	734.7	650.6	818.5	0.23	11.6	11.6	10.1	13.4	0.29
	8000-11999	TEU	13.4	13.4	12.1	15.0	0.21	8.1	8.1	7.3	9.0	0.22	887.4	885.0	819.9	948.9	0.15	14.5	14.4	13.1	16.0	0.20
	12000-1449	TEU	10.5	10.2	9.5	11.5	0.20	6.9	6.8	6.4	7.3	0.12	1031.8	1017.0	941.0	1111.9	0.17	17.0	16.9	15.2	18.6	0.20
	14500-1999	TEU	8.2	8.5	6.9	9.3	0.28	5.5	5.9	4.8	6.3	0.26	1019.7	1094.1	854.7	1186.4	0.30	17.6	17.8	15.0	21.1	0.35
General cargo	0-4999	dwt	34.6	36.1	28.6	48.8	0.56	23.2	23.2	18.9	29.9	0.47	74.8	70.5	60.0	82.6	0.32	0.7	0.6	0.5	0.7	0.45
	5000-9999	dwt	31.1	31.4	25.6	41.4	0.50	19.2	18.9	16.1	22.6	0.34	138.5	130.2	111.8	154.8	0.33	1.4	1.3	1.0	1.6	0.47
	10000-1999	dwt	30.4	29.2	24.5	39.2	0.51	16.9	16.7	14.8	19.0	0.26	229.4	213.7	189.4	256.6	0.31	2.7	2.5	2.1	3.2	0.42
	20000-+	dwt	14.9	15.1	11.8	20.3	0.57	8.5	8.7	7.0	11.1	0.47	309.7	293.6	256.5	340.7	0.29	3.8	3.6	3.0	4.3	0.36
Liquefied gas tanker	0-49999	cbm	43.0	61.0	42.1	82.9	0.67	21.1	34.1	20.4	49.1	0.84	237.9	223.6	178.0	290.7	0.50	3.0	2.7	2.1	3.8	0.66
	50000-9999	cbm	20.9	21.3	18.6	25.3	0.31	9.6	9.6	8.8	10.7	0.20	507.0	511.6	472.3	560.2	0.17	7.4	7.6	6.9	8.2	0.17
	100000-199	cbm	16.4	16.4	13.6	19.7	0.37	11.1	10.6	9.1	12.9	0.35	900.4	868.0	756.5	1006.5	0.29	13.2	12.3	10.1	15.5	0.44
	200000-+	cbm	17.5	17.1	15.3	24.0	0.51	10.6	10.3	10.0	11.8	0.18	1302.5	1291.4	1223.3	1333.7	0.09	21.0	20.9	19.8	22.0	0.11
Oil tanker	0-4999	dwt	77.8	103.6	55.0	228.8	1.68	54.8	73.0	37.5	165.7	1.76	175.9	199.7	125.8	407.6	1.41	1.5	1.6	1.1	2.9	1.16
	5000-9999	dwt	50.6	58.9	38.7	126.1	1.48	32.9	34.3	26.1	59.3	0.97	225.9	230.2	177.7	400.1	0.97	2.1	2.1	1.6	3.3	0.80
	10000-1999	dwt	40.9	49.5	29.9	101.6	1.45	22.7	23.4	17.6	38.3	0.88	322.9	329.3	247.6	537.1	0.88	3.3	3.3	2.6	5.1	0.75
	20000-5999	dwt	22.4	22.5	18.2	31.8	0.61	10.2	9.9	8.6	12.9	0.43	460.4	453.0	401.5	527.5	0.28	5.5	5.4	4.9	6.4	0.29
	60000-7999	dwt	14.6	14.5	12.6	17.3	0.32	7.0	6.9	6.2	7.8	0.23	511.9	508.2	458.5	558.9	0.20	6.3	6.2	5.6	7.0	0.24
	80000-1199	dwt	11.9	12.0	10.0	15.4	0.45	5.3	5.2	4.7	5.9	0.23	576.4	565.3	506.7	638.6	0.23	6.8	6.6	5.9	7.5	0.25
	120000-199	dwt	9.4	9.0	7.7	11.3	0.39	4.4	4.2	3.9	4.8	0.21	695.6	662.1	613.3	750.3	0.21	8.2	8.0	7.2	9.1	0.23
	200000-+	dwt	5.7	5.7	4.9	6.7	0.33	2.9	2.8	2.6	3.1	0.17	891.3	862.8	792.4	952.3	0.19	11.2	10.8	9.7	12.3	0.24

Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	895.4	1311.8	805.3	2105.6	0.99	761.2	1123.0	685.2	1921.4	1.10	248.7	704.1	389.2	970.8	0.83	2.0	4.4	2.5	5.7	0.74
	1000-+	dwt	26.4	28.0	22.6	111.0	3.15	16.4	18.4	13.2	81.7	3.73	412.2	314.0	273.3	406.1	0.42	5.7	4.6	3.4	5.9	0.54
Ferry-pax only	0-299	GT	644.6	1430.1	850.9	1898.8	0.73	533.2	1290.2	730.6	1653.4	0.72	48.0	51.5	39.2	61.2	0.43	0.9	0.9	0.6	1.3	0.77
	300-999	GT	1390.4	1830.7	1160.3	2382.2	0.67	1198.8	1409.8	946.6	1878.3	0.66	76.9	71.7	57.3	94.7	0.52	1.7	1.4	1.0	2.2	0.85
	1000-1999	GT	355.9	272.0	235.6	427.8	0.71	233.3	222.0	192.5	270.8	0.35	109.7	109.8	80.0	132.0	0.47	1.0	1.0	0.8	1.1	0.36
	2000-+	GT	211.9	199.8	137.3	317.7	0.90	186.4	187.4	101.2	298.0	1.05	191.8	189.1	150.9	307.6	0.83	2.3	2.5	1.7	3.8	0.87
Cruise	0-1999	GT	544.8	819.1	501.5	1546.2	1.28	510.6	768.3	470.4	1400.5	1.21	160.7	172.3	129.6	234.8	0.61	1.4	1.6	1.2	2.2	0.63
	2000-9999	GT	226.7	327.1	190.0	1005.9	2.49	210.3	297.1	172.1	925.3	2.54	208.3	189.8	150.5	342.8	1.01	2.1	2.0	1.5	2.8	0.69
	10000-5999	GT	146.8	154.2	110.5	263.8	0.99	131.3	143.2	100.5	217.1	0.81	556.7	540.1	464.6	620.9	0.29	7.7	7.4	6.4	9.0	0.35
	60000-9999	GT	162.8	164.9	144.2	188.4	0.27	146.7	149.4	128.6	165.6	0.25	1204.0	1202.3	1119.3	1292.1	0.14	18.4	18.3	16.8	20.5	0.20
	100000-149	GT	140.6	143.2	127.1	163.9	0.26	128.3	133.5	115.6	151.0	0.27	1419.2	1398.7	1289.7	1511.5	0.16	23.2	22.9	21.0	25.2	0.18
	150000-+	GT	116.9	129.9	103.9	142.3	0.29	105.3	112.1	97.6	131.3	0.30	1429.1	1391.6	1305.4	1454.3	0.11	23.0	23.6	21.3	24.3	0.13
Ferry-RoPax	0-1999	GT	763.4	784.6	471.1	1484.6	1.29	519.4	553.2	318.3	1282.5	1.74	147.3	146.1	91.5	215.7	0.85	1.7	1.6	0.8	3.1	1.44
	2000-4999	GT	372.3	377.5	229.0	1036.6	2.14	286.0	265.7	181.5	562.1	1.43	219.8	213.3	169.7	277.3	0.50	2.8	2.4	1.6	3.3	0.72
	5000-9999	GT	209.5	288.1	151.5	543.1	1.36	160.1	202.5	92.8	355.1	1.30	341.7	321.3	253.8	396.1	0.44	4.7	3.7	2.3	5.8	0.95
	10000-1999	GT	154.0	177.9	116.7	302.8	1.05	114.8	132.2	89.8	201.3	0.84	457.5	448.8	376.2	543.7	0.37	6.4	6.3	5.1	8.1	0.48
	20000-+	GT	149.3	156.3	114.5	220.1	0.68	114.7	115.1	85.6	167.0	0.71	734.5	697.1	586.9	882.9	0.42	12.4	11.7	9.2	16.0	0.58
Refrigerated bulk	0-1999	dwt	164.8	189.0	127.1	382.4	1.35	134.6	158.1	110.7	353.0	1.53	180.3	198.5	141.8	261.6	0.60	1.7	1.8	1.3	2.5	0.69
	2000-5999	dwt	111.5	107.6	88.3	156.4	0.63	72.9	73.7	59.1	97.4	0.52	298.3	287.4	244.4	348.9	0.36	3.5	3.5	2.8	4.2	0.41
	6000-9999	dwt	79.6	84.6	71.2	109.2	0.45	46.0	49.9	40.4	60.4	0.40	353.3	376.0	314.0	427.6	0.30	5.1	5.2	4.3	6.2	0.38
	10000-+	dwt	59.1	63.2	51.4	76.2	0.39	35.4	36.3	31.8	40.8	0.25	444.2	433.9	401.5	475.2	0.17	7.3	7.2	6.5	7.8	0.18
Ro-Ro	0-4999	dwt	128.4	213.6	110.8	541.0	2.01	95.3	165.1	76.2	373.2	1.80	234.4	254.5	171.9	421.9	0.98	2.0	2.1	1.3	3.3	0.98
	5000-9999	dwt	68.4	64.6	53.1	85.6	0.50	47.8	44.3	36.0	60.9	0.56	350.5	342.8	249.5	401.4	0.44	4.7	4.3	2.8	5.8	0.72
	10000-1499	dwt	55.1	53.9	45.0	67.0	0.41	38.1	37.5	30.5	46.2	0.42	473.2	471.1	394.4	527.0	0.28	7.4	7.3	5.7	9.3	0.50
	15000-+	dwt	27.1	27.7	19.9	44.3	0.88	18.3	16.8	12.1	30.1	1.07	521.7	533.5	406.3	627.4	0.41	7.9	8.3	6.1	10.1	0.48
Vehicle	0-29999	GT	134.4	133.4	105.6	194.9	0.67	42.5	49.4	35.2	68.2	0.67	264.3	252.4	207.9	302.2	0.37	3.6	3.3	2.7	4.3	0.49
	30000-4999	GT	75.6	74.7	64.5	91.0	0.36	21.6	22.0	19.1	25.5	0.29	296.0	295.8	273.2	318.4	0.15	4.4	4.5	4.0	4.9	0.20
	50000-+	GT	58.8	59.2	50.1	73.0	0.39	16.6	16.7	15.3	18.5	0.19	348.2	339.9	319.0	371.7	0.15	5.5	5.4	5.0	5.9	0.18
Yacht	0-+	GT	426.3	609.9	411.9	920.7	0.83	378.3	528.4	354.8	795.7	0.83	95.2	71.3	54.6	96.6	0.59	1.1	0.8	0.6	1.2	0.74
Service - tug	0-+	GT	186.9	355.4	149.7	732.8	1.64	146.6	279.1	115.3	602.1	1.74	139.6	126.5	83.9	184.1	0.79	1.0	0.9	0.5	1.4	1.03
Miscellaneous - fishing	0-+	GT	128.3	295.5	148.7	706.1	1.89	108.6	255.6	129.4	632.6	1.97	85.2	81.3	65.6	106.3	0.50	0.7	0.7	0.5	0.9	0.74
Offshore	0-+	GT	52.5	210.6	115.3	515.5	1.90	26.1	137.3	72.4	343.9	1.98	311.0	277.9	177.7	451.6	0.99	2.7	2.3	1.4	3.9	1.10
Service - other	0-+	GT	70.8	168.0	81.8	474.5	2.34	51.6	129.2	58.5	377.6	2.47	206.3	171.9	118.7	281.5	0.95	1.8	1.4	0.9	2.4	1.07
Miscellaneous - other	0-+	GT	40.5	48.8	27.8	64.2	0.75	30.0	32.8	21.6	50.8	0.89	474.4	437.3	287.0	598.3	0.71	5.6	5.2	3.2	7.3	0.80

Carbon intensity per ship type and size category in year 2017 (Option 2)

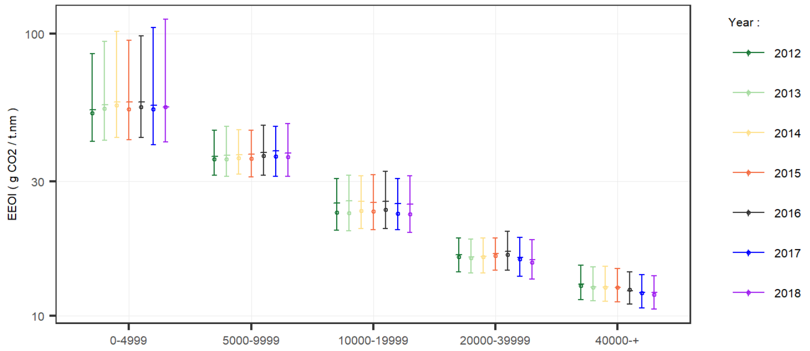
Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Bulk carrier	0-9999	dwt	33.9	38.2	27.1	59.6	0.85	20.1	21.9	16.8	28.6	0.54	110.4	109.8	85.1	137.6	0.48	1.0	1.0	0.7	1.4	0.63
	10000-3499(	dwt	12.1	12.1	10.3	15.2	0.40	7.5	7.4	6.7	8.6	0.26	215.6	210.6	190.6	235.3	0.21	2.4	2.4	2.1	2.8	0.29
	35000-5999(	dwt	9.0	9.1	7.8	10.7	0.32	5.4	5.4	4.9	6.0	0.22	268.7	270.2	240.8	298.6	0.21	3.1	3.1	2.7	3.5	0.25
	60000-9999(	dwt	7.8	7.7	6.8	9.0	0.28	4.1	4.1	3.7	4.5	0.21	311.9	304.0	279.4	339.5	0.20	3.6	3.5	3.2	4.0	0.23
	100000-199(	dwt	5.3	5.3	4.7	6.1	0.27	2.8	2.7	2.5	3.0	0.20	471.4	466.9	420.4	513.8	0.20	5.3	5.3	4.6	6.0	0.26
	200000-+	dwt	4.8	4.8	4.2	5.5	0.26	2.4	2.4	2.2	2.6	0.20	596.5	560.8	482.5	671.5	0.34	7.1	6.7	5.5	8.3	0.42
Chemical tanker	0-4999	dwt	53.9	55.7	40.5	105.1	1.16	40.9	41.9	31.5	70.1	0.92	140.1	135.9	108.7	192.8	0.62	1.4	1.4	1.0	1.8	0.59
	5000-9999	dwt	36.7	38.4	31.2	46.9	0.41	27.0	27.6	23.0	33.8	0.39	200.5	199.9	173.4	231.7	0.29	2.2	2.1	1.8	2.5	0.34
	10000-1999(	dwt	23.0	24.9	20.1	30.6	0.42	16.2	17.0	14.1	20.5	0.38	253.4	255.4	222.3	296.8	0.29	3.0	3.0	2.6	3.6	0.32
	20000-3999(	dwt	15.9	16.1	13.8	18.9	0.32	11.1	11.1	9.7	13.1	0.30	359.1	362.1	312.0	422.1	0.30	4.5	4.5	3.9	5.1	0.27
	40000-+	dwt	12.0	12.1	10.7	14.0	0.27	7.5	7.6	6.6	8.5	0.24	366.3	366.4	328.0	403.9	0.21	4.5	4.4	4.0	5.0	0.23
Container	0-999	TEU	34.2	34.8	28.8	45.6	0.48	22.6	23.0	19.3	28.7	0.41	216.2	211.3	180.4	245.4	0.31	2.8	2.7	2.1	3.3	0.43
	1000-1999	TEU	26.5	27.3	23.6	31.5	0.29	16.7	17.1	14.7	20.0	0.31	319.5	314.8	276.2	356.7	0.26	4.4	4.3	3.6	5.0	0.33
	2000-2999	TEU	19.8	19.6	17.0	22.5	0.28	11.8	11.2	10.2	13.1	0.27	408.6	389.9	355.6	439.8	0.22	5.9	5.6	4.8	6.6	0.32
	3000-4999	TEU	17.3	17.1	15.1	19.7	0.27	10.6	10.4	9.2	11.8	0.25	561.5	530.8	475.7	618.1	0.27	8.5	8.0	6.8	9.6	0.35
	5000-7999	TEU	16.6	16.6	14.9	18.3	0.20	10.3	10.2	9.0	11.4	0.23	771.7	773.1	665.0	857.3	0.25	12.6	12.5	10.4	14.6	0.33
	8000-11999	TEU	13.5	13.7	12.3	15.1	0.21	8.3	8.4	7.5	9.2	0.20	913.1	910.6	840.9	989.3	0.16	15.2	15.0	13.7	17.0	0.22
	12000-1449(	TEU	10.6	10.5	9.6	11.5	0.18	6.9	6.9	6.4	7.4	0.15	1025.4	1041.5	933.3	1142.2	0.20	17.1	17.3	15.2	19.5	0.25
	14500-1999(	TEU	8.2	8.3	7.3	8.9	0.20	5.6	5.7	4.7	6.0	0.23	1024.4	1089.8	835.0	1152.2	0.29	17.4	18.4	14.5	20.0	0.30
	20000-+	TEU	8.0	9.1	6.4	11.1	0.52	4.2	4.0	3.3	7.2	0.95	819.4	767.4	639.0	1365.4	0.95	12.5	12.2	10.1	23.8	1.12
General cargo	0-4999	dwt	33.7	35.4	28.0	47.6	0.55	22.8	22.7	18.7	29.2	0.46	74.0	69.9	59.2	81.6	0.32	0.6	0.6	0.5	0.7	0.45
	5000-9999	dwt	30.3	30.7	25.0	39.8	0.48	18.9	18.7	16.0	22.6	0.35	136.9	128.9	110.8	154.2	0.34	1.4	1.3	1.0	1.6	0.48
	10000-1999(	dwt	28.1	27.9	23.2	35.2	0.43	16.5	16.4	14.5	18.7	0.26	225.2	209.5	184.7	255.2	0.34	2.6	2.4	2.0	3.1	0.43
	20000-+	dwt	13.9	14.1	11.2	19.0	0.55	8.3	8.5	6.8	10.9	0.48	306.5	292.5	251.2	336.7	0.29	3.7	3.6	3.0	4.2	0.34
Liquefied gas tanker	0-49999	cbm	39.8	58.2	41.1	80.2	0.67	19.8	32.2	18.9	45.2	0.82	231.5	217.6	166.3	286.4	0.55	2.9	2.6	1.9	3.7	0.68
	50000-9999(	cbm	20.5	20.7	17.9	25.4	0.36	9.4	9.4	8.6	10.4	0.20	500.7	495.2	467.9	537.5	0.14	7.2	7.3	6.7	7.9	0.17
	100000-199(	cbm	16.3	16.3	13.5	19.2	0.34	10.8	10.4	9.1	12.3	0.30	890.4	860.7	755.1	1009.3	0.30	13.2	12.6	10.5	15.5	0.40
	200000-+	cbm	17.8	17.6	14.8	25.0	0.58	10.4	10.1	9.7	11.5	0.18	1273.3	1251.1	1197.7	1308.8	0.09	20.3	19.9	19.0	21.3	0.12
Oil tanker	0-4999	dwt	78.5	109.1	53.5	283.3	2.10	54.0	67.9	37.4	170.7	1.96	172.2	182.5	120.0	377.9	1.41	1.5	1.5	1.0	2.6	1.03
	5000-9999	dwt	50.6	59.8	39.9	112.6	1.22	31.8	32.8	25.7	57.6	0.97	220.7	226.4	175.2	374.5	0.88	2.1	2.1	1.6	3.0	0.70
	10000-1999(	dwt	34.1	42.1	26.0	81.2	1.31	20.6	21.6	16.7	31.5	0.68	301.7	305.7	243.1	434.5	0.63	3.1	3.2	2.4	4.0	0.50
	20000-5999(	dwt	22.2	23.0	18.1	32.5	0.63	9.7	9.3	8.2	11.9	0.40	435.5	422.4	380.7	496.1	0.27	5.2	5.0	4.5	5.7	0.25
	60000-7999(	dwt	14.3	14.4	11.9	18.0	0.42	6.6	6.6	5.9	7.4	0.23	484.1	479.5	436.0	538.0	0.21	5.8	5.7	5.2	6.5	0.23
	80000-1199(	dwt	11.6	11.6	9.6	15.0	0.47	5.0	4.9	4.4	5.6	0.25	549.1	533.7	485.3	608.8	0.23	6.3	6.2	5.5	7.1	0.26
	120000-199(	dwt	8.9	8.6	7.3	10.7	0.39	4.3	4.1	3.8	4.6	0.20	675.6	646.5	599.6	718.6	0.18	7.9	7.7	6.9	8.6	0.22
	200000-+	dwt	5.5	5.5	4.6	6.6	0.36	2.8	2.7	2.5	3.0	0.20	851.9	834.6	750.8	926.0	0.21	10.4	10.2	8.9	11.6	0.27

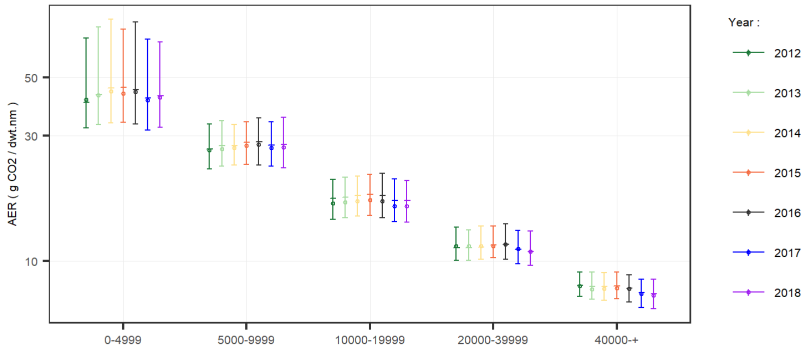
Ship type	Size category	Units	EEOI (gCO2/t.nm)					AER (gCO2/t.nm)					DIST (kgCO2/nm)					TIME (tCO2/h)				
			mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale	mean	median	lower quartile	upper quartile	spread scale
Other liquids	0-999	dwt	1185.5	1116.2	1065.1	1389.2	0.29	871.6	1042.3	873.5	1232.6	0.34	456.2	501.4	426.8	696.8	0.54	3.0	3.3	2.8	4.3	0.44
	1000-+	dwt	24.0	23.0	19.0	46.2	1.18	15.6	16.8	13.2	25.3	0.72	411.5	313.1	287.6	423.1	0.43	5.7	4.7	3.8	6.3	0.54
Ferry-pax only	0-299	GT	864.5	1175.6	801.7	1780.4	0.83	689.7	1046.2	699.8	1580.7	0.84	46.3	46.1	37.1	54.8	0.38	0.8	0.7	0.6	1.2	0.83
	300-999	GT	1119.3	1527.9	1053.0	2016.2	0.63	874.8	1216.5	774.9	1541.9	0.63	62.8	63.5	46.7	77.2	0.48	1.2	1.2	0.7	1.7	0.84
	1000-1999	GT	140.8	343.7	183.8	511.2	0.95	104.3	160.2	147.5	322.4	1.09	84.0	103.2	91.4	116.6	0.24	0.7	0.9	0.9	0.9	0.06
	2000-+	GT	176.3	245.2	134.9	455.1	1.31	145.8	230.0	118.3	426.6	1.34	179.3	191.2	146.9	296.8	0.78	2.0	2.1	1.6	4.2	1.26
Cruise	0-1999	GT	709.3	1152.9	517.6	1781.3	1.10	662.8	1063.2	485.5	1670.9	1.11	246.1	214.9	142.4	392.7	1.17	2.2	1.9	1.4	3.1	0.91
	2000-9999	GT	214.9	312.9	192.4	753.4	1.79	197.7	285.4	166.1	707.4	1.90	201.9	196.2	149.6	287.0	0.70	2.0	1.9	1.6	2.8	0.64
	10000-59999	GT	149.4	155.9	107.9	262.1	0.99	132.3	144.0	100.9	222.2	0.84	566.2	541.6	462.4	625.6	0.30	7.8	7.7	6.4	9.0	0.33
	60000-99999	GT	162.3	168.6	139.6	186.4	0.28	146.2	147.2	127.6	170.3	0.29	1193.8	1197.5	1120.8	1288.6	0.14	18.4	18.4	16.8	20.6	0.20
	100000-149999	GT	139.3	146.3	122.9	162.0	0.27	126.6	135.9	112.0	148.4	0.27	1409.3	1374.1	1305.9	1500.1	0.14	22.9	22.5	20.5	24.6	0.18
	150000-+	GT	109.4	125.6	94.5	138.8	0.35	96.7	106.7	88.7	123.7	0.33	1374.5	1333.2	1285.0	1468.9	0.14	21.6	21.6	20.9	24.1	0.15
Ferry-RoPax	0-1999	GT	387.9	573.6	293.5	1410.2	1.95	326.8	414.8	254.8	1133.7	2.12	113.9	119.7	97.7	158.3	0.51	1.3	1.2	0.8	2.4	1.29
	2000-4999	GT	354.4	325.7	221.8	784.6	1.73	287.5	243.0	196.6	542.6	1.42	195.7	194.6	171.7	235.6	0.33	2.3	1.9	1.5	2.7	0.64
	5000-9999	GT	245.7	308.0	142.5	614.8	1.53	174.4	211.6	107.5	422.8	1.49	335.5	301.2	237.5	394.4	0.52	4.7	3.7	2.3	6.8	1.21
	10000-19999	GT	149.3	192.1	113.0	284.6	0.89	110.9	124.8	84.0	194.0	0.88	437.2	437.2	343.3	548.0	0.47	6.0	6.2	4.8	8.0	0.53
	20000-+	GT	143.4	154.3	112.9	216.3	0.67	110.3	114.2	81.1	160.7	0.70	707.1	668.4	563.5	849.1	0.43	11.8	11.0	8.8	15.1	0.57
Refrigerated bulk	0-1999	dwt	184.3	207.3	127.6	402.1	1.32	145.5	165.1	101.0	295.5	1.18	160.4	159.1	124.3	248.9	0.78	1.5	1.5	1.2	2.1	0.63
	2000-5999	dwt	109.9	109.2	88.1	168.1	0.73	70.9	72.1	57.0	97.8	0.57	289.6	287.0	240.6	350.8	0.38	3.3	3.3	2.7	4.2	0.46
	6000-9999	dwt	79.9	84.2	69.2	103.0	0.40	46.4	48.7	41.2	60.4	0.39	356.5	366.0	314.1	433.3	0.33	5.0	5.0	4.3	6.0	0.34
	10000-+	dwt	59.0	62.6	50.1	76.4	0.42	36.1	37.1	32.4	42.0	0.26	453.6	443.3	414.2	497.4	0.19	7.4	7.3	6.7	8.1	0.20
Ro-Ro	0-4999	dwt	139.2	238.7	107.3	559.8	1.90	97.9	170.1	82.7	375.1	1.72	239.1	248.6	170.2	438.3	1.08	2.0	1.9	1.3	3.3	1.06
	5000-9999	dwt	70.1	67.8	54.7	92.7	0.56	48.4	46.7	38.1	62.1	0.51	356.0	342.4	273.7	408.7	0.39	4.7	4.4	2.8	5.8	0.68
	10000-14999	dwt	53.8	51.4	43.7	65.2	0.42	38.3	37.1	30.6	45.5	0.40	475.3	462.5	385.5	531.7	0.32	7.4	7.4	5.4	9.4	0.53
	15000-+	dwt	26.6	26.6	17.7	41.7	0.90	18.8	18.5	12.7	28.7	0.86	531.0	527.5	415.4	652.7	0.45	8.1	8.0	6.4	10.1	0.46
Vehicle	0-29999	GT	135.8	146.2	106.3	198.0	0.63	43.5	50.5	35.9	70.4	0.68	266.3	252.9	203.2	299.2	0.38	3.6	3.3	2.5	4.5	0.61
	30000-49999	GT	72.4	72.8	64.0	82.8	0.26	21.3	21.4	19.2	24.6	0.25	292.4	292.5	265.7	311.4	0.16	4.4	4.4	4.0	4.8	0.19
	50000-+	GT	58.3	59.9	49.9	70.6	0.34	16.5	16.6	15.2	18.6	0.21	347.3	340.8	314.8	371.9	0.17	5.5	5.4	4.9	6.0	0.20
Yacht	0-+	GT	426.8	584.3	393.1	896.8	0.86	370.4	506.2	334.7	765.2	0.85	89.0	68.5	51.6	93.6	0.61	1.0	0.8	0.5	1.2	0.80
Service - tug	0-+	GT	194.5	382.7	158.0	758.4	1.57	153.3	296.4	121.0	611.5	1.65	132.0	121.7	79.1	180.2	0.83	0.9	0.8	0.5	1.3	1.04
Miscellaneous - fishing	0-+	GT	118.4	255.9	135.9	629.9	1.93	97.9	207.7	111.7	512.5	1.93	84.1	80.0	64.9	105.5	0.51	0.7	0.6	0.5	0.9	0.73
Offshore	0-+	GT	73.2	199.2	106.3	470.7	1.83	43.8	119.6	66.6	310.9	2.04	303.2	272.9	171.2	438.9	0.98	2.6	2.2	1.3	3.7	1.09
Service - other	0-+	GT	56.9	164.2	72.2	490.0	2.54	41.8	127.9	51.9	360.9	2.42	207.3	173.8	116.5	283.2	0.96	1.7	1.4	0.9	2.3	1.04
Miscellaneous - other	0-+	GT	37.8	50.4	30.2	67.2	0.73	24.4	32.8	19.8	53.3	1.02	466.3	485.4	267.9	645.6	0.78	5.7	5.4	2.9	7.8	0.93

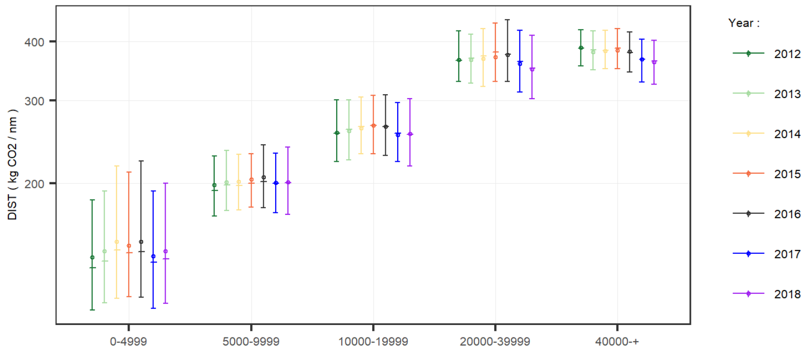
F Figures on carbon intensity ranges of typical ship types

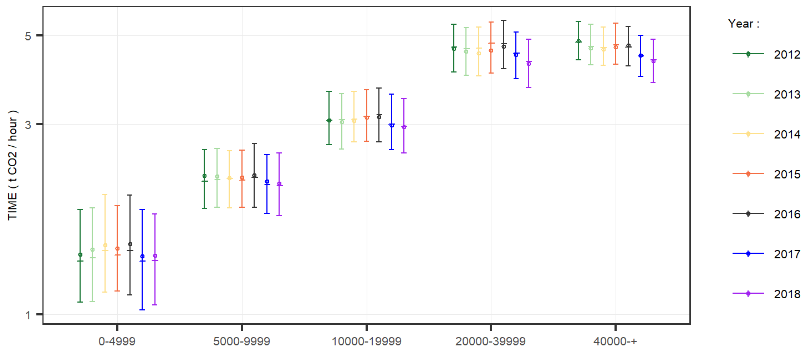
This annex presents figures on carbon intensity ranges of chemical tankers, container ships, general cargo ships, liquefied gas tankers, oil tankers and refridgerated bulk ships.

Chemical tanker

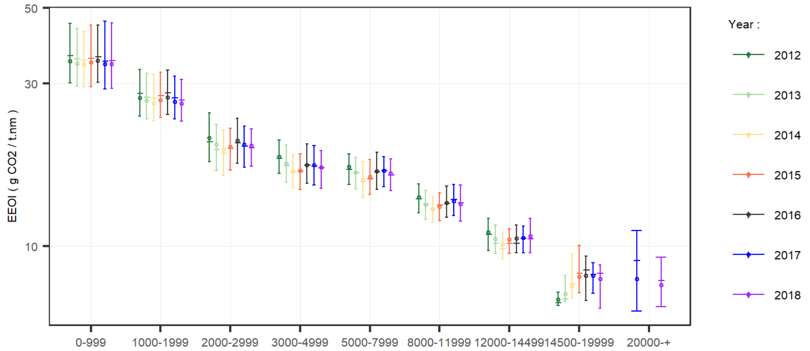


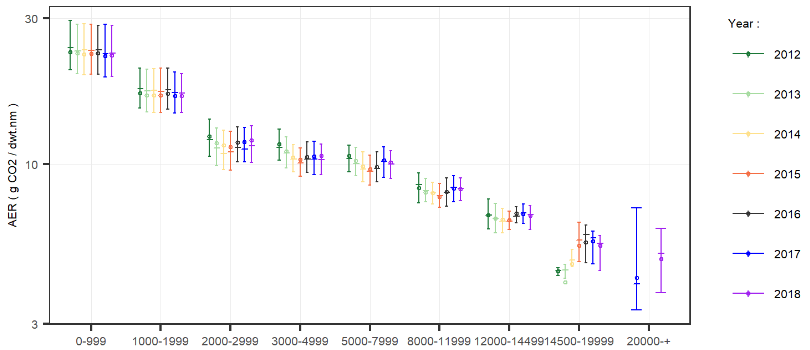


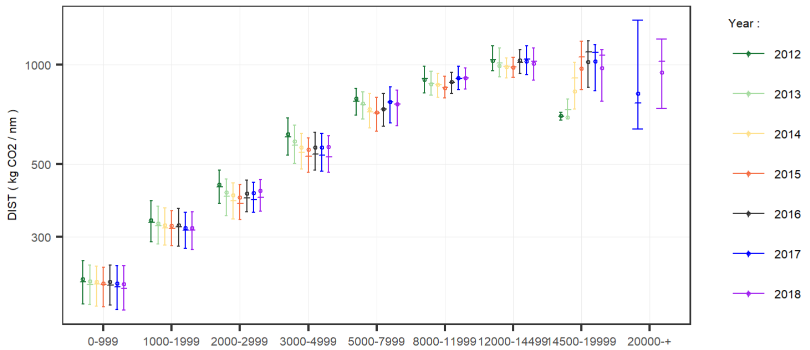


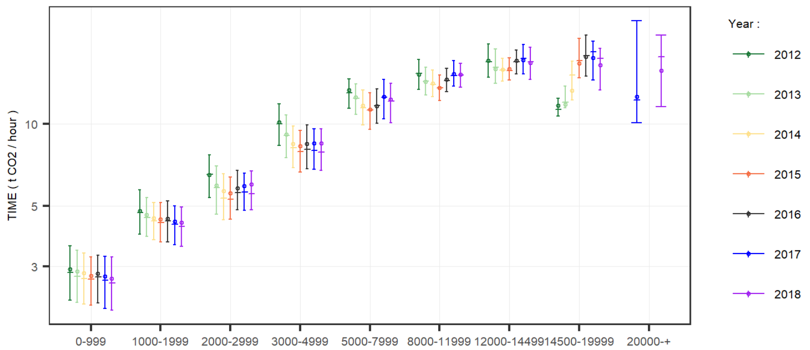


Container ship

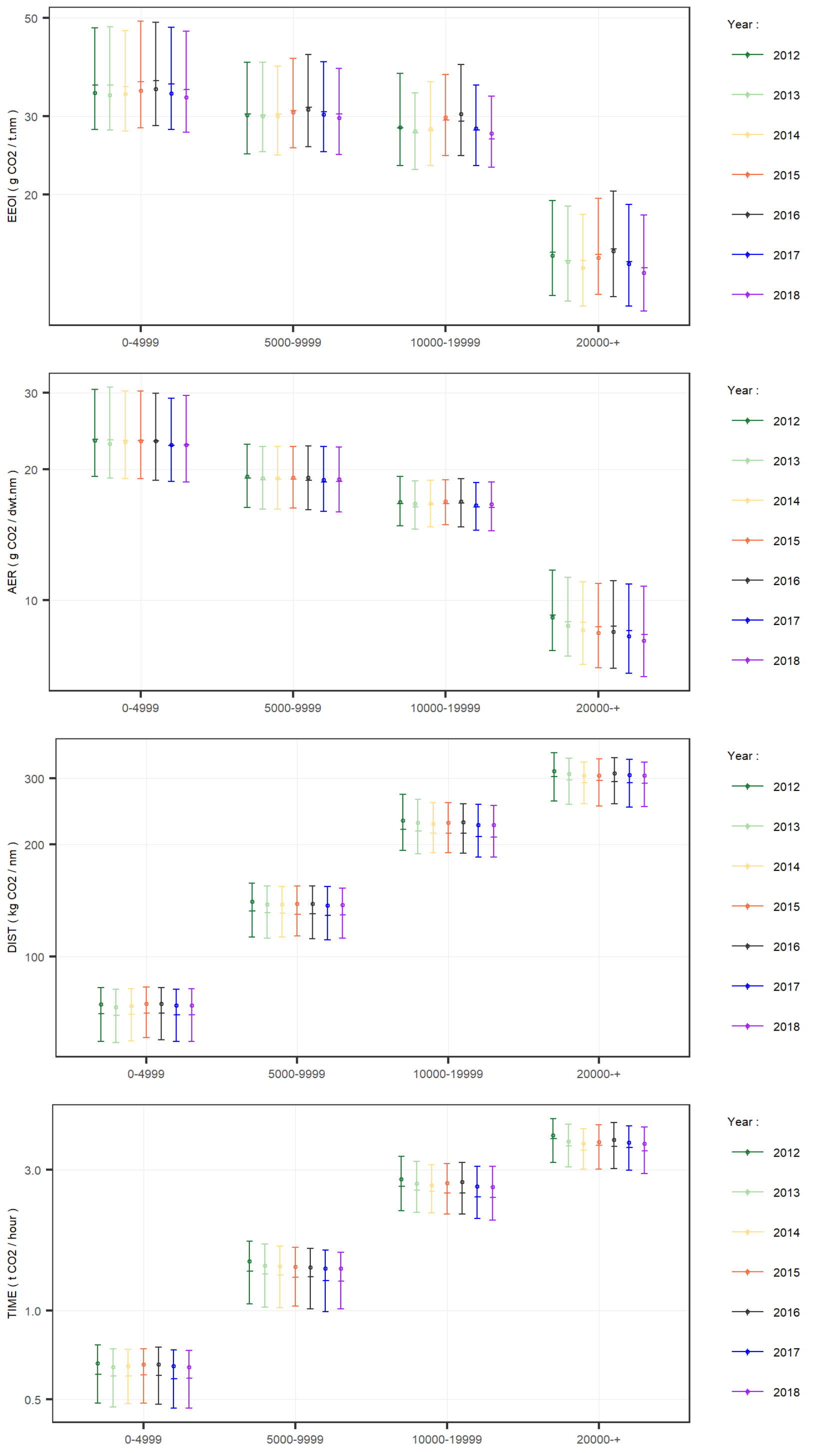




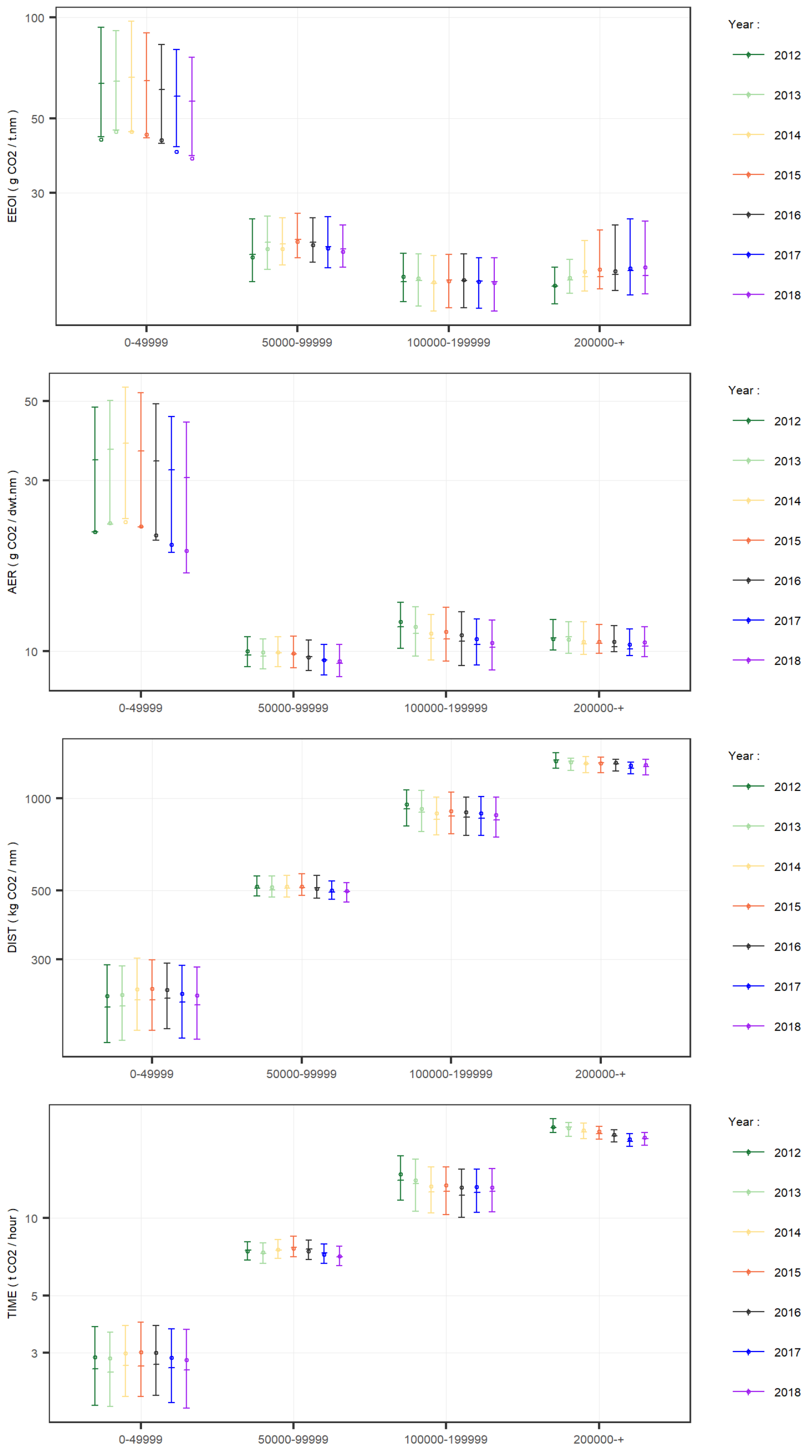




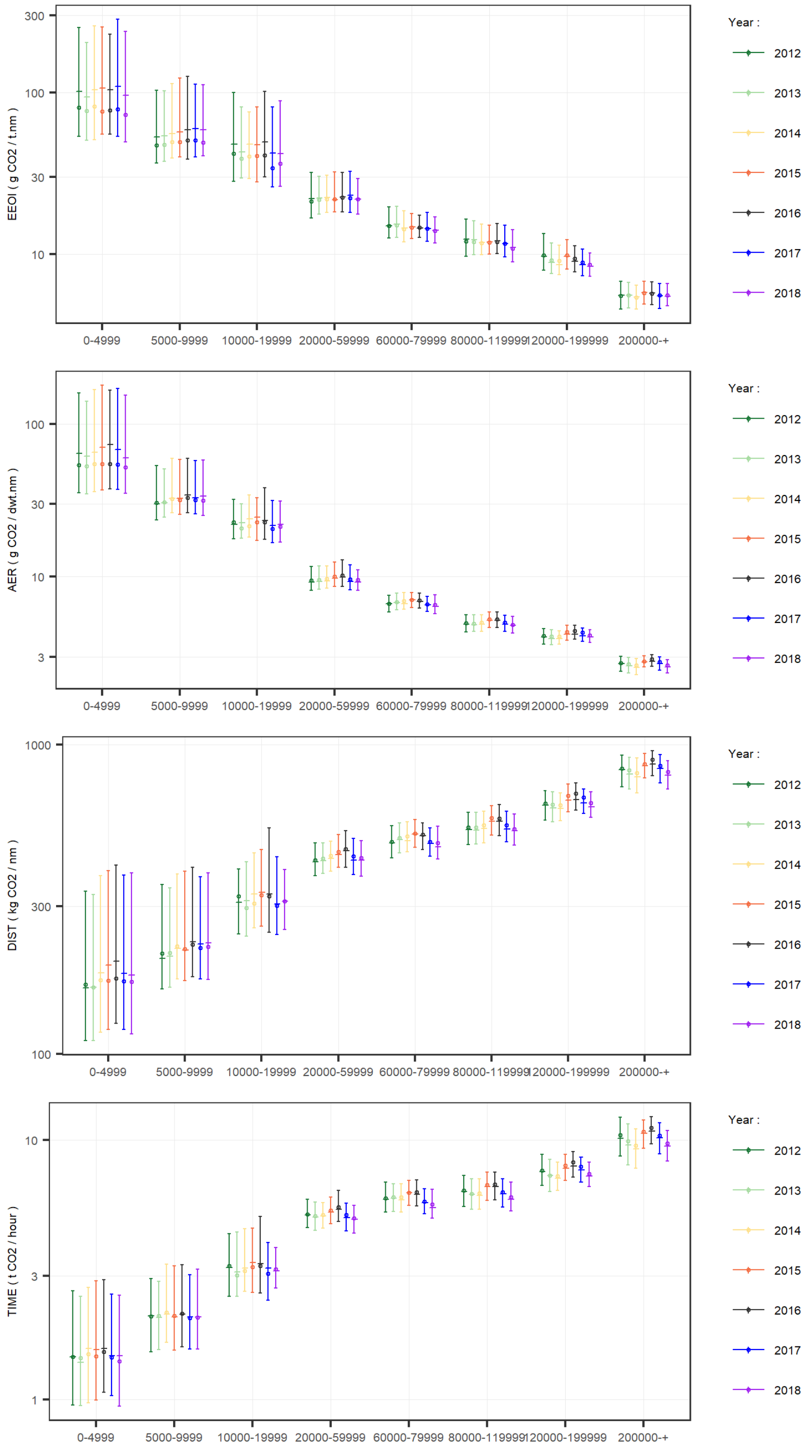
General cargo ship



Liquefied gas tanker

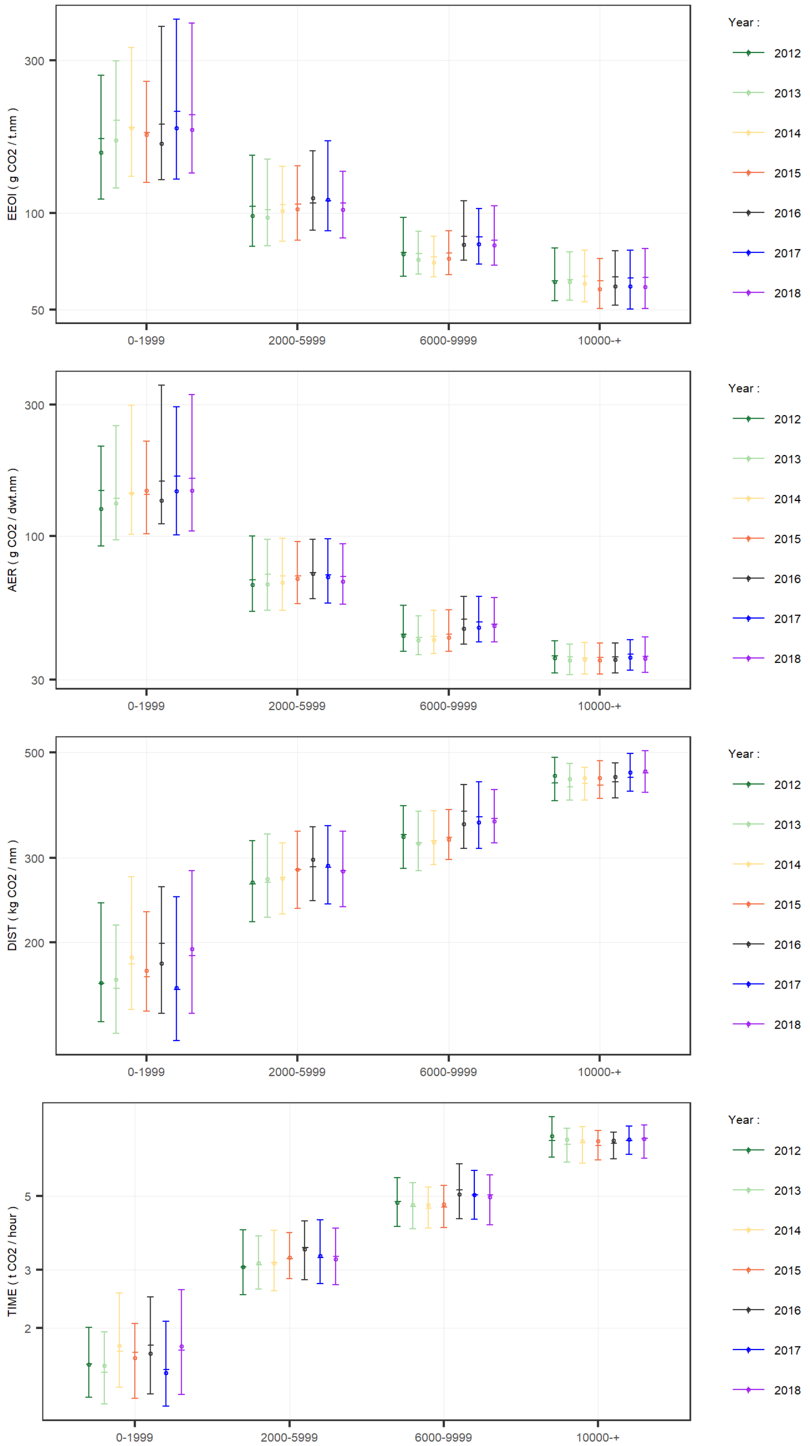


Oil tanker



EEOI (g CO2 / t.nm)
AER (g CO2 / dwt.nm)
DIST (kg CO2 / nm)
TIME (t CO2 / hour)
0-4999
5000-9999
10000-19999
20000-59999
60000-79999
80000-119999
120000-199999
200000-+
Year :
2012
2013
2014
2015
2016
2017
2018

Refrigerated bulk



G Proposed auxiliary engine and boiler power demand assumptions for the Fourth IMO GHG Study

Auxiliary engine power demand assumptions (unit: kW)

					Proposed Aux Engine Power Demand (kW)			
type_category	size_category	unit	type_bin	size_bin	Berth	Anchor	Maneuvering	Sea
Bulk carrier	0-9,999	dwt	1	1	150	250	680	260
Bulk carrier	10,000-34,999	dwt	1	2	150	250	680	260
Bulk carrier	35,000-59,999	dwt	1	3	200	340	920	360
Bulk carrier	60,000-99,999	dwt	1	4	320	550	1500	570
Bulk carrier	100,000-199,999	dwt	1	5	320	550	1500	570
Bulk carrier	200,000-+	dwt	1	6	320	550	1500	570
Chemical tanker	0-4,999	dwt	3	1	260	190	300	230
Chemical tanker	5,000-9,999	dwt	3	2	790	550	900	660
Chemical tanker	10,000-19,999	dwt	3	3	790	550	900	660
Chemical tanker	**20,000-39999**	**dwt**	**3**	**4**	1900	890	1250	890
Chemical tanker	**40,000-+**	**dwt**	**3**	**5**	1900	890	1250	890
Container	0-999	TEU	4	1	370	450	790	410
Container	1,000-1,999	TEU	4	2	820	910	1750	900
Container	2,000-2,999	TEU	4	3	610	910	1900	920
Container	3,000-4,999	TEU	4	4	1100	1350	2500	1400
Container	5,000-7,999	TEU	4	5	1100	1400	2800	1450
Container	8,000-11,999	TEU	4	6	1150	1600	2900	1800
Container	**12000-14499**	**TEU**	**4**	**7**	1300	1800	3250	2050
Container	**14500-19999**	**TEU**	**4**	**8**	1400	1950	3600	2300
Container	**20000-+**	**TEU**	**4**	**9**	1400	1950	3600	2300
General cargo	0-4,999	dwt	5	1	90	50	180	60
General cargo	5,000-9,999	dwt	5	2	240	130	490	180
General cargo	**10000-19999**	**dwt**	**5**	**3**	720	370	1450	520
General cargo	**20000-+**	**dwt**	**5**	**4**	720	370	1450	520
Liquefied gas tanker	0-49,999	cbm	6	1	240	240	360	240
Liquefied gas tanker	50000-99999	cbm	6	2	1700	1700	2600	1700
Liquefied gas tanker	**100000-199999**	**cbm**	**6**	**3**	2000	1900	2600	1750
Liquefied gas tanker	**200000-+**	**cbm**	**6**	**4**	2000	1900	2600	1750
Oil tanker	0-4,999	dwt	7	1	250	250	375	250
Oil tanker	5,000-9,999	dwt	7	2	375	375	560	375
Oil tanker	10,000-19,999	dwt	7	3	690	500	580	490
Oil tanker	20,000-59,999	dwt	7	4	720	520	600	510
Oil tanker	60,000-79,999	dwt	7	5	620	490	770	560
Oil tanker	80,000-119,999	dwt	7	6	800	640	910	690
Oil tanker	120,000-199,999	dwt	7	7	2500	770	1300	860
Oil tanker	200,000-+	dwt	7	8	2500	770	1300	860
Other liquids tankers	**0-999**	**dwt**	**8**	**1**	500	500	750	500
Other liquids tankers	**1000-+**	**dwt**	**8**	**2**	500	500	750	500
Ferry-pax only	**0-299**	**GT**	**9**	**1**	190	190	190	190
Ferry-pax only	**300-999**	**GT**	**9**	**2**	190	190	190	190
Ferry-pax only	**1000-1999**	**GT**	**9**	**3**	190	190	190	190
Ferry-pax only	2000-+	GT	9	4	520	520	520	520

Cruise	0-1,999	GT	10	1	450	450	580	450
Cruise	2,000-9,999	GT	10	2	450	450	580	450
Cruise	10,000-59,999	GT	10	3	3500	3500	5500	3500
Cruise	60,000-99,999	GT	10	4	5400	6400	9100	6300
Cruise	**100000-149999**	**GT**	**10**	**5**	11500	11500	14900	11500
Cruise	150000-+	GT	10	6	11500	11500	14900	11500
Ferry-RoPax	0-1999	GT	11	1	105	105	105	105
Ferry-RoPax	**2000-4999**	**GT**	**11**	**2**	330	330	330	330
Ferry-RoPax	**5000-9999**	**GT**	**11**	**3**	670	670	670	670
Ferry-RoPax	**10000-19999**	**GT**	**11**	**4**	1100	1100	1100	1100
Ferry-RoPax	**20000-+**	**GT**	**11**	**5**	1950	1950	1950	1950
Refrigerated bulk	**0-1999**	**dwt**	**12**	**1**	520	570	560	570
Refrigerated bulk	**2000-5999**	**dwt**	**12**	**2**	1100	1200	1150	1200
Refrigerated bulk	**6000-9999**	**dwt**	**12**	**3**	1500	1650	1600	1650
Refrigerated bulk	**10000-+**	**dwt**	**12**	**4**	2850	3100	3000	3100
Ro-Ro	0-4999	dwt	13	1	750	430	1300	430
Ro-Ro	**5000-9999**	**dwt**	**13**	**2**	1100	680	2100	680
Ro-Ro	**10000-14999**	**dwt**	**13**	**3**	1200	950	2700	950
Ro-Ro	**15000-+**	**dwt**	**13**	**4**	1200	950	2700	950
Vehicle	**0-29999**	**GT**	**14**	**1**	800	500	1100	500
Vehicle	**30000-49999**	**GT**	**14**	**2**	850	550	1400	510
Vehicle	**50000-+**	**GT**	**14**	**3**	850	550	1400	510
Yacht	0-+		15	1	130	130	130	130
Service - tug	0-+		16	1	100	80	210	80
Miscellaneous - fishing	0-+		17	1	200	200	200	200
Offshore	0-+		18	1	320	320	320	320
Service - other	0-+		19	1	220	220	220	220
Miscellaneous - other	0-+		20	1	150	150	430	410

Boiler power demand assumptions (unit: kW)

					Proposed Aux Boiler Power Demand (kW)			
type_category	size_category	unit	type_bin	size_bin	Berth	Anchor	Maneuvering	Sea
Bulk carrier	0-9,999	dwt	1	1	130	130	120	0
Bulk carrier	10,000-34,999	dwt	1	2	130	130	120	0
Bulk carrier	35,000-59,999	dwt	1	3	260	260	240	0
Bulk carrier	60,000-99,999	dwt	1	4	520	520	480	0
Bulk carrier	100,000-199,999	dwt	1	5	520	520	480	0
Bulk carrier	200,000-+	dwt	1	6	520	520	480	0
Chemical tanker	0-4,999	dwt	3	1	1350	320	270	0
Chemical tanker	5,000-9,999	dwt	3	2	1350	320	270	0
Chemical tanker	10,000-19,999	dwt	3	3	2000	480	410	0
Chemical tanker	**20,000-39999**	**dwt**	**3**	**4**	2700	640	540	0
Chemical tanker	**40,000-+**	**dwt**	**3**	**5**	2700	640	540	0
Container	0-999	TEU	4	1	250	250	240	0
Container	1,000-1,999	TEU	4	2	340	340	310	0
Container	2,000-2,999	TEU	4	3	460	450	430	0
Container	3,000-4,999	TEU	4	4	480	480	430	0
Container	5,000-7,999	TEU	4	5	590	580	550	0
Container	8,000-11,999	TEU	4	6	620	620	540	0
Container	**12000-14499**	**TEU**	**4**	**7**	630	630	630	0
Container	**14500-19999**	**TEU**	**4**	**8**	630	630	630	0
Container	**20000-+**	**TEU**	**4**	**9**	700	700	700	0
General cargo	0-4,999	dwt	5	1	0	0	0	0
General cargo	5,000-9,999	dwt	5	2	110	110	100	0
General cargo	**10000-19999**	**dwt**	**5**	**3**	150	150	130	0
General cargo	**20000-+**	**dwt**	**5**	**4**	150	150	130	0
Liquefied gas tanker	0-49,999	cbm	6	1	1000	200	200	100
Liquefied gas tanker	50000-99999	cbm	6	2	1000	200	200	100
Liquefied gas tanker	**100000-199999**	**cbm**	**6**	**3**	1500	300	300	150
Liquefied gas tanker	**200000-+**	**cbm**	**6**	**4**	3000	600	600	300
Oil tanker	0-4,999	dwt	7	1	500	100	100	0
Oil tanker	5,000-9,999	dwt	7	2	750	150	150	0
Oil tanker	10,000-19,999	dwt	7	3	1250	250	250	0
Oil tanker	20,000-59,999	dwt	7	4	2700	270	270	270
Oil tanker	60,000-79,999	dwt	7	5	3250	360	360	280
Oil tanker	80,000-119,999	dwt	7	6	4000	400	400	280
Oil tanker	120,000-199,999	dwt	7	7	6500	500	500	300
Oil tanker	200,000-+	dwt	7	8	7000	600	600	300
Other liquids tankers	**0-999**	**dwt**	**8**	**1**	1000	200	200	100
Other liquids tankers	**1000-+**	**dwt**	**8**	**2**	1000	200	200	100
Ferry-pax only	**0-299**	**GT**	**9**	**1**	0	0	0	0
Ferry-pax only	**300-999**	**GT**	**9**	**2**	0	0	0	0
Ferry-pax only	**1000-1999**	**GT**	**9**	**3**	0	0	0	0
Ferry-pax only	2000-+	GT	9	4	0	0	0	0
Cruise	0-1,999	GT	10	1	1100	950	980	0
Cruise	2,000-9,999	GT	10	2	280	240	250	0
Cruise	10,000-59,999	GT	10	3	1100	950	980	0
Cruise	60,000-99,999	GT	10	4	1100	950	980	0
Cruise	**100000-149999**	**GT**	**10**	**5**	1100	950	980	0
Cruise	150000-+	GT	10	6	1100	950	980	0
Ferry-RoPax	0-1999	GT	11	1	0	0	0	0
Ferry-RoPax	**2000-4999**	**GT**	**11**	**2**	0	0	0	0
Ferry-RoPax	**5000-9999**	**GT**	**11**	**3**	0	0	0	0
Ferry-RoPax	**10000-19999**	**GT**	**11**	**4**	0	0	0	0
Ferry-RoPax	**20000-+**	**GT**	**11**	**5**	0	0	0	0
Refrigerated bulk	**0-1999**	**dwt**	**12**	**1**	270	270	270	0
Refrigerated bulk	**2000-5999**	**dwt**	**12**	**2**	270	270	270	0
Refrigerated bulk	**6000-9999**	**dwt**	**12**	**3**	270	270	270	0
Refrigerated bulk	**10000-+**	**dwt**	**12**	**4**	270	270	270	0
Ro-Ro	0-4999	dwt	13	1	260	250	170	0
Ro-Ro	**5000-9999**	**dwt**	**13**	**2**	260	250	170	0
Ro-Ro	**10000-14999**	**dwt**	**13**	**3**	390	380	260	0
Ro-Ro	**15000-+**	**dwt**	**13**	**4**	390	380	260	0
Vehicle	**0-29999**	**GT**	**14**	**1**	310	300	250	0
Vehicle	**30000-49999**	**GT**	**14**	**2**	310	300	250	0
Vehicle	**50000-+**	**GT**	**14**	**3**	310	300	250	0
Yacht	0-+		15	1	0	0	0	0
Service - tug	0-+		16	1	0	0	0	0
Miscellaneous - fishing	0-+		17	1	0	0	0	0
Offshore	0-+		18	1	0	0	0	0
Service - other	0-+		19	1	0	0	0	0
Miscellaneous - other	0-+		20	1	110	110	90	0

H Choice of projection scenarios

H.1 Assumptions of SSP and RCP

In the Third IMO GHG Study (and in the Update of Maritime Greenhouse Gas Emission Projections Study 2017 – ISWG-GHG 1/2/3) the scenarios for estimating future emissions are based on Representative Concentration Pathways (RCP) and Shared Socio-Economic Pathways (SSP) which projects long-term changes in energy use and atmospheric concentrations and socio-economic parameters, respectively.

Initially a set of four RCPs[4] were produced that lead to radiative forcing levels of 8.5, 6, 4.5 and 2.6 W/m^2 (watts per square meter of the Earth`s surface) by the end of the century. The radiative forcing target levels named the RCPs: a) RCP 2.6 – mitigation scenario leading to a very low forcing level (compatible with 2°C warming limit); b) RCP 4.5 and RCP 6 – two medium stabilization; and, c) RCP 8.5 – a very high emission scenario.

After the adoption of the Paris Agreement, the RCPs were augmented by RCP 1.9, representing the mitigation pathways compatible with 1.5°C warming limit. In comparison to 2°C pathway (proxied by RCP 2.6), the 1.5°C pathway (compatible with RCP 1.9) characteristics are: (i) greater mitigation efforts on the demand side; (ii) energy efficiency improvements; (iii) CO_2 reductions beyond global net zero; (iv) additional GHG reductions mainly from CO_2; (v) rapid and profound near-term decarbonization of energy supply; (vi) higher mitigation costs; and (vii) comprehensive emission reductions implemented in the coming decade (Rogelj, et al., 2015). Each of the RCPs covers the 1,850–2,100 period, and extensions have been formulated for the period thereafter (up to 2,300).

The SSPs are based on five narratives describing alternative socio-economic developments, including sustainable development (SSP 1), middle-of-the-road development (SSP 2), regional rivalry (SSP 3), inequality (SSP 4) and fossil-fuelled development (SSP 5).

Based on the scenario matrix architecture (combination of RCPs and SSPs), Riahi et al. (2017) estimated the mitigation costs and carbon prices[5] of the four initial alternative forcing targets (RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5) across the SSPs and showed that not all combinations of RCP and SSP are possible.

Consistent with the narratives, mitigation costs and, thus, the challenge for mitigation is found lower in SSP1 and SSP4 relative to SSP3 and SSP5. Specifically, the 2.6 W/m^2 target was found by all Integrated Assessment Models[6] (IAMs) infeasible to reach from an SSP3 baseline,

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4 The socio-economic assumptions of the RCPs were based on individual model assumptions made within the context of the scenario selected from the literature meaning that there is no consistent design behind the position of the different RCPs relative to these parameters. Additionally, this implies that the socio-economic development pathway underlying each RCP should not be considered unique, in the sense that it is one of many possible scenarios that could be consistent with the concentration pathway (Vuuren, et al., 2011)

5 Mitigation costs are shown in terms of the net present value (NPV) of the average global carbon price over the course of the century. The price is calculated as the weighted average across regions using a discount rate of 5%.

6 The IAMs considered are: AIM, the Asia-pacific Integrated Model; GCAM4, the Global Change Assessment Model; IMAGE, the Integrated Model to Assess the Global Environment9; MESSAGE-GLOBIOM, the Model for Energy

and the WITCH-GLOBIOM model found it infeasible to reach the target in SSP5 (all other models reached 2.6 W/m^2 from SSP5). According to the authors, the fact that IAMs could not find a solution for some of the 2.6 W/m^2 scenarios may occur for different reasons, such as: (i) lack of mitigation options to reach the specified climate target; (ii) binding constraints for the diffusion of technologies; or (iii) extremely high price signals under which the modeling framework can no longer be solved. Thus, infeasibility in this case is an indication that under the specific socioeconomic and policy assumptions of the SSP3 scenario (and to a less extent also SSP5 scenario) the transformation cannot be achieved.

As Riahi et al. (2017), Rogelj et al. (2018) present a set of stringent climate change mitigation scenarios, consistent with an increase of 1.5°C in 2100 (RCP 1.9) and show that not all scenarios meet Paris agreement efforts. While all IAMs were able to produce
1.9 W/m^2 scenarios under SSP1, four IAMs were successful in SSP2, three in SSP4 and four in SSP5, none IAM was compatible with 1.9 W/m^2 under SSP3.

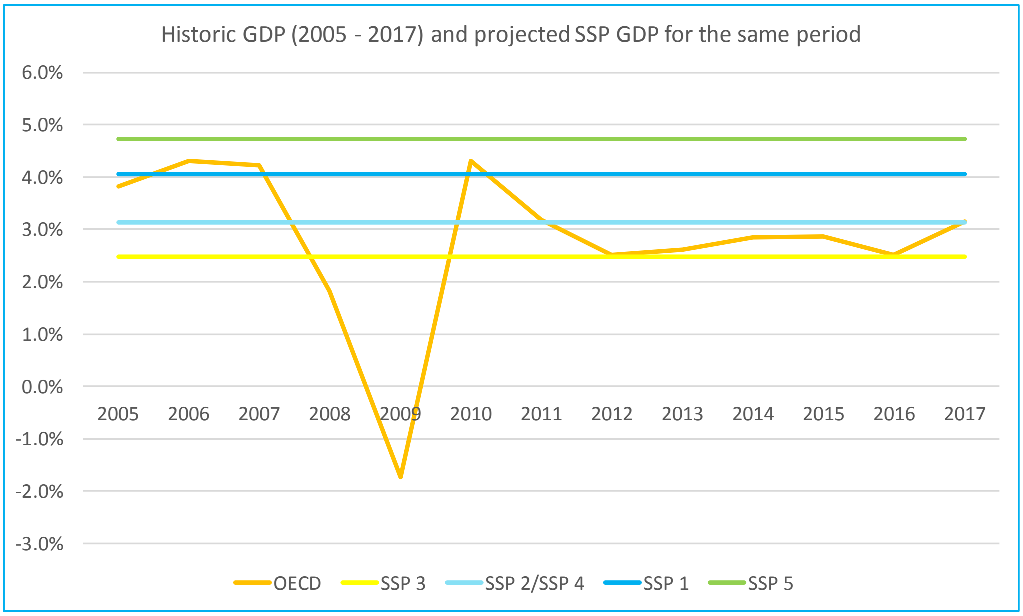
Among the scenarios/IAMs that lead to 1.9 W/m^2 radiative forcing, all limit warming below 1.5°C in 2100, but there are differences between their maximum peak median temperature estimates, varying from 1.5°C to 1.8°C. Additionally, mitigation challenges differ strongly across the SSPs: the amount of CO_2 emission that has to be avoided varies by a factor of two between SSP1 and SSP5 and the projected use of BECCS varies by a Factor 2 to almost 3 between SSP1, and SSP2 and SSP5, respectively (Rogelj, et al., 2018).

H.2 Discussion

SSPs have associated world GDP growth ranging from 200% to 700% (between 2005-2050). If we analyze the observed GDP growth rate in this period (the years from 2005 to 2017), we can see that the growth rate considered in the SSPs is particularly distant from the observed GDP growth as per OECD calculation, orange solid line (Figure 14):

Supply Strategy Alternatives and their General Environmental Impact combined with the Global Biosphere Management Model; REMIND-MAgPIE, the Regionalized Model of Investments and Development combined with the Model of Agricultural Production and its Impact on the Environment; and WITCH-GLOBIOM, the World Induced Technical Change Hybrid model combined with GLOBIOM.

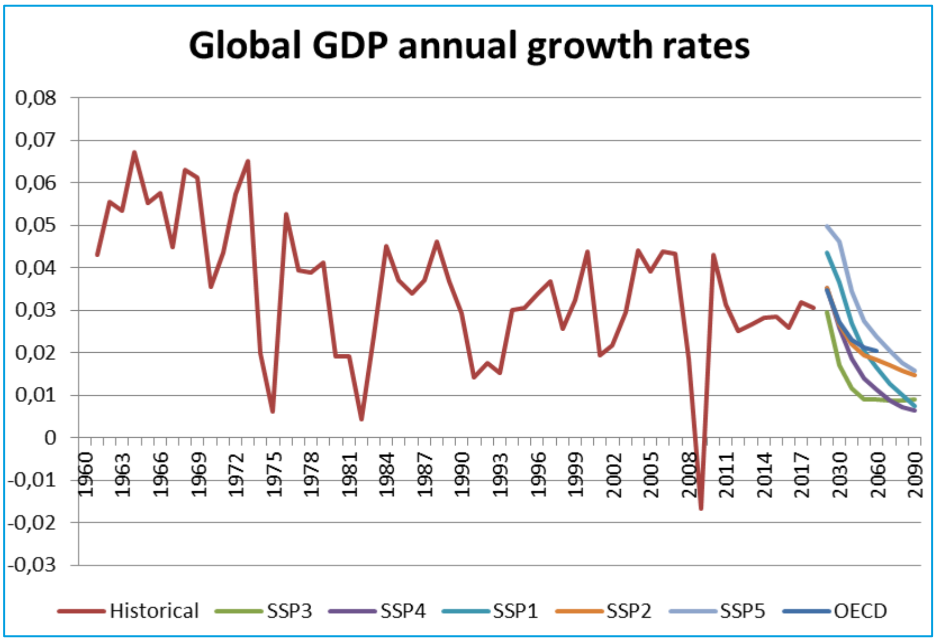
Figure 14 - Observed GDP 2005-2017



From 2012 on only one SSP scenario (SSP3) is below the observed GDP, indicating an overestimation of the GDP growth rate projections considered in the SSPs. The average world GDP growth (OECD) in the period was 2.80% per year, a little higher than the GDP growth considered in SSP 3 (2.47% per year), which presents the lower growth among all SSPs. In turn, the average annual GDP growth rate considered in SSP 2/4, SSP 1 and SSP 5 are 3.13, 4.06 and 4.73%, respectively.

Therefore, the Fourth IMO GHG Study also considered OECDs GDP projections as an additional scenario. Figure 15 shows OECD's long-term global GDP growth projection in comparison to SSPs GDP projections.

Figure 15 - Historic and future GDP growth rates



Source: IIASA, OECD, World Bank

H.3 Selection of projection scenarios

As mentioned in Section H, it is recognized by the academic literature that not all combination of RCP and SSP is viable ((Riahi, et al., 2017; Rogelj, et al., 2018). Therefore, to project emissions, were adopted all possible combinations between RCP and SSP, as well as, OECD scenario:

1. RCP 1.9 and SSP1 and OECD.
2. RCP 2.6 and SSP1, SSP2, SSP4 and OECD.
3. RCP 3.4 and SSP1, SSP2, SSP3, SSP4, SSP5 and OECD.
4. RCP 4.5 and SSP1, SSP2, SSP3, SSP4, SSP5 and OECD.
5. RCP 6.0 and SSP1, SSP2, SSP3, SSP4, SSP5 and OECD.

In particular, to project transport work related to energy products maritime transportation, were adopted the same RCP-SSP combinations used to project emissions, except for RCP 6.0-SSP1, and OECD scenario. Additionally, the transport work projections related to energy products considered also RCP 1.9-SSP2, RCP 1.9-SSP5, RCP 2.6-SSP5combinations and SSP1 to SSP5 baseline scenarios. In turn, to project transport work related to non-energy product transportation, were utilized all SSP scenarios and OECD`s GDP forecast.

In line with Paris Agreement goals, the scenarios using RCPs 8.5 were not considered.

H.4 References

RIAHI, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. **Global Environmental Change** 42, 153–168 (2017).

ROGELJ, J., *et al*. Scenarios towards limiting global mean temperature increase below 1.5 °C. **Nature Climate Change** 8**,** 325–332 (2018).

ROGELJ, J. et al. Energy system transformations for limiting end-of-century warming to below 1.5 °C. **Nature Climate Change** 5, 519–527 (2015).

van Vuuren, D.P., *et al* The 934 representative concentration pathways: An overview. Climatic Change 109, 5-31 (2011).

I Transport work projections

I.1 Introduction

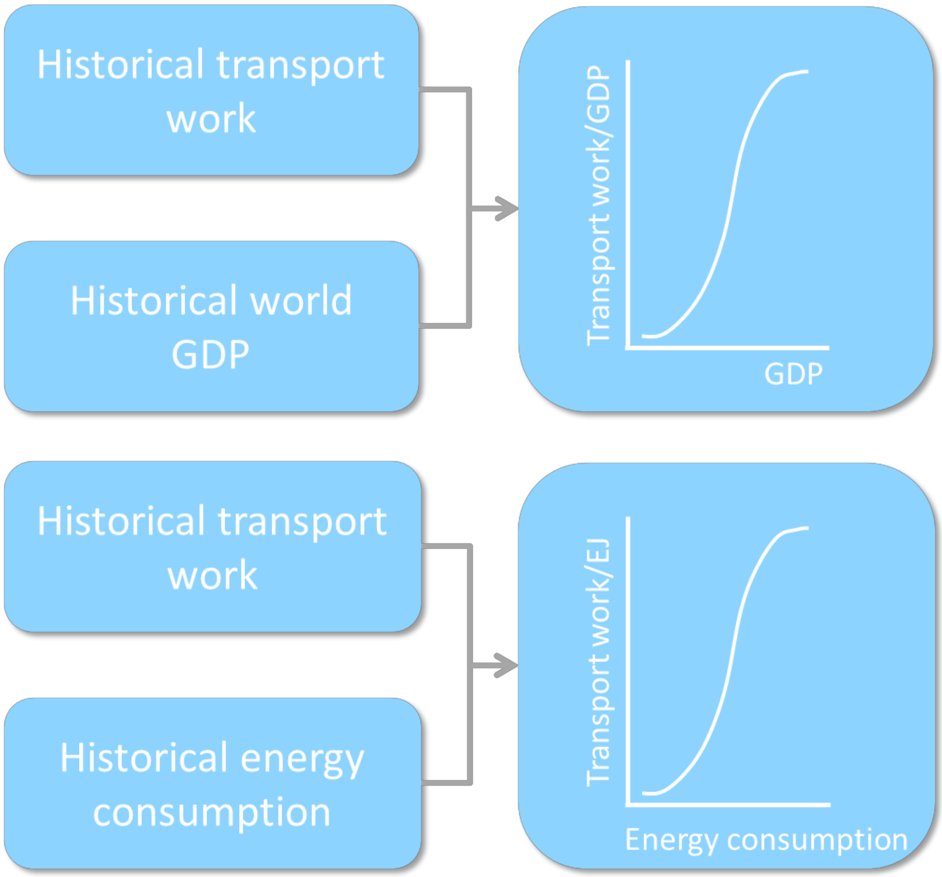
The method for projecting emissions from shipping in this Study comprises six steps:

1. Projecting transport work – non-energy products:
   a establishing the historical relation between maritime transport work and relevant economic parameters such as world (or country) per capita GDP and population (for transport of non-energy products, such as unitized cargo, chemicals and non-coal dry bulk);
   b projecting transport work on the basis of the relations described in (a) and long-term projections of GDP and population (global or by country).
2. Projecting transport work – energy products:
   c Collecting IPCC formal projections of evolution of energy consumption and energy consumption (for transport of energy products like coal, oil and gas);
   d Projecting transport work using the variation of energy consumption projection when considering seaborne transportation of energy products (coal dry bulk, oil tankers and gas tankers).
3. Making a detailed description of the fleet and its activity in the base year 2018. This involves assigning the transport work to ship categories and establishing the average emissions for each ship in each category.
4. Projecting the future fleet composition based on a literature review and a stakeholder consultation.
5. Projecting future energy efficiency of the ships, taking into account regulatory developments and market-driven efficiency changes using a marginal abatement cost curve (MACC).
6. Combining the results of Steps 2, 4 and 5 above to project shipping emissions.

Transport work projections are the basis of the emission projections. This annex presents the methodology used in this study to project transport work and the results.

The first step of the emissions model is the establishment of the historical relation between maritime transport work and relevant economic parameters such as world GDP (for transport for unitized cargo and non-coal dry bulk); crude oil consumption (for liquid bulk transport) and coal consumption (for coal transport) (see Figure 16).

Figure 16 – Establishing the historical relation between transport work and GDP or energy consumption



This study employs two methods to arrive at the historical relations. One has a global focus, the other is based on bilateral trade between countries. As both methods have strengths and weaknesses, this study does not recommend one over the other. Rather, it considers the results of both methods of to be possible projections of future transport work and interprets the differences as the uncertainty margin.

Both methods are described in more detail in respectively Sections I.2 and I.3. Section I.4 presents the merits of both methods.

I.2 Logistic analysis of global transport data

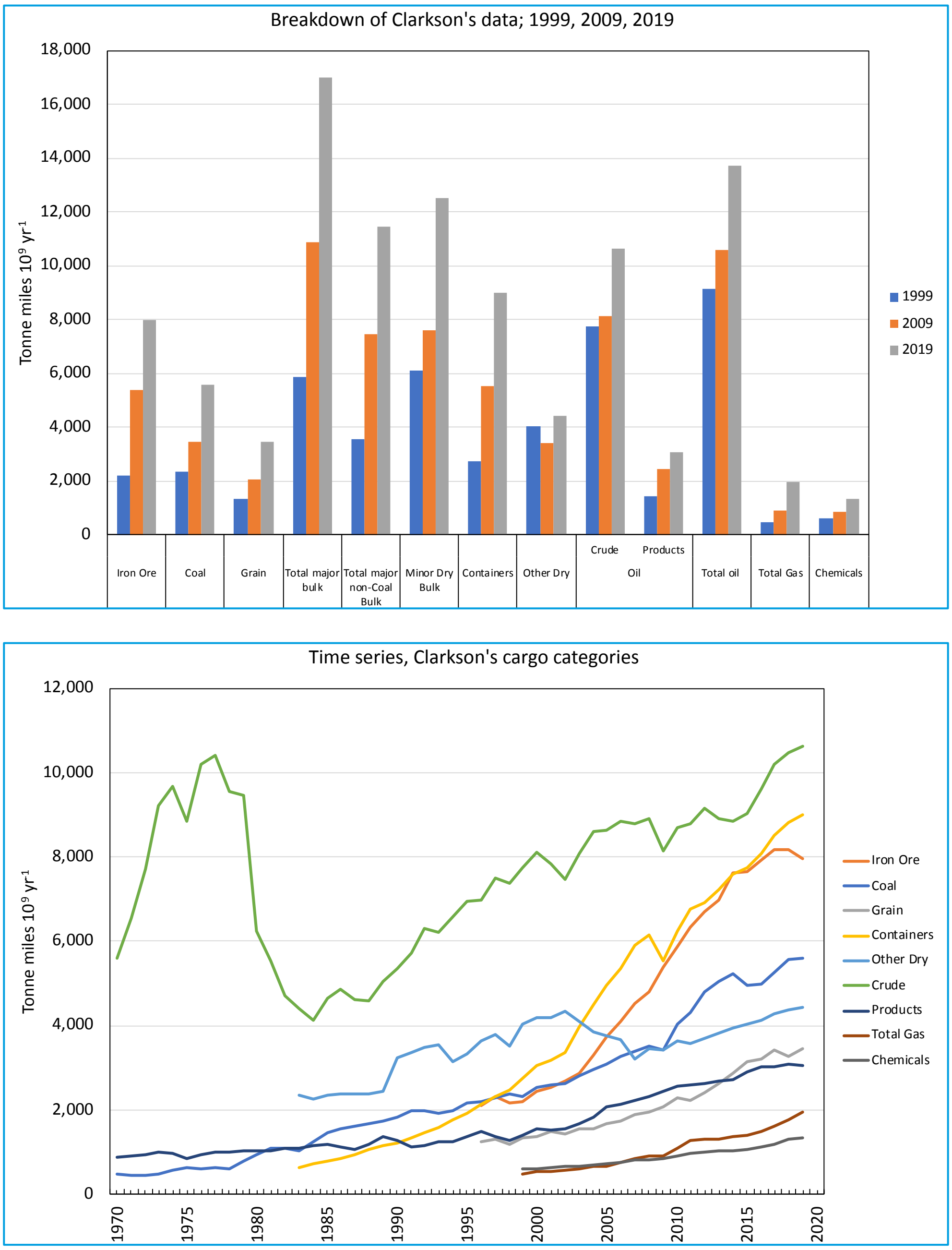
This method for establishing the relation between transport work and economic or consumption parameters resembles the method employed in the Third IMO Greenhouse Gas Study 2014, but updates and improves important elements.

In the Third IMO GHG Study (IMO, 2015), transport projections to 2050 were made using historical data on seaborne trade for different cargo types from 1970 to 2012 provided by the United Nations Conference on Trade and Development (UNCTAD) as part of their annual 'Review of Maritime Transport', which has been produced since 1968. The originator of the data was Fearnleys. The data used in the Third IMO GHG Study included the following cargo types: crude oil, other oil products, iron ore, coal, grain, bauxite and aluminia, phosphate, other dry cargos. These categories were combined to represent different ship types in the following ways: total oil, coal, total (non-coal) bulk dry goods, total dry goods. These groupings of seaborne trade approximate to three different ship types of, tankers, bulk raw material ships, container (and other) ships but discriminating between fossil-fuel transport and non-fossil fuel transport.

For this present work, data from Clarksons were used and the categories provided did not map exactly to the Fearnleys data, but provided better discrimination and more detail. On the negative side, some of the data did not go back as far as the Fearnleys data.

The categories provided were: iron ore, coal, grain, steel products, forest products, other dry bulk cargos, containers, other dry unitized cargos, crude oil, oil products, gas LPG, gas LNG, and chemicals. These categories were not available over a uniform period but had varying lengths of data availability. A breakdown in terms of transport work (billion tonne miles) for 2019 is shown in Figure 17(a) and compared with 1999, which was the first year that data on all cargo types was available and 2009. Figure 17(b) also shows the development over time, which also indicates the length of time that the various categories were available.

Figure 17 - Breakdown of Clarksons cargo types, 1999, 2009 and 2019 (upper panel, a) and time series of data (lower panel, b)



Source: Clarksons Research, 2020, Seaborne Trade Monitor, Volume 7 no. 2

Total seaborne trade between 1999 and 2019, as shown in Figure 17(a) doubled (increase of factor 2.1). The cargo types that showed the largest factor increases were iron ore (3.6), containers (3.3) and total gas (4.1).

Basic methodology and assumptions

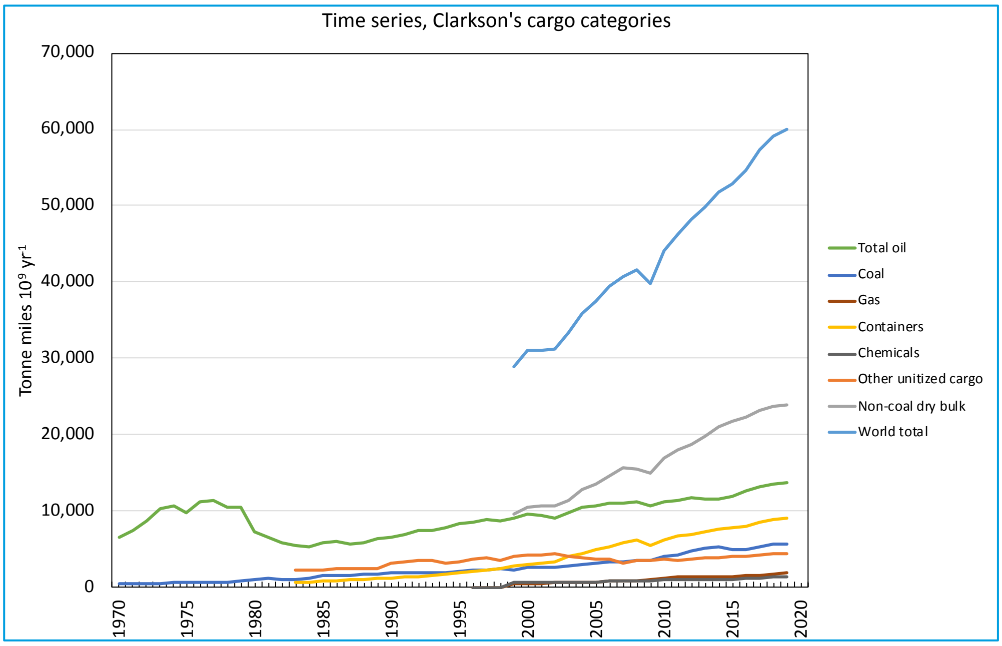
To project ship transport work, an external driver of transport growth is used, so that if external projections of the predictor data (e.g. economic growth) are available from other scenarios, then the historical relationship between the transport work data and the driver of the growth of transport can be used to determine potential future transport work growth. This assumes that the relationship in the past is causative and remains the same in the future. For shipping there is the widely-based assumption that there is a causative relationship between global economic growth (GDP) and shipping transport (e.g. (Eyring, et al., 2005; Buhaug, et al., 2009; IMO, 2015; Corbett, et al., 2010; Valentine, et al., 2013; UNCTAD, 2015). For the years of full data availability from Clarksons (1999–2015) (Clarksons Research Services, ongoing) vs World Bank global GDP (constant 2005 US$), the R^2 value is 0.98.

For the purposes of projections, whilst fossil fuel transport (oil, coal and gas) may have a causative relationship with GDP, this is less satisfactory for climate policy scenarios, where a clear decoupling between GDP and fossil fuel usage is envisaged. Similar to the method used in (IMO, 2015), an alternative correlating variable of coal, oil and gas consumption is used for coal, oil and gas transport. One of the limiting factors is that such an alternative variable needs to be available in the independent climate scenarios. The RCP/SSP data provide different energy scenarios, which is broken down into energy types by EJ yr^{-1} used. For oil, this is relatively straightforward, given that large amounts of the world's crude oil and derivatives (69% in 2018) are transported by ships. For coal and gas, evidently the proportions carried by ships is less, calculated here to be 16 and 15%, respectively in 2018, using the Clarksons data and BP Statistical data. Nonetheless, the R^2 value in all cases between consumption and transport work data are > 0.9, allowing energy projections to be used.

Grouping of cargo data and ship types

The 9 cargo types from the Clarksons data were grouped to retain clarity on ship types but also allowing consideration of the different historical growth rates apparent from the data into seven types as following: coal; total oil products (crude oil plus oil products); chemicals; total gas (LPG plus LNG); non-coal bulk (sum of iron ore, grain, steel products, forestry products, other dry bulk); containers; other unitized dry cargos.

Figure 18 - Transport work for all grouped categories of cargo provided in billion tonne-miles per year



Source: Clarksons Research, 2020, Seaborne Trade Monitor, Volume 7 no. 2

Figure 18 shows the groupings of data over time periods possible, because of different start dates of data collection. These groupings of time-series data were then used in the analysis to derive projections. The only exception in terms of data screening was the total oil data, where data prior to 1985 were excluded (as has been the case in other studies, e.g. ((Eyring, et al., 2005; Eide, et al., 2007; Buhaug, et al., 2009). There is a large excursion of the total oil data over the period 1970 to 1985, which was driven by political and economic factors, some of which are connected with the political situation over oil prices during this period. Moreover, the tanker sector was extremely volatile over this period (Stopford, 2009) with an over-supply of ships that in some cases led to ships being scrapped straight after being produced, and some being laid up uncompleted. The volatile situation in the Middle East also led to avoidance of the Suez Canal, and ships also increased dramatically in size such that the Panama Canal became un-navigable for some ships. Therefore, the period 1970 to 1985 is known to have a particular explicable data excursion for tonne-miles of total oil data, and these data were excluded from the analysis.

Transport work is related to historical GDP and energy consumption data. Historical GDP data were taken from Geiger and Frieler (2018) which is a harmonized database of past observations of GDP data with SSP projections of GDP and were normalized to constant 2005 USD, because the long-term economic projections use this price level. Extensive historical data on coal, oil, and gas consumption data are available from the BP Statistical Review of World Energy 2019[7] and were used to relate shipped total oil, coal, total gas converted to units of EJ yr^{-1} as projection data of total EJ yr^{-1} by oil, coal, gas were available from IIASA for SSP1-SSP5. Ratios of total coal, total oil, total gas seaborne trade (10^9 tonne miles) to respective EJ yr^{-1} consumption; and non-coal bulk, chemicals, containers, other unitized cargo to GDP (constant 2005 USD) are shown in Figure 19. Note that in Figure 19, the early

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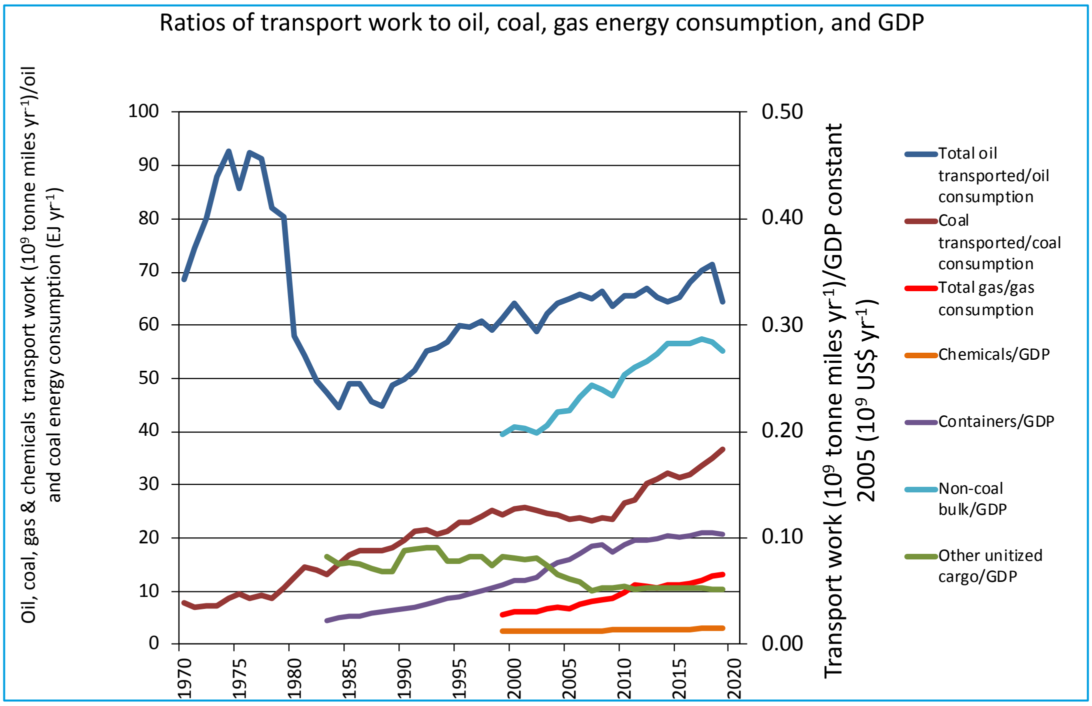
period of total oil data (1970–1985) are shown, but as outlined above, these data were excluded from the analysis.

Figure 19 - Ratios of 7 categories of seaborne trade (total oil, coal, total gas, chemicals, non-coal dry bulk, containers, other unitized cargo in 10^9 tonne miles) to global oil, coal, gas consumption data (EJ yr^{-1}, left hand y axis), or GDP (constant 2005 USD, right hand y axis)



Source: This report.

As in (IMO, 2015) we largely use a non-linear projection method as this represents an improvement over previous studies (e.g. that have based projections on linear regression models or the Second IMO GHG Study projections (Buhaug, et al., 2009), which were non-analytical Delphi consensus based. Non-linear statistical models have been for long-term projections of aviation transport (e.g. (Eyring, et al., 2005; Eide, et al., 2007)). Such non-linear models used are sometimes referred to as 'logistic models', or more simply 'non-linear regression models'. A range of these models exists, such as the Verhulst or Gompertz models, and they are commonly used in the econometric literature where the requirement is to simulate some form of market saturation (Jarne, et al., 2005).

The sigmoid curve in these models mimics the historical evolution of many markets with three typical phases: emergence, inflexion (maturation), and saturation, where the period of expansion and contraction are equal with symmetrical emergent and saturation phases. The phase first involves accelerated growth; the second, approximately linear growth; and the third decelerated growth. Logistic functions are characterized by constantly declining growth rates. The Verhulst function is particularly attractive as it calculates its own asymptote from the data and is described as follows, where *x* is the future demand and *t* is time in years and *a*, *b* and *c* are model constants:

$$x = a / (1 + b * \exp(- c * t)) \qquad [3]$$

The constants *a*, *b*, and *c* are estimated from initial guesses of asymptote, intercept and slope, and solved by converged iterative solution. SPSS v23 provided a suitable program for this model.

The exception to this modelling approach was the treatment of other unitized cargo. Figure 18 and Figure 19 show that there has only been a small decrease in this category over time, as opposed to containerized cargo which shows large increases. These fundamental differences in behavior justify their separate treatment, otherwise a combination would greatly overestimate the growth in other unitized cargo. Figure 19 shows that the ratio of other unitized cargo to GDP shows a small decrease over time. Here, there is no justification for using a non-linear model, since it would imply a reverse sigmoid curve that declined to zero, for which there is no basis to assume such behavior. In the absence of any other evidence, a simple linear model has been assumed for this category. The R^2 value for such a model is 0.638.

Figure 20 shows the historical and modelled growth ratios according to the non-linear models derived from the analysis for all seaborne trade types, other than the other unitized cargo category, which has a linear model fitted for the reasons described above.

Figure 20 - Historical and modelled growth to 2050 for ratios of total oil, coal, non-coal bulk dry goods, total gas, chemicals, containers and other unitized cargo to either consumption or GDP

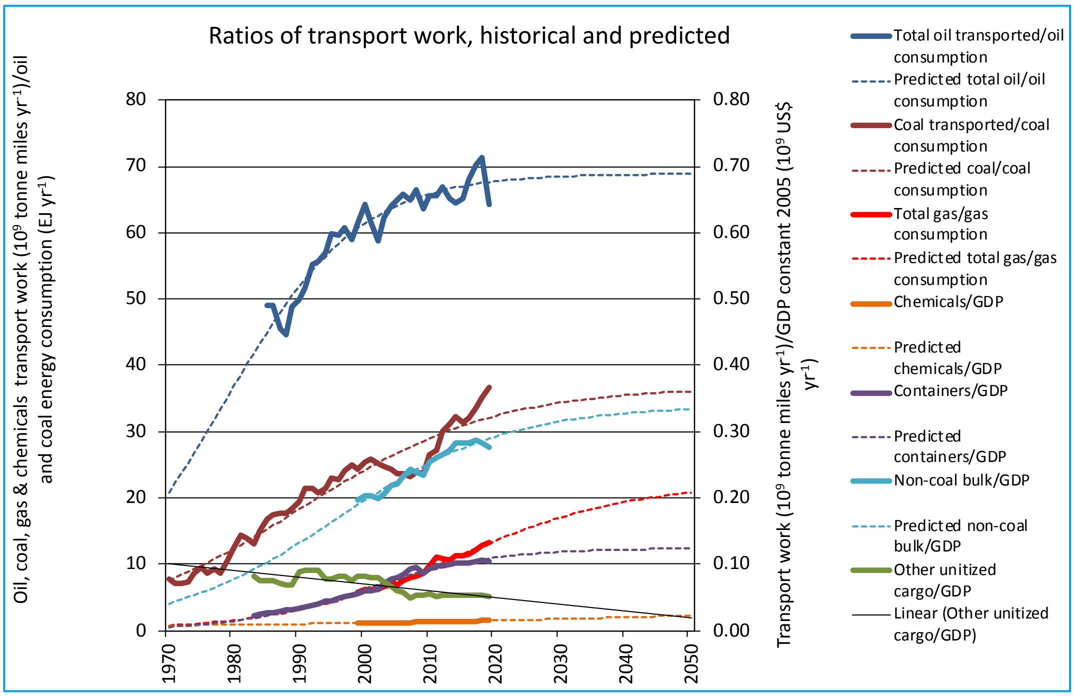
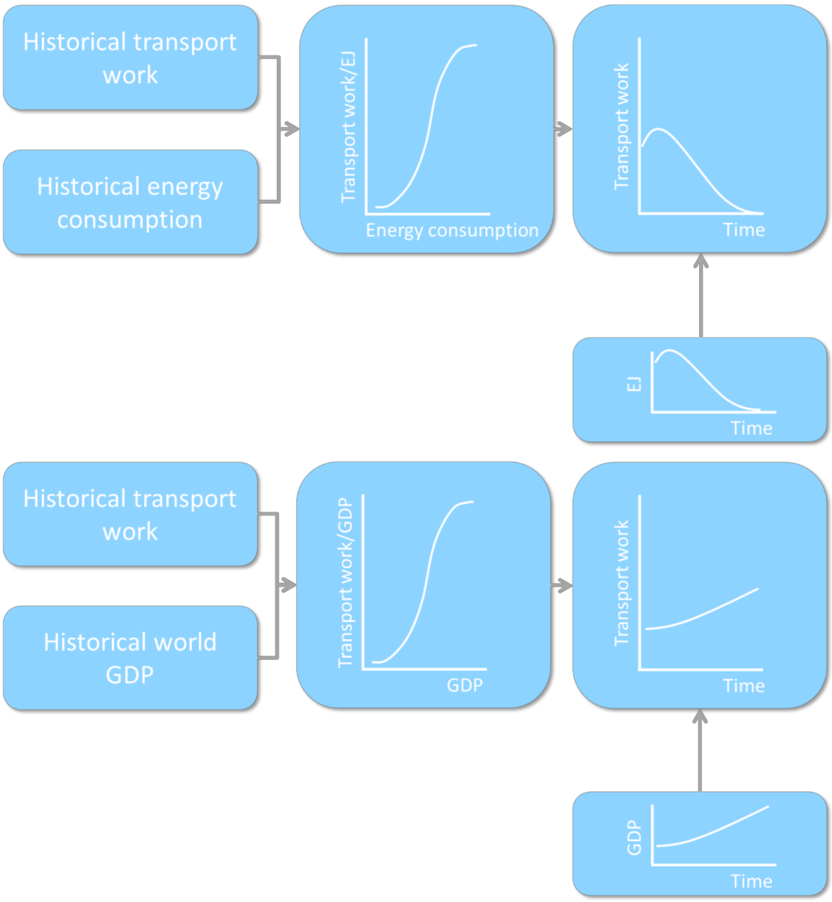


Figure 20 shows that future growth rates of total seaborne trade can be successfully modelled in a non-linear fashion, for six different cargo types that clearly indicate different levels of market maturity, as modelled.

Projection results

The second step in the transport work projections is to use the historical relation between transport work and its drivers, in combination with projections of GDP and energy use, to project transport work into the future.

Figure 21 - Projecting transport work into the future



Projection data of global GDP and oil, coal and gas consumption data were used, as outlined above, so that low fossil fuel scenarios could be dealt with by decoupling fossil fuel from GDP. GDP projection data for the five SSP scenarios obtained from the IIASA website. OECD 2018 data on their long-term GDP projections were obtained from the OECD website.

The following ratios and coefficients were calculated, as given in Table 12.

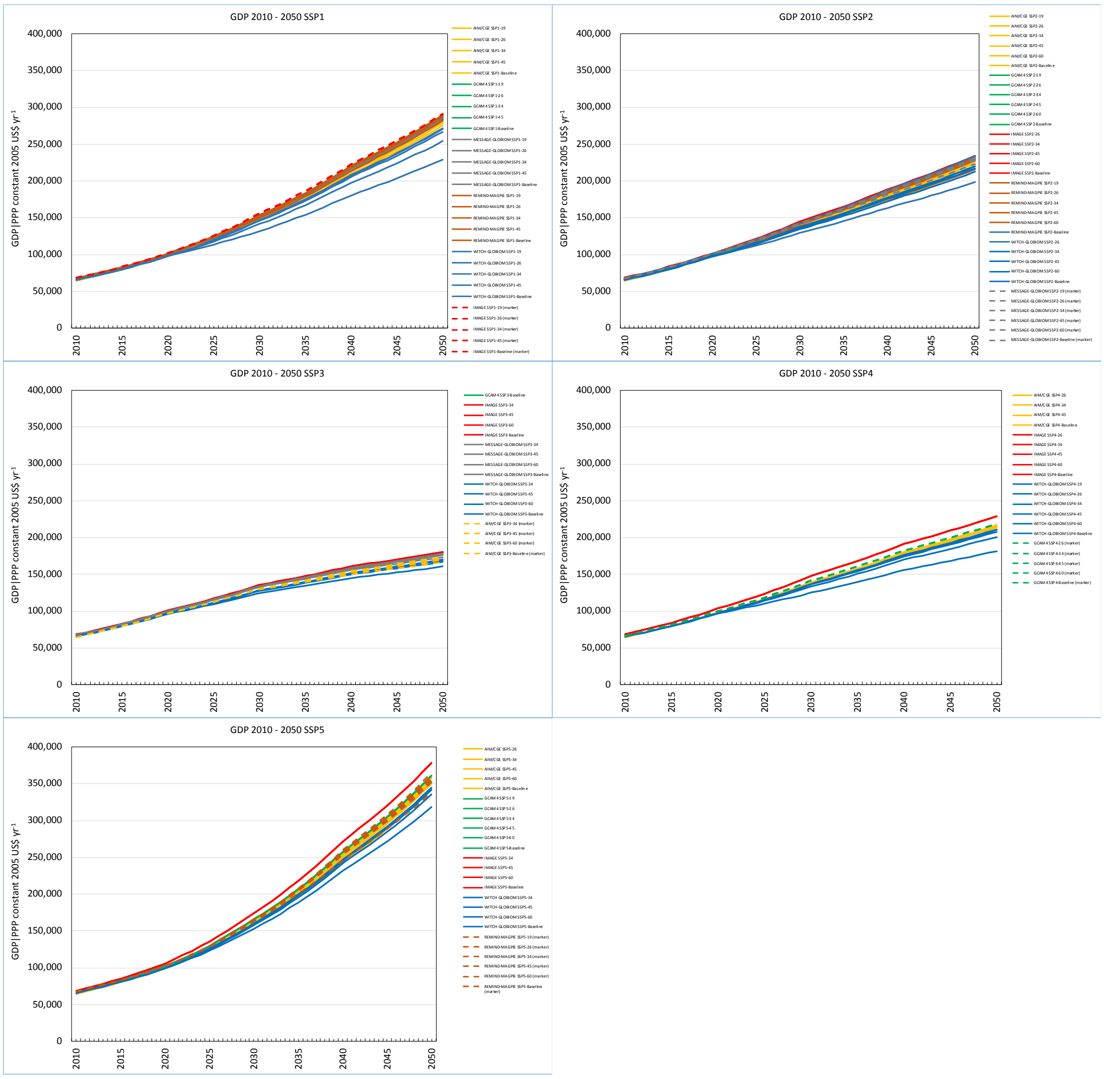
Table 12 – ratios and coefficients of best-fit logistic curves for different cargo types

Model	Parameter	Estimate	Std. Error	95% confidence interval;	
				Lower Bound	Upper Bound
Containers	a	0.124	0.005	0.115	0.134
	b	22.554	2.606	17.257	27.851
	c	0.101	0.006	0.089	0.113
	R^2	0.986			
Non-coal Bulk	a	0.339	0.036	0.263	0.415
	b	7.829	3.785	-0.123	15.782
	c	0.077	0.022	0.030	0.123
	R^2	0.945			
Chemicals	a	1.3 E06	9.9 E11	-2.1E12	2.1E12
	b		1.3 E14	-2.8E14	2.8E14
	c		0.001	0.012	0.016
	R^2	0.900			
Containers	a	0.124	0.005	0.115	0.134
	b	22.554	2.606	17.257	27.851
	c	0.101	0.006	0.089	0.113
	R^2	0.986			
Total oil products	a	68.919	1.393	66.082	71.756
	b	2.553	0.658	1.213	3.892
	c	0.098	0.015	0.067	0.129
	R^2	0.913			
Coal	a	36.796	2.587	31.593	42.000
	b	4.107	0.346	3.412	4.803
	c	0.067	0.008	0.051	0.082
	R^2	0.939			
Total gas products	**a**	**22.141**	**5.989**	**9.558**	**34.725**
	b	**30.077**	**5.746**	**18.005**	**42.149**
	c	**0.076**	**0.016**	**0.043**	**0.109**
	R^2	**0.974**			

As can be seen from the above Table 12, all models return large R^2 values. The model that is most suspect is that for chemicals. However, in practice, the predicted model is a very small departure from linear, which would be the most obvious alternative model.
The next step is to multiply the modelled ratios for each transport type by the predictor variables (projected GDP; coal, oil and gas consumption) by SSP scenario and combine with historical data. The SSP scenarios are matched to a corresponding RCP forcing level of 6.0, 4.5, 3.4, 2.6 and more recently 1.9 W m^{-2}. Also included in the IIASA database are 'baseline' scenarios. Many interpretations of both SSP/RCP combinations are available from a range of modelling groups. In order to down-select, an initial selection of the 'marker' scenarios was made, these being representative of each SSP (Riahi, et al., 2017). The 'baseline' SSP GDP scenarios were selected, on the basis of them being described as; "The baseline SSP scenarios should be considered as reference cases for mitigation, climate impacts and adaptation analyses (Riahi, et al., 2017). In order to understand this choice further, the baselines for the SSP marker scenarios were compared with the SSP/RCP levels for the GDP projections, showing that use of these baselines for the marker scenarios represents a reasonable choice within the large range of available scenarios (see Figure 22). Figure 24 shows the projected annual GDP growth rates for each SSP and Figure 26 the resulting world GDP up to 2050.

The resultant transport work projections are shown in Figure 27 to Figure 30. The 'raw' GDP data from the IIASA database were, however, processed and not used as published. This is because the base year for this study is 2018, and therefore uses observed historical data to 2018. In order to utilize the IIASA and OECD projected GDPs, growth factors from the 2018 database year were calculated, and then applied to the base year of observed 2018 GDP data.

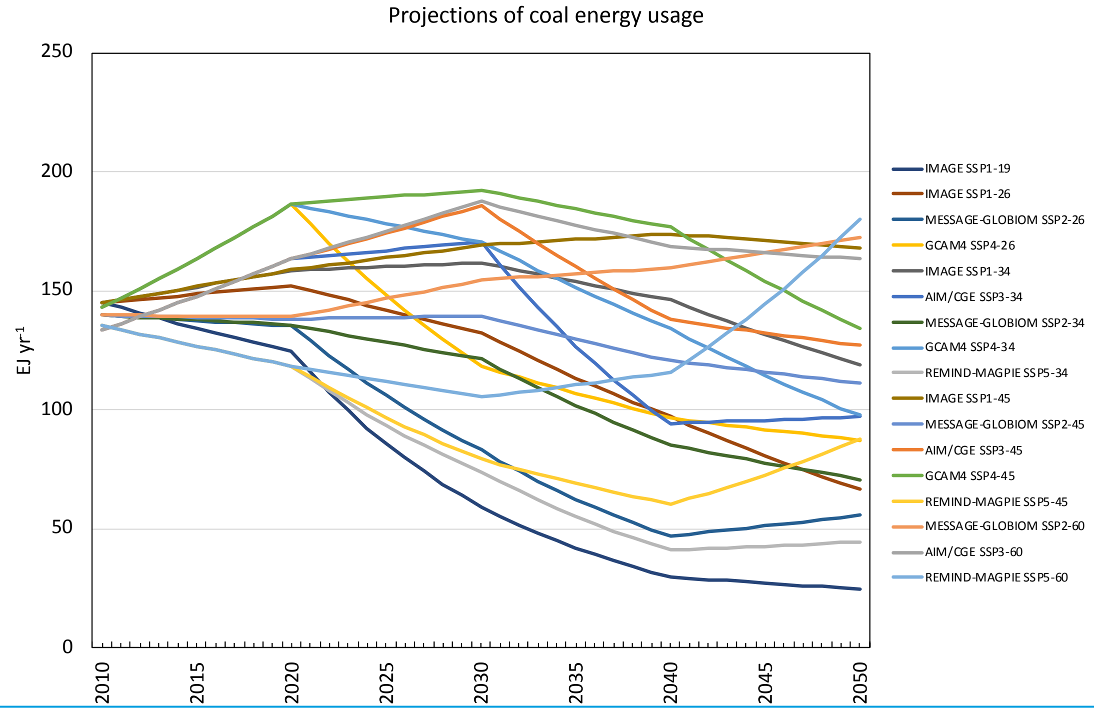
Figure 22 - SSP/RCP combinations by modelling group SSP1 - SSP5

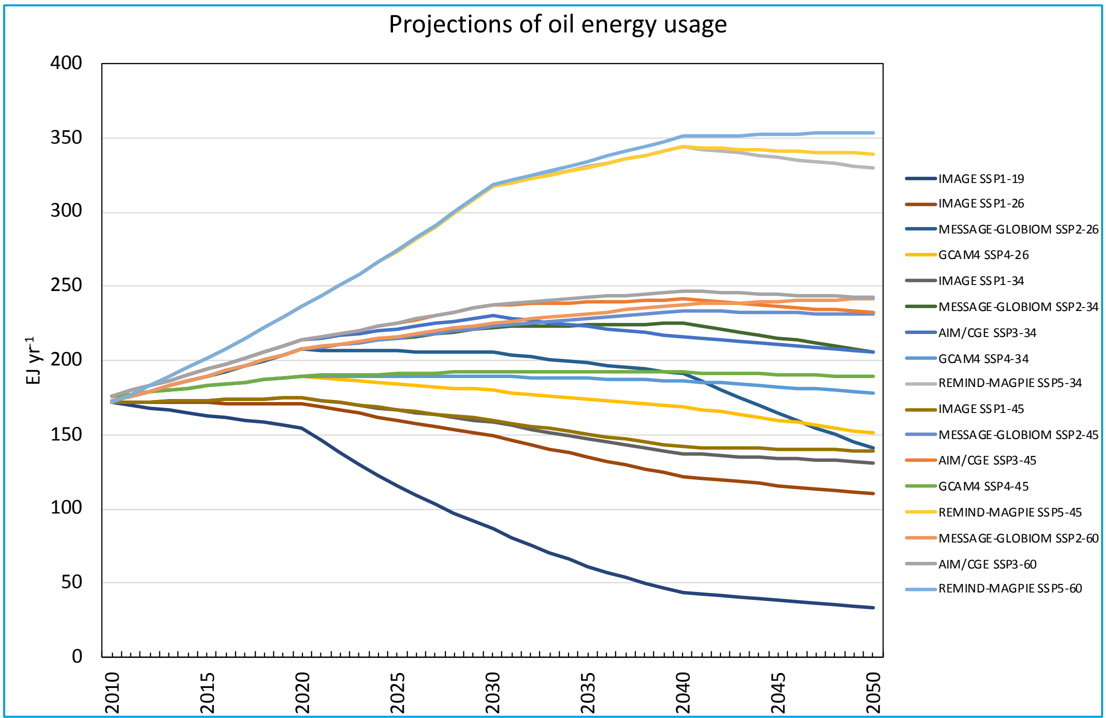


Source: IIASA

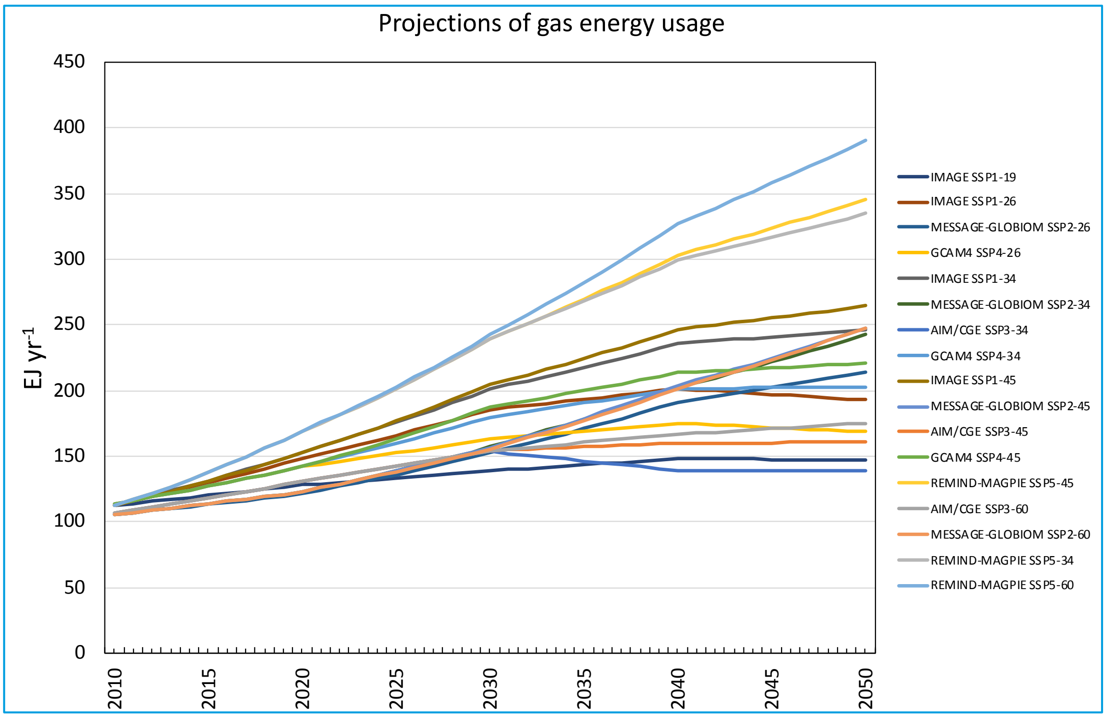
For the projections of coal, oil and gas transport work, as noted earlier, a decoupling from GDP was necessary and historical data on energy usage was utilized to calculate logistic regressions of the ratio of historical shipping transport work to total global energy usage (in EJ yr^{-1}), in order to project to 2050 using SSP/RCP projections of fossil energy utilization in terms of EJ yr^{-1}, once again taken from the IIASA database. These data, shown in Figure 23 show much more variability between SSP/RCP combinations than for GDP. Not all SSP/RCP combinations were deemed plausible by the originating modelling groups[8], so only those 'plausible' combinations were initially selected.

Figure 23 - Projections of coal, oil and gas energy usage to 2050 from IIASA database



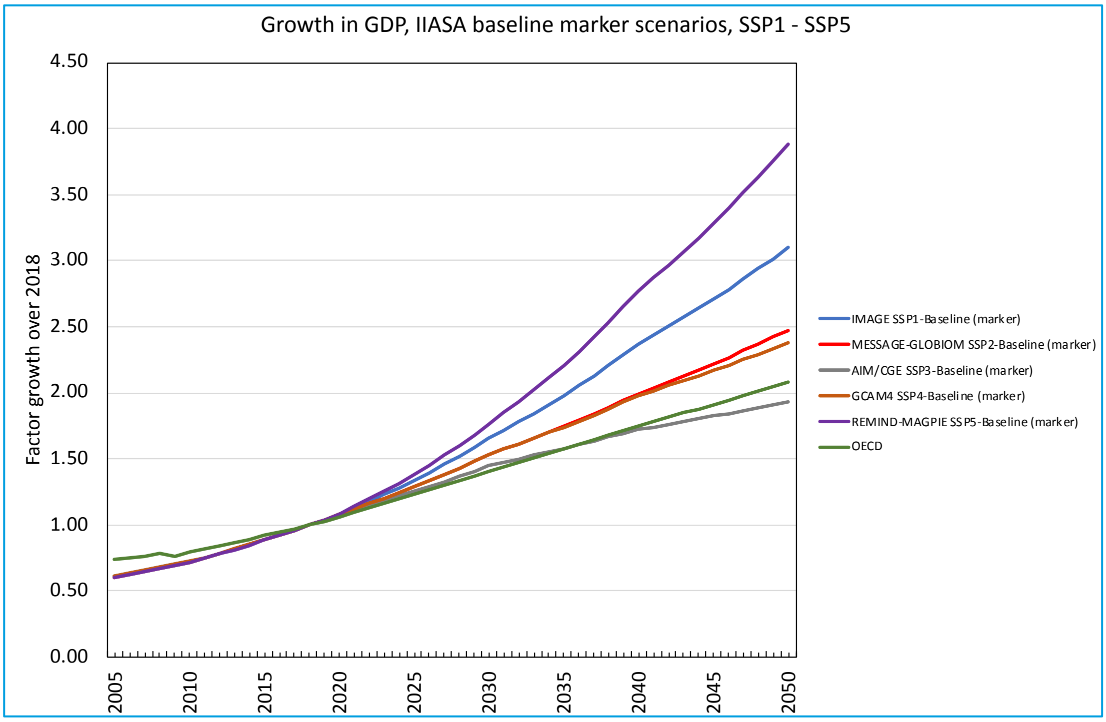


8 Primer to Climate Scenarios : Mitigation



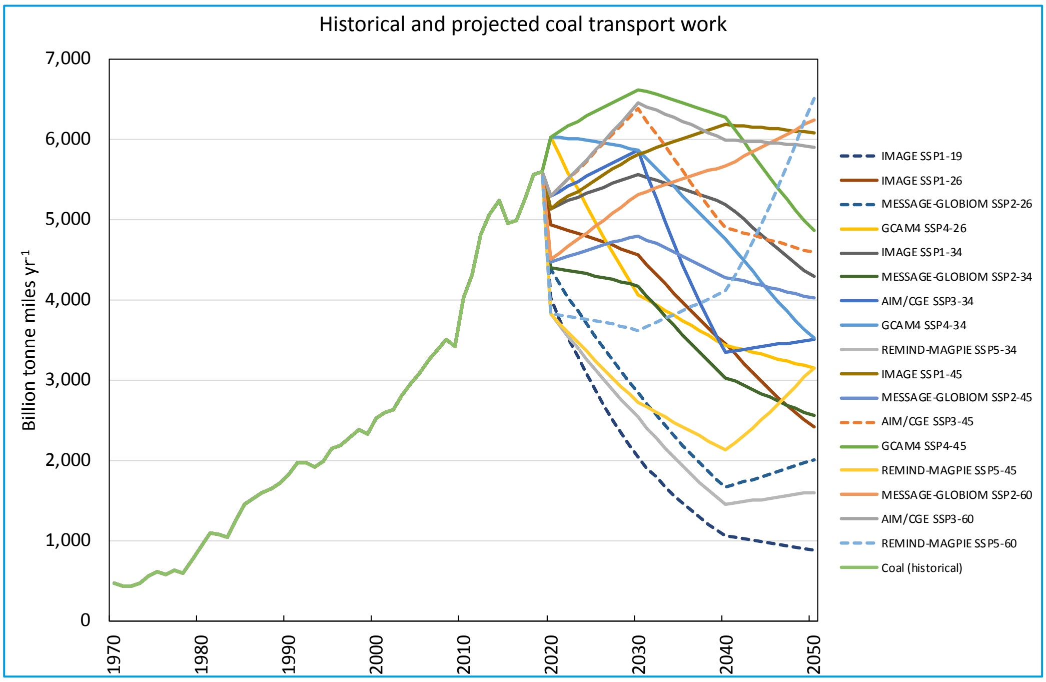
Source: IIASA.

Figure 24 - Historical and projected world GDP (constant USD, index: 2018 = 1)



Source: IIASA.

Figure 25 - Historical and projected transport work (109 tonne miles yr-1) to 2050 for coal and oil according to RCP/SSP scenarios



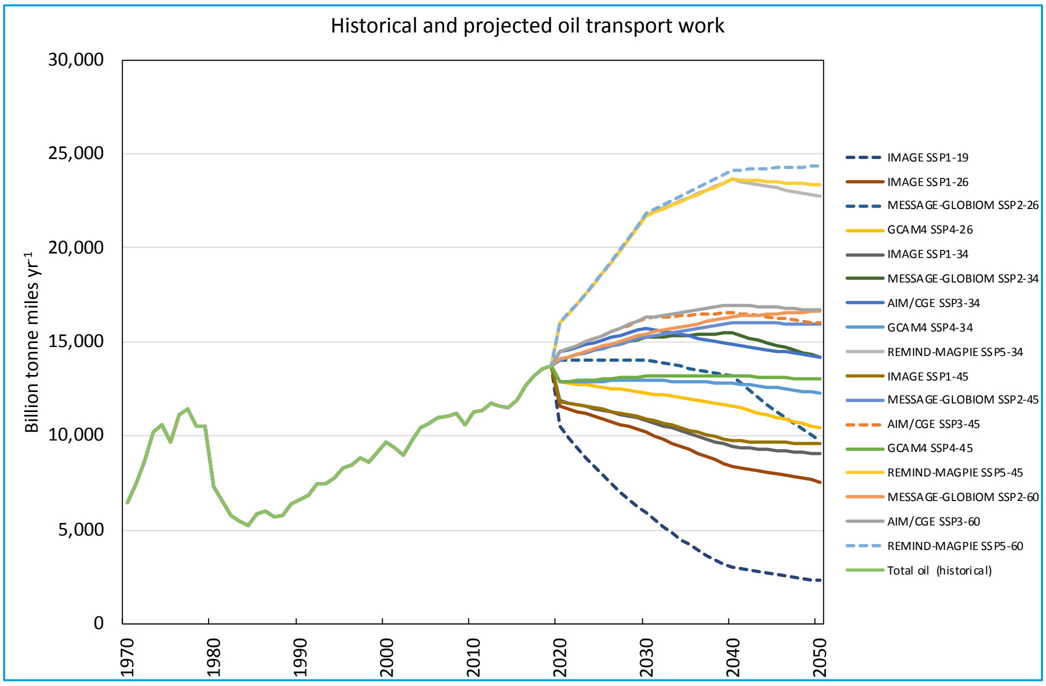


Figure 26 - Historical and projected transport work (10^9 tonne miles yr^{-1}) to 2050 for gas according to RCP/SSP scenarios

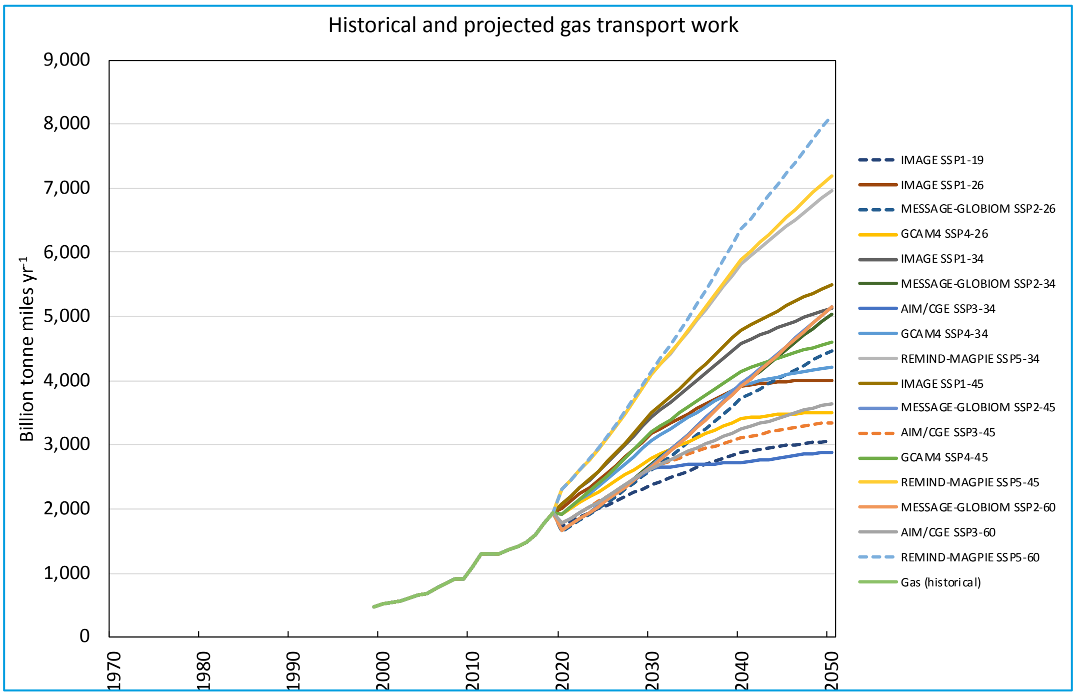


Figure 27 - Historical and projected transport work (10^9 tonne miles yr^{-1}) to 2050 for container shipping according to SSP scenarios

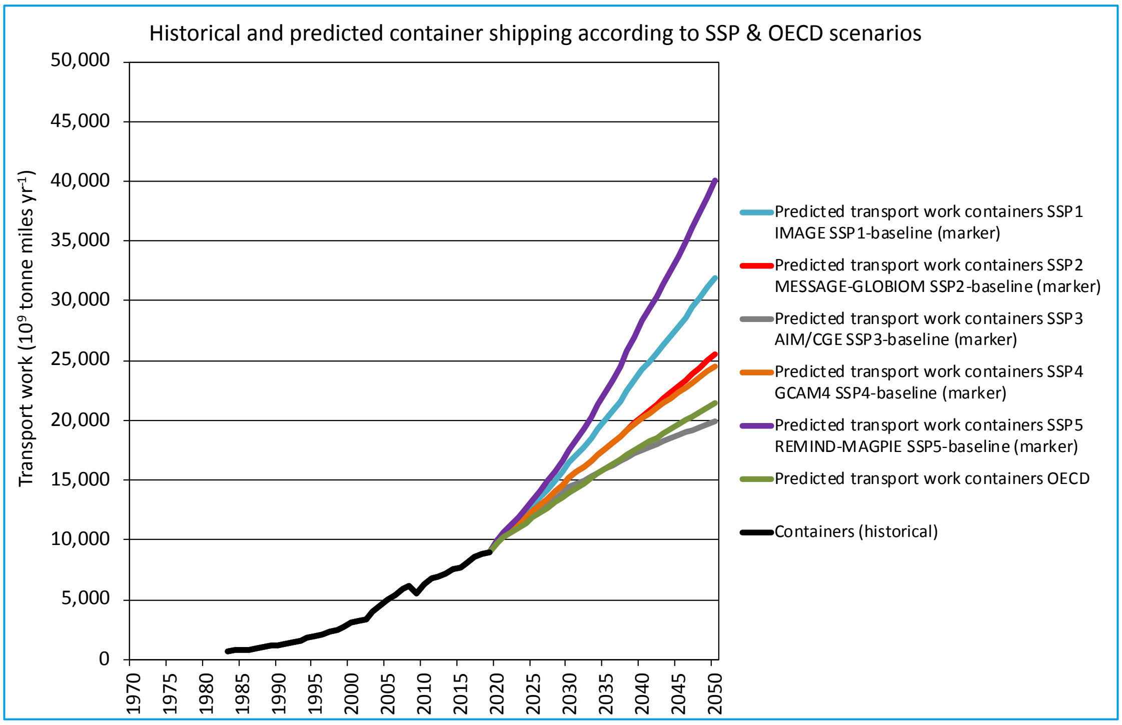


Figure 28 - Historical and projected transport work (10^9 tonne miles yr^{-1}) to 2050 for non-coal dry bulk shipping according to SSP scenarios

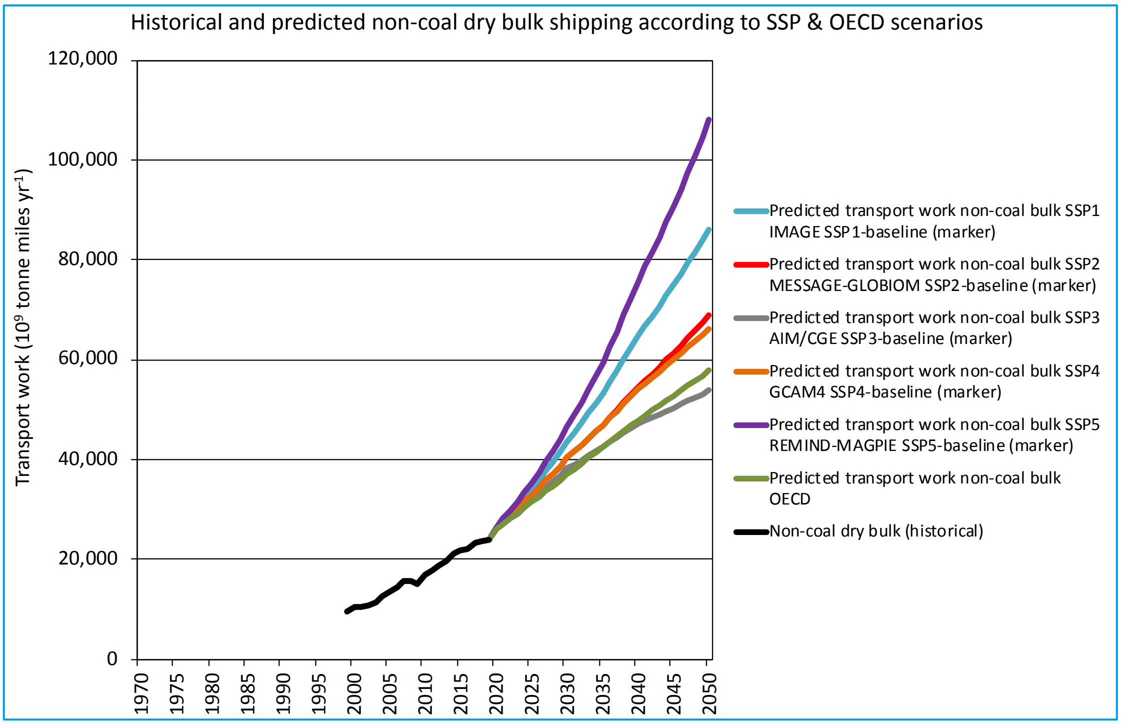


Figure 29 - Historical and projected transport work (10^9 tonne miles yr^{-1}) to 2050 for other unitized cargo shipping according to SSP scenarios

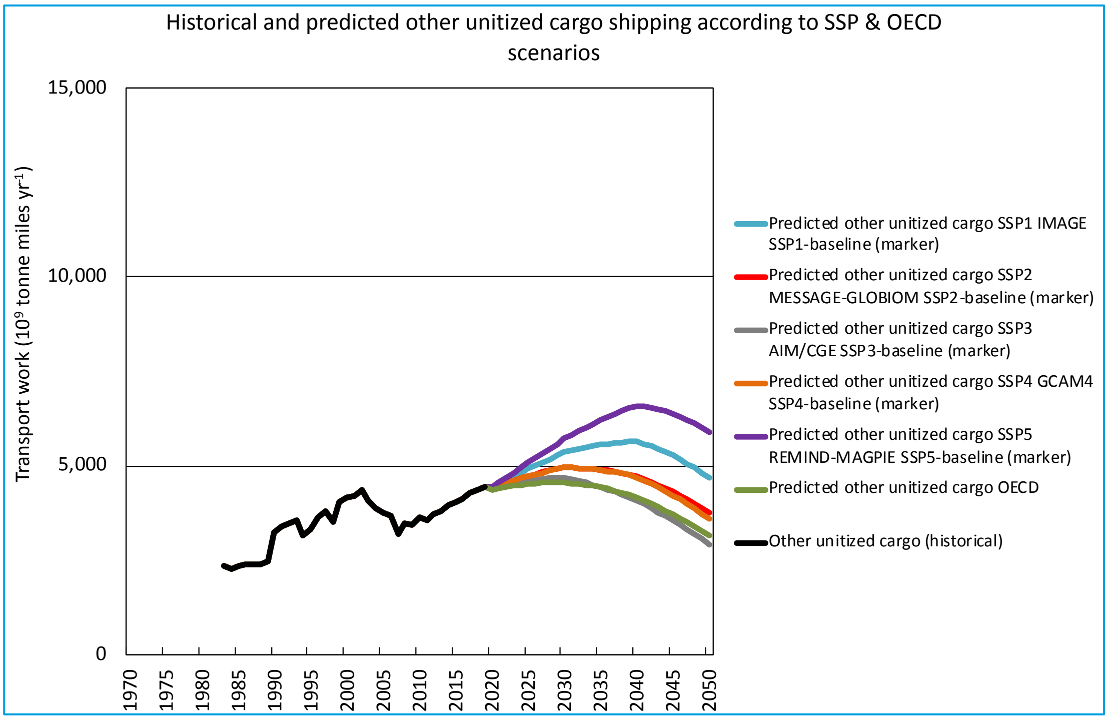
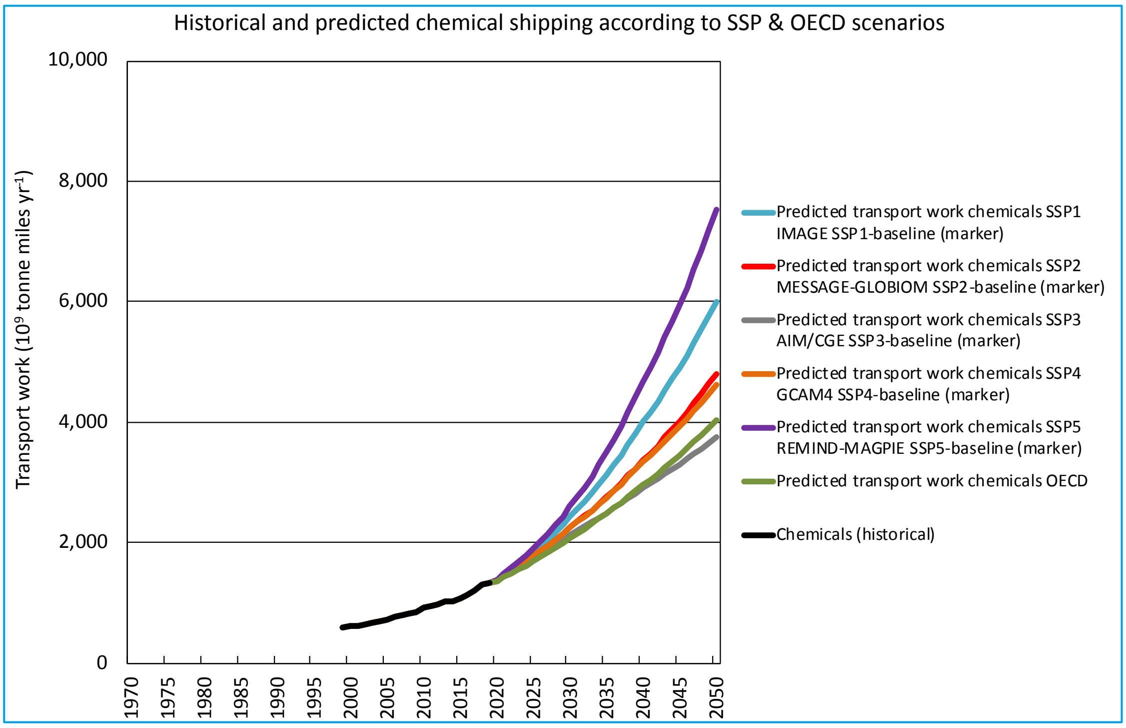


Figure 30 - Historical and projected transport work (10^9 tonne miles yr^{-1}) to 2050 for chemicals shipping according to SSP scenarios



Uncertainties in transport work projections

The uncertainties in any study of projections of emissions (or underlying driver such as transport work performed) are inherently large and not quantifiable. The best approach to minimize uncertainties is to adopt reasonable models of behaviour, use data as appropriately as possible, use assumptions that appear reasonable, and diagnose the statistics of the model outputs. The adoption of a non-linear conventional economic growth model is more appropriate than a linear model, and the visual and statistical fit of the models produced (Figure 20) bears this out. The exception is the other unitized ship traffic, which shows a marginal growth or level emissions over the data period of 2018 to 2040 and thereafter declines in transport work. This form of shipping shows a historical behaviour that is different from the other transport types, with the ratio to GDP showing a small decline. Hence, a (declining) linear growth of the ratio of transport to GDP was used as the model in the absence of a better-informed model. Nonetheless, splitting the containerized from the other unitized cargos is an appropriate treatment of the data that minimizes uncertainties, as if they had been combined, the other unitized cargo would have been greatly overestimated. The most uncertain non-linear model is the shipment of chemicals. This ratio (to GDP) only shows a very small increase, which implies that the market is in emergent phase, which implies an asymptote greatly beyond the observed data. Nonetheless, the non-linear approach has not 'failed' since the projected ratio shows an increase over the projection that is only marginally greater than a linear projection with a small slope (Figure 20.

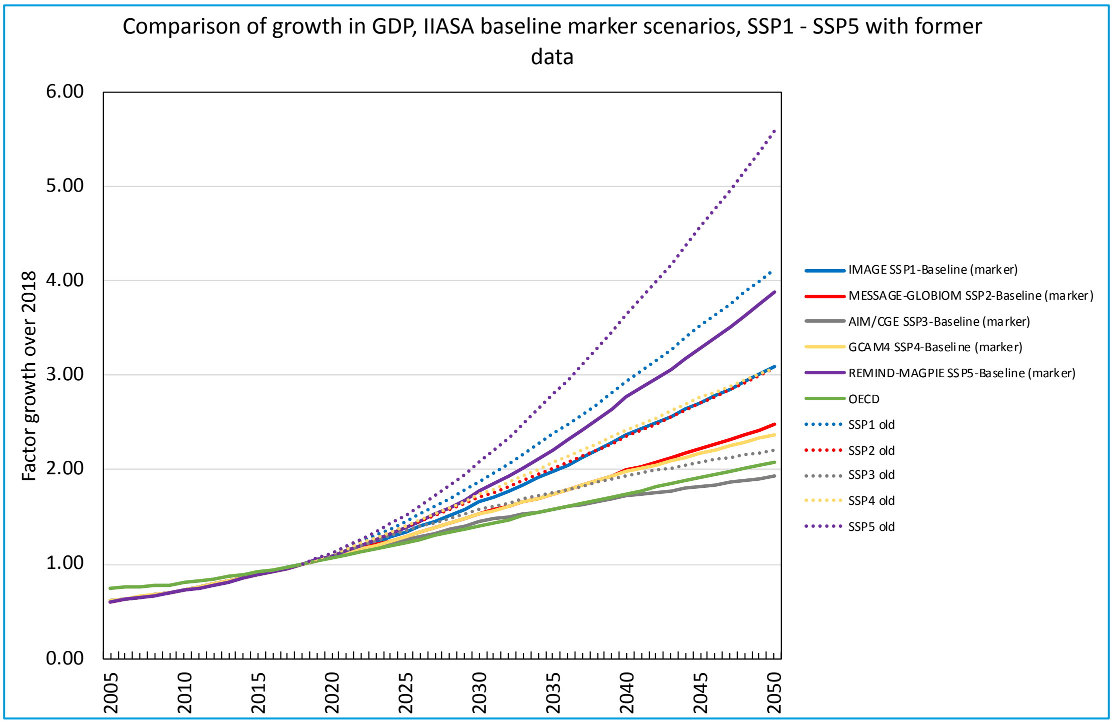
The magnitudes of the contributions of the split in types also needs to be considered: so, the models which show the clearest fit are those of e.g. total oil, containers, non-coal dry bulk which all have large contributions to the total. By contrast, the uncertainties with the chemicals shipping are small since the overall contribution to total sea-borne trade is small.

Lastly, the appropriateness of the projection should be considered with other assumptions, or 'storylines'. So, for the low-fossil fuel scenarios of RCP2.6, for example, it is important to decouple shipping traffic of fossil fuels from GDP.

Overall, the representation in this work of different ship cargo types with different stage economic non-linear models and inherently different growth rates along with decoupling of fossil fuel transport from GDP represents a large step up in 'appropriateness' from the original projections of shipping transport that were simple linear projections of total sea-borne trade against GDP.

The transport work projections show significant differences (lower) than previously calculated. However, the cause of this is not the shape or magnitudes of the predicted ratios but rather an inherent change in the GDP projections in the IIASA database. As described earlier, the absolute projected GDP data from IIASA are not used as part of the projections now predate the present day. Hence, historical observed GDP data have been used to 2018, and thereafter individual SSP GDP growth rates over a 2018 datum, using the baseline marker SSP scenarios as described earlier. The following figure of the previous GDP data (adjusted as growth factors over 2018) compared with the present set of data in the IIASA database.

Figure 31 - Comparison of formerly used SSP GDP projections from IIASA database (calculated as growth rates over 2018 historical datum)



As can be seen from the above Figure 31, there are substantial differences. The old data show increases over 2018 by factors of 4.13, 3.08, 2.21, 3.08, 5.59 by 2050 (SSP1, SSP2, SSP3, SSP4, SSP5) compared with factors of 3.10, 2.48, 1.93, 2.38, 3.89 (SSP1, SSP2, SSP3, SSP4, SSP5) for the same period with the new GDP data.

I.3 Gravity-model analysis of bilateral transport data

This alternative proposes to model the transport work for each pair of origin and destination country (and ship types) in terms of each country's GDP per capita and population measures using a gravity model, panel data approach and machine learning techniques. Once we establish the relationship between GDP, population and transport work measures, we use the selected SSP+RCP scenarios to forecast the future transport work for 2018-2050. We present the basic ideas of the model, as well as the data sources in the next subsections.

Methodology

The transport work demand can be estimated by using gravity equation (or trade models). The model estimate (and project) demand in specific markets and countries using regionally disaggregated data (e.g. it is possible to use country's GDP per capita growth and population to project trade flows).
The main reference for trade models is the gravity model[9] (Korinek and Sourdin, 2009). It is established that the country's j imports $\boldsymbol{M}$ in the year t from the exporter country i ($\boldsymbol{M_{ijt}}$) follows:

$$M_{ijt} = G.\frac{Y_{it}.Y_{jt}}{Dist_{ij}}$$

Where Y_{it} is the GDP's exporter country i, Y_{jt} is the GDP's importer country j, $Dist_{ij}$ is the distance between both countries and G is an adjustment coefficient. One possibility is to take the natural logarithm in both sides of gravity equation and considers a random error (η):

$$\ln M_{ijt} = \gamma_0 + \gamma_1 \ln(Y_{it}.Y_{jt}) + \gamma_2 \ln Dist_{ij} + \eta_{ijt}$$

As mentioned by Korinek and Sourdin (2009),Clark et al. (2004) and Limão and Venables (2001), the distance in the traditional gravity models represents a proxy to the transport costs. The improvement of the databases available allowed a deployment in the non-artificial trade barrier component, since the distance has been replaced for a set of elements such as the transport costs and geographical factors. Based on the academic discussion, an augmented gravity model can be estimated to project trade flows between an exporter country i and an importer country j concerning the commodity k in year t ($\boldsymbol{TF_{kijt}}$)[10] transported by the sea (m: maritime transport). This variable can represent both export and import values: i) when aggregating trade flows by exporter countries i, we obtain exports value in a given year; and, ii) in the same way, when aggregating the trade flow variable by the importer countries j, we obtain imports value in a specific year.
Korinek and Sourdin (2009), using a panel database for OECD countries, expanded the gravity model including a set of geographical and historical variables and specific effects, such as indicators of early colonial relationship between the countries, or common language between them, as well as variables that describe the existence of regional trade agreement between the trade partners. To simplify the model, but still control for those important variables, some authors include origin-destination fixed effects (Kabir et al., 2017).

In the Fourth IMO GHG Study, we convert each product trade flow (transported by sea) into the following ship types (s): Container carrier; Bulk carrier (without coal); Ro-Ro; and

[9] The gravity equation derives from the Newton's law of universal gravitation, under which the attraction force between two masses is proportional to the product of the two masses and inversely proportional to the square of the distance between them. Similarly, a country imports from a specific exporter are taken as proportional to the product of the two countries' GDP and inversely proportional to the square of the distance.

[10] Later in the methodology we show that we will disaggregate the data into ship types, instead of commodities.

Chemical Tanker. To convert the products into ship types, we propose a correspondence matrix between products and ship types in the data subsection of this appendix. Finally, we convert those trade flows by ship type into transport work measure by multiplying the trade quantity (calculated using LASSO regression[11]) by sea distance between the pairs of countries. The final gravity model to be estimated is the following (for each ship type):

$$\ln TW_{ijt,s} = \theta_{t,s} + \alpha_s \ln(GDPpc_{it}) + \beta_s \ln\left(GDPpc_{jt}\right) + \lambda_{1,s}\ln(Pop_{it}) + \lambda_{2,s}\ln(Pop_{jt}) + \boldsymbol{X}_{ij}\boldsymbol{\gamma_s} + \eta_s \log(TWinitial_{ij,s}) + \varepsilon_{ijt,s}$$

In which:
- $TW_{ijt,s}$ is the transport work measure for origin country i, destination country j in year t and for ship type s;
- $GDPpc_{it}$ and $GDPpc_{jt}$ are the GDP per capita measures for country i and j in year t;
- Pop_{it} and Pop_{jt} are the population estimates of countries i and j in year t;
- $\boldsymbol{X}_{ij}$ is a vector of origin and destination (and origin-destination) controls;$TWinitial_{ij,s}$ is the initial transport work measure for origin country i, destination country j in year t and for ship type s to control for idiosyncratic changes in the outcome variable;
- θ_t represents time fixed effects (common aggregate shocks);
- $\alpha, \beta, \gamma, \eta, \lambda$ are parameters to be estimated;
- $\varepsilon_{ijt,s}$ is an error term.

We consider GDP per capita and population separately to be able to account for income and size effects differently. We also consider the possibility of a second-order polynomial form for GDP (for both origin and destination), as the Third Study GHG Study has already shown a non-linear relationship between these variables.

The parameters of the above equation can be estimated by Ordinary Least Squares (OLS) considered clusters for origin-destination pairs and weights based on total GDP of the country pairs in 2014.

Data

a Trade flows:

We use trade flows data provided by the United Nation Commodity Trade (UN Comtrade[12]). The UN Comtrade dataset is collected and maintained by the United Nation Statistics Division (UNSD). UNSD collects, compiles, and disseminates detailed trade data by commodity category (here called "Product") and by trading partner (200 partners or countries) for merchandise trade (here called "Region"). This dataset provides not only values for exports and imports but also data on and net weight, detailed by product and partner. In UN Comtrade, weight and quantity are reported as net/gross weight in kg, following the WCO (World Customs Organization) and UNSD extended quantity units.[13] In UN Comtrade, the

[11] To calculate the total seaborne trade (volume) by each pair of countries and product aggregation, we employ a machine learning process called LASSO (least absolute shrinkage and selection operator) based on data from Cristea et al. (2013): quantity share of trade by 40 countries/regions and 23 products (aggregated from GTAP). The aim of using LASSO is to predict each mode of transport's shares of trade volume as a function of each origin-destination pair's geographical controls for each product aggregation we have. After obtaining the estimated coefficients using Lasso regression, we apply the same coefficients to all pair of countries of origin and destination using the same product aggregation of the paper.

[12] https://unstats.un.org/unsd/trade/default.asp

[13] "Except for a few goods, […] quantity is expressed in kilograms. For certain goods, a supplementary quantity is provided in addition to the net mass. This quantity is expressed in a unit that provides useful information.

aggregation of quantity information (net weight and quantity) is informed up to the 4-digit level in Harmonized System (HS) (UN, 2010) an international nomenclature for the classification of products. We use HS with 4-digits that comprises approximately 1,200 products. We use data from 2014 to 2018.

It is important to notice that UN Comtrade's trade flow data does not specify the transportation mode utilized. Hence, one important challenge is to decompose original trade flows into transportation modes. To do that, we use data from Cristea et al. (2013) on the value and quantity share of trade by 40 countries/regions and 23 products (aggregated from GTAP). We employ a machine learning process called LASSO (least absolute shrinkage and selection operator) to predict each mode of transport's shares of trade volume as a function of each origin-destination pair's geographical controls for each product aggregation (Ahrens et al., 2019). In the same Cristea et al. (2013) paper, the authors provide modal share for the imports and exports of each continent in 2004, by trade value and transport services (kg-km), transportation modal share differs greatly between regions. Worldwide, 50% of trade by value is sea-borne, with much higher ratios in South America, Middle East/Africa, and Oceania exports. Excluding land-based modes, maritime transport represents 73% of international cargo for World exports. When trade is measured by transport services (kg-km), sea transport is found to dominate, with 95% of transportation services provided.

The authors based their data on GTAP database. To obtain trade in kilograms, Cristea et al. (2013) draw on three primary data sources that report trade by value and weight at the 6-digit level of the Harmonized system. These are: US Imports and Exports of Merchandise; Eurostats Trade (covering the imports and exports of 27 EU countries), and the ALADI trade database, covering the imports of 11 Latin American countries (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Mexico, Paraguay, Peru, Uruguay and Venezuela) from all exporters worldwide. The data for modal shares comes from these same three sources (where needed, the authors use supplementary data from the Transborder Surface Freight Data).

b Sea Distances

When it comes to the sea distances measures (in nautical miles and travel time), we access the nautical distances from the portal sea-distances.org. This is an online tool that calculates seagoing distances between international seaports. The database consists of more than 4,000 seaports and 4,000,000 pairwise sea voyage distances. The online system returns the distances in nautical miles for direct routes (eventually passing by Panama Canal, strait of Magellan, Cape Horn, Suez Canal or Cape of Good Hope). We considered the average of the minimum distance between ports of each pair of countries. For some pairs of countries, the distance was not possible to be calculated (as the website do not account a port in the country). In such cases, we consider the measure of indirect distance from Cristea et al. (2013).

In Cristea et al. (2013), the authors calculated distances between each country pair as follows: (i) They use a database with country-hub locations for each origin-destination pair; (ii) for country pairs that are only connected via indirect routes, they calculate the indirect distance as "direct distance origin to hub" + "direct distance hub to destination". Because there could be multiple hubs per origin-destination pair, they choose the minimum indirect distance per origin-destination pair; (iii) Due to asymmetries in the data between indirect distance by direction of travel (i.e., A to B indirect distance may be different from B to A indirect distance), the authors choose the minimum indirect distance among any direction of

Supplementary units are units other than kilograms such as, for example, litres, numbers of pieces, carats, terajoules or square metres".

travel within a bilateral pair; and (iv) if a country pair has both direct and indirect routes, they use direct distance.[14]

c **GDP and population**:

GDP and population data are from the World Bank (WB). GDP and population predictions were developed by the International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR)[15] for all the SSP scenarios (SSP1 to SSP5)[16], from 2020 to 2050 by 187 countries. We complement these scenarios with updated OECD data of 2019 (OECD.Stat) and we also include a new socio-economic scenario that considers population and GDP long-term forecast by OECD from 2020 to 2050[17].

IIASA's population and GDP per capita projections for each SSP are presented in Table 13 (in in average growth rate per year). We use the data disaggregated by country as an input for the projections.

Table 13 - Population and GDP per capita growth (in % per year) - World - IIASA

SSPs	GDP per capita growth 2010-2050 (per year)	Population growth 2010-2050 (per year)
SSP1	2.8%	**0.5%**
SSP2	2.4%	**0.7%**
SSP3	1.6%	**0.9%**
SSP4	1.8%	**0.7%**
SSP5	3.2%	**0.5%**

d **Energy data:**

Energy data is obtained from SSP's integrated assessment scenarios at IIASA (International Institute for applied systems research, Cuaresma, 2017)[18]. We use projection data on annual percentage consumption growth considering primary energy variables (Primary Energy – Coal, Primary Energy – Gas and Primary Energy – Oil) for the world and for five aggregated regions[19] (Asia, Latin America, Middle East and Africa, OECD and Reforming economies of

14 Information obtained in communication with the authors.

15 See Cuaresma (2017) and Samir and Lutz (2017).

16 Data is available at https://tntcat.iiasa.ac.at/SspDb/

17 Data is available at https://data.oecd.org/gdp/gdp-long-term-forecast.htm

18 Data is available at https://tntcat.iiasa.ac.at

19 Asia region (R5.2ASIA) includes Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China (incl. Hong Kong and Macao, excl. Taiwan) Democratic People's Republic of Korea, Fiji, French Polynesia, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Micronesia (Fed. States of), Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Timor-Leste, Vanuatu, Viet Nam. OECD (R5.2OECD) region includes Albania, Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Guam, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, New Zealand, Norway, Poland, Portugal, Puerto Rico, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Turkey, United Kingdom, United States of America. Reforming Economies region (R5.2REF) includes Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Middle East and Africa (R5.2MAF) Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic,

Eastern Europe and the former Soviet Union), from 2020 to 2050. We use SSP 1 to 5 baseline (considering each SSP marker IAM[20] — integrated assessment model) and all possible combinations between SSP 1 to 5 and RCP 1.9 to 6.0, according to the marker IAM as can be seen in Table 14.

Table 14 - SSP and RCP possible combinations and Marker integrated assessment model (IAM)

SSP	Baseline	RCP					Marker IAM
		1.9	2.6	3.4	4.5	6.0	
1	SSP1-Baseline	SSP1-19	SSP1-26	SSP1-34	SSP1-45		IMAGE
2	SSP2-Baseline	SSP2-19	SSP2-26	SSP2-34	SSP2-45	SSP2-60	MESSAGE GLOBIOM
3	SSP3-Baseline			SSP3-34	SSP3-45	SSP3-60	AIM/CGE
4	SSP4-Baseline		SSP4-26	SSP4-34	SSP4-45	SSP4-60	GCAM4
5	SSP5-Baseline	SSP5-19	SSP5-26	SSP5-34	SSP5-45	SSP5-60	REMIND MAGPIE

Table 15 presents SSPs baseline projections and SSP-RCP projections in EJ/year and % growth between 2010-50, considering the world energy demand estimation and Marker IAM for each SSP. When it comes to gas projections, we expect a higher demand for this energy source in almost all scenarios, except for SSP5 combination with RCP 1.9. The total increase in demand for gas might reach a maximal of 248% (in 2050 compared with 2010) in SSP5 combined with RCP 6.0. On the other hand, coal demand decreases in almost all scenario combinations, except for SSP baselines and for all RCP 6.0 combinations, as well as SSP1 combined with RCP 4.5. The change in demand for oil depends on the scenarios. It is expected to increase in almost all SSP3, 4 and 5 combinations with RCPs. All SSP1 combinations are expected to generate decreases in oil demand, from 19% (SSP1-RCP 4.5) to 80% (SSP1-RCP 1.9).

Chad, Comoros, Congo, Côte d`Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Occupied Palestinian Territory, Oman, Qatar, Rwanda, Réunion, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe. Latin America region (R5.2LAM) includes Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, United States Virgin Islands, Uruguay, Venezuela (Bolivarian Republic of).

[20] Each SSP has been implemented by multiple IAM models. There are thus alternative interpretations from different IAM models for each of the SSPs. For each SSP, a so-called Marker Scenario was selected from the available model interpretations. For instance, the marker scenarios can be interpreted as representatives of the different storylines. As much as possible, we have ensured that the elaborations of the different markers provide a consistent story across the different SSPs. In addition, other IAM elaborations for specific SSPs can be used as an indication of the SSP uncertainty space.

Table 15 - Energy demand projection - World EJ/year and cumulative percentage (2010-50)

SSP_RCP	Primary Energy (EJ/year and cumulative % 2010-50)											
	Coal				Oil				Gas			
	2010	2050	2100	*% var. 2010-50*	2010	2050	2100	*% var. 2010-50*	2010	2050	2100	*% var. 2010-50*
SSP1-Baseline	145	180	116	*24%*	172	141	54	*-18%*	113	269	217	*138%*
SSP1-19	145	25	12	*-83%*	172	34	20	*-80%*	113	147	60	*31%*
SSP1-26	145	67	30	*-54%*	172	110	37	*-36%*	113	193	101	*71%*
SSP1-34	145	119	44	*-18%*	172	131	34	*-24%*	113	247	96	*119%*
SSP1-45	145	168	56	*16%*	172	139	45	*-19%*	113	265	157	*135%*
SSP2-Baseline	140	207	359	*48%*	173	246	299	*42%*	106	241	347	*128%*
SSP2-19	140	38	0	*-73%*	173	34	3	*-81%*	106	128	53	*21%*
SSP2-26	140	56	87	*-60%*	173	141	2	*-18%*	106	215	107	*103%*
SSP2-34	140	71	187	*-49%*	173	206	19	*19%*	106	243	209	*130%*
SSP2-45	140	111	247	*-20%*	173	231	52	*33%*	106	247	283	*134%*
SSP2-60	140	172	220	*23%*	173	242	259	*40%*	106	248	333	*135%*
SSP3-Baseline	134	307	543	*128%*	177	250	205	*41%*	107	203	256	*90%*
SSP3-34	133	97	44	*-27%*	176	206	91	*17%*	107	139	73	*30%*
SSP3-45	133	127	101	*-5%*	176	232	143	*32%*	107	161	130	*51%*
SSP3-60	133	163	199	*22%*	176	242	189	*38%*	107	176	203	*65%*
SSP4-Baseline	143	288	218	*101%*	176	188	202	*7%*	114	241	210	*112%*
SSP4-26	143	87	2	*-39%*	176	151	14	*-14%*	114	169	42	*48%*
SSP4-34	143	98	8	*-32%*	176	178	42	*1%*	114	202	71	*78%*
SSP4-45	143	134	44	*-6%*	176	189	144	*7%*	114	221	163	*94%*
SSP4-60	143	246	66	*72%*	176	198	193	*12%*	114	243	204	*113%*
SSP5-Baseline	135	353	888	*161%*	172	362	196	*111%*	112	379	447	*237%*
SSP5-19	135	4	1	*-97%*	172	116	9	*-32%*	112	58	3	*-48%*
SSP5-26	135	6	3	*-96%*	172	273	9	*59%*	112	221	16	*97%*
SSP5-34	135	44	5	*-67%*	172	330	34	*92%*	112	335	73	*198%*
SSP5-45	135	87	107	*-35%*	172	339	149	*98%*	112	346	266	*208%*
SSP5-60	135	180	281	*33%*	172	354	209	*106%*	112	391	344	*248%*

Source: IIASA SSP database.

To project transport work related to energy products' maritime transportation, the change in energy demand projections was applied to the total transport work measures calculated using Clarkson (2020) and the Comtrade data by ship type (for Oil Tankers, Gas Tankers and Coal Bulk Carriers). Historical transport work data (from 2014-19) per energy type (Coal, Gas and Oil) was obtained using Clarkson data in billion tonnes-miles by ship type (Clarkson, 2020).

e Relevant Assumptions

Several aggregation operators are used in order to simulate the seaborne transportation of loads and transport work. Below we describe all aggregations used and the reasons for using each of them.

Product's categorization: We created a categorization using both Cristea et al. (2013) Classification, which is based on the Global Trade Analysis Project (GTAP)[21], and the

[21] GTAP is a global data base which contains complete bilateral trade information, transport and protection linkages among 113 regions for all 57 GTAP commodities for a single year (2004 in the case of the GTAP 7 Data Base). In addition, GTAP 7 allows one to model production and trade for 57 traded and non-traded sectors between 113 countries (Ibid). GTAP database also includes information on the value of output and trade.

Harmonized System (HS). GTAP provides data on 57 sectors aggregation. Cristea et al. (2013) aggregate those sectors further into 27 categories, 23 of which are composed by tradable goods and, therefore, are relevant to the sea transport market. We further disaggregate those into 37 categories. Table 16 describes the classification developed for the purposes of this study.

Table 16 - Description of the product´s categories

Classification	Cristea et al. (2013)	hs07 CODES
Bulk Agriculture - High Added Value	Bulk Agriculture	0601; 0603; 0604; 0903; 0904; 0905; 0906; 0907; 0908; 0909; 0910; 1203; 1204; 1210; 1211; 1302; 1801; 2401; 5301; 5302; 5303; 5305; 5306; 5307; 5308
Bulk Agriculture - Low Added Value	Bulk Agriculture	0602; 0901; 1001; 1002; 1003; 1004; 1005; 1006; 1007; 1008; 1201; 1202; 1205; 1206; 1207; 1209; 1212; 1213; 1214; 5201
Chemical, rubber, plastic products - Bulk solid	Chemical, rubber, plastic products	2827; 2828; 2829; 2830; 2831; 2832; 2833; 2834; 2835; 2839; 3101; 3102; 3103; 3104; 3105; 3214; 3824; 3825; 3901; 3902; 3903; 3904; 3905; 3906; 3907; 3908; 3909; 3910; 3911; 3912; 3913; 3914; 3915; 4001; 4002; 4003; 4004; 4005; 4006
Chemical, rubber, plastic products - High Added Value	Chemical, rubber, plastic products	2712; 2801; 2802; 2803; 2805; 2812; 2813; 2817; 2819; 2820; 2821; 2822; 2823; 2824; 2825; 2826; 2837; 2840; 2841; 2842; 2843; 2844; 2845; 2846; 2942; 3001; 3002; 3003; 3004; 3005; 3201; 3202; 3203; 3204; 3205; 3206; 3207; 3208; 3209; 3210; 3211; 3212; 3213; 3215; 3301; 3303; 3304; 3305; 3306; 3307; 3401; 3404; 3405; 3407; 3501; 3502; 3503; 3504; 3505; 3506; 3507; 3601; 3602; 3603; 3604; 3605; 3701; 3702; 3703; 3704; 3705; 3706; 3707; 3802; 3803; 3805; 3806; 3807; 3808; 3809; 3810; 3811; 3812; 3813; 3814; 3815; 3817; 3818; 3819; 3820; 3821; 3822; 3916; 3917; 3918; 3919; 3920; 3921; 3922; 3923; 3924; 3925; 3926; 4007; 4008; 4009; 4010; 4011; 4012; 4013; 4014; 4015; 4016; 4017; 5904; 5906
Chemical, rubber, plastic products - High Added Value Solid	Chemical, rubber, plastic products	2914
Chemical, rubber, plastic products – Liquid	Chemical, rubber, plastic products	1520; 2207; 2707; 2708; 2804; 2806; 2807; 2808; 2809; 2810; 2811; 2814; 2815; 2816; 2836; 2847; 2848; 2849; 2850; 2852; 2853; 2901; 2902; 2903; 2904; 2905; 2906; 2907; 2908; 2909; 2910; 2911; 2912; 2913; 2914; 2915; 2916; 2917; 2918; 2919; 2920; 2921; 2922; 2923; 2924; 2925; 2926; 2927; 2928; 2929; 2930; 2931; 2932; 2933; 2934; 2935; 2936; 2937; 2938; 2939; 2940; 3302; 3402; 3403; 3823
Electronic equipment	Electronic equipment	7321; 7322; 8418; 8422; 8450; 8451; 8471; 8501; 8502; 8503; 8504; 8505; 8506; 8507; 8508; 8509; 8510; 8511; 8512; 8513; 8515; 8516; 8517; 8518; 8519; 8521; 8522; 8523; 8525; 8526; 8527; 8528; 8529; 8530; 8531; 8532; 8533; 8534; 8535; 8536; 8537; 8538; 8539; 8540; 8541; 8542; 8543; 8544; 8545; 8548; 9001; 9002; 9005; 9006; 9007; 9008; 9010; 9011; 9012; 9013; 9014; 9015; 9016; 9018; 9022; 9024; 9025; 9026; 9027; 9028; 9029; 9030; 9031; 9032; 9033; 9101; 9102; 9103; 9104; 9105; 9106; 9107; 9108; 9109; 9110; 9111; 9112; 9113; 9114; 9405; 9504
Ferrous metals - Bulk	Ferrous metals	2618; 2619; 7201; 7203; 7204; 7208; 7209; 7210; 7211; 7212; 7213; 7214; 7215; 7219; 7225
Ferrous metals - Semi-Finished	Ferrous metals	7202; 7205; 7206; 7207; 7216; 7217; 7218; 7220; 7221; 7222; 7223; 7224; 7226; 7227; 7228; 7229; 7301; 7302; 7303; 7304; 7305; 7306; 7307
Fishing	Fishing	0301; 0302; 0307; 0508; 7101
Forestry	Forestry	1301; 1401; 4401; 4501
Leather products	Leather products	4104; 4105; 4106; 4107; 4112; 4113; 4114; 4115; 4201; 4202; 4205; 4302; 6401; 6402; 6403; 6404; 6405; 6406; 9605
LNG	GAS	271111

Classification	Cristea et al. (2013)	hs07 CODES
LPG	GAS	271112; 271113; 271114; 271119; 271121; 271129
Machinery and equipment nec	Machinery and equipment nec	8405; 8406; 8410; 8412; 8413; 8414; 8415; 8416; 8417; 8419; 8420; 8421; 8423; 8424; 8425; 8426; 8427; 8428; 8429; 8430; 8431; 8432; 8433; 8434; 8435; 8436; 8437; 8438; 8439; 8440; 8441; 8442; 8443; 8444; 8445; 8446; 8447; 8448; 8449; 8452; 8453; 8454; 8455; 8456; 8457; 8458; 8459; 8460; 8461; 8462; 8463; 8464; 8465; 8466; 8467; 8468; 8469; 8470; 8472; 8473; 8474; 8475; 8476; 8477; 8478; 8479; 8481; 8482; 8483; 8484; 8486; 8514; 8805; 9017; 9508
Manufactures nec	Manufactures nec	0501; 3006; 3406; 3606; 4206; 6601; 6602; 6603; 6701; 6702; 6703; 6704; 7105; 7113; 7114; 7116; 7117; 7118; 9003; 9004; 9019; 9020; 9021; 9023; 9201; 9202; 9205; 9206; 9207; 9208; 9209; 9402; 9403; 9404; 9503; 9505; 9506; 9507; 9601; 9602; 9603; 9604; 9606; 9607; 9608; 9609; 9610; 9611; 9612; 9613; 9614; 9615; 9616; 9617; 9618
Metal products - Large	Metal products	7308; 8401; 8402; 8403; 8404; 9406
Metal products - Small	Metal products	7309; 7310; 7311; 7312; 7313; 7314; 7315; 7316; 7317; 7318; 7319; 7320; 7323; 7324; 7325; 7326; 8201; 8202; 8203; 8204; 8205; 8206; 8207; 8208; 8209; 8210; 8211; 8212; 8213; 8214; 8215; 8301; 8302; 8303; 8304; 8305; 8306; 8307; 8308; 8309; 8310; 8311; 8480; 8487; 8607; 8608; 9301; 9302; 9303; 9304; 9305; 9306; 9307
Metals nec - Bulk	Metals nec	2818; 7601
Metals nec - High Added Value	Metals nec	2620; 7106; 7107; 7108; 7109; 7110; 7111; 7112; 7115; 7401; 7402; 7403; 7404; 7405; 7406; 7407; 7408; 7409; 7410; 7411; 7412; 7413; 7415; 7418; 7419; 7501; 7502; 7503; 7504; 7505; 7506; 7507; 7508; 7602; 7603; 7604; 7605; 7606; 7607; 7608; 7609; 7610; 7611; 7612; 7613; 7614; 7615; 7616; 7801; 7802; 7804; 7806; 7901; 7902; 7903; 7904; 7905; 7907; 8001; 8002; 8003; 8007; 8101; 8102; 8103; 8104; 8105; 8106; 8107; 8108; 8109; 8110; 8111; 8112; 8113
Mineral products nec - Bulk	Mineral products nec	2518; 2521; 2522; 2523; 2715; 3801; 3816; 6807
Mineral products nec - High Added Value	Mineral products nec	6801; 6802; 6803; 6804; 6805; 6806; 6808; 6809; 6810; 6811; 6812; 6813; 6814; 6815; 6901; 6902; 6903; 6904; 6905; 6906; 6907; 6908; 6909; 6910; 6911; 6912; 6913; 6914; 7001; 7002; 7003; 7004; 7005; 7006; 7007; 7008; 7009; 7010; 7011; 7013; 7014; 7015; 7016; 7017; 7018; 7019; 7020; 7104; 8546; 8547
Minerals - Bulk	Minerals	2501; 2502; 2503; 2504; 2505; 2506; 2507; 2508; 2509; 2510; 2511; 2512; 2513; 2514; 2515; 2516; 2517; 2519; 2520; 2524; 2525; 2526; 2528; 2529; 2530; 2601; 2602; 2603; 2604; 2605; 2606; 2607; 2608; 2609; 2610; 2611; 2612; 2613; 2614; 2615; 2617; 2621; 2703
Minerals - High Added Value	Minerals	2616; 7102; 7103
Motor vehicles and parts - Parts	Motor vehicles and parts	8708; 8708
Motor vehicles and parts - Vehicles	Motor vehicles and parts	8701; 8702; 8703; 8704; 8705; 8706; 8709; 8716
Oil	OIL	2709
Paper products, publishing - Bulk	Paper products, publishing	3804; 4701; 4702; 4703; 4704; 4705; 4706; 4707

Classification	Cristea et al. (2013)	hs07 CODES
Paper products, publishing - High Added Value	Paper products, publishing	4801; 4802; 4803; 4804; 4805; 4806; 4807; 4808; 4809; 4810; 4811; 4812; 4813; 4814; 4816; 4817; 4818; 4819; 4820; 4821; 4822; 4823; 4901; 4902; 4903; 4904; 4905; 4906; 4907; 4908; 4909; 4910; 4911; 5905; 9704
Petroleum, coal products - Liquid	Petroleum, coal products	2710
Petroleum, coal products - Solid	Petroleum, coal products	2701; 2702; 2704; 2706; 2713; 2714
Processed Agriculture - High Added Value	Processed Agriculture	0201; 0202; 0203; 0204; 0205; 0206; 0207; 0208; 0209; 0210; 0303; 0304; 0305; 0306; 0401; 0402; 0403; 0404; 0405; 0406; 0407; 0408; 0409; 0410; 0502; 0504; 0505; 0506; 0507; 0510; 0511; 0701; 0702; 0703; 0704; 0705; 0706; 0707; 0708; 0709; 0710; 0711; 0712; 0713; 0714; 0801; 0802; 0803; 0804; 0805; 0806; 0807; 0808; 0809; 0810; 0811; 0812; 0813; 0814; 0902; 1101; 1102; 1103; 1104; 1105; 1106; 1107; 1108; 1109; 1208; 1404; 1501; 1502; 1503; 1504; 1505; 1506; 1507; 1508; 1509; 1510; 1511; 1512; 1513; 1514; 1515; 1516; 1517; 1518; 1521; 1522; 1601; 1602; 1603; 1604; 1605; 1701; 1702; 1703; 1704; 1802; 1803; 1804; 1805; 1806; 1901; 1902; 1903; 1904; 1905; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; 2101; 2102; 2103; 2104; 2105; 2106; 2201; 2202; 2203; 2204; 2205; 2206; 2208; 2209; 2301; 2302; 2303; 2304; 2305; 2306; 2307; 2308; 2309; 2402; 2043; 4101; 4102; 4103; 4301; 5001; 5002; 5003; 5004; 5005; 5006; 5007; 5101; 5102; 5103; 5104; 5105; 5106; 5107; 5108; 5109; 5110
Processed Agriculture - Live animals	Processed Agriculture	0101; 0102; 0103; 0104; 0105; 0106
Textiles	Textiles	5111; 5112; 5113; 5202; 5203; 5204; 5205; 5206; 5207; 5208; 5209; 5210; 5211; 5212; 5309; 5310; 5311; 5401; 5402; 5403; 5404; 5405; 5406; 5407; 5408; 5501; 5502; 5503; 5504; 5505; 5506; 5507; 5508; 5509; 5510; 5511; 5512; 5513; 5514; 5515; 5516; 5601; 5602; 5603; 5604; 5605; 5606; 5607; 5608; 5609; 5701; 5702; 5703; 5704; 5705; 5801; 5802; 5803; 5804; 5805; 5806; 5807; 5808; 5809; 5810; 5811; 5901; 5902; 5903; 5907; 5908; 5909; 5910; 5911; 6001; 6002; 6003; 6004; 6005; 6006; 6301; 6302; 6303; 6304; 6305; 6306; 6307; 6308; 6309; 6310; 8804
Transport equipment nec	Transport equipment nec	8407; 8408; 8409; 8411; 8601; 8602; 8603; 8604; 8605; 8606; 8609; 8710; 8711; 8712; 8713; 8714; 8715; 8801; 8802; 8803; 9401
Wearing apparel	Wearing apparel	4203; 4303; 4304; 6101; 6102; 6103; 6104; 6105; 6106; 6107; 6108; 6109; 6110; 6111; 6112; 6113; 6114; 6115; 6116; 6117; 6201; 6202; 6203; 6204; 6205; 6206; 6207; 6208; 6209; 6210; 6211; 6212; 6213; 6214; 6215; 6216; 6217; 6501; 6502; 6504; 6505; 6506; 6507
Wood products	Wood products	4402; 4403; 4404; 4405; 4406; 4407; 4408; 4409; 4410; 4411; 4412; 4413; 4414; 4415; 4416; 4417; 4418; 4419; 4420; 4421; 4502; 4503; 4504; 4601; 4602

Product and ship type correspondence matrix: For each type of product described before, a ship type correspondence has been chosen as shown in Table 17. The correspondence between the type of ship and each product is done to minimize the matching errors and based on seaborne trade data.

Table 17 - Products and its correspondent ship type

ID	Product	Ship type
1	Bulk Agriculture - High Added Value	Container Carrier
2	Bulk Agriculture - Low Added Value	Bulk Carrier
3	Chemical, rubber, plastic products - Bulk solid	Bulk Carrier
4	Chemical, rubber, plastic products - High Added Value	Container Carrier
5	Chemical, rubber, plastic products - High Added Value Solid	Container Carrier
6	Chemical, rubber, plastic products - Liquid	Chemical Tanker
7	Electronic equipment	Container Carrier
8	Ferrous metals - Bulk	Bulk Carrier
9	Ferrous metals - Semi-Finished	Container Carrier
10	Fishing	Container Carrier
11	Forestry	Bulk Carrier
12	Leather products	Container Carrier
13	LNG	LNG Tanker
14	LPG	LPG Tanker
15	Machinery and equipment nec	Container Carrier
16	Manufactures nec	Container Carrier
17	Metal products - Large	Bulk Carrier
18	Metal products - Small	Container Carrier
19	Metals nec - Bulk	Bulk Carrier
20	Metals nec - High Added Value	Container Carrier
21	Mineral products nec - Bulk	Bulk Carrier
22	Mineral products nec - High Added Value	Container Carrier
23	Minerals - Bulk	Bulk Carrier
24	Minerals - High Added Value	Container Carrier
25	Motor vehicles and parts - Parts	Container Carrier
26	Motor vehicles and parts - Vehicles	RoRo
27	Oil	Oil Tanker
28	Paper products, publishing - Bulk	Bulk Carrier
29	Paper products, publishing - High Added Value	Container Carrier
30	Petroleum, coal products - Liquid	Oil Tanker
31	Petroleum, coal products - Solid	Bulk Carrier
32	Processed Agriculture - High Added Value	Container Carrier
33	Processed Agriculture - Live animals	Container Carrier
34	Textiles	Container Carrier
35	Transport equipment nec	Container Carrier
36	Wearing apparel	Container Carrier
37	Wood products	Container Carrier

Results

a Ships that transport energy products:

Table 18 presents the results to total transport work projections (in billion ton-miles and cumulative percentage variation between 2018 and 2050), to Coal (transported by Bulk Carriers), Oil (transported by Oil Tankers), and Gas (transported by Gas Tankers), considering SSP 1 to 5 baseline scenarios. To project transport work the change in energy demand projections was applied on the total transport work measures calculated using Clarkson (2020) and the Comtrade data by ship type (for Oil Tankers, Gas Tankers and Coal Bulk Carriers).

Analyzing Table 18 cumulative variations (2018-2050) one can observe that Oil Tanker presents the lower cumulative rates in the period, followed by Coal Bulk Carrier and Gas Tanker (shows the highest cumulative variations, except for SSP3). Among the different baseline SSPs, SSP1 registers the lowest cumulative variation for all ship types considered, being followed by SSP4 (for Oil Tanker and Gas Tanker). In turn, SSP5 shows the highest cumulative variation for the three types of ships analyzed.

Table 18 - Transport Work projection - Energy products - World Bln ton-miles and cumulative percentage (2018-2050)

SSP	Coal_Bulk Carier			Oil_Tanker			Gas_Tanker		
	2018 (ton-miles)	2050	*% var. 2018-2050*	2018 (ton-miles)	2050	*% var. 2018-2050*	2018 (ton-miles)	2050	*% var. 2018-2050*
SSP1-Baseline	5563	6415	*15%*	13561	11115	*-18%*	1781	3562	*100%*
SSP2-Baseline	5563	8091	*45%*	13561	16520	*22%*	1781	3875	*118%*
SSP3-Baseline	5563	9988	*80%*	13561	16077	*19%*	1781	3076	*73%*
SSP4-Baseline	5563	8316	*49%*	13561	13535	*-0.2%*	1781	3308	*86%*
SSP5-Baseline	5563	14362	*158%*	13561	21640	*60%*	1781	4882	*174%*

Source: IIASA SSP Database.

In turn, Table 19 presents the results to total transport work projections considering SSP and RCP possible combinations (and utilizing marker IAMs). The projections are expressed in billion tonnes-miles and cumulative percentage variation between 2018 and 2050, to Coal Bulk Carrier, Oil tanker and Gas Tanker. Considering Coal Bulk Carrier, Table 19 shows that all SSP+RCP combinations register negative cumulative variations between 2018-2050, except for the highest RCP (radiative forcing levels in W/m^2) for each SSP1, that is SSP1_45 (8%), SSP2_60 (24%), SSP3_60 (2%), SSP4_60 (36%), SSP5_60 (49%).

Oil Tanker presents negative cumulative variation in the period 2018-2050 for all SSP1_RCPs combinations (from -78% to -20%) and to the lowest radiative forcing levels in SSP2 (+RCP1.9: -83% and RCP2.6: -30%), SSP3 (+RCP3.4: -1%), SSP4 (+RCP2.6: -19% and RCP3.4: -4%) and SSP5

(+RCP1.9: -48%). The highest cumulative variation to Oil Tanker is registered by SSP5 combined with RCP 6.0, indicating 56% growth to the period analyzed.

Regarding Gas Tanker all SSP+RCP combinations shows positive cumulative variations between 2018-2050 ranging from 16% (SSP2, RCP1.9) to 163% (SSP5, RCP6.0), except for SSP5xRCP1.9 which totalizes -63%.

In comparison to SSP+RCP combinations, SSPs baseline scenarios (Table 19) register higher cumulative variation between 2018-2050 to all ship types in almost all cases, except to SSP4+RCP combinations to Oil Tanker. When comparing each SSP baseline to its correspondent SSP+RCP combinations, we can see that:

1. Coal Bulk Carrier SSP baseline scenarios range from 15% (SSP1) to 158% (SSP5), while SSP1+RCP combinations range from -80% (SSP1, RCP 1.9) to 8% (SSP1, RCP4.5) and SSP5+RCP varies from -97% (SSP5, RCP1.9) to 46% (SSP5, RCP6.0);
2. Considering Gas Tanker, SSP baseline scenarios range from 73% (SSP3) to 174% (SSP5) while SSP3+RCP combinations register variations between 18% (SSP3, RCP3.4) and 50% (SSP3, RCP6.0) and SSP5+RCP between -61% (SSP5, RCP1.9) and 163% (SSP5, RCP6.0); and,
3. Regarding Oil Tanker SSP baseline scenarios cumulative variation varies between -18% (SSP1) to 60% (SSP5), while SSP1+RCP combinations ranges between -78% (SSP1, RCP1.9) and -20% (SSP1, RCP4.5) SSP5+RCP between -48% (SSP5, RCP1.9) and 56% (SSP5, RCP6.0).

Table 19 - Transport Work projection - Energy products - SSP+RCP combinations - World Bln ton-miles and cumulative percentage (2018-2050)

SSP+RCP	Coal - Bulk Carrier			Gas Tanker			Oil Tanker		
	2018 (bln ton-miles)	2050	*% var. 2018-2050*	2018 (bln ton-miles)	2050	*% var. 2018-2050*	2018 (bln ton-miles)	2050	*% var. 2018-2050*
SSP1_19	5,563	1,098	*-80%*	1,781	2,245	*26%*	13,561	2,989	*-78%*
SSP1_26	5,563	2,440	*-56%*	1,781	2,589	*45%*	13,561	8,792	*-35%*
SSP1_34	5,563	4,205	*-24%*	1,781	3,260	*83%*	13,561	10,358	*-24%*
SSP1_45	5,563	5,982	*8%*	1,781	3,458	*94%*	13,561	10,894	*-20%*
SSP2_19	5,563	1,553	*-72%*	1,781	2,075	*16%*	13,561	2,256	*-83%*
SSP2_26	5,563	2,289	*-59%*	1,781	3,505	*97%*	13,561	9,491	*-30%*
SSP2_34	5,563	2,912	*-48%*	1,781	3,871	*117%*	13,561	13,798	*2%*
SSP2_45	5,563	4,517	*-19%*	1,781	3,947	*122%*	13,561	15,561	*15%*
SSP2_60	5,563	6,884	*24%*	1,781	3,986	*124%*	13,561	16,195	*19%*
SSP3_34	5,563	3,361	*-40%*	1,781	2,107	*18%*	13,561	13,405	*-1%*
SSP3_45	5,563	4,457	*-20%*	1,781	2,449	*37%*	13,561	15,263	*13%*
SSP3_60	5,563	5,687	*2%*	1,781	2,678	*50%*	13,561	15,886	*17%*
SSP4_26	5,563	2,703	*-51%*	1,781	2,356	*32%*	13,561	10,961	*-19%*
SSP4_34	5,563	3,000	*-46%*	1,781	2,842	*60%*	13,561	13,003	*-4%*
SSP4_45	5,563	4,106	*-26%*	1,781	3,075	*73%*	13,561	13,671	*1%*
SSP4_60	5,563	7,570	*36%*	1,781	3,393	*91%*	13,561	14,372	*6%*
SSP5_19	5,563	173	*-97%*	1,781	693	*-61%*	13,561	6,986	*-48%*
SSP5_26	5,563	274	*-95%*	1,781	2,621	*47%*	13,561	16,299	*20%*
SSP5_34	5,563	2,073	*-63%*	1,781	3,969	*123%*	13,561	19,786	*46%*
SSP5_45	5,563	4,090	*-26%*	1,781	4,128	*132%*	13,561	20,390	*50%*
SSP5_60	5,563	8,298	*49%*	1,781	4,687	*163%*	13,561	21,219	*56%*

Source: IIASA SSP Database.

b. Ships that transport non-energy products:

Table 20 shows the result of the gravity model by ship type considering the relationship between GDP per capita and population (both for origin and destination countries) and transport work, respectively. The table shows that the elasticity of transport work on GPD per capita of origin countries varies from 0.97 (Container Carrier) to 1.17 (RoRo), i.e. a 1% increase in GDP per capita raises transport work of Container Carriers in 0.97%. The elasticity of destination countries is lower in all specifications (from 0.24 for Container Carriers to 0.39 for Bulk Carriers and Chemical Tankers). The same behaviour is observed for transport work and population elasticities, as the origin population seems to be higher than the destination population to trade transport work (almost the double effect).

Table 20 - Impacts of GDP per capita and population on transport work, by ship, 2014-2018

	(1)	(2)	(3)	(4)
	Bulk Carrier	Chemical Tanker	Container Carrier	RoRo
Log(GDP pc - origin)	1.1269***	1.0430***	0.9674***	1.1730***
	-0.0708	-0.0759	-0.0672	-0.0792
Log(Pop. - origin)	1.0595***	0.8368***	0.7928***	0.8576***
	-0.0661	-0.0539	-0.0565	-0.0523
Log(GDP pc - dest.)	0.3930***	0.3952***	0.2401***	0.2790***
	-0.0528	-0.0495	-0.047	-0.0551
Log(Pop. - dest.)	0.5529***	0.4354***	0.3214***	0.3387***
	-0.0487	-0.0416	-0.0388	-0.0403
	144412	144412	144412	144412
Observations	0.7433	0.7976	0.7126	0.7188
R squared	1.1269***	1.0430***	0.9674***	1.1730***

Standard errors in parentheses.

Notes: All standard errors are clustered by pairs of origin-destination. All columns include year fixed effects, controls (contiguity among countries, common primary language, colonial relationship, same colonizer, distance between capitals, origin and destination coast extension, data if country is landlocked) and the base year logarithm of transport work (2014) to control for idiosyncratic country-pair variation. All regressions are weighted by total GDP of country pairs.

*p < 0.10, **p < 0.05, ***p < 0.01

Based on the results of the above table and on GDP and population growth predictions, the next step is to predict total transport work, globally and by country. To be consistent with the inventory measures, our baseline measure of transport work is the Clarkson's measurement of 2018. Table 21 summarizes the total predictions in 2050.

For all ship types, OECD, SSP 3 and SSP4 scenarios predict the lowest transport work, while SSP 5 is the scenario of higher global transport work. For Bulk Carriers in 2050, global transport work might reach 42,493 billion tonnes miles in SSP3 (80% increase when compared with 2018 levels) and 61,234 billion tonnes miles in SSP5 (159% increase from 2018). In the case of Chemical Tankers, the lowest increase in 2050 is observed in OECD scenario (2,083

billion tonnes-miles, or a 61% increase from 2050-2018) and higher increase in SSP 5 scenario (2,825 billion tonnes-miles, 118% increase when compared with 2018).
When it comes to Container Carriers, the total transport work might reach from 14,259 billion tonnes-miles (SSP3) to 19,479 billion tonnes-miles (SSP5) in 2050 (62% to 121% increase, respectively). Total transport work from RoRo ships will increase less reaching 5,937 billion tonnes miles in SSP3 compared with 9,029 billion tonnes-miles in SSP5 scenario.

Table 21 - Total transport work per ship type and scenario in 2050, in billion-tonnes (bln-ton) and cumulative percentage (cum. %)

Ship type	Scenario	Transport Work (in bln-ton)	Transport Work (in cum. %)
Bulk Carrier	OECD	42,493	80%
	SSP1	53,919	128%
	SSP2	51,506	118%
	SSP3	41,414	75%
	SSP4	44,219	87%
	SSP5	61,234	159%
Chemical Tanker	OECD	2,083	61%
	SSP1	2,488	92%
	SSP2	2,398	85%
	SSP3	2,044	58%
	SSP4	2,134	65%
	SSP5	2,825	118%
Container Carrier	OECD	14,815	68%
	SSP1	17,468	98%
	SSP2	16,856	91%
	SSP3	14,259	62%
	SSP4	14,890	69%
	SSP5	19,479	121%
RoRo	OECD	7,589	74%
	SSP1	7,815	79%
	SSP2	7,362	69%
	SSP3	5,937	36%
	SSP4	6,695	53%
	SSP5	9,029	107%

b Consolidated results:

When it comes to the total transport work estimated by scenario, Table 22 summarizes the main results.

Table 22 - Global transport-work in 2050 by scenario, in billion tonnes-miles and in percent change to 2018 levels

Scenario	Total Transport-Work in 2050 (in billion tonnes-miles)	% change (2018-2050)
OECD	96,119.58	62.8%
SSP1	102,780.60	74.1%
SSP2	106,608.48	80.6%
SSP3	92,795.11	57.2%
SSP4	93,097.82	57.7%
SSP5	133,452.33	126.1%

I.4 Comparison of logistic and gravity models

The objective of this subsection is to compare the gravity model and logistic model approaches adopted in the Fourth IMO GHG Study to identify a causal link between income (GDP), population and the demand for maritime transport.

In the gravity model, we compare the trade flow data spanning the years of 2014-2018 and exploit annual GDP per capita and population measures for both origin and destination countries with other covariates and also controlling for time-invariant factors that affect trade (e.g. trade specificities between pairs of countries). The time-invariant factors also allow us to deal with trade composition bias that likely plagues estimates obtained from models without controlling for trade specificities.

The logistic model captures historical correlations between income, population and transport work, but not covariate variables or time-invariant factors that affect trade. The same happens when we estimate using trade flow pooled data without considering covariates and lime-invariant factors. In fact, OLS (estimates using trade flow pooled data) mimic a time series model (logistic model).

To explore this matter further, we compare the projections using trade model without other control variables with the projections from the logistic model: Projections gravity model are identified by “G”, while logistic model is identified by “L” for Bulk Carriers (Figure 32), Chemical Tanker (Figure 33) and Container Carrier (Figure 34). Then, Figures Figure 35, Figure 36 and Figure 37 show the comparison between the gravity model using all relevant variables as controls (“G” results) and projections using logistic model (“L” results) for Bulk Carriers, Chemical Tanker and Container Carrier, respectively.

Figure 32 - Transport work Predictions: Logistic (L) Vs gravity model (G) based on Table 2's estimates, 2018-2050, Bulk Carriers

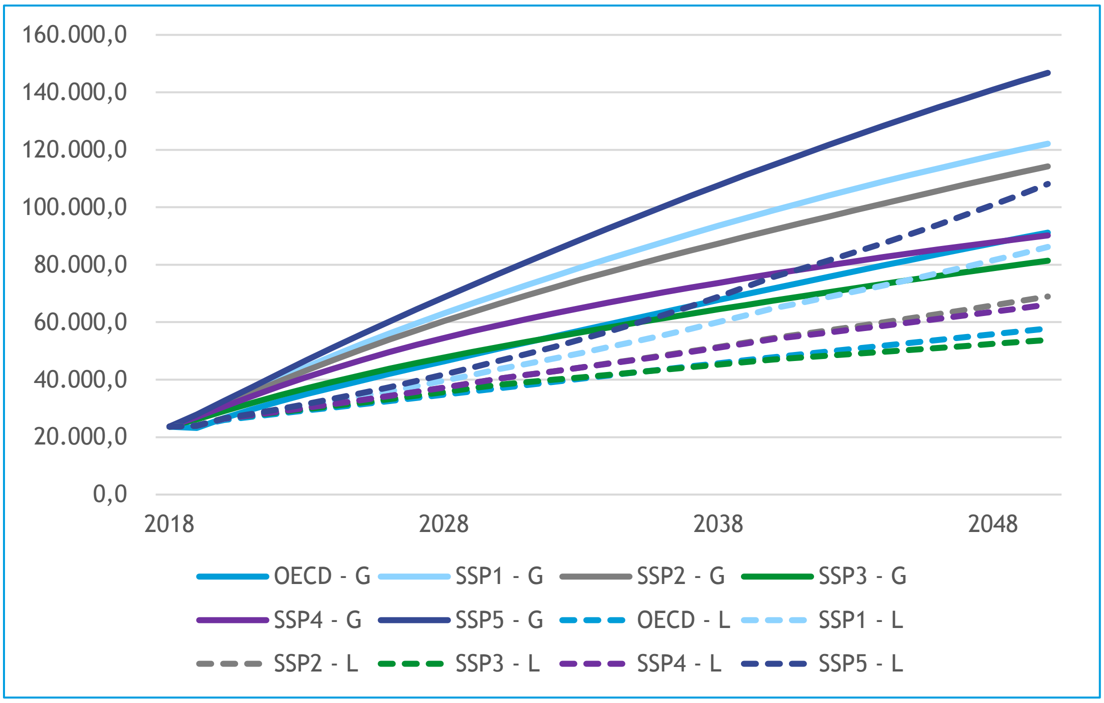


Figure 33 - Transport work Predictions: Logistic (L) Vs gravity model (G) based on Table 2's estimates, 2018-2050, Chemical Tankers

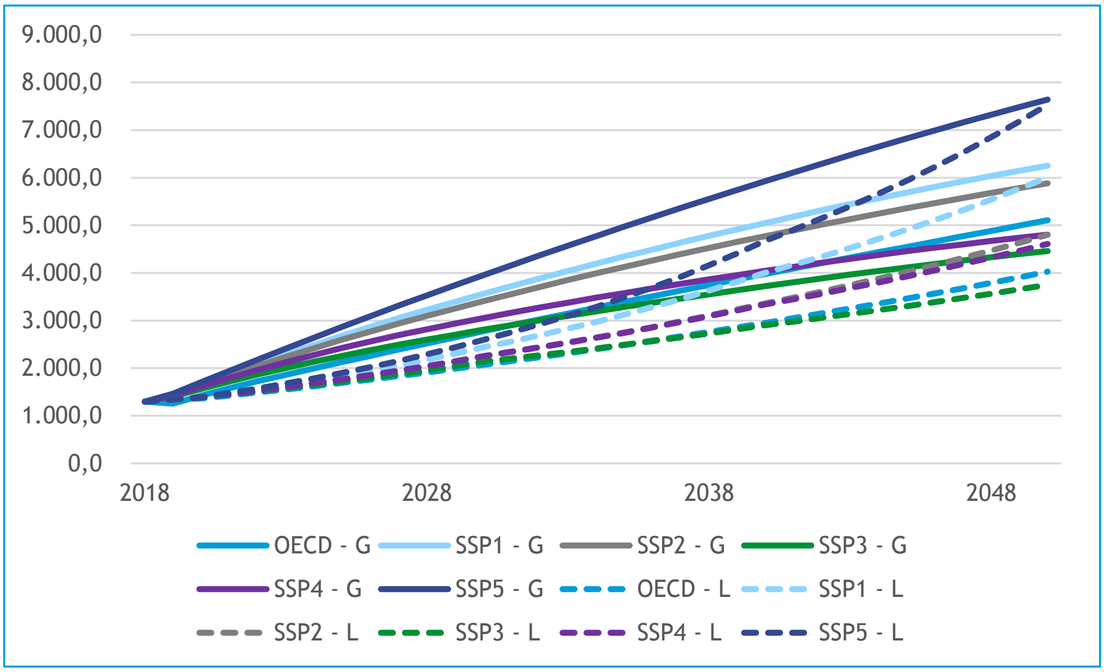


Figure 34 - Transport work Predictions: Logistic (L) Vs gravity model (G) based on Table 2's estimates, 2018-2050, Container Carriers

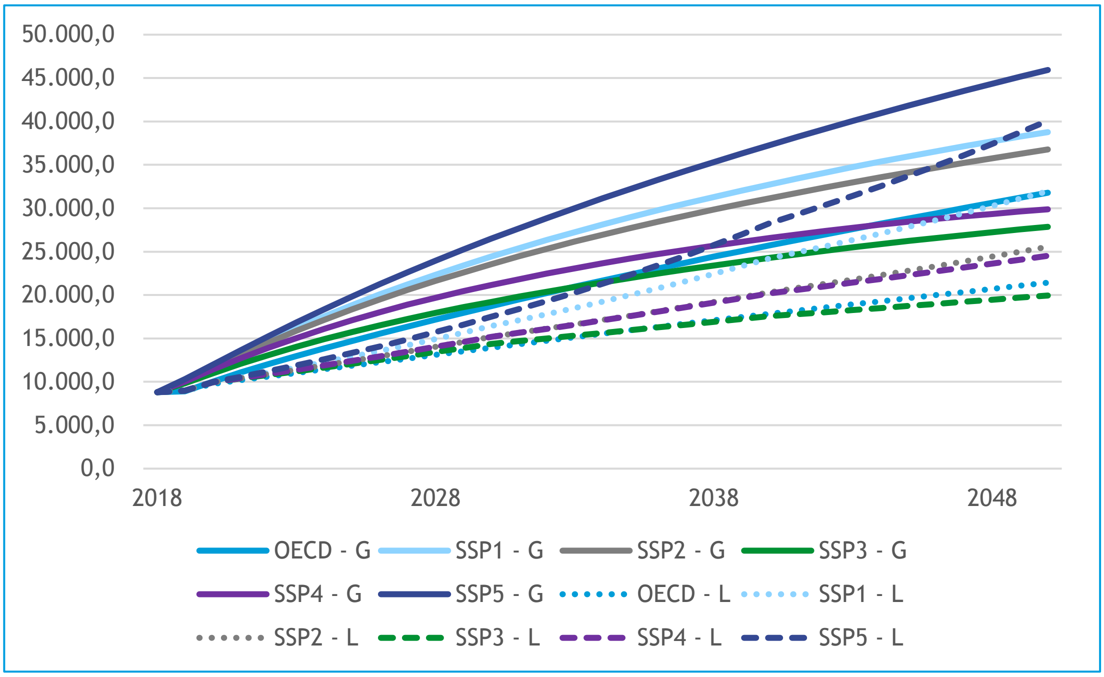


Figure 35 - Transport work Predictions: Logistic (L) Vs gravity model (G) based on Table 3's estimates, 2018-2050, Bulk Carriers

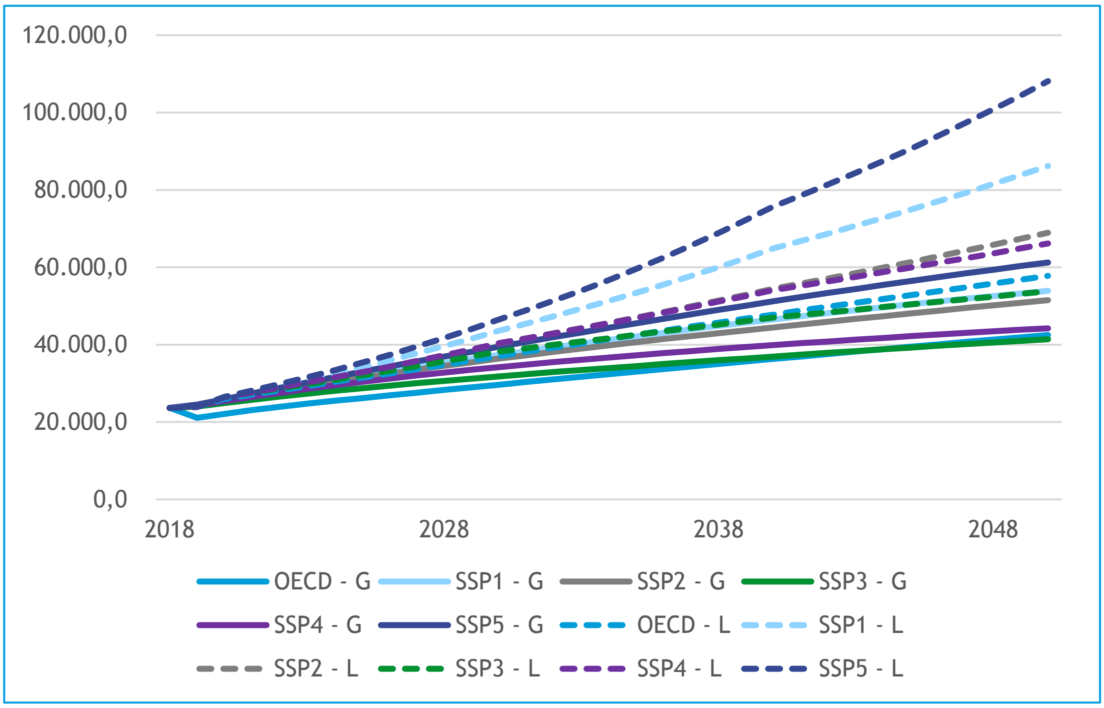


Figure 36 - Transport work Predictions: Logistic (L) Vs gravity model (G) based on Table 3's estimates, 2018-2050, Chemical Tankers

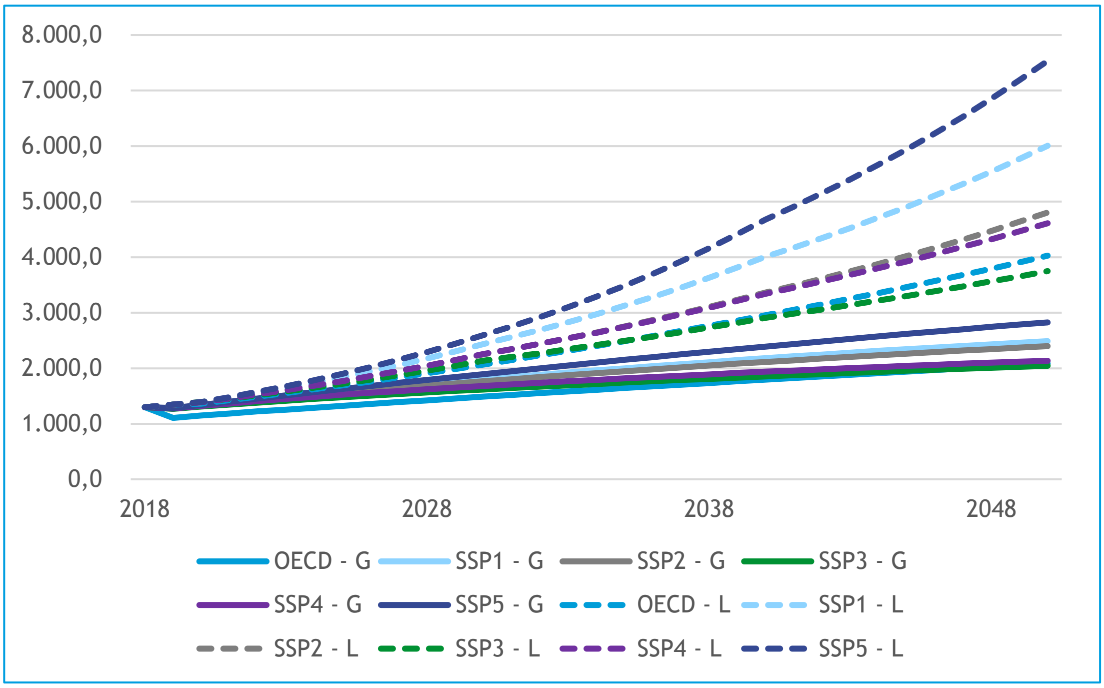
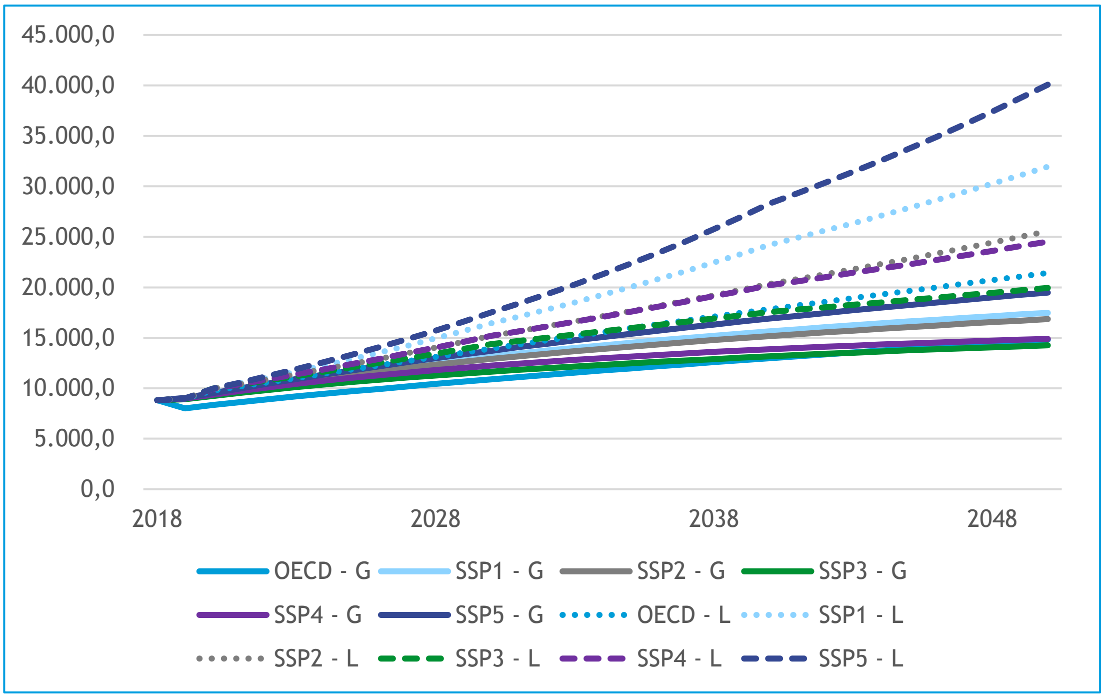


Figure 37 - Transport work Predictions: Logistic (L) Vs gravity model (G) based on Table 3's estimates, 2018-2050, Container Carriers



From the comparisons above it is clear that the inclusion of control variables that are considered to capture the particularities of bilateral trade flows (such as historical linkages, production facilities of multinational corporations, similar languages or legal systems, port infrastructure) reduces the elasticity of transport work with regards to per capita GDP and population.

Table 23 presents a comparison of the advantages and disadvantages of both models: the logistic model using time series data compared to the trade model using panel data.

Table 23 - Comparison of Logistic Model and Gravity Model, Advantages and Disadvantages

	Logistic Model	Gravity Model
Data requirement	Low	Medium
Historical Analysis	1983-2018	2014-2018
Computational requirement	Low	Medium
Need for data assumptions	Low	High
Need for statistical assumptions	High	Low

Because both methods have their strengths and weaknesses, this study presents both as plausible projections of transport work related to non-energy products transportation. The difference between the two can be interpreted as the uncertainty inherent in making projections about future developments.

J Ship size projections

The distribution of the ships over their size categories can be expected to change over time according to the number of the ships that are scrapped and that enter the fleet as well as their respective size.

The age of a ship and its cost efficiency determine when a ship is to be scrapped. In the emissions projection model, a uniform lifetime of 25 years for all ships is assumed.

The size of the ships that enter the market is determined by several factors:
- the overall demand for the type of cargo transported by the ship type;
- the trade patterns regarding these cargoes, which depend on the geographical location of the supplying and demanding countries/regions;
- the cargo load factors on the specific trades that can be expected depending on the potential size of the ship; these load factors are not only determined by the total scope of the trade but also by the frequency of the deliveries expected by the demanding party;
- the physical restrictions that a ship faces in terms of the dimensions of canals, waterways and the extra costs of a detour (which could be lower than the cost saving when employing a larger ship);
- the physical restrictions a ship may face in terms of the dimensions (e.g. depth) of the ports and the equipment of the terminals;
- the productivity of the ports/terminals, which has an impact on the amount of time that a ship is non-active.

In the emissions projection model, it is assumed that, per size category, the average size of the ships will not change, whereas the number of ships per size bin will change compared to 2018. The total capacity per ship type, given a certain productivity level (in tonne-miles per dwt), is therefore assumed to be sufficient to meet the projected transport demand.

We know for each ship type, except for chemical tankers the following for 2018:
1. The average size of ships per size category.
2. The distribution of ships over the size categories in terms of capacity. And
3. The distribution of ships over the size categories in terms of numbers.

Based on a literature review, we then argue how we expect the distribution of ships over the size categories will develop until 2050. Historical developments of the distribution, expected structural changes in the markets and infrastructural constraints are taken into account.

The projection of the ship distribution until 2050 is associated with a high level of uncertainty. Future structural changes and their impacts are difficult to assess, and some markets, such as the LNG market, are rapidly evolving and highly uncertain future markets, making it difficult to draw conclusions from developments in the past. Even if a clear historical trend can be established, the question remains as to whether the trend will last or come to a halt.

This Annex discusses the developments in ship size for respectively container ships (Section J.1), oil tankers (Section J.2), bulk carriers (Section J.3), general cargo ships (Section J.4), and liquefied gas carriers (Section J.5).

J.1 Container ships

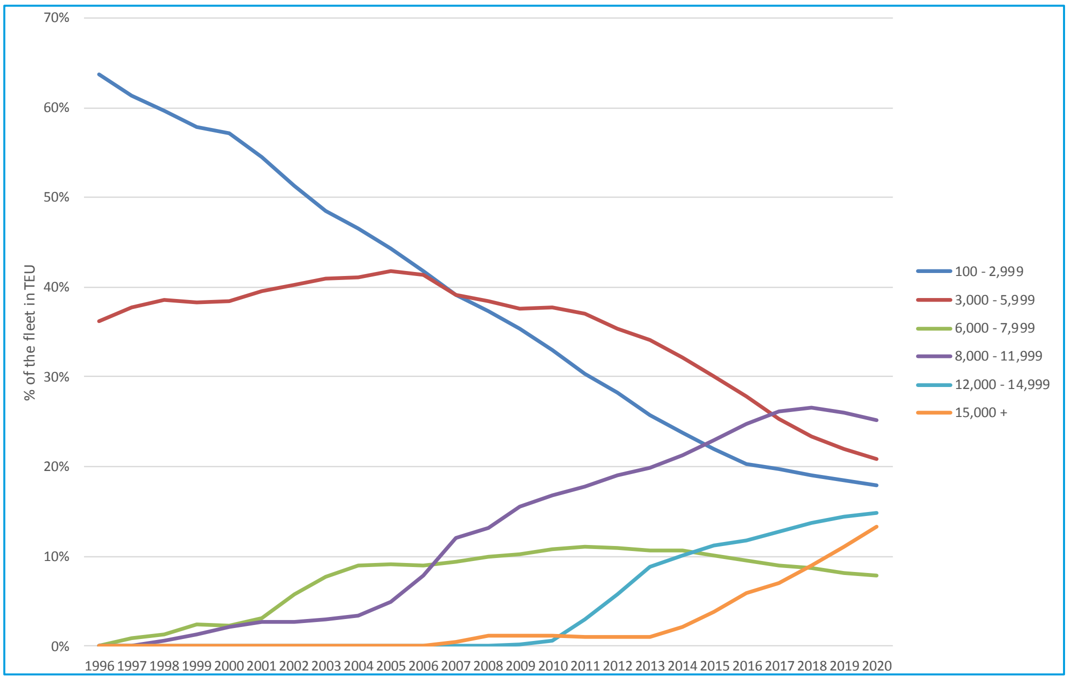
The starting point of this analysis is the 2018 distribution of the containerships over the size categories, see Table 24.

Table 24 - 2018 distribution of containerships over the size categories in terms of numbers and in terms of capacity

Capacity range (TEU)	Size category	Distribution of ships in terms of numbers	Distribution of ships in terms of capacity
100 – 2,999	Feeder containership	56%	19%
3,000 – 5,999	Intermediate containership	21%	23%
6,000 – 7,999	Intermediate containership	5%	9%
8,000 – 11,999	Neo-Panamax containership	12%	27%
12,000 – 14,999	Neo-Panamax containership	4%	14%
15,000+	Post-Panamax containership	2%	9%

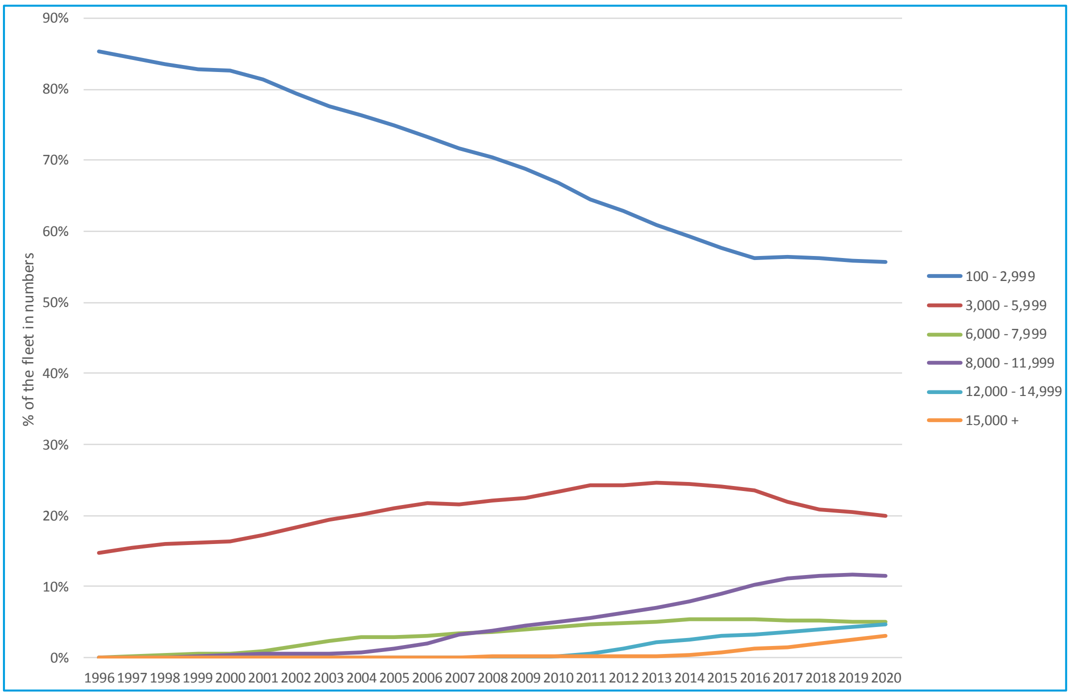
The capacity distribution of the containerships over the size categories is shown in Figure 38 and the distribution in terms of numbers over the size categories is shown in
Figure 39.

Figure 38 - Capacity distribution of containerships over size categories



Source: Clarksons World Fleet Register March 2020.

Figure 39 - Distribution of containerships in terms of numbers over size categories



Source: Clarksons World Fleet Register March 2020.

Above figures show that the distribution of the ships both in terms of capacity and in terms of numbers is decreasing over the years in the 100 – 2,999 TEU and 3,000 – 5,999 TEU ranges. The 6,000 – 7,999 TEU ships decrease moderately. The larger ship types increase both in terms of numbers and in terms of capacity. The 8,000 – 11,999 TEU range predominate the market, but their market share slowly decreases since 2018.

There are several factors between the increase in size:

- Owing to economies of scale, there has been a trend towards using larger ships, especially on the Asia-Europe routes, and trickling down to other routes. Even on routes where traditionally small ships were active, larger ships are currently being deployed.
- The locks of the Panama Canal were extended in 2016. Before this extension, the maximum capacity of a containership entering the canal was approximately 5,000 TEU. After the commissioning of the new locks, the maximum capacity is approximately 13,000 TEU. This has led to the replacement of intermediate containerships by post-panamax containerships.

Although, there is a trend in the increase of lager ship types, costs savings from bigger container ships are decreasing (ITF, 2015) and is dependent on the current and future market conditions in the container shipping market, the adaptive capacity of ports and terminals (both economically and technically) and on environmental requirements and considerations (Ge, et al., 2019).The limits in container-ship size seems much more limited by business strategy and canal dimensions than by technical constraints (PierNext, 2019).

The Post-Panamax containerships are deployed on the Europe-Asia and Transpacific trade. 20,000 TEU containerships are mainly deployed on the Europe-Asia trade, but their market share is increasing on the Transpacific trade. We expect that the capacity and the number of the Post-Panamax containerships will increase in the coming years, but that the growth factor will decrease. Ports and terminals need to change their infrastructure in order to handle these ships more efficiently. A balance must be made between the associated costs and the potential effectiveness for both port and ship owners.

Whether for the other trades even larger ships will be utilized by 2050 is, of course, debatable. Utilization rates may not be sufficient in the future, or intensive growth (i.e. higher capacity utilization) could, for example, lead to a slowing downs of the ship size growth. For our projection, we therefore assume that the number of larger ships does increase, but that this increase is not very pronounced.

Table 25 gives an overview of the development of the distribution of ships over the size categories that we expect, along with the respective estimation of the 2050 distribution.

Table 25 - Development of the distribution of container ships over size categories (share of TEU)

Capacity range (TEU)	2018 distribution	Development until 2050	2050 distribution
0 - 999	17%	Part of this size will be replacement by larger ship sizes because of port development.	13%
1,000 - 1,999	25%	Part of this size will be replacement by larger ship sizes because of port development.	20%
2,000 - 2,999	13%	Part of this size will be replacement by larger ship sizes because of port development.	10%
3,000 - 4,999	16%	Replacement by larger ships that can transit the expanded Panama Canal (until 15,000 TEU)	11%
5,000 - 7,999	11%	Share as in 2018	11%
8,000 - 11,999	12%	Share increases because of expansion of the Panama Canal and replacement of ships until 6,000 TEU	20%
12,000 - 14,499	4%	Share increases because of expansion of the Panama Canal and replacement of ships until 6,000 TEU	9%
14,500 - 19,999	2%	Share increase because of ongoing trend of using larger ships on the Transpacific and Asia-Europa trade.	4%
20,000 +	1%	Share increase because of ongoing trend of using larger ships on the Transpacific and Asia-Europa trade.	2%

If the average ship size per size bin does not change compared to 2018, the average size of a container ship will be approximately 5,800 TEU in 2050.

Figure 40 and Figure 41 show graphically what this implies for containerships. The average size of 5,800 TEU in 2050 means that this trend will slow down in the period until 2050.

Figure 40 - Expected 2050 distribution of containerships in terms of numbers over size categories

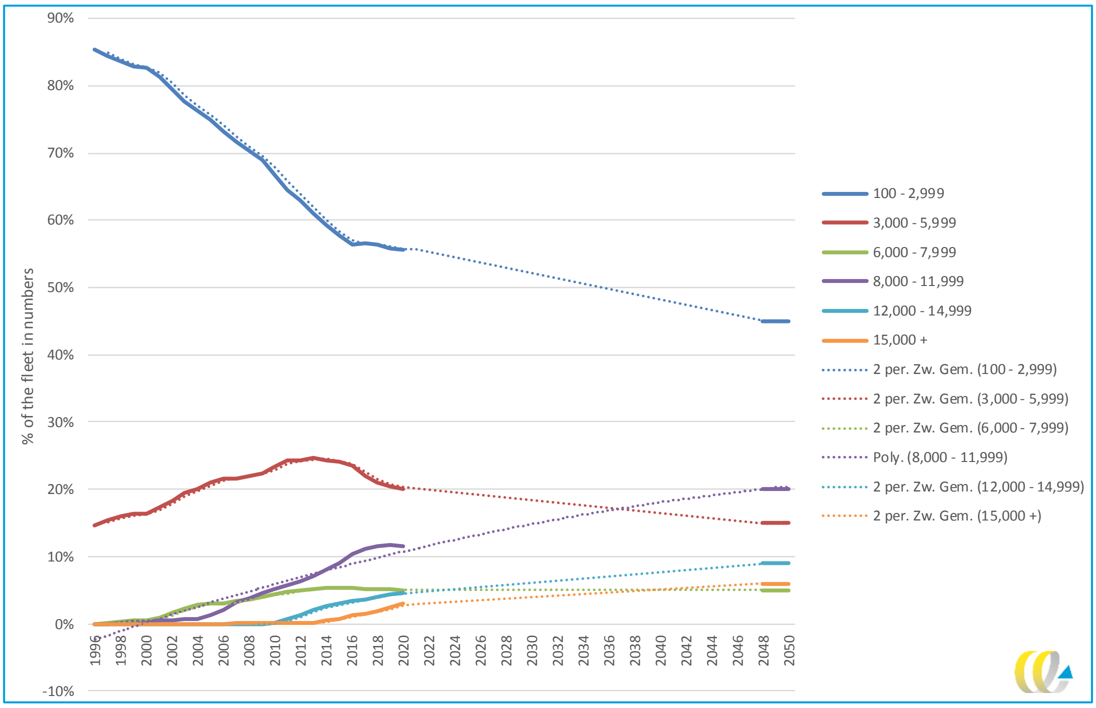
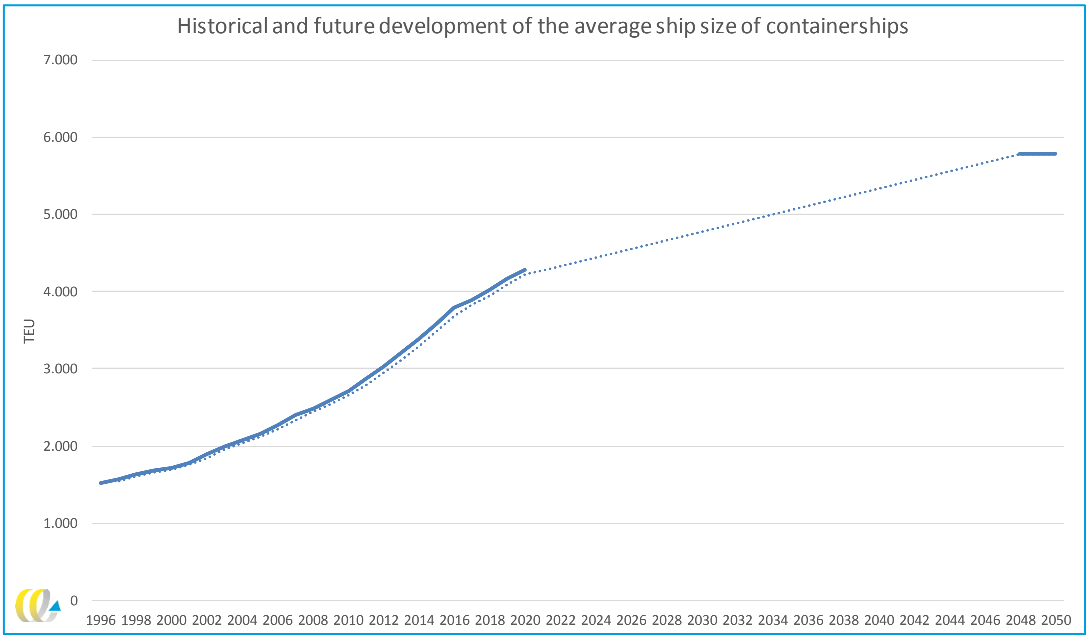


Figure 41 - Historical and future development of the average ship size of containerships



J.2 Oil tankers

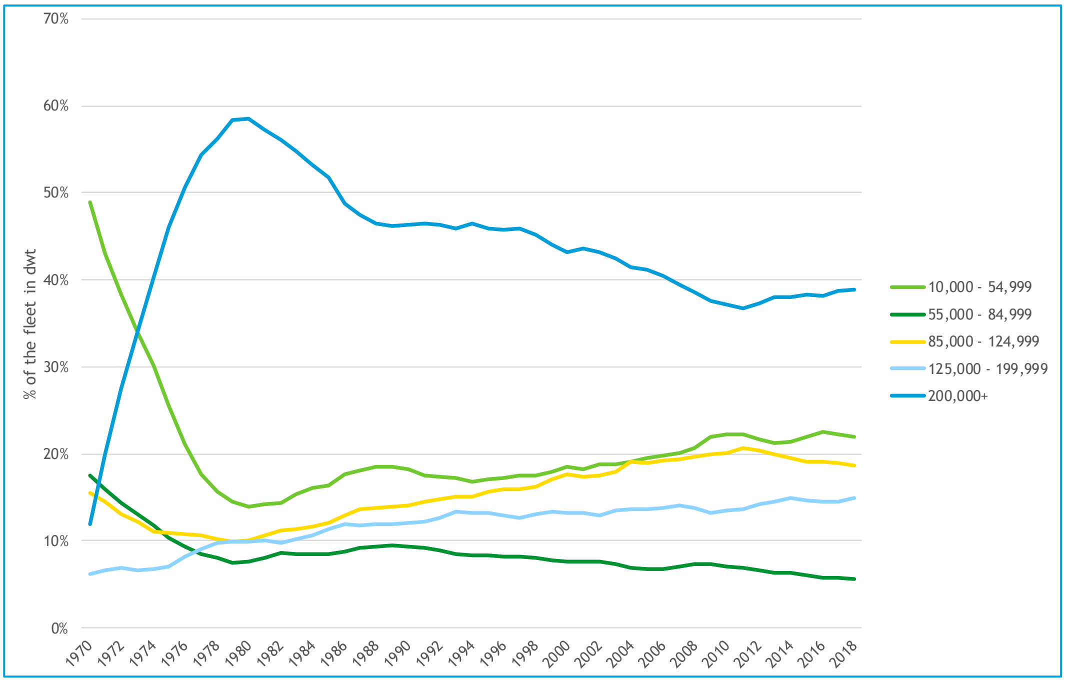
The starting point of this analysis is the 2018 distribution of the oil tankers over the size categories, see Table 26.

Table 26 - 2018 distribution of oil tankers over the size categories in terms of numbers and in terms of capacity

Capacity range (DWT)	Size category	Distribution of ships in terms of numbers	Distribution of ships in terms of capacity
10,000 - 54,999	Handysize	59%	22%
55,000 - 84,999	Panamax	7%	6%
85,000 - 124,999	Aframax	15%	19%
125,000 - 199,000	Suezmax	8%	15%
200,000 +	UL/VLCC	11%	39%

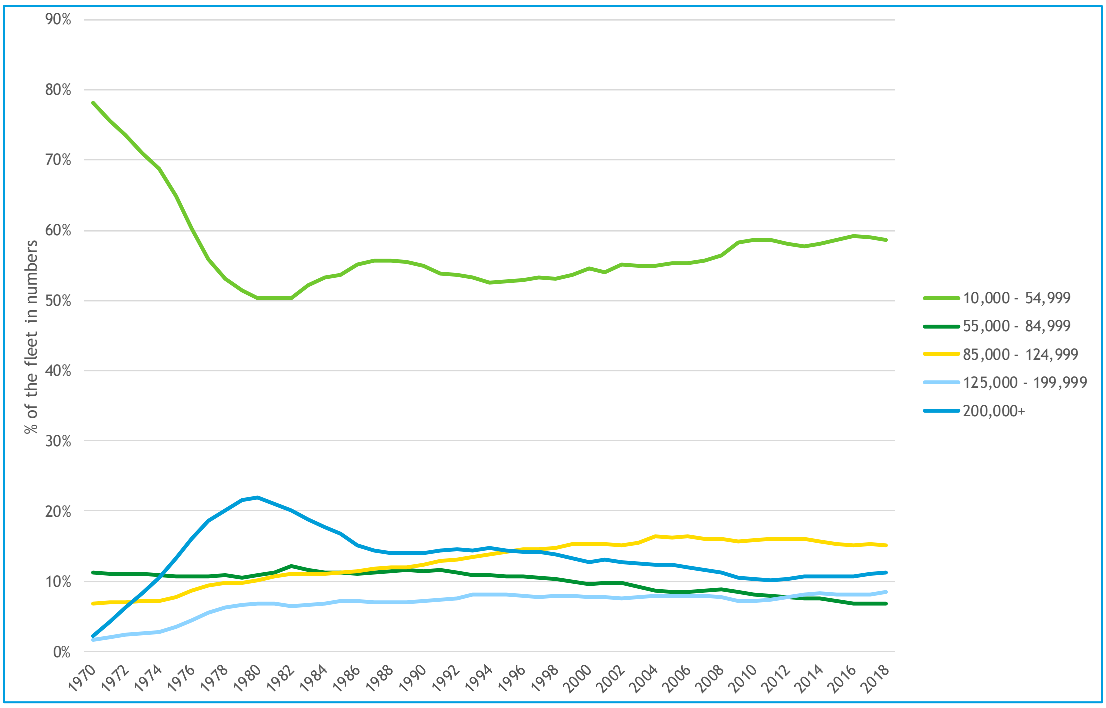
The capacity distribution of the oil tankers over the size categories is shown in Figure 42 and the distribution in terms of numbers over the size categories is shown in Figure 43 for the period 1970-2018.

Figure 42 - Capacity distribution of oil tankers over size categories



Source: Clarksons World Fleet Register March 2020.

Figure 43 - Distribution of oil tankers in terms of numbers over size categories



Source: Clarksons World Fleet Register March 2020.

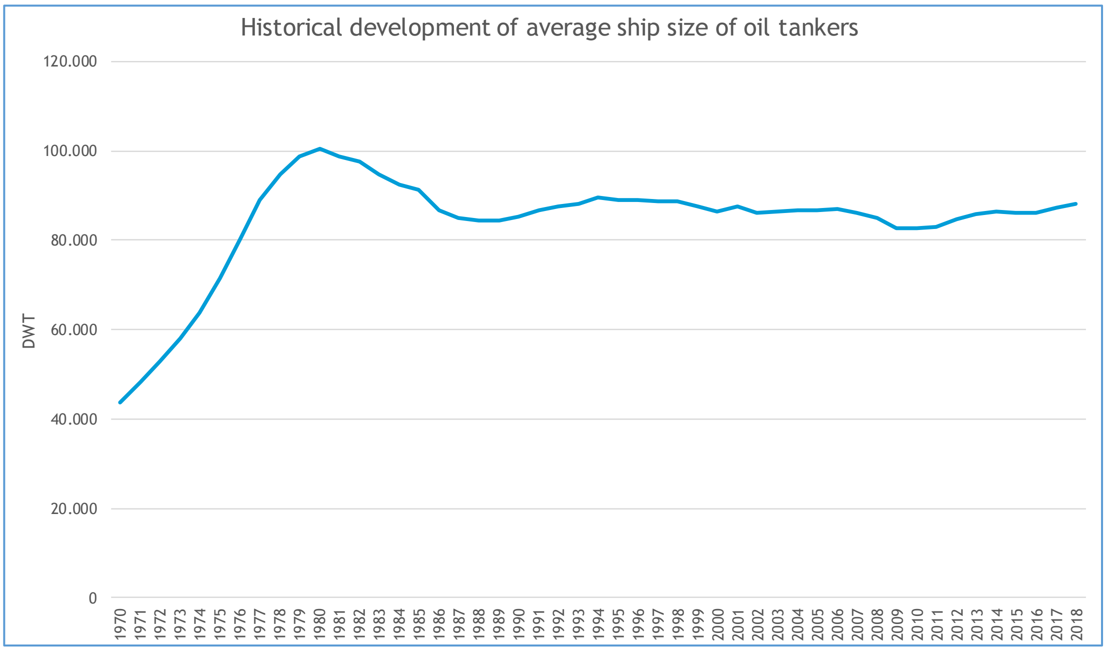
ULCCs have been built in the 1970s and had a peak in the market share around 1980. They are currently used as floating storage units. We do not expect a breakthrough of larger tankers in the coming decades.

The market share of oil tankers in the capacity range between 10,000 dwt and 54,999 dwt decreased quickly in the 1970s and slowly increase after 1980.

The market share of the ships between 55,000 dwt and 199,999 dwt remained quite stable over the years.

Figure 44 shows the average capacity of oil tankers over the period 1970-2018. After 1980, the average size of oil tankers decreased. This is mainly due to the market share decrease of the ULCCs. After this period the average ship size remained stable.

Figure 44 - Development of average capacity of oil tankers over the period 1970-2018



Source: Clarksons World Fleet Register March 2020.

From the available evidence, we conclude that:

— The shift from UL/VLCCs towards the other smaller tanker sizes seems to have come to a halt. It is uncertain whether the ship will play a role in the future once again, so we assume that the shares of classes will remain stable in the coming decades.
— VLCCs are likely to remain the largest tanker class.

Table 27 shows the development of the distribution of oil tankers over size categories.

Table 27 - Development of the distribution of oil tankers over size categories (dwt)

Capacity range (DWT)	2018 distribution	Development until 2050	2050 distribution
0 - 4,999	28%	None	28%
5,000 - 9,999	13%	None	13%
10,000 - 19,999	4%	None	4%
20,000 - 59,999	10%	None	10%
60,000 - 79,999	7%	None	7%
80,000 - 119,999	17%	None	17%
120,000 - 199,999	10%	None	10%
200,000 +	12%	None	12%

J.3 Bulk carriers

The starting point of this analysis is the 2018 distribution of the bulk carriers over the size categories, see Table 28.

Table 28 - 2018 distribution of bulk carriers over the size categories in terms of numbers and in terms of capacity

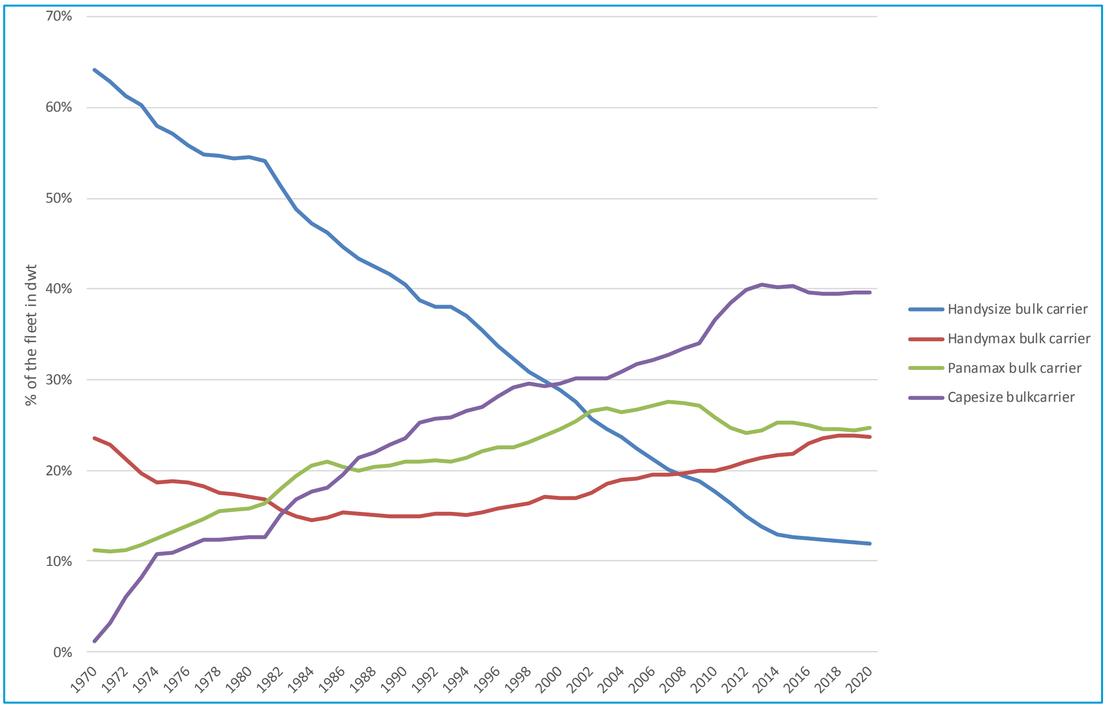
Size category	Distribution of ships in terms of numbers	Distribution of ships in terms of capacity
Handysize bulk carrier	32%	12%
Handymax bulk carrier	31%	24%
Panamax bulk carrier	22%	25%
Capesize bulk carrier	15%	39%

Very large ore carriers (VLOCs) and ultra large ore carriers (ULOCs) fall into the last category, the capsize bulk carriers.

The capacity distribution of the bulk carriers over the size categories is shown in Figure 45 and the distribution in terms of numbers over the size categories is shown in Source: Clarksons World Fleet Register March 2020.

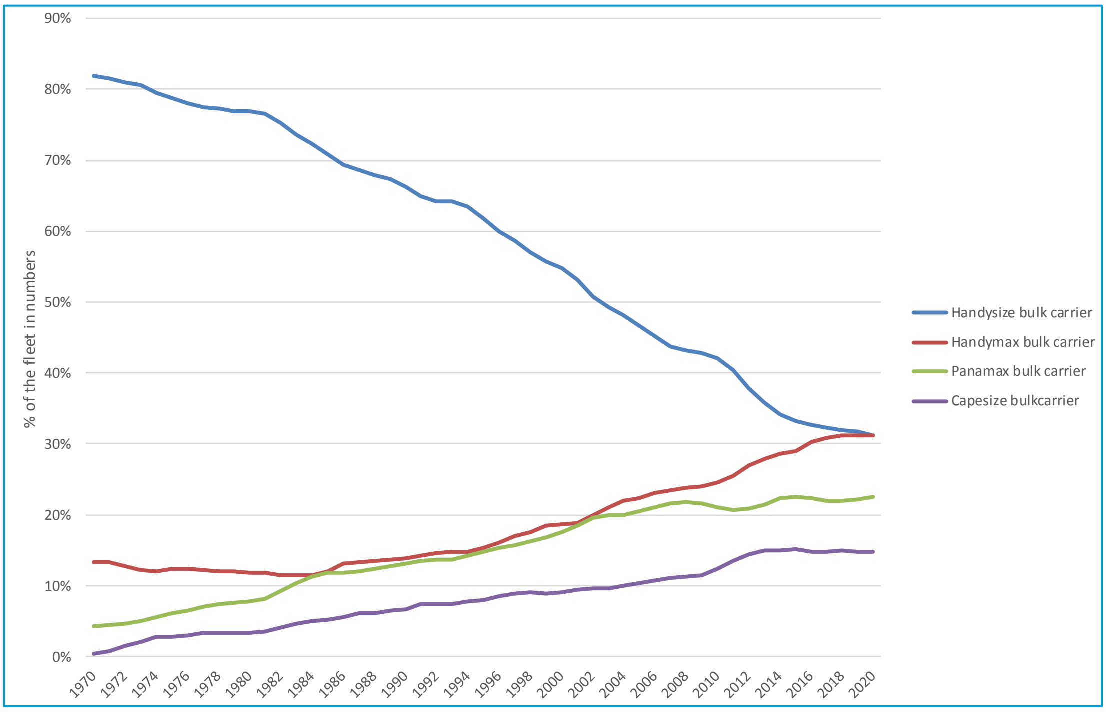
for the period 1970-2018. Figure 47 shows the development of the average ship size.

Figure 45 - Capacity distribution of bulk carriers over size categories



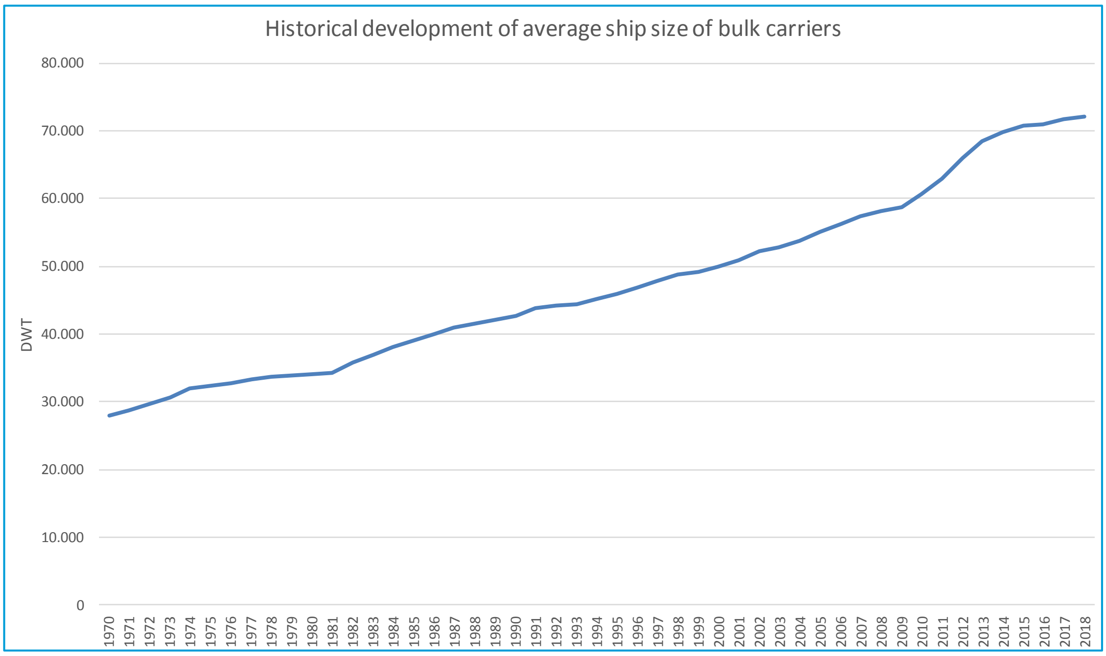
Source: Clarksons World Fleet Register March 2020.

Figure 46 - Distribution of bulk carriers in terms of numbers over size categories



Source: Clarksons World Fleet Register March 2020.

Figure 47 - Development of average capacity of bulk carriers over the period 1970-2018



Above figures show that the average size of bulk carriers has increased significantly, especially between 2008 and 2013, and that the growth of bulk carriers is slowing down in recent years. Both the decrease of handy size bulk carriers and the increase of the larger ships are flattened. A possible explanation for this is the anticipation of the market to the expansion of the Panama Canal.
Most orders for newbuilding are in the size of the Panamax and Handymax bulk carriers (Clarkson Shipping Intelligence Network) and are able to go through the Panama Canal.

We expect the increase in the average size to continue into the future but the growth rate to taper off as the impact of the widening of the Panama Canal has been absorbed in the fleet.

Table 29 shows the 2018 and 2050 distribution of the bulk carriers over size categories in terms of numbers. With these numbers, we expect an average ship size of 77,472 dwt in 2050 and that the growth will slow down.

Table 29 - Development of the distribution of bulk carriers over size categories (dwt)

Size category (dwt)	2018 distribution	Development until 2050	2050 distribution
0 - 9,999	6%	Small decrease	4%
10,000 - 34,999	18%	Small decrease	13%
35,000 - 59,999	30%	Small increase because of newbuilding vessel which can use the Panama Canal	32%
60,000 - 99,999	30%	Small increase because of newbuilding vessel which can use the Panama Canal	33%
100,000 - 199,999	11%	Small increase	12%
200,000 +	5%	Small increase	6%

Figure 48 and Figure 49 show graphically which projections are used in this study.

Figure 48 - Expected 2050 distribution of bulk carriers in terms of numbers over size categories

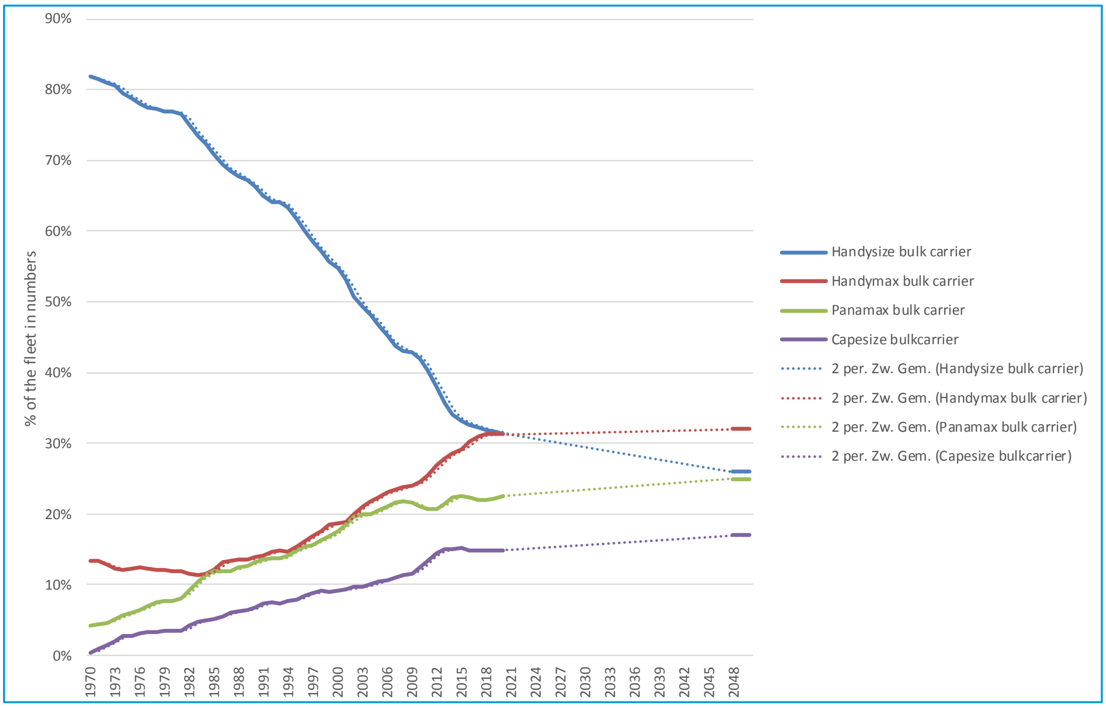
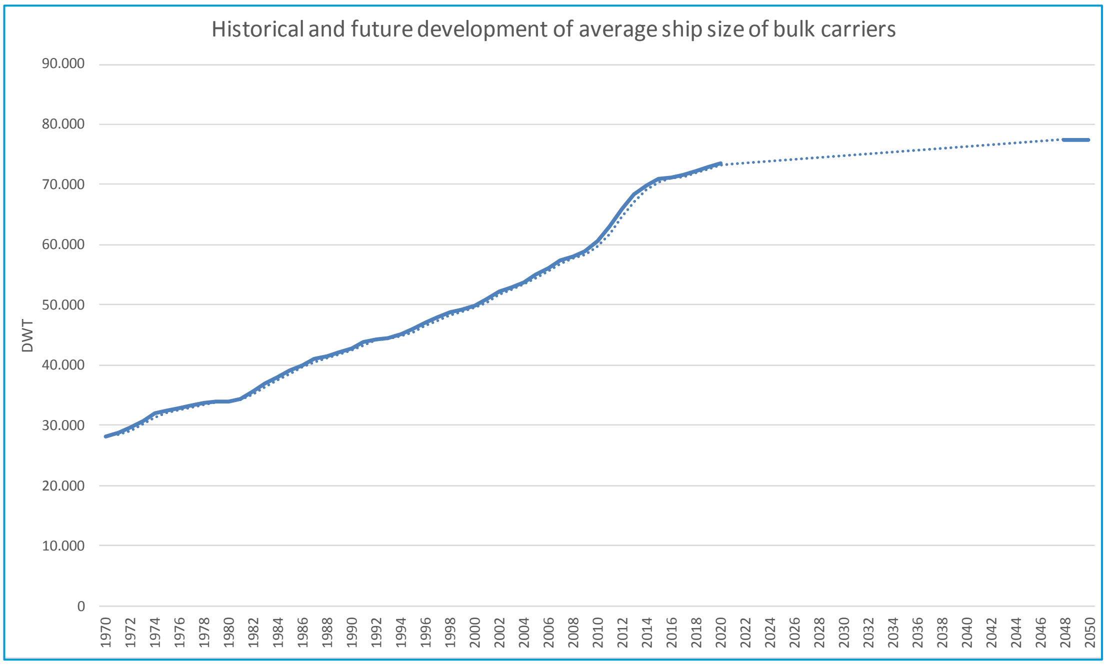


Figure 49 - Historical and future development of average ship size of bulk carriers



J.4 General cargo ships

The starting point of this analysis is the 2018 distribution of the general cargo ships over the size categories, see Table 30.

Table 30 - 2018 distribution of general cargo ships over the size categories in terms of numbers and in terms of capacity

Capacity range	Distribution of ships in terms of numbers	Distribution of ships in terms of capacity
5,000-7,499	55%	43%
7,500-9,999	28%	30%
10,000-14,999	14%	22%
15,000-19,999	2%	5%
20,000+	0%	1%

The capacity distribution of general cargo ships over the size categories is shown in Figure 50 and the distribution in terms of numbers over the size categories is shown in Figure 51 for the period 1996-2020. Figure 52 shows the development of the average ship size.

Figure 50 - Capacity distribution of general cargo ships over size categories

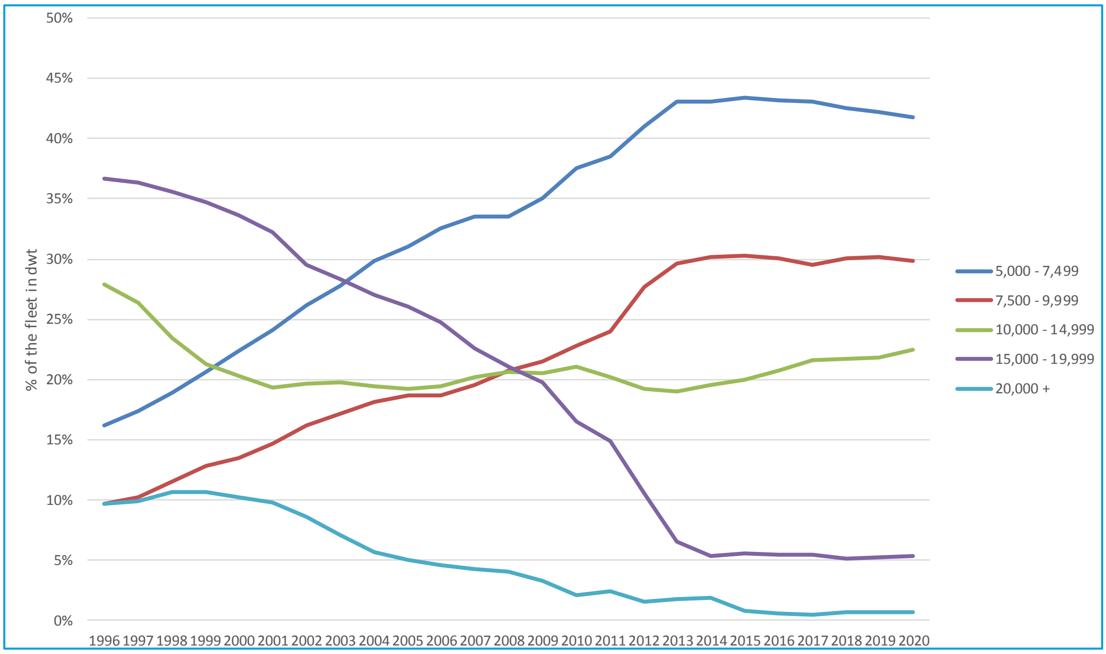


Figure 51 - Distribution of general cargo ships in terms of numbers over size categories

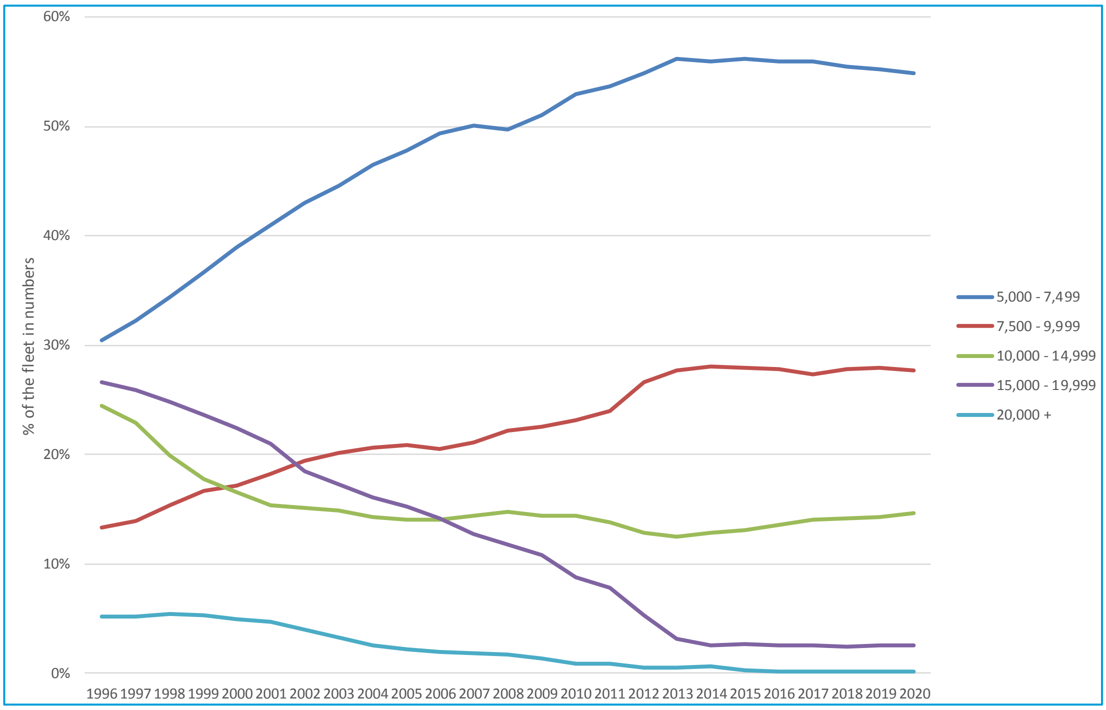
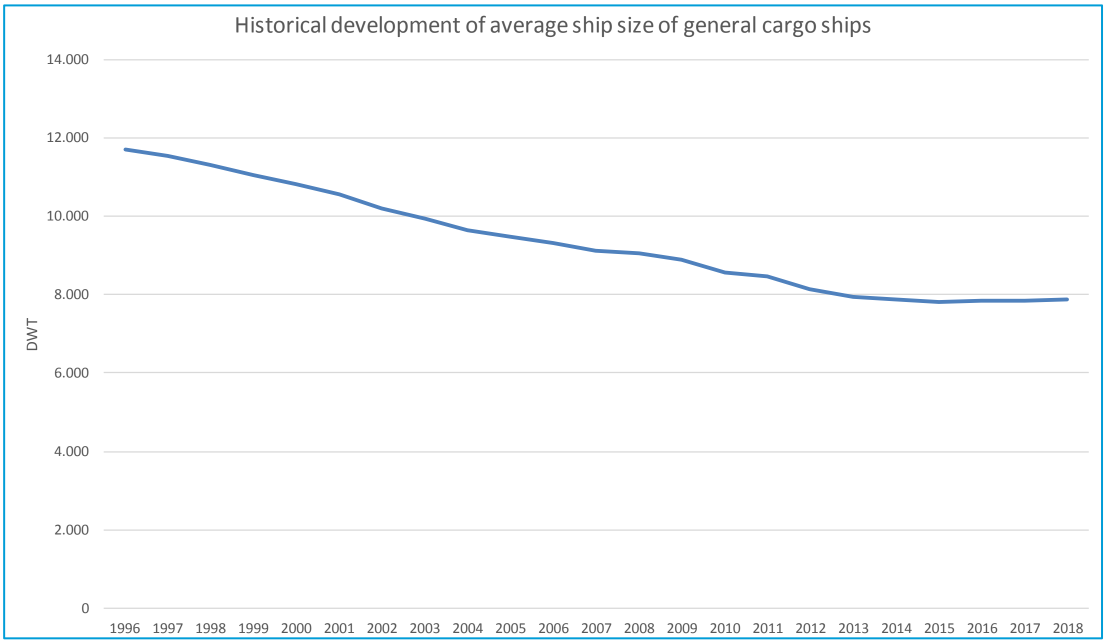


Figure 52 - Development of average capacity of general cargo ships over the period 1996-2018



In contrast to the ship types analysed above, the average size of general cargo ships has decreased in the past decades. After 2013, however, both the average size and the number of ships in each size category have remained constant. We project this to continue in the next decades.

Table 31 shows the 2018 and 2050 distribution of the general cargo ships over size categories in terms of numbers.

Table 31 - Development of the distribution of general cargo ships over size categories (dwt)

Size category (dwt)	2018 distribution	Development until 2050	2050 distribution
0 - 4,999	54%	None	54%
5,000 - 9,999	25%	None	25%
10,000 - 19,999	12%	None	12%
20,000+	9%	None	9%

J.5 Liquefied gas carriers

Liquefied gas carriers are divided into liquefied natural gas (LNG) carriers and liquefied petroleum gas (LPG) carriers. The starting point of this analysis is the 2018 distribution of the liquefied gas carriers over the size categories, see Table 32.

Table 32 - 2018 distribution of liquefied gas carriers over the size categories in terms of numbers and in terms of capacity

Capacity range (Cu. M.)	Ship type	Distribution of ships in terms of numbers	Distribution of ships in terms of capacity
0-19,999	LPG	50%	4%
20,000-64,999	LPG	11%	6%
65,000+	LPG	14%	20%
0-59,999	LNG	2%	1%
60,000-139,999	LNG	7%	16%
140,000+	LNG	17%	53%

The capacity distribution of the liquefied gas carriers over the size categories is shown in Figure 53 and the distribution in terms of numbers over the size categories is shown in Figure 54 for the period 1996-2020. Figure 55 shows the development of the average ship size.

Figure 53 - Capacity distribution of liquefied gas carriers over size categories

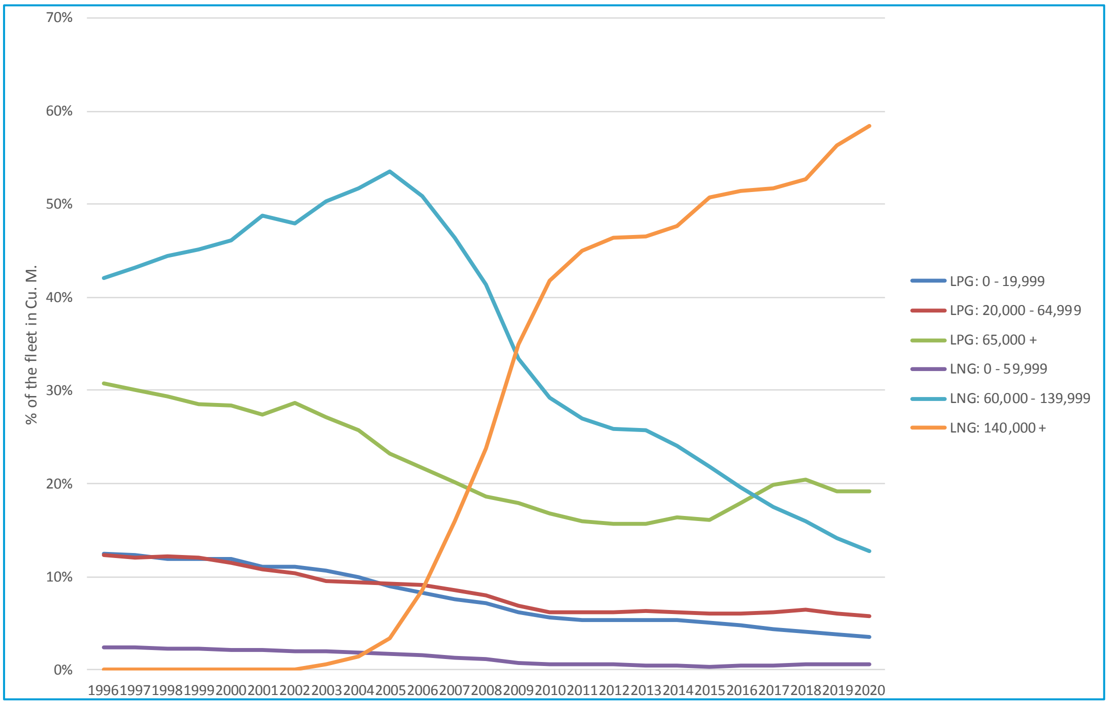


Figure 54 - Distribution of liquefied gas carriers in terms of numbers over size categories

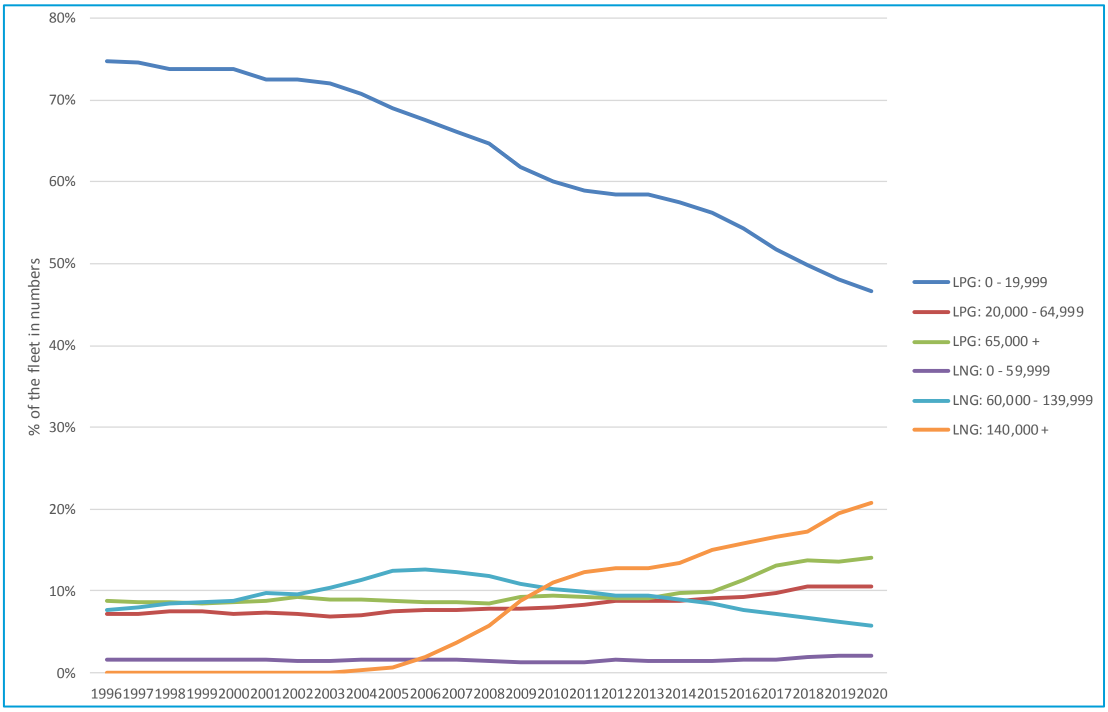


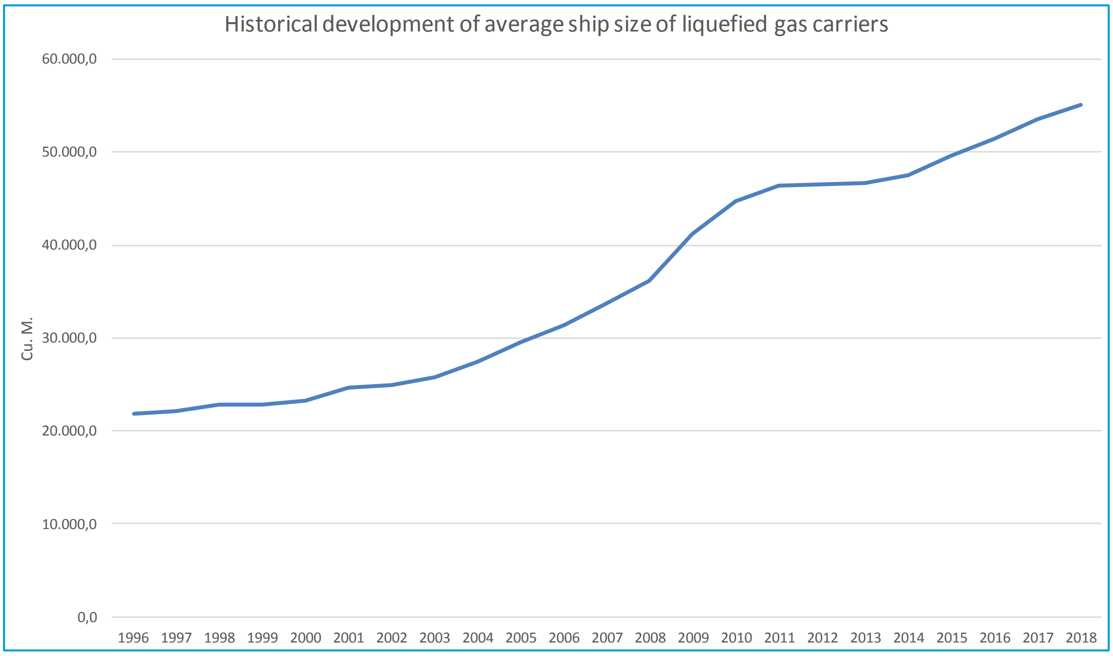
Figure 54 shows that the number of LPG carriers in the 0 – 19,999 m^3 category has declined the last years, but that this is still the largest category. The number of LPG carriers in the

20,000 – 64,999 m^3 range is quite stable and the number of 65,000+ m^3 LPG carriers increase slowly since 2014.

The number of LNG carriers in the 0 – 59,999 m^3 category is stable over the years. The number of LNG carriers in the 60,000 – 139,999 m^3 category has declined since 2005 and the number of LNG carriers in the 140,000+ m^3 category is increased since 2005.

Figure 55 shows that the average size of the total liquefied gas carrier fleet is growing stably.

Figure 55 - Development of average capacity of liquefied gas carriers over the period 1996-2018



The small LNG carriers are typically used in domestic and coastal trades. The smallest cross-border LNG ships, typically 18,000 – 40,000 m^3, are mostly used to transport LNG from South-East Asia to smaller terminals in Japan. The most common class of LNG carrier has a capacity of more than 140,000 m^3. This category with the largest LNG ships contains also the Q-Flex and Q-Max ships. A Q-Max ship have a capacity of 263,000–266,000 m^3. At the moment there is a very small percentage of these type of ships in the market.

The Panama Canal is expanded in 2016 and this can be an explanation for the increase in amount of 140,000 m^3 liquefied gas ships. The only LNG carriers that have been identified as unable to transit the new locks due to their size are the Q-Flex ships of 216,000 m^3 and the 14 Q-Max ships of 266,000 m^3. Very large LNG carriers (> 200,000 m^3) could play an increasing role in LNG trade between the US East Coast and Europe and the US West Coast and Asia, but on the other hand, these large ships would call for pipelines to meet the demand needs in the different regions of the importing country/continent as well as for pipelines within the US to avoid the Panama Canal transit.

Table 33 shows the 2018 and 2050 distribution of the liquefied gas carriers over size categories in terms of numbers. With these numbers, we expect an average ship size of 82,849 Cu. M. in 2050 and that the growth will slow down.

Table 33 - Development of the distribution of liquefied gas carriers over size categories (capacity)

Size category (Cu. M.)	2018 distribution	Development until 2050	2050 distribution
0 - 49,999	58%	Decrease due to decrease in small LPG segment	40%
50,000 - 99,999	16%	Small increase because of small increase in large LPG segment	18%
100,000 - 199,999	23%	Increase because of trend in use of larger LNG carriers	38%
200,000+	2%	Small increase in Q-Flex and Q-Max LNG carriers	4%

Figure 56 and Figure 57 show graphically which projections are used in this study.

Figure 56 - Expected 2050 distribution of liquefied gas carriers in terms of numbers over size categories

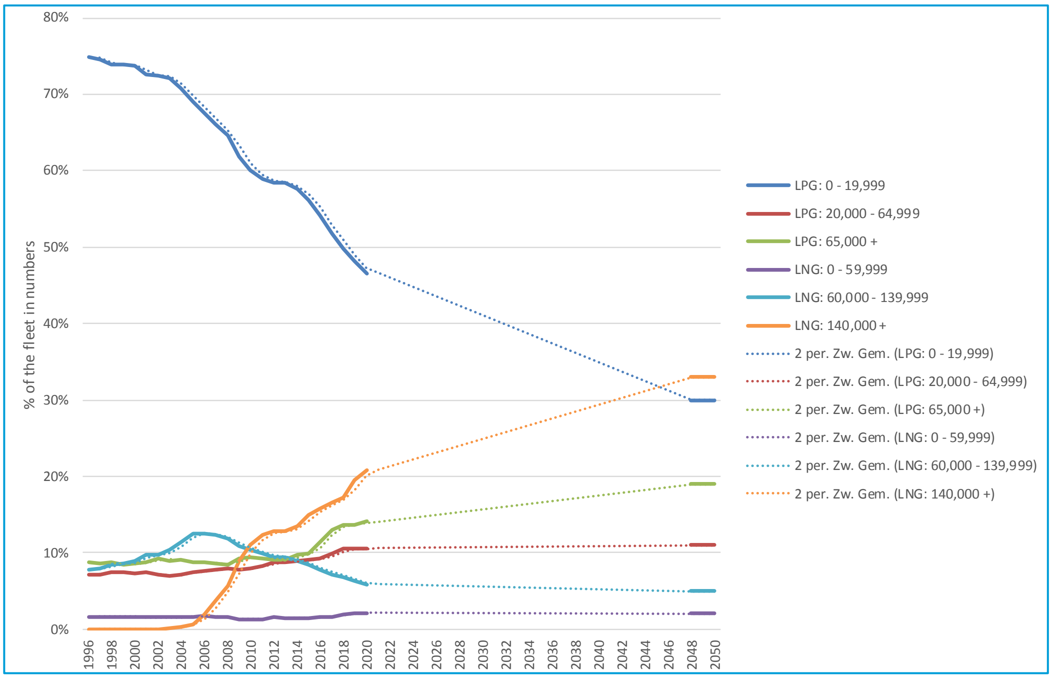
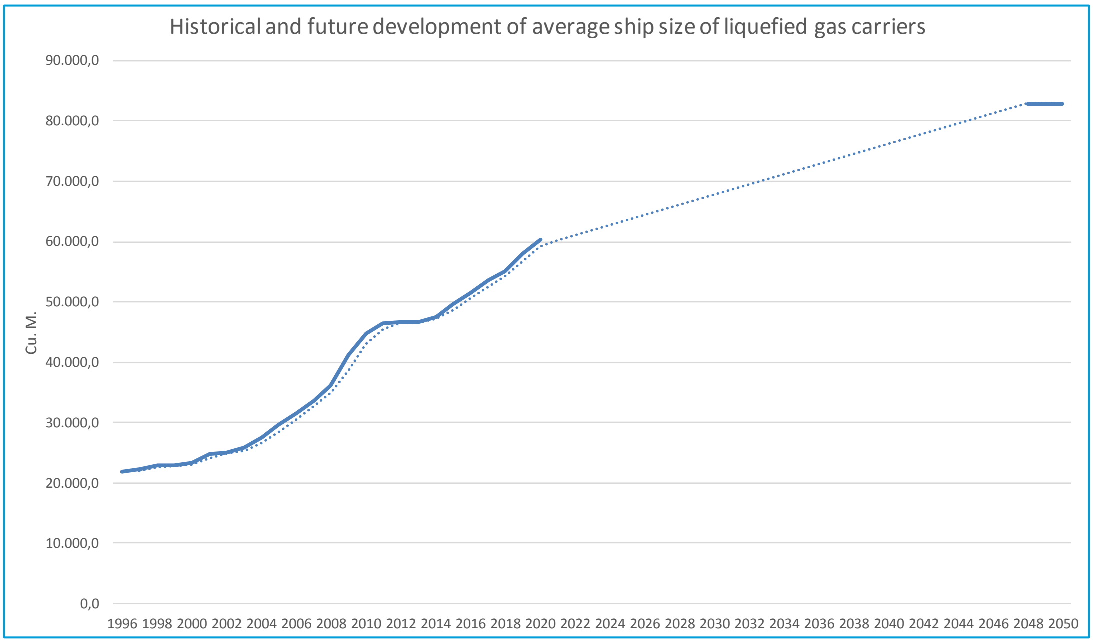


Figure 57 - Historical and future development of average ship size of liquefied gas carriers



K Emission projections

K.1 Introduction

This annex presents the CO_2 emission projections of maritime transport of all scenarios analysed in this report.

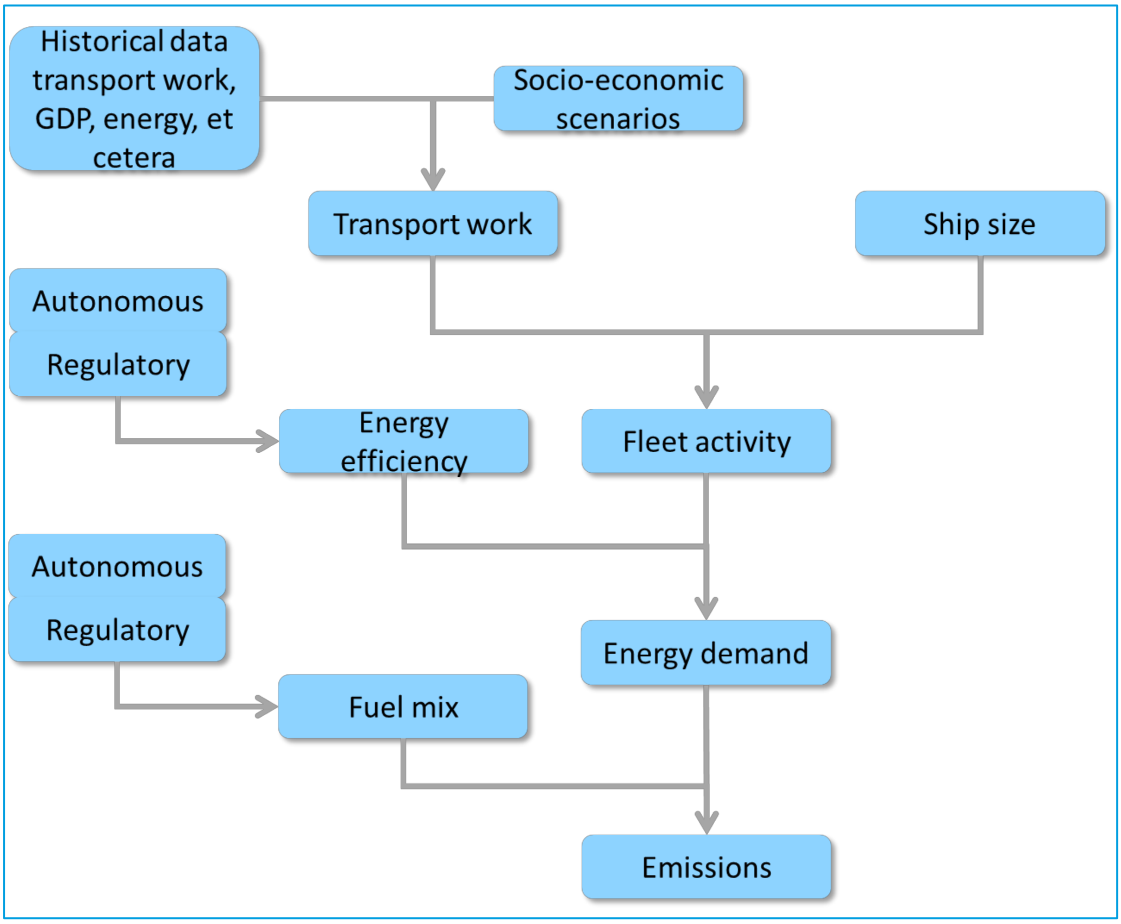
The method for projecting emissions from shipping in this Study comprises six steps:

1. Establishing the historical relation between maritime transport work and relevant economic parameters such as world per capita GDP and population (for transport of non-energy products, such as unitized cargo, chemicals and non-coal dry bulk); and energy consumption (for transport of energy products like coal, oil and gas).
2. Projecting transport work on the basis of the relations described above and long term projections of GDP, and population, when considering the transportation of non-energy products (for container carries, bulk carriers, chemical tankers and ro-ro vessels) and energy consumption projection when considering seaborne transportation of energy products (for coal bulk carriers, oil tankers and gas tankers).
3. Making a detailed description of the fleet and its activity in the base year 2018. This involves assigning the transport work to ship categories and establishing the average emissions for each ship in each category.
4. Projecting the future fleet composition based on a literature review and a stakeholder consultation.
5. Projecting future energy efficiency of the ships, taking into account regulatory developments and market-driven efficiency changes using a marginal abatement cost curve (MACC).

Combining the results of Steps 2, 4 and 5 above to project shipping emissions.

Figure 58 is a graphical representation of the methodology.

Figure 58 - Graphical representation of methodology to develop emission projections



Transport work projections are elaborated in Annex I; ship size projections in Annex J; efficiency improvements and changes in the fuel mix in Annex Q. This Annex presents the results of the emission projections of all plausible combinations of socio-economic and energy scenarios. In order to put them into context, we provide graphs and tables of:

a transport work projections;

b projected efficiency improvements; and

c emission projections.

All graphs and tables are fleet total (transport work and emissions) or fleet averages (efficiency improvements). A spreadsheet associated with this report contains results disaggregated per ship type.

All scenarios are based on transport work projections which, in turn, are characterised by three factors:

1. The socio-economic scenario projecting future income (GDP per capita) and population, which is assumed to be related to the maritime transport demand for non-energy products, such as non-coal dry bulks, chemicals, containerized and other unitized cargoes.
2. The energy scenario projecting the future use of fossil and non-fossil primary energy sources, which is assumed to be related to the maritime transport demand for fossil energy products: coal, oil and oil products, and gas. And
3. The method to determine the relation between transport works on the one hand and GDP per capita and population on the other.

Socio-economic scenarios can be one of the so-called Shared Socio-economic Pathways (SSPs) developed by Riahi, et al, (2017) or the OECD long-term baseline projections. Energy-scenarios can be one of the so-called Representative Concentration Pathways as developed by (Vuuren, et al., 2011). The method to determine the relation between transport works on the one hand and GDP per capita and population on the other can be either Logistics analysis or Gravity-model analysis. Thus a projection can, for example, be identified as SSP1_RCP1.9_G, meaning that it is based on GDP and population projections of SSP1 (comparatively high economic growth), results in a temperature increase of about 1.5 degrees in 2100 (i.e. assumes a sharp reduction in emissions of greenhouse gases from all sectors) and has used a gravity model to analyze the relation between GDP per capita, population, and transport work.

Table 34 - Characteristics of transport demand projections

Long-term socio-economic scenario	**Long-term energy scenario**	**Relation between transport work and relevant drivers**
Transport demand of non-coal dry bulk, containers, other unitized cargo, and chemicals	**Transport demand of coal-oil and gas**	
SSP1 (Sustainability - Taking the Green Road)	RCP1.9 (1.5°C)	Logistics (denoted by _L)
SSP2 (Middle of the Road)	RCP2.6 (2°C, very low GHG emissions)	Gravitation model (denoted by _G)
SSP3 (Regional Rivalry - A Rocky Road)	RCP3.4 (extensive carbon removal)	
SSP4 (Inequality - A Road Divided)	RCP4.5 (2.4°C, medium-low mitigation or very low baseline)	
SSP5 (Fossil-fueled Development - Taking the Highway)	RCP6.0 (2.8°Cmedium baseline, high mitigation	
OECD long-term baseline projections		

Source: (Vuuren, et al., 2011) (Riahi, et al., 2017), www.climatechangescenario.org.

Emission projections in this annex are labelled consequently by the long-term socio-economic scenario, the long-term energy scenario and the method to relate transport work to relevant drivers. So for example, a scenario labelled SSP3_RCP34_G means that it is based on the socio-economic projections of the SSP3 scenario, energy demand projections of RCP 3.4, and that the relation between transport work on the one hand and drivers like GDP and energy consumption on the other is established by applying a gravity model.

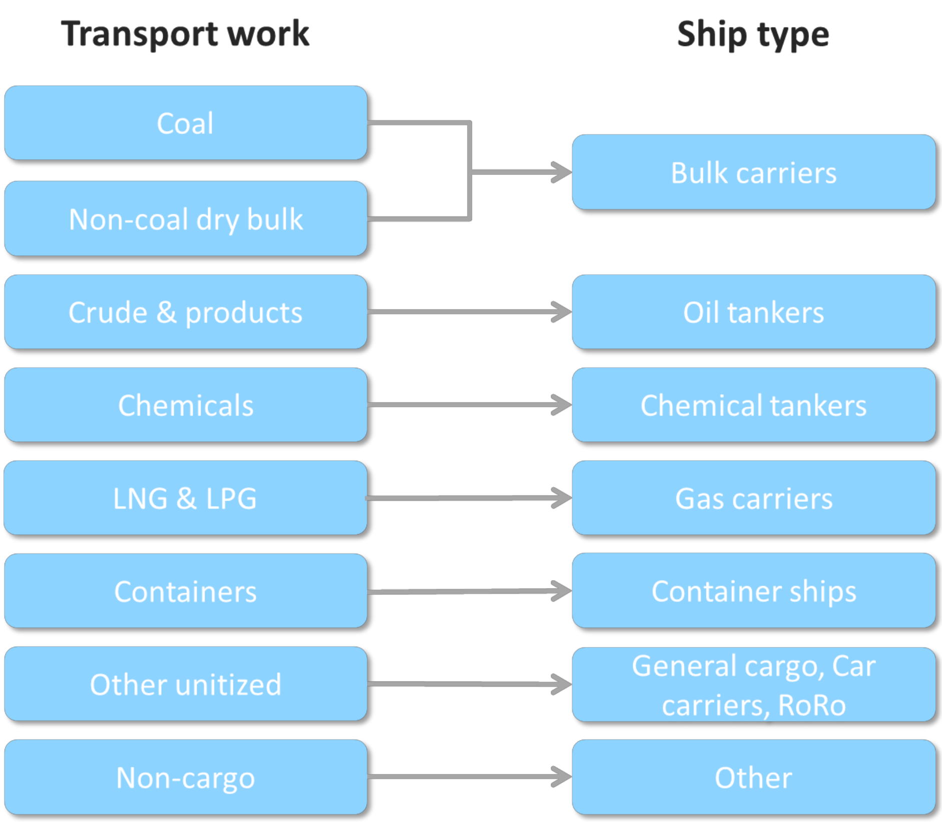
Fuel prices used in the emissions modelling were taken from the World Bank Commodities Price Forecast, April 2020.

K.2 Defining the base year for ship emissions

The base year for the ship emissions and ship efficiency is 2018.

In this year, the number of type 1 and type 2 ships and their emissions have been used as a basis. For the following years, the number of ships evolve in line with the projected transport work demand. This development is specific for specific ship types. Transport work of different types of cargo is assigned to different ship types as shown in Figure 59.

Figure 59 - Mapping of cargo types to ship types



This assignment is unproblematic for all ship types except for chemical tankers. The IBC code distinguishes three types of chemical tankers:

1. A type 1 ship is a chemical tanker intended to transport products mentioned in Chapter 17 of the IBC Code with very severe environmental and safety hazards which require maximum preventive measures to preclude an escape of such cargo.
2. A type 2 ship is a chemical tanker intended to transport products mentioned in Chapter 17 of the IBC Code with appreciably severe environmental and safety hazards which require significant preventive measures to preclude an escape of such cargo.
3. A type 3 ship is a chemical tanker intended to transport products mentioned in Chapter 17 of the IBC Code with sufficiently severe environmental and safety hazards which require a moderate degree of containment to increase survival capability in a damaged condition.

Many chemical tankers of type 2 are capable of transporting clean oil products and are often engaged in doing so. As a result, if we would assume that all chemical tankers are engaged in the transport of chemicals, and if the transport work of chemicals and oil products is projected to follow different trajectories, this would result in unrealistic projections. We have corrected for this by reassigning a number of chemical tankers to oil tankers according to Table 35.

Table 35 - Reassignment of chemical tankers

Ship type	Ship size (dwt)	Type 1 and 2 ships in the 2018 bottom-up analysis	Number of ships in the base year for the emission projections	Difference
Chemical tanker	0-4,999	1032	619	-413
Chemical tanker	5,000-9,999	844	506	-338
Chemical tanker	10,000-19,999	1088	870	-218
Chemical tanker	20,000-39,999	706	565	-141
Chemical tanker	40,000-+	1289	1031	-258
Oil tanker	0-4,999	1734	2147	+413
Oil tanker	5,000-9,999	779	1117	+338
Oil tanker	10,000-19,999	235	453	+218
Oil tanker	20,000-59,999	615	1014	+399

In order to reflect the fact that a share number of chemical tankers is capable of transporting oil products, and there is evidence that they are often engages in transport of oil tankers, we have moved a number of chemical tankers to the oil tankers.

K.3 Emission projections based on transport work projections made with a gravity model

This section presents the transport work projections, projected changes in fleet efficiency as well as projected emissions for all plausible scenarios, using a gravity model to establish the relation between transport work and its drivers. As discussed in Annex I, these projections tend to be lower than the transport work projections that are based on a logistics model. We interpret the difference as a reflection of the uncertainty that is inherent in projecting developments into the future. Thus the projections presented in this section could be considered as the lower end of the range of possible outcomes.

Table 36 presents the transport work projections of all modelled scenarios which have employed a gravity model to establish the relation between transport work on the one hand and GDP per capita, population and energy consumption on the other. presents the same data in a graphical format. Scenarios with higher economic growth until 2050 have higher transport work projections as the transport work of non-coal dry bulk, chemicals, containers and other unitized cargo is related to GDP (SSP5 has the highest economic growth until 2050, followed by SSP1, SSP2 and 4, and SSP3 and the OECD long-term economic scenario). Scenarios with higher fossil energy consumption have higher transport work projections because the transport of coal, oil, and gas are related to fossil energy consumption (RCP 6 has the highest fossil energy consumption, followed by RCP 4.5, RCP 2.6 and RCP 1.9).

Table 36 Transport work projections for gravity model scenarios (billion tonne miles)

Scenario	2018	2020	2025	2030	2035	2040	2045	2050
SSP1_RCP19_G	59,230	62,325	66,513	70,718	74,748	78,894	83,850	88,222
SSP1_RCP60_G	59,230	62,658	71,758	79,580	86,313	92,376	98,000	102,981
SSP2_RCP19_G	59,230	62,616	67,206	71,907	75,242	78,475	80,895	84,206
SSP2_RCP60_G	59,230	62,619	72,318	80,691	87,696	94,013	99,853	105,388
SSP3_RCP34_G	59,230	61,733	68,249	73,563	75,337	77,171	80,097	82,728
SSP3_RCP60_G	59,230	61,733	68,844	74,810	78,730	82,325	85,366	88,107
SSP4_RCP26_G	59,230	62,331	68,305	72,744	76,570	79,750	82,162	84,157
SSP4_RCP60_G	59,230	62,331	70,864	77,742	82,722	87,030	90,479	93,472
SSP5_RCP19_G	59,230	63,289	74,133	85,008	89,869	95,049	97,299	100,620
SSP5_RCP60_G	59,230	63,289	75,973	88,207	98,646	108,584	117,920	126,971
OECD_RCP26_G	59,230	57,679	62,826	67,471	71,613	75,799	79,073	82,464
OECD_RCP45_G	59,230	57,692	64,656	70,875	76,384	81,766	86,549	91,204

Figure 60 - Transport work projections for gravity model scenarios

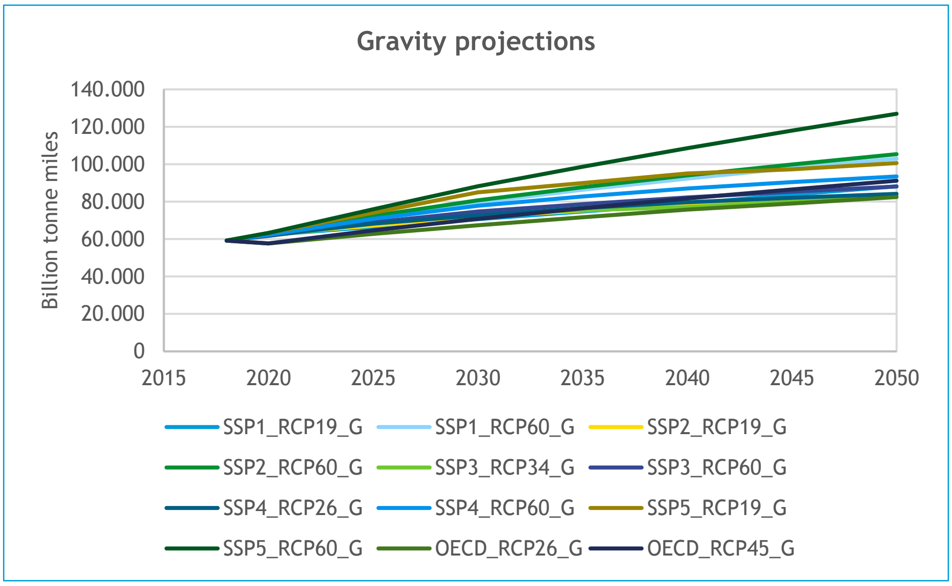


Table 37 presents the projections of fleet average efficiency improvements. Scenarios with higher transport growth have a larger share of new ships in the fleet which results in larger efficiency improvements.

Table 37 - Projections of fleet average efficiency improvements for gravity model scenarios

	2018	2020	2025	2030	2035	2040	2045	2050
SSP1_RCP19_G	0%	1%	5%	9%	12%	13%	14%	15%
SSP1_RCP60_G	0%	1%	5%	10%	12%	14%	15%	16%
SSP2_RCP19_G	0%	1%	5%	9%	11%	13%	14%	15%
SSP2_RCP60_G	0%	1%	5%	10%	13%	15%	15%	16%
SSP3_RCP34_G	0%	1%	5%	9%	11%	13%	14%	15%
SSP3_RCP60_G	0%	1%	5%	9%	12%	14%	14%	15%
SSP4_RCP26_G	0%	1%	5%	9%	12%	14%	14%	15%
SSP4_RCP60_G	0%	1%	5%	10%	12%	14%	15%	15%
SSP5_RCP19_G	0%	1%	5%	10%	13%	14%	15%	16%
SSP5_RCP60_G	0%	1%	6%	11%	13%	15%	16%	17%
OECD_RCP26_G	0%	1%	5%	9%	11%	13%	14%	15%
OECD_RCP45_G	0%	1%	5%	9%	12%	14%	15%	15%

It should be noted that the efficiency improvements shown in Table 37 are fleet average values and also include non-cargo ships and ships below the EEDI threshold. Table 38 shows the disaggregated efficiency improvements for scenario OECD_RCP2.6_G in which the fleet-average improvement is 15%.

Table 38 - Projected efficiency improvements per ship type, OECD_RCP2.6_G

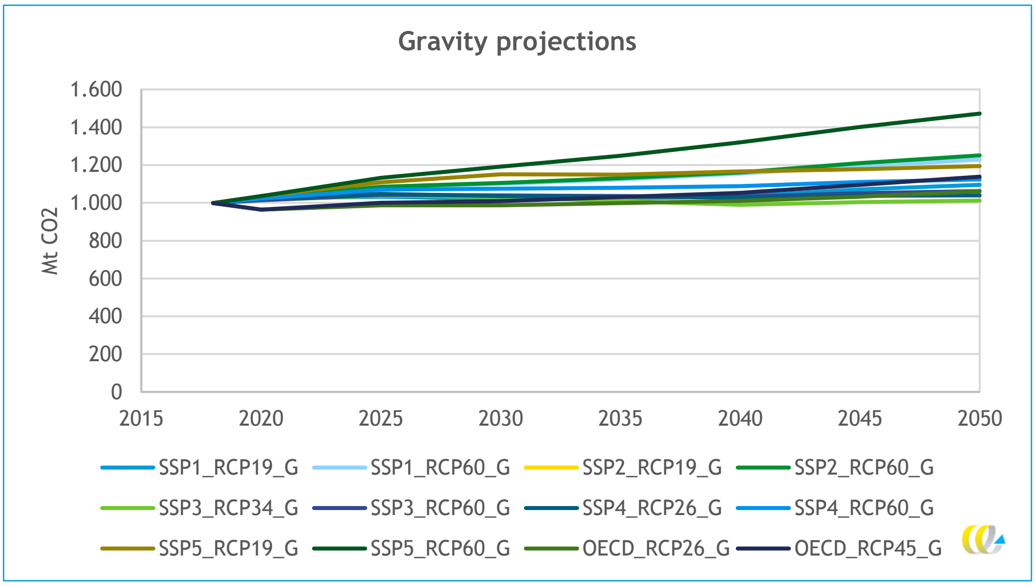
	2018	2020	2025	2030	2035	2040	2045	2050
Bulker	0%	1%	8%	15%	19%	24%	25%	26%
Tanker	0%	2%	8%	15%	18%	22%	23%	24%
Container	0%	1%	8%	15%	19%	23%	24%	25%
Other unitized	0%	2%	7%	12%	14%	16%	16%	17%
Passenger	0%	1%	5%	9%	11%	12%	13%	14%
Miscellaneous	0%	0%	0%	0%	0%	0%	0%	0%
Total	**0%**	**1%**	**5%**	**9%**	**11%**	**13%**	**14%**	**15%**

Table 39presents the CO_2 emissions projections of all modelled scenarios which have employed a gravity model to establish the relation between transport work on the one hand and GDP per capita, population and energy consumption on the other. Figure 61 presents the same data in a graphical format. The emission projections are a combination of transport work projections and efficiency projections.

Table 39 - Emissions projections for gravity model scenarios

	2018	2020	2025	2030	2035	2040	2045	2050
SSP1_RCP19_G	999	1,023	1,033	1,022	1,023	1,034	1,071	1,096
SSP1_RCP60_G	999	1,027	1,083	1,101	1,124	1,154	1,196	1,229
SSP2_RCP19_G	999	1,026	1,046	1,040	1,031	1,029	1,035	1,048
SSP2_RCP60_G	999	1,026	1,085	1,105	1,131	1,161	1,210	1,251
SSP3_RCP34_G	999	1,015	1,039	1,030	1,008	990	1,004	1,013
SSP3_RCP60_G	999	1,015	1,044	1,040	1,036	1,033	1,051	1,063
SSP4_RCP26_G	999	1,022	1,047	1,036	1,032	1,028	1,037	1,040
SSP4_RCP60_G	999	1,022	1,069	1,076	1,081	1,088	1,110	1,124
SSP5_RCP19_G	999	1,035	1,109	1,151	1,150	1,166	1,178	1,195
SSP5_RCP60_G	999	1,035	1,132	1,192	1,249	1,321	1,402	1,472
OECD_RCP26_G	999	964	987	987	999	1,011	1,033	1,061
OECD_RCP45_G	999	964	1,000	1,010	1,032	1,053	1,095	1,138

Figure 61 - Emissions projections for gravity model scenarios



K.4 Emission projections based on transport work projections made with a logistics model

This section presents the transport work projections, projected changes in fleet efficiency as well as projected emissions for all plausible scenarios, using a logistics model to establish the relation between transport work and its drivers. As discussed in Annex I, these projections tend to be higher than the transport work projections that are based on a gravity model. We interpret the difference as a reflection of the uncertainty that is inherent in projecting developments into the future. Thus the projections presented in this section could be considered as the higher end of the range of possible outcomes.

Table 40 presents the transport work projections of all modelled scenarios which have employed a logistics model to establish the relation between transport work on the one hand and GDP and energy consumption on the other. Figure 62 presents the same data in a graphical format. Scenarios with higher economic growth until 2050 have higher transport work projections as the transport work of non-coal dry bulk, chemicals, containers and other unitized cargo is related to GDP (SSP5 has the highest economic growth until 2050, followed by SSP1, SSP2 and 4, and SSP3 and the OECD long-term economic scenario). Scenarios with higher fossil energy consumption have higher transport work projections because the transport of coal, oil, and gas are related to fossil energy consumption (RCP 6 has the highest fossil energy consumption, followed by RCP 4.5, RCP 2.6 and RCP 1.9).

Table 40 - Transport work projections for logistics model scenarios

	2018	2020	2025	2030	2035	2040	2045	2050
SSP1_RCP19_L	59,230	58,636	66,845	78,392	90,607	105,857	119,712	135,294
SSP1_RCP60_L	59,230	60,814	72,387	86,377	99,868	115,827	129,859	145,592
SSP2_RCP26_L	59,230	62,518	71,707	82,460	91,448	101,604	109,958	119,429
SSP2_RCP60_L	59,230	62,701	73,797	86,348	97,154	108,977	119,677	131,266
SSP3_RCP34_L	59,230	63,995	73,511	83,876	88,057	92,706	96,945	101,211
SSP3_RCP60_L	59,230	63,995	74,049	85,020	91,437	97,987	102,412	106,850
SSP4_RCP26_L	59,230	63,215	71,880	82,111	91,109	101,000	108,323	116,159
SSP4_RCP60_L	59,230	62,331	70,864	77,742	82,722	87,030	90,479	93,472
SSP5_RCP34_L	59,230	64,642	80,768	100,914	121,332	146,431	167,993	193,078
SSP5_RCP60_L	59,230	64,642	81,417	102,096	123,785	150,111	173,533	200,778
OECD_RCP26_L	59,230	61,757	69,421	77,278	84,544	91,502	97,094	102,780
OECD_RCP45_L	59,230	61,889	71,165	80,497	89,094	97,247	104,526	111,656

Figure 62 - Transport work projections for logistics model scenarios

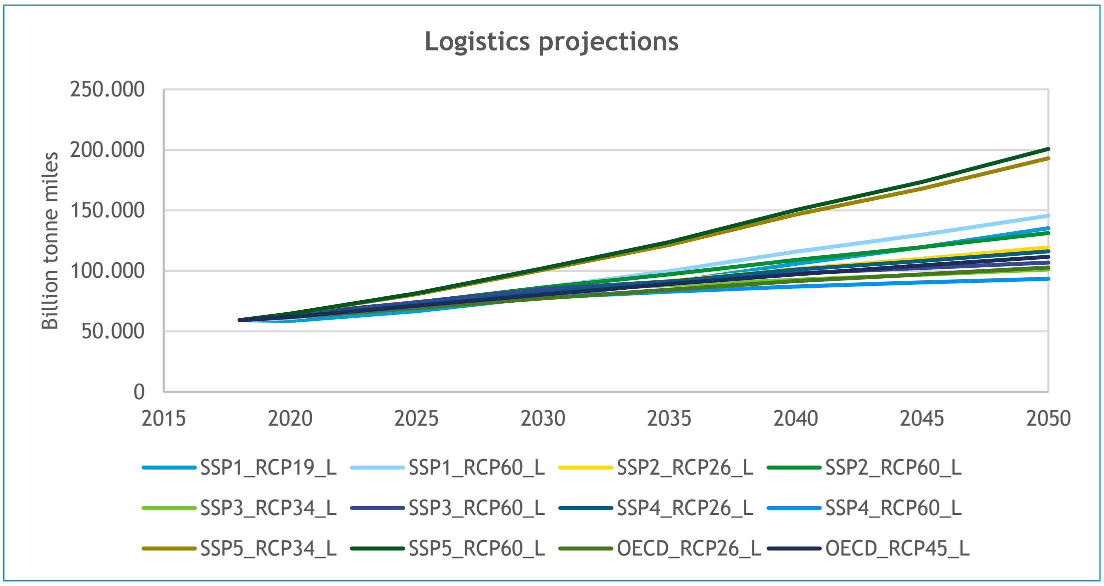


Table 41 presents the projections of fleet average efficiency improvements. Scenarios with higher transport growth have a larger share of new ships in the fleet which results in larger efficiency improvements.

Table 41 - Projections of fleet average efficiency improvements for logistics model scenarios

	2018	2020	2025	2030	2035	2040	2045	2050
SSP1_RCP19_L	0%	1%	5%	10%	13%	15%	16%	18%
SSP1_RCP60_L	0%	1%	5%	11%	14%	16%	17%	18%
SSP2_RCP26_L	0%	1%	5%	10%	13%	15%	16%	17%
SSP2_RCP60_L	0%	1%	5%	10%	13%	16%	16%	18%
SSP3_RCP34_L	0%	1%	5%	10%	13%	14%	15%	16%
SSP3_RCP60_L	0%	1%	5%	10%	13%	15%	16%	16%
SSP4_RCP26_L	0%	1%	5%	10%	13%	15%	16%	17%
SSP4_RCP60_L	0%	1%	5%	10%	12%	14%	15%	15%
SSP5_RCP34_L	0%	1%	6%	12%	15%	17%	18%	19%
SSP5_RCP60_L	0%	1%	6%	12%	15%	17%	18%	19%
OECD_RCP26_L	0%	1%	5%	10%	12%	15%	15%	16%
OECD_RCP45_L	0%	1%	5%	10%	13%	15%	16%	17%

It should be noted that the efficiency improvements shown in Table 41 are fleet average values and also include non-cargo ships and ships below the EEDI threshold. Table 42 shows the disaggregated efficiency improvements for scenario OECD_RCP2.6_L in which the fleet-average improvement is 15%.

Table 42 - Projected efficiency improvements per ship type, OECD_RCP2.6_L

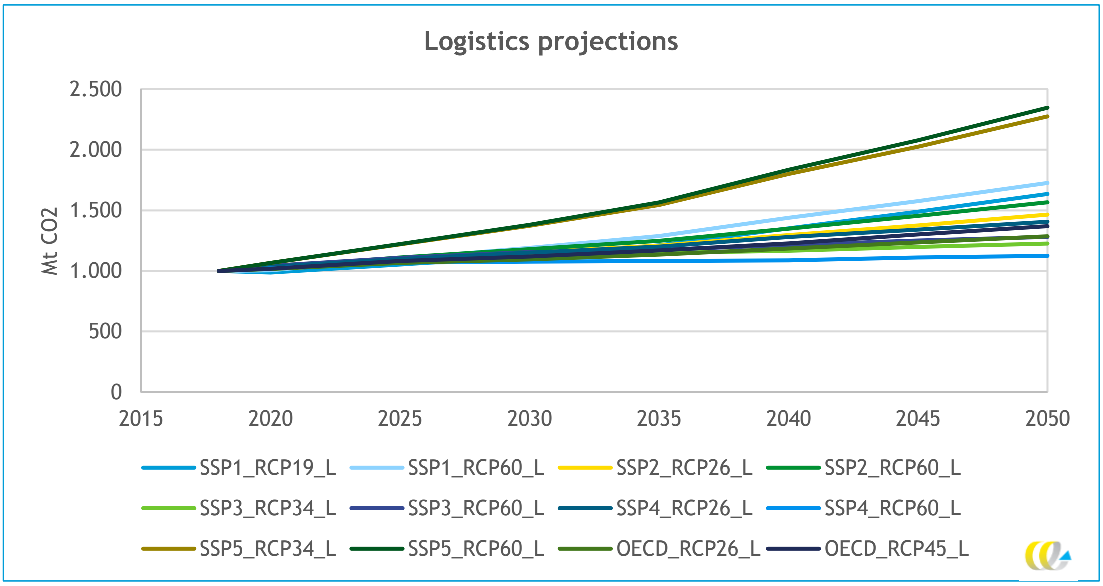
	2018	2020	2025	2030	2035	2040	2045	2050
Bulker	0%	2%	9%	16%	21%	25%	25%	0%
Tanker	0%	2%	8%	16%	20%	22%	24%	0%
Container	0%	3%	9%	17%	21%	23%	24%	0%
Other unitized	0%	2%	6%	11%	13%	15%	16%	0%
Passenger	0%	1%	5%	9%	11%	12%	13%	0%
Miscellaneous	0%	0%	0%	0%	0%	0%	0%	0%
Total	**0%**	**1%**	**5%**	**10%**	**12%**	**15%**	**15%**	**0%**

Table 43 presents the CO_2 emissions projections of all modelled scenarios which have employed a logistics model to establish the relation between transport work on the one hand and GDP per capita, population and energy consumption on the other. Figure 63 presents the same data in a graphical format. The emission projections are a combination of transport work projections and efficiency projections.

Table 43 - Emissions projections for logistics model scenarios

	2018	2020	2025	2030	2035	2040	2045	2050
SSP1_RCP19_L	999	986	1,051	1,122	1,211	1,352	1,487	1,635
SSP1_RCP60_L	999	1,005	1,100	1,189	1,288	1,438	1,576	1,726
SSP2_RCP26_L	999	1,026	1,095	1,154	1,209	1,295	1,376	1,465
SSP2_RCP60_L	999	1,028	1,111	1,180	1,248	1,347	1,454	1,566
SSP3_RCP34_L	999	1,041	1,104	1,148	1,147	1,167	1,199	1,226
SSP3_RCP60_L	999	1,041	1,108	1,156	1,175	1,213	1,250	1,281
SSP4_RCP26_L	999	1,033	1,097	1,150	1,199	1,279	1,340	1,405
SSP4_RCP60_L	999	1,022	1,069	1,076	1,081	1,088	1,110	1,124
SSP5_RCP34_L	999	1,067	1,218	1,372	1,545	1,802	2,025	2,276
SSP5_RCP60_L	999	1,067	1,222	1,379	1,564	1,835	2,077	2,347
OECD_RCP26_L	999	1,016	1,067	1,095	1,135	1,183	1,235	1,286
OECD_RCP45_L	999	1,018	1,080	1,118	1,168	1,228	1,301	1,369

Figure 63 - Emissions projections for logistics model scenarios



L Main engine power correction factors due to weather and fouling

Factors are applied to the Admiralty formula to correct for adverse weather conditions and hull fouling. 0.917 (9% power increase) is assumed as the fouling correction factor ηf for all ship types and sizes, 0.909 (10% power increase) as the weather correction factor η_w for mainly small ships, and 0.867 (15% power increase) for all other ship types and sizes. Table 44 lists the corresponding values.

Table 44 - Categories of ships types and sizes with a weather correction factor of 10%

Type bin	Capacity	Unit	Weather correction factor (η_w)	Fouling correction factor (ηf)
Bulk carrier	0-9,999	DWT	0.909	0.917
	10,000-34,999	DWT	0.867	0.917
	35,000-59,999	DWT	0.867	0.917
	60,000-99,999	DWT	0.867	0.917
	100,000-199,999	DWT	0.867	0.917
	200,000-+	DWT	0.867	0.917
Chemical tanker	0-4,999	DWT	0.909	0.917
	5,000-9,999	DWT	0.909	0.917
	10,000-19,999	DWT	0.867	0.917
	20,000-39999	DWT	0.867	0.917
	40,000-+	DWT	0.867	0.917
Container	0-999	TEU	0.909	0.917
	1,000-1,999	TEU	0.867	0.917
	2,000-2,999	TEU	0.867	0.917
	3,000-4,999	TEU	0.867	0.917
	5,000-7,999	TEU	0.867	0.917
	8,000-11,999	TEU	0.867	0.917
	12,000-14,499	TEU	0.867	0.917
	14,500-19,999	TEU	0.867	0.917
	20000-+	TEU	0.867	0.917
General cargo	0-4,999	DWT	0.909	0.917
	5,000-9,999	DWT	0.909	0.917
	10,000-19,999	DWT	0.867	0.917
	20,000-+	DWT	0.867	0.917
Liquefied gas tanker	0-49,999	CBM	0.867	0.917
	50,000-99,999	CBM	0.867	0.917
	100,000-199,999	CBM	0.867	0.917
	200,000-+	CBM	0.867	0.917
Oil tanker	0-4,999	DWT	0.909	0.917

Type bin	Capacity	Unit	Weather correction factor (η_w)	Fouling correction factor (ηf)
	5,000-9,999	DWT	0.909	0.917
	10,000-19,999	DWT	0.867	0.917
	20,000-59,999	DWT	0.867	0.917
	60,000-79,999	DWT	0.867	0.917
	80,000-119,999	DWT	0.867	0.917
	120,000-199,999	DWT	0.867	0.917
	200,000-+	DWT	0.867	0.917
Other liquids tankers	0-999	DWT	0.867	0.917
	1,000-+	DWT	0.867	0.917
Ferry-pax only	0-299	GT	0.909	0.917
	300-999	GT	0.909	0.917
	1,000-1,999	GT	0.909	0.917
	2000-+	GT	0.909	0.917
Cruise	0-1,999	GT	0.909	0.917
	2,000-9,999	GT	0.867	0.917
	10,000-59,999	GT	0.867	0.917
	60,000-99,999	GT	0.867	0.917
	100,000-149,999	GT	0.867	0.917
	150,000-+	GT	0.867	0.917
Ferry-RoPax	0-1,999	GT	0.909	0.917
	2,000-4,999	GT	0.909	0.917
	5,000-9,999	GT	0.909	0.917
	10,000-19,999	GT	0.909	0.917
	20,000-+	GT	0.909	0.917
Refrigerated bulk	0-1,999	DWT	0.867	0.917
	2,000-5,999	DWT	0.867	0.917
	6,000-9,999	DWT	0.867	0.917
	10,000-+	DWT	0.867	0.917
Ro-Ro	0-4,999	DWT	0.909	0.917
	5,000-9,999	DWT	0.867	0.917
	10,000-14,999	DWT	0.867	0.917
	15,000-+	DWT	0.867	0.917
Vehicle	0-29,999	GT	0.867	0.917
	30,000-49,999	GT	0.867	0.917
	50,000-+	GT	0.867	0.917
Yacht	0-+	GT	0.867	0.917
Service - tug	0-+	GT	0.909	0.917
Miscellaneous - fishing	0-+	GT	0.909	0.917
Offshore	0-+	GT	0.909	0.917
Service - other	0-+	GT	0.909	0.917
Miscellaneous - other	0-+	GT	0.909	0.917

M Fuel-based and energy-based emission factors

This appendix lists the emission factors used in the model to estimate each of the pollutants with reported results. It follows the same order as in the emission section.

CO_2 emission factors

CO_2 is given as fuel-based emission factors since this is the most common form in the literature. For CO_2 the data was taken from the 2018 EEDI Guidelines (International Maritime Organization, 2018), these values where presented in Table 17 but are added here in Table 45 for the reader convenience.

Table 45 - CO_2 fuel-based emission factors (EF_f)

Fuel type	EF_{f}, CO_2 (g CO_2/g fuel)
HFO	3.114
MDO	3.206
LNG	2.750
Methanol	1.375
LSHFO 1.0%	3.114

SO_x emission factors

For the SO_x EF_f, Equation (15) is used per fuel type and year of the study to account for the different sulphur content. For the convenience of the reader Table 46 shows the average Sulphur content for HFO and MDO between 2012 and 2018. The EF_f are shown in Tables 47 and 48.

Table 46 - Global average fuel sulfur content in percentage per year

Fuel type	2012	2013	2014	2015	2016	2017	2018
HFO	2.51	2.43	2.46	2.45	2.58	2.60	2.60
MDO	0.14	0.13	0.12	0.08	0.08	0.08	0.07

Table 47 - Fuel-based emission factor for SO_x per fuel type for HFO and MDO (g SO_x / g fuel)

Fuel type	2012	2013	2014	2015	2016	2017	2018
HFO	0.0491	0.0480	0.0481	0.0479	0.0504	0.0508	0.0508
MDO	0.0027	0.0025	0.0023	0.0016	0.0016	0.0016	0.0014

Table 48 - Fuel-based emission factor for SO_x per fuel type other than HFO and MDO

Fuel type	EF_f, SO_x (g SO_x/g fuel)
LNG	3.17×10^{-5}
Methanol	2.64×10^{-3}
LSHFO 1.0%	1.96×10^{-2}

NO_X emission factors

The energy-based EF for NO_x for engines that consume other fuel than LNG are calculated by the limits imposed by IMO's Regulation 13 which is synthesised in Table 5 and presented in Table 49 (International Maritime Organization, 2013). For medium-speed engines (MS) it was assumed the engine speed as 500 RPM as it was assumed in the 3rd IMO GHG study. It is important to highlight that Tier III NO_x limits apply only to vessels operating in NECA, outside such areas Tier II limits apply.

Table 49 - Energy-based emissions factors for NO_x for different engine types, tiers and all fuels, except LNG

Engine type	HFO, LSHFO & MDO EF_e,NO_x (g NO_x/kWh)				Methanol EF_e,NO_x (g NO_x/kWh)			
	Tier 0	Tier 1	Tier 2	Tier 3	Tier 0	Tier 1	Tier 2	Tier 3
SS	18.1	17.0	14.4	3.4	18.1	17.0	14.4	3.4
MS	14.0	13.0	10.5	2.6	14.0	13.0	10.5	2.6
HS	10.0	9.8	7.7	2.0	-	-	-	-
Auxiliary Engine	11.2				-			
Boiler and Steam Turbine	2.1				-			
Gas Turbine	6.1				-			

Table 50 presents the EF_e, NO_x when the engine is consuming LNG, the classification per tier is only applicable to LNG-Diesel.

Table 50 - Energy-based emissions factors for NO_x for different engine types and tiers — where applicable — when consuming LNG

Engine type	LNG EF_e. NO_x (g NO_x/kWh)			
	Tier 0	Tier 1	Tier 2	Tier 3
Otto-SS	1.3			
Otto-MS	1.3			
LNG-Diesel	18.1	17.0	14.4	3.4
LBSI	1.3			
Auxiliary Engine	1.3			
Boiler and Steam Turbine	1.3			
Gas Turbine	1.3			

PM_{10} and $PM_{2.5}$ emission factors

As per equations Table 51 and Table 52, PM_{10} is dependent on SFC and fuel's sulphur content. The results shown in Tables 51-54 are obtained using *SFC*.

Table 51 - LSHFO at 1.0% sulphur EF_e per engine generation for the years 2012-2015

Engine	Gen I EF_{e}, PM_{10} (g PM_{10}/kWh)	Gen II EF_{e}, PM_{10} (g PM_{10}/kWh)	Gen III EF_{e}, PM_{10} (g PM_{10}/kWh)
SSD	0.88	0.93	0.95
MSD	0.86	0.90	0.93
HSD	0.83	0.88	0.90
Turbines	0.65	0.65	0.65
Steam/Boilers	0.57	0.57	0.57
AE	0.83	0.88	0.90

Table 52 - Energy-based emission factor for PM_{10} per fuel type and year for generation I engines

Engine	Fuel	EF_{e}, PM_{10} (g PM_{10}/kWh)						
		2012	2013	2014	2015	2016	2017	2018
SSD	HFO	1.37	1.34	1.35	1.35	1.39	1.40	1.40
	MDO	0.20	0.20	0.19	0.18	0.18	0.18	0.18
MSD	HFO	1.37	1.34	1.35	1.35	1.39	1.40	1.40
	MDO	0.20	0.20	0.19	0.18	0.18	0.18	0.18
HSD	HFO	1.37	1.34	1.35	1.35	1.39	1.40	1.40
	MDO	0.20	0.19	0.19	0.18	0.18	0.18	0.17
Turbine	HFO	1.37	1.34	1.35	1.35	1.41	1.42	1.42
	MDO	0.18	0.18	0.17	0.15	0.15	0.15	0.15
Steam/ Boiler	HFO	1.38	1.33	1.35	1.34	1.41	1.42	1.42
	MDO	0.18	0.17	0.17	0.15	0.15	0.15	0.14
	LNG	0.03	0.03	0.03	0.03	0.03	0.03	0.03
AE	HFO	1.37	1.34	1.35	1.35	1.39	1.40	1.40
	MDO	0.20	0.19	0.19	0.18	0.18	0.18	0.17

Table 53 - Energy-based emission factor for PM_{10} per fuel type and year for generation II engines

Engine	Fuel	EF_{e}, PM_{10} (g PM_{10}/kWh)						
		2012	2013	2014	2015	2016	2017	2018
SSD	HFO	1.36	1.34	1.35	1.35	1.38	1.39	1.39
	MDO	0.20	0.20	0.20	0.19	0.19	0.19	0.18
MSD	HFO	1.37	1.34	1.35	1.35	1.39	1.39	1.39
	MDO	0.20	0.20	0.20	0.18	0.18	0.18	0.18
HSD	HFO	1.37	1.34	1.35	1.35	1.39	1.40	1.40
	MDO	0.20	0.20	0.19	0.18	0.18	0.18	0.18
Otto-MS	LNG	0.02	0.02	0.02	0.02	0.02	0.02	0.02
LBSI	LNG	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Turbine	HFO	1.37	1.34	1.35	1.35	1.41	1.42	1.42
	MDO	0.18	0.18	0.17	0.15	0.15	0.15	0.15
Steam/ Boiler	HFO	1.38	1.33	1.35	1.34	1.41	1.42	1.42
	MDO	0.18	0.17	0.17	0.15	0.15	0.15	0.14

Engine	Fuel	EF_e, PM_{10} (g PM_{10}/kWh)						
		2012	2013	2014	2015	2016	2017	2018
	LNG	0.03	0.03	0.03	0.03	0.03	0.03	0.03
AE	HFO	1.37	1.34	1.35	1.35	1.39	1.40	1.40
	MDO	0.20	0.20	0.19	0.18	0.18	0.18	0.18
	LNG	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Table 54 - Energy-based emission factor for PM_{10} per fuel type and year for generation III engines

Engine	Fuel	EF_e, PM_{10} (g PM_{10}/kWh)						
		2012	2013	2014	2015	2016	2017	2018
SSD	HFO	1.36	1.34	1.35	1.35	1.38	1.39	1.39
	MDO	0.20	0.20	0.20	0.19	0.19	0.19	0.19
	MeOH	0.14	0.13	0.14	0.13	0.14	0.14	0.14
MSD	HFO	1.36	1.34	1.35	1.35	1.38	1.39	1.39
	MDO	0.20	0.20	0.20	0.19	0.19	0.19	0.18
	MeOH	0.14	0.13	0.14	0.13	0.14	0.14	0.14
HSD	HFO	1.37	1.34	1.35	1.35	1.39	1.39	1.39
	MDO	0.20	0.20	0.20	0.18	0.18	0.18	0.18
Otto-SS	LNG	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Otto-MS	LNG	0.02	0.02	0.02	0.02	0.02	0.02	0.02
LNG-Diesel	LNG	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LBSI	LNG	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Turbine	HFO	1.37	1.34	1.35	1.35	1.41	1.42	1.42
	MDO	0.18	0.18	0.17	0.15	0.15	0.15	0.15
	LNG	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Steam/ Boiler	HFO	1.38	1.33	1.35	1.34	1.41	1.42	1.42
	MDO	0.18	0.17	0.17	0.15	0.15	0.15	0.14
	LNG	0.03	0.03	0.03	0.03	0.03	0.03	0.03
AE	HFO	1.37	1.34	1.35	1.35	1.39	1.39	1.39
	MDO	0.20	0.20	0.20	0.18	0.18	0.18	0.18
	LNG	0.02	0.02	0.02	0.02	0.02	0.02	0.02

The EF_e for $PM_{2.5}$ are obtained multiplying by 92% the PM_{10} EF_e shown in Tables 51-54.

CH_4 emission factors

Methane EF_e are presented in Tables 55 and 56.

Table 55 - Energy-based emissions factors for CH_4 for different engine types, tiers and all fuels, except LNG. The same values are used for all engine generations and tiers

Engine type	HFO, LSHFO & MDO EF_e, CH_4 (g CH_4/kWh)	Methanol EF_e, CH_4 (g CH_4/kWh)
SS	0.010	0.001
MS	0.010	0.001
HS	0.010	-

Auxiliary Engine	0.010	-
Boiler and Steam Turbine	0.002	-
Gas Turbine	0.002	-

Table 56 - Energy-based emissions factors for CH_4 for different engine types and tiers — where applicable — when consuming LNG

Engine type	LNG $EF_{e.}$ CH_4 (g CH_4/kWh)
Otto-SS	2.5
Otto-MS	5.5
LNG-Diesel	0.2
LBSI	4.1
Auxiliary Engine	5.5
Boiler and Steam Turbine	0.04
Gas Turbine	0.06

CO emission factor

The EF_e for CO are presented in Tables 57 and 58.

Table 57 - Energy-based emissions factors for CO for different engine types, tiers and all fuels, except LNG. The same values are used for all engine generations and tiers

Engine type	HFO & LSHFO $EF_{e,CO}$ (g CO/kWh)	MDO $EF_{e,CO}$ (g CO/kWh)	Methanol $EF_{e,CO}$ (g CO/kWh)
SS	0.540	0.044	0.054
MS	0.540	0.046	0.054
HS	0.540	0.540	-
Auxiliary Engine	0.540	0.540	-
Boiler and Steam Turbine	0.200	0.200	-
Gas Turbine	0.100	0.100	-

Table 58 - Energy-based emissions factors for CO for different engine types and tiers - where applicable - when consuming LNG

Engine type	LNG $EF_{e.}$ CO (g CO/kWh)
Otto-SS	1.3
Otto-MS	1.3
LNG-Diesel	1.04
LBSI	1.3
Auxiliary Engine	1.3
Boiler and Steam Turbine	0.2
Gas Turbine	0.2

N_2O emission factors

The EF_e for N_2O are presented in Tables 59 and 60.

Table 59 - Energy-based emissions factors for N_2O for different engine types, tiers and all fuels, except LNG. The same values are used for all engine generations and tiers

Engine type	HFO & LSHFO EF_{e,N_2O} (g N_2O/kWh)	MDO EF_{e,N_2O} (g N_2O/kWh)	Methanol EF_{e,N_2O} (g N_2O/kWh)
SS	0.031	0.030	0.003
MS	0.034	0.030	0.003
HS	0.030	0.034	-
Auxiliary Engine	0.040	0.036	-
Boiler and Steam Turbine	0.040	0.049	-
Gas Turbine	0.040	0.049	-

Table 60 - Energy-based emissions factors for N_2O for different engine types and tiers — where applicable — when consuming LNG

Engine type	LNG EF_{e,N_2O} (g N_2O/kWh)
Otto-SS	0.020
Otto-MS	0.020
LNG-Diesel	0.030
LBSI	0.020
Auxiliary Engine	0.020
Boiler and Steam Turbine	0.020
Gas Turbine	0.020

NMVOC emission factors

The EF_e for NMVOC are presented in Tables 61 and 62.

Table 61 - Energy-based emissions factors for NMVOC for different engine types, tiers and all fuels, except LNG. The same values are used for all engine generations and tiers

Engine type	HFO, MDO & LSHFO $EF_{e,NMVOC}$ (g NMVOC/kWh)	Methanol $EF_{e,NMVOC}$ (g NMVOC/kWh)
SS	0.632	0.063
MS	0.527	0.053
HS	0.527	-
Auxiliary Engine	0.421	-
Boiler and Steam Turbine	0.105	-
Gas Turbine	0.105	-

Table 62 - Energy-based emissions factors for NMVOC for different engine types and tiers — where applicable — when consuming LNG

Engine type	LNG $EF_{e,NMVOC}$ (g NMVOC/kWh)
Otto-SS	0.500
Otto-MS	0.500

LNG-Diesel	0.400
LBSI	0.500
Auxiliary Engine	0.500
Boiler and Steam Turbine	0.105
Gas Turbine	0.105

Black carbon (BC) emission factors

Black carbon depending on the fuel and engine time uses either fuel- or energy-based emission factors. For the case where BC EF_f are used, emissions are estimated in a similar way to CO_2 emissions by directly using the EF_f and multiplying it by the fuel consumed. Values of the EF_f are provided in Tables Table 63, Table 64 and 66. In the case of EF_e, emissions are calculated using the values from

Table 65. These were obtained by using equations to, based on the work from the ICCT, and presented in Olmer et al. (2017a) and Comer et al. (2017).

Table 63 - Black carbon EFs for all fuels and internal combustion engines as main engines except when consuming LNG and methanol

Load (%)	Engine	HFO & LSHFO EF_{f}, BC (g BC/g fuel)		MDO EF_{f}, BC (g BC/g fuel)	
		2-stroke	4-stroke	2-stroke	4-stroke
< 5	SS/MS/HS	4.40×10^{-4}	4.52×10^{-3}	1.00×10^{-5}	3.48×10^{-3}
10	SS/MS/HS	3.40×10^{-4}	2.31×10^{-3}	8.00×10^{-6}	1.60×10^{-3}
20	SS/MS/HS	2.70×10^{-4}	1.18×10^{-3}	6.00×10^{-6}	7.30×10^{-4}
30	SS/MS/HS	2.30×10^{-4}	8.00×10^{-4}	5.00×10^{-6}	4.60×10^{-4}
40	SS/MS/HS	2.10×10^{-4}	6.00×10^{-4}	4.00×10^{-6}	3.40×10^{-4}
50	SS/MS/HS	1.90×10^{-4}	4.90×10^{-4}	4.00×10^{-6}	2.60×10^{-4}
60	SS/MS/HS	1.80×10^{-4}	4.10×10^{-4}	4.00×10^{-6}	2.10×10^{-4}
70	SS/MS/HS	1.70×10^{-4}	3.50×10^{-4}	4.00×10^{-6}	1.80×10^{-4}
80	SS/MS/HS	1.60×10^{-4}	3.10×10^{-4}	3.00×10^{-6}	1.50×10^{-4}
90	SS/MS/HS	1.60×10^{-4}	2.80×10^{-4}	3.00×10^{-6}	1.40×10^{-4}
100	SS/MS/HS	1.50×10^{-4}	2.50×10^{-4}	3.00×10^{-6}	1.20×10^{-4}

Table 64 - Black carbon EFe for auxiliary engines, turbines and boilers when consuming all fuels except for methanol

Load (%)	Engine	HFO & LSHFO EF_{e}, BC (g BC/kWh)	MDO EF_{e}, BC (g BC/kWh)	LNG EF_{e}, BC (g BC/kWh)
All	Otto-SS	-	-	0.003
All	Otto-MS	-	-	0.003
All	LNG-Diesel	-	-	0.002
All	LBSI	-	-	0.003
All	AE *	-	-	0.003
All	Steam/Boiler	0.080	0.060	0.003
All	Turbine	0.005	0.004	0.003

*The emission factor is covered by Table 52 when consuming HFO, LSHFO or MDO.

Table 65 - Energy-based emissions factors for BC for different engine types and tiers - where applicable - when consuming LNG

Engine type	LNG EF_e, *BC* (g BC/kWh)
Otto-SS	0.003
Otto-MS	0.003
LNG-Diesel	0.002
LBSI	0.003
Auxiliary Engine	0.003
Boiler and Steam Turbine	0.003
Gas Turbine	0.003

Table 66 - Black carbon EF_f for methanol-fuelled engines

Load (%)	Engine	Methanol EF_f, *BC* (g BC/g fuel)	
		2-stroke	4-stroke
< 5	SS/MS	$4.40X10^{-5}$	$4.52X10^{-4}$
10	SS/MS	$3.40X10^{-5}$	$2.31X10^{-4}$
20	SS/MS	$2.70X10^{-5}$	$1.18X10^{-4}$
30	SS/MS	$2.30X10^{-5}$	$8.00X10^{-5}$
40	SS/MS	$2.10X10^{-5}$	$6.00X10^{-5}$
50	SS/MS	$1.90X10^{-5}$	$4.90X10^{-5}$
60	SS/MS	$1.80X10^{-5}$	$4.10X10^{-5}$
70	SS/MS	$1.70X10^{-5}$	$3.50X10^{-5}$
80	SS/MS	$1.60X10^{-5}$	$3.10X10^{-5}$
90	SS/MS	$1.60X10^{-5}$	$2.80X10^{-5}$
100	SS/MS	$1.50X10^{-5}$	$2.50X10^{-5}$

N Fuel consumption and emissions calculation examples and its comparison to the Third IMO GHG Study 2014

N.1 Introduction

This appendix recreates the mathematical process to estimate emissions for a single vessel, at an hourly and annual level, using the methodologies of both the Third and Fourth IMO GHG Studies. It aims to illustrate the methodological differences that explain the variations in the aggregated results for fuel consumption (as well as closely-linked CO_2 emissions) and other emissions. It is important to remember that the Third IMO GHG Study converted energy-based emission factors to fuel-based which is a different approach taken in the Fourth IMO GHG Study. This implies that to showcase the main difference between both studies it will be necessary to replicate the same conversion but with the Fourth IMO Study assumptions.

The key points covered in this section are as follows:
- The mathematical decomposition, with a specific focus on the differences, of the formulas used to convert energy-based emission factors (EF_e) into fuel-based emission factors (EF_f) for both studies.
- The mathematical implications, in terms of total emission reductions/increases, of the interaction of these factors concerning fuel consumption.
- A numerical exercise to highlight the addition of uncertainty at each level of the estimation process.
- A summary of the findings and the impact of the differences between both studies for each pollutant.

N.2 Mathematical interpretation

The key equations used to estimate fuel consumption and emissions in the Third IMO GHG Study which present the most relevant differences with the Fourth IMO GHG are compared below. The general equations to get hourly emissions (EM_i), which are the same as with the Third IMO GHG Study are given by Equations 7 to 21 of the main document. An important concept to bring forward to help with the relevant differences in the emission factor methodology from both studies is the load correction factor (CF_L) — Equation (16) which represents the quadratic behaviour between SFC and the engine load (*Load*):

$$CF_L = (0.455 \cdot Load^2 - 0.71 \cdot Load + 1.28) \qquad (16)$$

Up to this point, the Third and the Fourth IMO GHG Studies' respective methodologies are the same. However, they differ on the approach taken to calculate the hourly emissions (EM_i). The basic rationale of the Third IMO GHG Study was to convert from EF_e to EF_f to quantify EM_i. Under this approach, the intention was to capture in the fuel-based emission factor, the change of engine efficiency seen in the SFC. To achieve this, it was needed to convert the base SFC from the available literature on emission factors. This reference SFC from the literature will be known from now onwards as SFC_{BE}. It is important to highlight that SFC_{BE} is different to SFC_{base} in the Third IMO GHG Study due to the emission factors coming from a different reference than the one used for SFC_{base}. However, as explained before, in the Fourth IMO GHG Study, the assumption taken was that the EF_f do not change with the change in engine efficiency but rather the reduction of emissions is solely achieved by the fuel savings due to a lower SFC.

To appreciate the differences in methodology, the Fourth IMO GHG Study EF_e are being converted to EF_f. As mentioned before, the Third IMO GHG Study 2014 uses SFC_{BE} multiplied by CF_L to convert from EF_e to EF_f while for the Fourth IMO GHG Study simply divides it by the *generation-dependent* SFC_{base}, the same value used to estimate fuel consumption.

Table 67 - Fuel-based emissions factor differences between studies

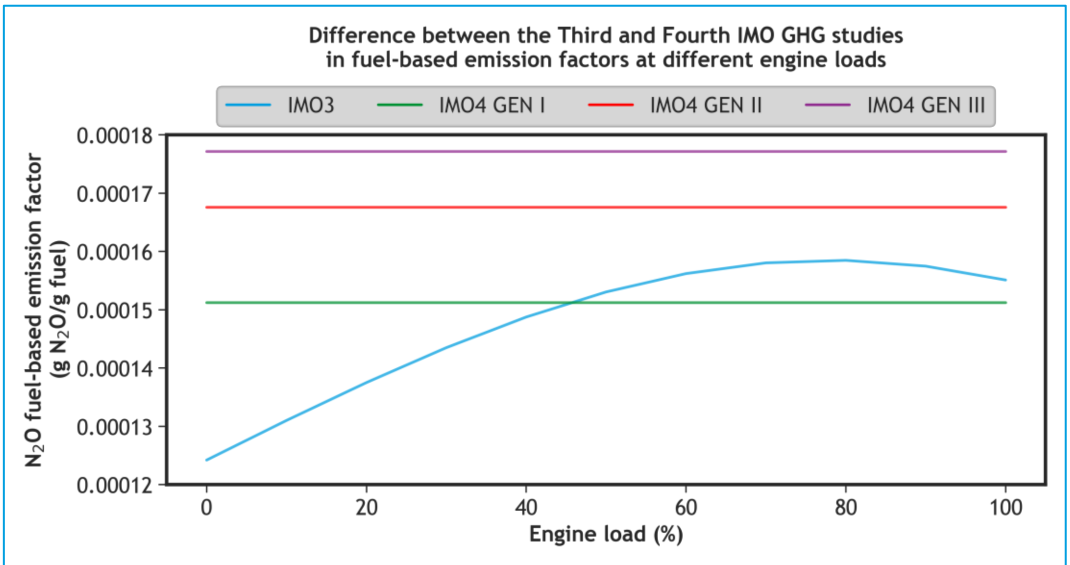
Third IMO GHG Study (IMO3)	Fourth IMO GHG Study (IMO4)
$EF_f = \frac{EF_e}{CF_L \cdot SFC_{BE}}$ (17)	$EF_f = \frac{EF_e}{SFC_{base}}$ (18)

There are two implications of these differences:

- Equation (17 produces a variable EF_f dependent on CF_L, while equation (18 produces a constant result across engine loads;
- Equation (17 produces a single value for all ship ages while, equation (18 produces three different values depending on each ship's generation due to the change in SFC_{base}.

These differences can be illustrated by Figure 64, which shows the resulting EF_f values for N_2O for an SSD engine running on HFO and for different engine loads. Please note that the Third IMO GHG Study 2014 methodology implies that EF_f generally changes with engine load while in this study, if we were to use the converted EF_f as shown in equation (18, it would remain constant but with three different magnitudes depending on the engine generation. It is important to remember that in the Fourth IMO GHG Study, the EF_e are used directly with the power being demanded by the ship and they are not converted to EF_f to then being multiplied by the fuel consumed.

Figure 64 - N_2O fuel-based emission factors vs engine load. Note that there are three different lines (constants) for IMO4 depending on SFC_B



Continuing with the mathematical interpretation of the differences, the next step is the implementation of Equations (19 and (20 to calculate the hourly emissions (EM_i) which becomes the following for each respective study:

Table 68 - Calculation to obtain the hourly emissions by the two studies

IMO3		IMO4	
$EM_{i\_IMO3} = \frac{EF_e}{CF_L \cdot SFC_{BC}} \cdot CF_L \cdot SFC_{base} \cdot \dot{W}_i$ $EM_{i\_IMO3} = EF_e \cdot \frac{SFC_{base}}{SFC_{BC}} \cdot \dot{W}_i$	(19)	$EM_{i\_IMO4} = \frac{EF_e}{SFC_{base}} \cdot CF_L \cdot SFC_{base} \cdot \dot{W}_i$ $EM_{i\_IMO4} = EF_e \cdot CF_L \cdot \dot{W}_i$	(20)

As noted by equations above, for both studies the expression $EF_e \cdot \dot{W}_i$ remains unchanged making both methodologies dependant on the engine load. The difference, therefore, is a result of the following:

4. For the Fourth IMO GHG Study, EM_i changes with engine load ($\dot{W}_i$) but also changes in line with CF_L (see equation 20). Since CF_L is higher at lower engine loads, emissions will be higher the lower the power demand of the vessel is when compared against the results of in the Third IMO GHG Study, where EM_i only changed with $\dot{W}_i$ (see equation 19). Due to the parabolic shape of CF_L, the difference induced by this factor can be up to 20% when the engine operates below 20% MCR and a minimum of 0.3% when operating at 80% MCR.
5. This is in contrast with the Third IMO GHG Study, where hourly emissions are multiplied by a constant factor (SFC_{base}/SFC_{BE}), as shown in equation 19. This is because the Third IMO GHG Study, as mentioned before, used a generation and engine type specific fuel consumption (SFC_{base}) value to estimate FC_i (Table 49, Smith *et al.*, 2014) while using the constant fuel and engine dependant SFC_{BE} for the conversion of EF_e to EF_f (Annex 6, Table 24 Smith *et al.*, 2014). The impact of this age-related factor results in emissions being reduced to 90% for vessels built later than the year 2000, to 95% for vessels built between 1984 and 2000, and increased by 5% for vessels built before 1984.

N.3 Fuel consumption and emissions estimates: a numerical example

A random ship was selected for this exercise (see Table 69). First, its technical specifications are used to estimate hourly values of fuel consumption (FC_i) and load dependant EF_f. Subsequently, the results that would be obtained for both the Third and Fourth IMO GHG Studies are presented in parallel. Using data from the current bottom-up model, corresponding fuel consumption at different engine loads is used to estimate emissions for a sample pollutant. The aim is to illustrate the effects of the differences between the methodologies of both studies.

Table 69 - Sampled ship's main engine technical specifications (Chemical tanker, 5,000-9,999 dwt)

Engine type	SSD
Fuel	HFO
Tier	0
Year of built	1990
Main engine installed power (kW)	3,328

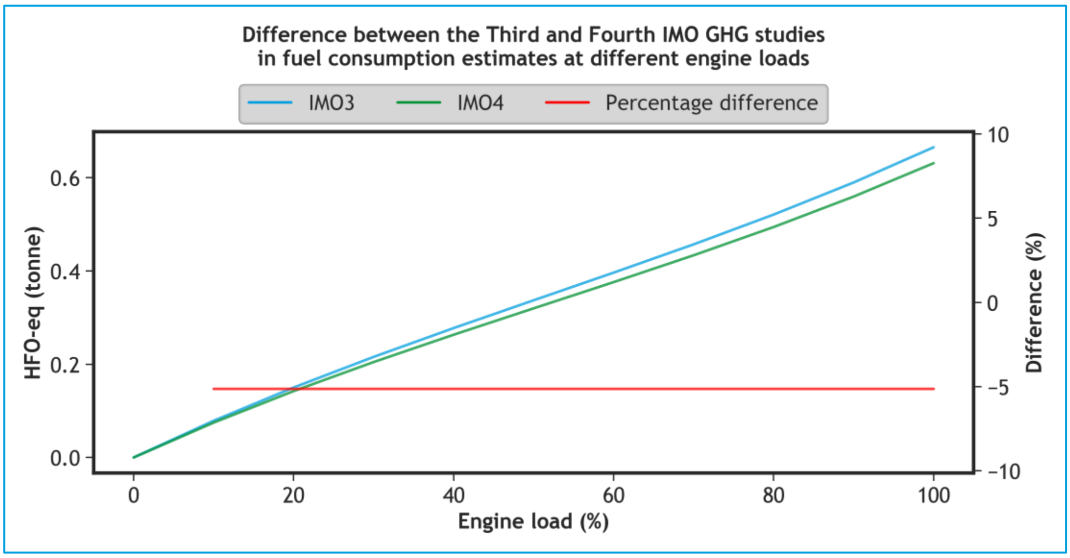
N.4 Fuel consumption estimation

The resulting fuel consumption for both methodologies are presented in Table 70 and Figure 65. It should be noted that the SFC_{base} values for this type of engine have changed between both studies. Whereas for the Third IMO GHG Study it was equal to 195 g HFO/kWh, for the Fourth IMO GHG Study it decreased to 185 g HFO/kWh. Therefore, there is a constant change of -5.13% for all engine loads in the estimated *FC*.

Table 70 – Fuel consumption results for the sampled vessel at different engine loads

IMO3					IMO4					Difference IMO4-IMO3 (%)
Load (%)	SFC_{base} (g HFO /kWh)	CF_L	$\dot{W}_i$ (kW)	FC_{SSD_HFO} (g)	*Load* (%)	SFC_{base} (g HFO /kWh)	CF_L	$\dot{W}_i$ (kW)	FC_{SSD_HFO} (g)	
0	195	1.280	0	0	0	185	1.280	0	0	0.00
10	195	1.214	333	78,755	10	185	1.214	332.8	74,716	-5.13
20	195	1.156	666	150,066	20	185	1.156	665.6	142,370	-5.13
30	195	1.108	998	215,705	30	185	1.108	998.4	204,643	-5.13
40	195	1.069	1,331	277,443	40	185	1.069	1,331.2	263,216	-5.13
50	195	1.039	1,664	337,054	50	185	1.039	1,664	319,769	-5.13
60	195	1.018	1,997	396,307	60	185	1.018	1,996.8	375,983	-5.13
70	195	1.006	2,330	456,975	70	185	1.006	2,329.6	433,540	-5.13
80	195	1.003	2,662	520,829	80	185	1.003	2,662.4	494,120	-5.13
90	195	1.010	2,995	589,642	90	185	1.010	2,995.2	559,404	-5.13
100	195	1.025	3,328	665,184	100	185	1.025	3,328	631,072	-5.13

Figure 65 – Main engine FC of the sample vessel and the difference between the Third and Fourth IMO GHG Study



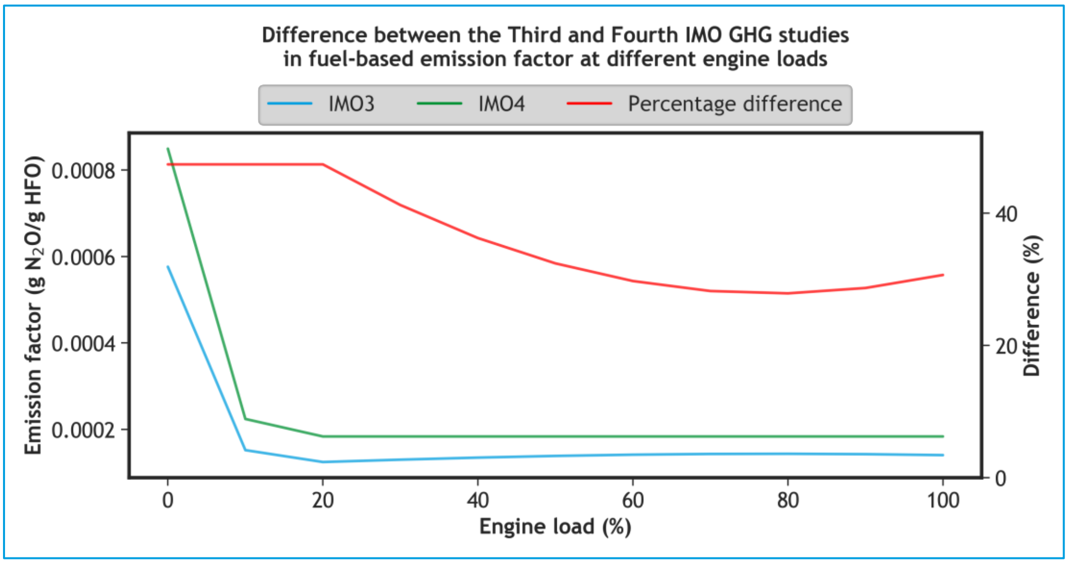
N.5 Fuel-based emission factors calculation

Equations (17 and (18 are used in this example to calculate N_2O EF_f for the example ship. The results from the calculation are shown in Table 71 and Figure 66. There is an important difference in EF_e between both studies, it was used 0.031 g/kWh for the Third IMO GHG Study and 0.034 g/kWh for the Fourth IMO GHG Study (a difference of 9.7%). However, the EF_f for both studies gives a greater difference, reaching above 47% for low loads while for higher loads the difference is around 28%. This implies that the net difference is explained in its majority by the addition of the factors seen in equation (17 which reduces, in this example, the amount of pollutant emitted in comparison to the Fourth IMO GHG study.

Table 71 - N_2O EF_f for the Third and Fourth IMO GHG Study.

IMO3					IMO4				Difference IMO4-IMO3
Load (%)	EF_e (g N_2O/kWh)	SFC_{base} (g HFO/kWh)	CF_L	EF_f (g N_2O/g HFO)	*Load* (%)	EF_e (g N_2O/kWh)	SFC_{base} (g HFO/kWh)	EF_f (g N_2O/g HFO)	(%)
0	0.031	215	1.28	5.76×10^{-4}	0	0.034	185	8.49×10^{-4}	47.4
10	0.031	215	1.21	1.52×10^{-4}	10	0.034	185	2.24×10^{-4}	47.4
20	0.031	215	1.16	1.25×10^{-4}	20	0.034	185	1.84×10^{-4}	47.4
30	0.031	215	1.11	1.30×10^{-4}	30	0.034	185	1.84×10^{-4}	41.2
40	0.031	215	1.07	1.35×10^{-4}	40	0.034	185	1.84×10^{-4}	36.2
50	0.031	215	1.04	1.39×10^{-4}	50	0.034	185	1.84×10^{-4}	32.4
60	0.031	215	1.02	1.42×10^{-4}	60	0.034	185	1.84×10^{-4}	29.7
70	0.031	215	1.01	1.43×10^{-4}	70	0.034	185	1.84×10^{-4}	28.2
80	0.031	215	1.00	1.44×10^{-4}	80	0.034	185	1.84×10^{-4}	27.9
90	0.031	215	1.01	1.43×10^{-4}	90	0.034	185	1.84×10^{-4}	28.7
100	0.031	215	1.03	1.41×10^{-4}	100	0.034	185	1.84×10^{-4}	30.6

Figure 66 - Fuel based emission factors and difference, IMO3 vs IMO4



N.6 Emission calculation

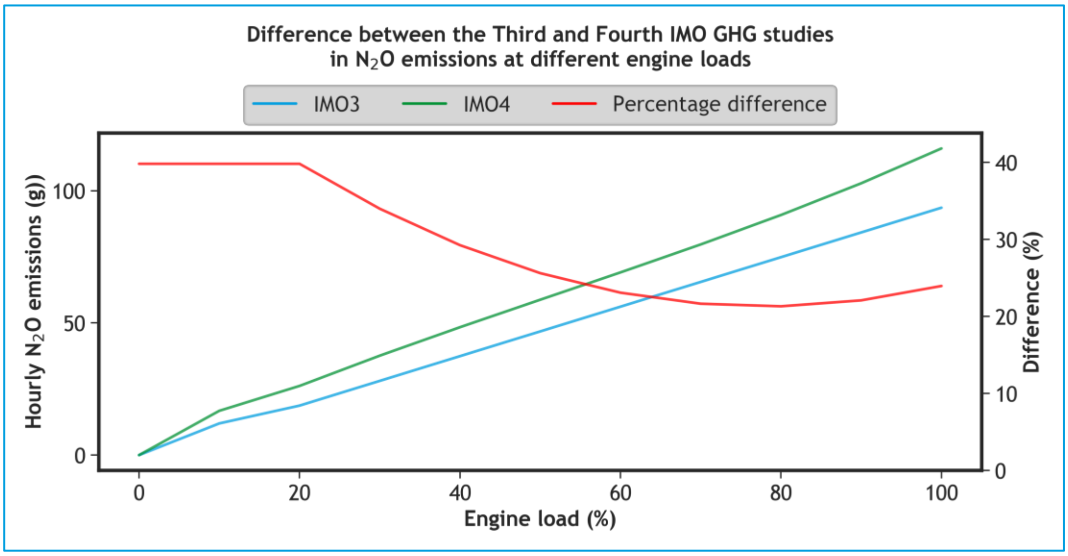
With the results shown previously, it is possible to estimate the total N_2O emissions (*EM*) is grams for each load bracket (see Table 72). The column "*Difference*" represents the aggregated variation in the measurement of the pollutant, in this case, N_2O, for each load between the two studies. This column shows that the extra production of fuel resulted from a higher SFC_{base} in the Third IMO GHG Study (i.e. -5.3%), partially compensates for the larger EF_f in the Fourth IMO GHG Study, reducing the differences to a range of 39.8% at low engine loads and 21.3% at high engine loads.

Table 72 - N_2O emissions estimated at different engine loads with the difference between the Third and Fourth IMO GHG Studies

IMO3				IMO4				Difference
Load (%)	FOC_{SSD_HFO} (g)	EF_{foc} (g N_2O/g HFO)	EM_{N2O} (g)	*Load* (%)	FOC_{SSD_HFO} (g)	EF_{foc} (g N_2O/g HFO)	EM_{N2O} (g)	IMO4-IMO3 (%)
0	0.0	5.76x10^{-4}	0.0	0	0.0	8.49x10^{-4}	0.0	0.0
10	78,754	1.52x10^{-4}	12.0	10	74,716	2.24x10^{-4}	16.8	39.8
20	150,065	1.25x10^{-4}	18.7	20	142,370	1.84x10^{-4}	26.2	39.8
30	215,704	1.30x10^{-4}	28.1	30	204,643	1.84x10^{-4}	37.6	34.0
40	277,443	1.35x10^{-4}	37.4	40	263,216	1.84x10^{-4}	48.4	29.2
50	337,054	1.39x10^{-4}	46.8	50	319,769	1.84x10^{-4}	58.8	25.6
60	396,307	1.42x10^{-4}	56.1	60	375,984	1.84x10^{-4}	69.1	23.1
70	456,975	1.43x10^{-4}	65.5	70	433,540	1.84x10^{-4}	79.7	21.6
80	520,829	1.44x10^{-4}	74.9	80	494,120	1.84x10^{-4}	90.8	21.3
90	589,641	1.43x10^{-4}	84.2	90	559,404	1.84x10^{-4}	102.8	22.1
100	665,184	1.41x10^{-4}	93.6	100	631,072	1.84x10^{-4}	116.0	23.9

Figure 67 highlights the difference in the estimated emissions for both studies and its relationship with engine load. Please note that by following the trend of CF_L the difference (right-hand vertical axis) is at its lowest at 80% MCR.

Figure 67 - Engine load-specific hourly N_2O emissions for the sample vessel and the difference between the Third and Fourth IMO GHG studies



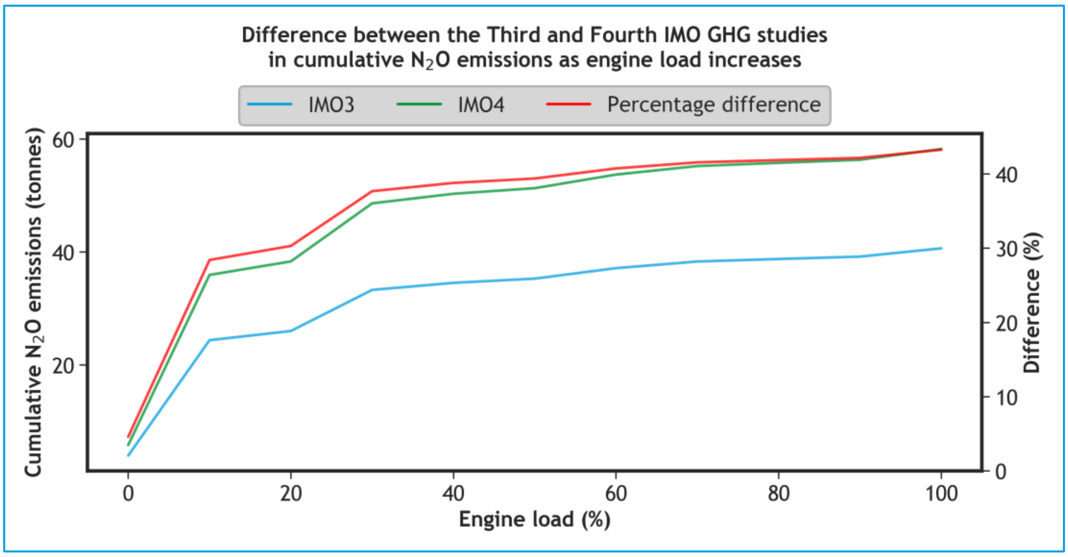
N.7 Effect on annually aggregated N_2O emissions

Given that the differences in hourly emissions shown in Table 73 are not constant across engine loads, the cumulative difference in annual emissions measured between the two studies will depend on the operational profile exhibited by each vessel. As per this table, ships operating mainly on engine loads above 50% MCR will tend to have smaller differences in their annual emissions (around 22%) than vessels operating below 50% MCR (between 25.6 and 39.8%). To illustrate this Table 73 presents the cumulative fuel consumption (*C_FC*) for the year 2012 using the example specification. It also presents the estimated emission per load bracket (EM_{N2O}) and its buildup throughout the whole load range (C_EM_{N2O}) for both studies. Alongside Figure 68 provides insight into the influence of engine loading in the differences of N_2O emissions between studies.

Table 73 - Difference between the Third and Fourth IMO GHG studies in regards to the cumulative FC and N_2O emissions for the sampled vessel observed in 2012

Load (%)	Load range (%)		*FC* (tonnes)	*C_FC* (tonnes)	IMO3		IMO4		Diff. per load bracket (%)	C_EM_{N2O} diff. (%)
	From	To			EM_{N2O} (kg)	C_EM_{N2O} (kg)	EM_{N2O} (kg)	C_EM_{N2O} (kg)		
0	7	10	6.86	6.86	3.95	3.95	5.83	5.83	47.4	4.6
10	10	20	134.32	141.18	20.44	24.39	30.12	35.94	39.7	28.4
20	20	25	13.01	154.19	1.62	26.01	2.39	38.33	3.0	30.3
30	25	35	55.95	210.14	7.28	33.29	10.28	48.62	9.0	37.7
40	35	45	9.23	219.37	1.25	34.54	1.70	50.31	1.3	38.8
50	45	55	5.38	224.75	0.75	35.28	0.99	51.30	0.7	39.4
60	55	65	13.11	237.86	1.86	37.14	2.41	53.71	1.5	40.8
70	65	75	8.22	246.09	1.18	38.32	1.51	55.22	0.9	41.6
80	75	85	3.07	249.16	0.44	38.76	0.56	55.79	0.3	41.9
90	85	95	2.96	252.12	0.42	39.19	0.54	56.33	0.3	42.2
100	95	100	10.40	262.52	1.46	40.65	1.91	58.24	1.1	43.3

Figure 68 - 2012 estimated cumulative N_2O emissions for the sample vessel between the Third and Fourth IMO GHG studies



For this exercise, around 80% of the yearly fuel consumption was burnt below 30% MCR (Table 73). At this point, the cumulative difference in N_2O emissions already reaches 37.7%. Similarly, only an extra 5.6% difference is built for engine loads higher than 30% MCR. In summary, the differences presented in Table 73 and Figure 68 are a combination of the effect of starting with different EF_e, the effect of the operation on EF_f and the effect of an operational profile centred around low loads.

N.8 Analysis of GHG emissions results in the Third and Fourth IMO GHG Studies

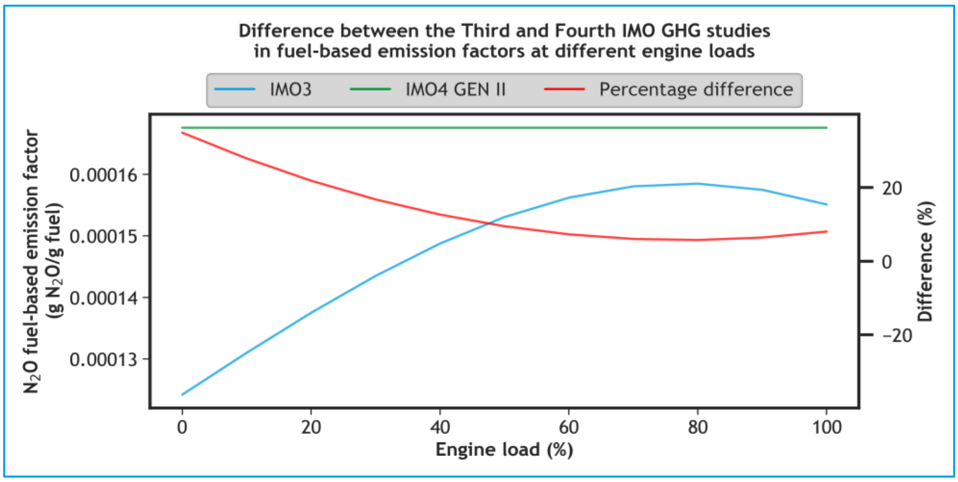
Figure 112 in section 2.7.1 shows the comparison between both studies for the total emissions. Results vary from an underestimation of 78.2% for methane (CH_4) to an overestimation of 27.0% for Non-methane VOC. Using the mathematical example above as a reference, the increments on estimated emissions induced by the changes in methodology vary depending on different factors that are explored in this section in a qualitatively way but they can be summarized as follows:

- around 10% of the difference is due to changes in for main engine's Speed-power correction factor (δw) (Section 2.2.5).
- up to 30% difference is caused by the yearly operational profile through CF_L in equation (20)
- up to 10% difference in the final emissions depend on the age of the vessel caused by the factor SFC_{base}/SFC_{BC}.

Due to the interactions of the root causes that created the difference between the Third and Fourth IMO GHG studies, this section illustrates these in a more qualitatively approach rather than specifically quantify them. This is done with the aid of the methodology comparison between studies and the example developed previously. The main causes that produce the differences in emissions between the IMO studies are:

- Some of the energy-based emission factors have been updated to reflect new research on the field.
- All pollutants, with the exemption of black carbon (BC), were affected by the change in δ_w in the Fourth IMO GHG Study methodology. This amounts to a 10% increment in GHG emissions from main engines for the majority of the world's fleet. The exemptions are cruise ships and container carriers of more than 14,500 TEU, for which the δ_w was increased from 10% to 25%-30%. More details on the changes due to this factor can be found in Section 2.2.5.
- With the exemption of Low Load correction factors, equation 18 shows that the fuel-based emission factors (EF_f) of all pollutants were kept constant across engine loads in the Fourth IMO GHG Study. In contrast, equation 17 shows that for the Third IMO GHG Study these varied inversely proportionally to the engine load factor (CF_L), giving a curve shape inverse to that as seen in Figure 69 provides an example of the values that the EF_f would take using the methodologies of both studies for N_2O from an SSD engine, built between 1984 and 2000 and running on HFO. As seen on the secondary axis, the difference change from around 30% MCR at low engine loads to a minimum of around 5 at 80% MCR. This means that the Fourth IMO GHG Study sees a difference of 30% in the main engine emissions for vessels operating mainly on low engine loads. Finally, since the denominators of equations (18) and (20) are the same for all pollutants (with the exemption of CO_2 and BC) this example of overprediction is valid for them as well.

Figure 69 - Comparison of fuel-based emission factor between the third and 4th IMO GHG studies



- As addressed in equation (20), the Fourth IMO GHG Study opted not to correct emission factors dependant on the engine's age, as advised by the opinion of industry and marine engine experts. In contrast, the Third IMO GHG Study 2014 applied an emission factor ratio (EF_c) based in SFC_{base}/SFC_{BE}[22] shown in equation and presented in Table 74 that resulted in a relevant change on the hourly emissions.

Table 74 - SFC numbers from the Third IMO GHG study used to calculate EF_f and their SFC correction ratios

Emissions efficiency/age correction factor SFC_{base}/SFC_{BE}												
	SSD		MSD		HSD		Turbine		Steam/Boilers		Auxiliary	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
SFC_{BE} IMO3	195	185	215	205	215	205	305	300	305	300	227	217
Gen I SFC_{base} IMO3	205	205	215	215	225	225	305	300	305	300	225	225
EF_c (SFC_{base} /SFC_{BE})	1.051	1.108	1.000	1.049	1.047	1.098	1.000	1.000	1.000	1.000	0.991	1.037
Gen II SFC_{base} IMO3	185	185	195	195	205	205	305	300	305	300	225	225
EF_c (SFC_{base} /SFC_{BE})	0.949	1.000	0.907	0.951	0.953	1.000	1.000	1.000	1.000	1.000	0.991	1.037
Gen III SFC_{base} IMO3	175	175	185	185	195	195	305	300	305	300	225	225
EF_c (SFC_{base} /SFC_{BE})	0.897	0.946	0.860	0.902	0.907	0.951	1.000	1.000	1.000	1.000	0.991	1.037

As per Table 74, for an SSD engine running on HFO, this factor reduced emissions by about 10% for ships built from 2001, 5% for ships built between 1984 and 2000 and increased by about 5% for ships built before 1984.

Black carbon is one of the new contributions of the current study; as such, no results of this pollutant were reported in the Third IMO GHG Study to compare against.

— In the case of CH_4, the Fourth IMO GHG Study reduces its prediction by 78.2% due to the division of LNG powered engines into five categories: Otto SS, Otto MS, LNG-Diesel, LBSI, and turbines. For 2012, the predominant LNG engine type found in the Fourth IMO GHG Study was steam turbines which had a CH_4 energy-based emission factor of 0.002 g/kWh, low enough to render its methane emissions closer to zero. Other LNG-fuelled ships in 2012 included LNG-Otto MS ($EF_{e,CH4}$ equal to 5.5 g/kWh) and LNG-Diesel ($EF_{e,CH4}$ equal to 0.2 g/kWh). This compares against a generic methane EF_e of 8.5 g/kWh for LNG-fuelled ships — assumed to be Otto cycle only — in the Third IMO GHG Study 2014.
— The Fourth IMO GHG Study estimates a reduction in emissions of 9% for Carbon Monoxide (CO) against the Third IMO GHG Study, quite distant from the 30% increase estimated for other pollutants. Although this pollutant is affected by the changes presented above, for steam and gas turbines, in particular, the Third IMO GHG Study kept the same baseline emission factors used for SSD engines when the turbines were consuming HFO or MDO, and a single emission factor value for all LNG-fuelled ships. By contrast, the Fourth IMO GHG Study allocated a specific factor, roughly seven times smaller, for these engine types and fuels.

[22] For example, For an SSD engine generation III the SFC_{base} was given as 175 g/kWh while the SFC_{BE} was set to 195 g/kWh, this gave a ratio of 0.897 which reduced by about 10% any GHG emission except for CO_2.

O Detailed bottom-up results

O.1 Detailed 2012 results

Table 75 - Detailed results for 2012 describing the fleet (international, domestic and fishing) analysed using the bottom-up method

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	634	388	72	4,265	2,087	11.7	191	95	27	9.8	25.8	1.2	0.3	0.1	3.8	3.8
	10000-34999	dwt	2,302	1	0	26,544	6,076	13.9	181	270	25	11.5	8.0	3.1	0.3	0.1	25.6	25.2
	35000-59999	dwt	3,145	0	0	49,436	8,379	14.3	185	282	15	11.8	5.7	4.2	0.4	0.2	47.7	47.0
	60000-99999	dwt	2,375	0	0	77,287	10,115	14.4	210	304	20	12.0	4.4	5.6	0.7	0.3	50	49.2
	100000-199999	dwt	1,277	0	0	167,032	16,362	14.5	241	337	10	11.8	3.0	10.0	0.7	0.3	44.4	43.8
	200000-+	dwt	311	0	0	255,525	20,606	14.5	232	334	3	12.2	2.6	13.1	0.7	0.3	13.9	13.7
Chemical tanker	0-4999	dwt	831	1,906	135	3,742	1,248	12.2	183	41	53	10.1	55.1	1.0	0.3	0.8	8.2	8.1
	5000-9999	dwt	755	11	0	7,348	3,185	13.0	190	223	46	10.9	28.1	1.8	0.8	0.7	7.9	7.8
	10000-19999	dwt	954	0	0	15,080	5,161	13.8	200	259	58	11.9	17.9	3.2	0.8	0.9	14.9	14.6
	20000-39999	dwt	563	0	0	32,497	8,528	14.7	208	289	63	12.6	11.5	5.4	1.2	1.2	13.7	13.5
	40000-+	dwt	836	0	0	48,460	9,448	14.6	200	282	44	12.4	8.3	5.4	1.2	1.2	20.3	20.0
Container	0-999	teu	912	64	1	8,887	5,887	16.3	197	228	49	12.7	24.2	3.1	0.7	0.3	12	11.8
	1000-1999	teu	1,332	0	0	19,595	12,234	19.0	202	284	21	14.1	17.8	5.6	1.5	0.4	31.7	31.2
	2000-2999	teu	689	0	0	35,435	21,559	21.4	214	301	22	15.0	12.1	8.9	1.6	0.6	23.9	23.6
	3000-4999	teu	977	0	0	52,662	35,421	23.3	249	295	29	16.3	11.4	16.5	2.4	0.5	59.8	58.9
	5000-7999	teu	578	0	0	74,426	54,341	24.8	265	309	25	16.6	10.3	23.7	2.5	0.5	48.7	48.0
	8000-11999	teu	363	0	0	108,058	64,912	24.9	272	317	30	16.6	8.5	28.0	2.9	0.5	36	35.5
	12000-14499	teu	107	0	0	151,357	70,696	24.3	266	310	26	16.4	6.6	30.2	3.3	0.5	11.5	11.3
	14500-19999	teu	11	0	0	159,496	78,443	24.6	260	321	69	16.3	4.4	18.4	3.6	0.5	0.8	0.8

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	20000-+	teu	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
General cargo	0-4999	dwt	4,893	4,907	1,611	2,364	1,675	11.1	186	104	62	9.0	24.6	0.8	0.1	0.0	20.8	20.5
	5000-9999	dwt	2,583	253	0	7,034	3,100	12.9	188	238	35	10.2	19.3	1.6	0.3	0.2	16.9	16.7
	10000-19999	dwt	1,124	0	0	13,753	5,562	14.3	191	275	24	11.9	16.9	3.1	0.8	0.2	14.7	14.4
	20000-+	dwt	778	0	0	34,033	9,072	15.2	195	285	25	12.4	9.4	4.9	0.8	0.2	14.6	14.4
Liquefied gas tanker	0-49999	cbm	937	1,116	12	7,619	2,324	13.9	202	91	39	12.1	42.6	2.6	0.4	1.1	13.2	13.0
	50000-99999	cbm	176	0	0	51,692	13,256	16.5	235	322	11	14.3	9.8	9.8	3.0	0.7	7.5	7.4
	100000-199999	cbm	282	0	0	78,648	28,630	19.5	283	338	3	15.5	11.6	26.7	4.5	0.9	29.6	28.2
	200000-+	cbm	45	0	0	121,311	36,751	19.3	253	349	3	17.2	10.8	31.0	11.7	1.7	6.3	6.2
Oil tanker	0-4999	dwt	1,480	4,034	626	3,053	1,174	11.5	139	30	19	9.4	78.0	0.6	0.4	0.7	15.3	15.1
	5000-9999	dwt	659	0	0	6,740	2,790	12.1	147	147	12	9.6	34.4	1.1	0.6	0.8	5.3	5.2
	10000-19999	dwt	227	0	0	14,650	4,657	13.0	144	187	34	10.0	25.5	1.6	1.0	1.4	2.9	2.9
	20000-59999	dwt	706	0	0	42,832	8,538	14.6	176	221	29	11.9	10.4	3.9	1.0	2.8	17.2	16.9
	60000-79999	dwt	399	0	0	72,249	11,963	14.9	202	284	37	12.2	7.0	6.0	1.0	2.8	12.4	12.2
	80000-119999	dwt	893	0	0	107,314	13,423	14.8	201	292	55	11.7	5.0	6.1	1.2	3.0	29	28.6
	120000-199999	dwt	472	0	0	155,325	17,832	15.2	223	315	37	11.8	4.1	8.6	1.8	3.4	20.7	20.4
	200000-+	dwt	586	0	0	306,071	27,252	15.6	254	340	9	12.5	2.7	16.3	1.7	3.0	39	38.4
Other liquids tankers	0-999	dwt	16	97	65	565	615	9.1	79	70	90	7.0	1,586.2	0.1	0.6	2.2	0.9	0.8
	1000-+	dwt	28	72	0	10,280	2,241	13.8	196	51	21	12.1	70.1	4.5	0.9	1.2	0.7	0.7
Ferry-pax only	0-299°	gt	463	2,529	1,459	1,220	1,399	21.3	132	26	95	16.5	1,539.5	0.5	0.3	0.0	5.6	5.5
	300-999°	gt	509	396	0	878	2,426	25.3	135	36	66	18.3	1,083.6	1.0	0.3	0.0	2.2	2.2
	1000-1999°	gt	34	0	0	402	2,421	13.6	132	43	105	9.3	442.8	0.7	0.3	0.0	0.1	0.1

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	2000-+	gt	49	0	0	1,888	6,938	16.3	220	77	40	12.8	121.1	4.3	0.9	0.0	0.8	0.8
Cruise	0-1,999	gt	71	91	68	370	889	12.1	103	80	81	8.6	2,304.9	0.1	0.5	2.1	1.2	1.2
	2000-9999	gt	75	0	0	1,006	3,584	14.0	191	136	38	10.1	269.8	0.8	0.8	1.5	0.7	0.7
	10000-59999	gt	107	0	0	4,086	19,054	19.2	207	242	69	14.0	150.0	5.1	6.4	1.3	4.3	4.3
	60000-99999	gt	91	0	0	8,248	52,017	21.9	264	267	89	15.7	150.9	17.5	20.2	0.9	11.1	10.9
	100000-149999	gt	45	0	0	10,880	70,154	21.5	260	284	57	16.7	142.9	27.3	19.8	0.9	6.8	6.7
	150000-+	gt	6	0	0	13,692	83,552	22.1	268	328	28	16.3	131.2	27.6	19.7	0.8	0.9	0.9
Ferry-RoPax	0-1999°	gt	675	553	371	702	1,540	12.9	154	12	95	10.4	497.1	0.8	0.2	0.5	4.4	4.4
	2000-4999	gt	310	0	0	835	5,986	18.1	159	97	77	12.9	248.7	1.9	0.6	0.5	2.9	2.9
	5000-9999	gt	194	0	0	1,729	13,485	22.7	154	115	84	15.7	255.4	4.4	1.2	0.4	3.7	3.6
	10000-19999	gt	212	0	0	3,927	15,802	20.1	198	157	74	16.1	122.7	9.8	1.9	0.5	8.2	8.1
	20000-+	gt	277	0	0	6,565	28,005	22.5	205	204	150	17.6	112.2	16.3	3.3	0.5	17.6	17.4
Refrigerated bulk	0-1999	dwt	107	411	80	2,210	1,002	12.2	171	67	22	9.4	140.6	0.6	1.0	0.4	1.3	1.2
	2000-5999	dwt	258	0	0	3,885	3,178	14.7	165	302	25	11.4	69.7	1.4	2.1	0.4	3.2	3.2
	6000-9999	dwt	217	0	0	7,576	6,600	17.7	165	331	32	14.3	45.3	3.1	2.8	0.4	4.4	4.3
	10000-+	dwt	199	0	0	12,310	11,276	20.1	226	344	49	17.0	37.0	7.8	5.3	0.3	8.4	8.3
Ro-Ro	0-4999	dwt	443	299	350	1,306	1,931	11.4	148	112	22	9.0	163.4	1.0	0.9	0.5	5.2	5.1
	5000-9999	dwt	208	0	1	7,055	9,084	16.9	198	227	82	13.9	48.6	5.6	1.4	0.4	4.8	4.8
	10000-14999	dwt	138	0	0	12,157	14,716	19.1	207	284	139	14.9	38.1	8.3	1.9	0.5	4.6	4.6
	15000-+	dwt	80	0	0	26,320	19,210	19.1	230	311	117	15.1	22.0	12.8	1.8	0.4	3.8	3.7
Vehicle	0-29999	gt	173	15	0	5,423	7,302	17.4	221	186	66	14.4	54.7	5.4	0.9	0.4	3.7	3.6
	30000-49999	gt	238	0	0	13,950	11,493	19.2	268	317	24	15.2	21.0	8.1	1.0	0.2	7	6.9

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	50000-+	gt	399	0	0	21,492	14,851	19.9	280	316	36	16.1	17.1	11.3	0.9	0.2	15.7	15.4
Yacht	0-+°	gt	1,101	1,834	643	1,011	1,788	16.9	73	90	51	11.0	398.0	0.4	0.0	0.0	2.2	2.2
Service - tug	0-+°	gt	6,561	14,584	8,395	1,010	1,766	11.8	88	32	71	7.4	384.9	0.5	0.2	0.0	29.5	29.0
Miscellaneous - fishing	0-+°	gt	5,391	6,536	11,666	379	1,144	11.6	162	62	74	7.8	314.2	0.4	0.3	0.0	38.4	37.8
Offshore	0-+°	gt	3,651	3,422	830	7,176	2,966	13.3	92	47	99	8.8	150.2	0.9	0.5	0.0	19.3	19.0
Service - other	0-+°	gt	2,465	2,138	1,125	2,522	2,453	13.2	109	49	97	8.3	176.6	0.8	0.4	0.0	11.8	11.6
Miscellaneous - other	0-+°	gt	108	22	54	11,888	16,454	17.5	110	82	109	11.4	27.0	3.6	0.4	0.2	1.6	1.5

* Based on Type 1 and 2 vessels only

° These ship types are classified ‘domestic’ in the vessel-based method to distinguish domestic from international emissions. All other ship types are considered international in that option

O.2 Detailed 2013 results

Table 76 - Detailed results for 2013 describing the fleet (international, domestic and fishing) analysed using the bottom-up method

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	637	399	73	4,403	1,924	11.8	187	86	27	9.8	27.3	1.2	0.3	0.1	3.7	3.7
	10000-34999	dwt	2,287	1	0	26,717	6,013	13.8	178	270	33	11.3	7.7	2.9	0.3	0.1	24.1	23.7
	35000-59999	dwt	3,288	0	0	49,584	8,346	14.3	184	275	21	11.6	5.5	3.9	0.4	0.2	47.3	46.6
	60000-99999	dwt	2,560	0	0	77,614	10,083	14.4	206	304	25	11.7	4.2	5.1	0.7	0.3	49.9	49.1
	100000-199999	dwt	1,256	0	0	167,301	16,552	14.5	240	335	16	11.4	2.9	9.2	0.7	0.3	40.4	39.8
	200000-+	dwt	366	0	0	253,032	20,570	14.6	227	330	4	11.9	2.5	12.0	0.7	0.3	15	14.8
Chemical tanker	0-4999	dwt	895	2,974	134	3,716	1,068	12.2	175	32	51	10.1	61.5	1.0	0.3	0.8	10.5	10.3
	5000-9999	dwt	778	20	0	7,330	3,147	13.0	185	221	47	10.8	28.5	1.7	0.8	0.7	8	7.9
	10000-19999	dwt	963	0	0	15,106	5,159	13.8	195	259	62	11.7	18.3	3.0	0.8	1.0	14.6	14.4
	20000-39999	dwt	565	0	0	32,498	8,504	14.7	207	288	74	12.4	11.6	5.1	1.2	1.2	13.4	13.2
	40000-+	dwt	899	0	0	48,445	9,425	14.6	199	278	58	12.2	8.3	5.1	1.2	1.2	21.2	20.9
Container	0-999	teu	901	64	1	8,801	5,792	16.3	197	216	46	12.6	24.0	3.1	0.7	0.3	11.8	11.6
	1000-1999	teu	1,301	0	0	19,533	12,210	19.0	209	280	26	13.9	17.6	5.6	1.5	0.4	31	30.5
	2000-2999	teu	678	0	0	35,194	21,560	21.4	222	297	21	14.5	11.3	8.3	1.5	0.5	22.2	21.9
	3000-4999	teu	1,004	0	0	52,974	35,165	23.2	244	291	35	15.5	11.0	14.3	2.4	0.5	54.5	53.7
	5000-7999	teu	602	0	0	74,437	53,535	24.7	257	302	31	16.1	10.0	21.2	2.4	0.5	46	45.3
	8000-11999	teu	416	0	0	108,260	63,218	24.6	263	313	32	16.1	8.1	25.0	2.9	0.5	37.5	36.9
	12000-14499	teu	134	0	0	150,536	68,748	24.2	260	310	26	15.8	6.6	27.6	3.3	0.6	13.4	13.1
	14500-19999	teu	18	0	0	172,164	72,790	23.0	221	332	49	16.8	4.5	15.9	3.5	0.7	1.1	1.1
	20000-+	teu	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
General cargo	0-4999	dwt	5,041	5,543	1,592	2,350	1,482	11.1	181	96	59	8.9	24.9	0.8	0.1	0.0	21.4	21.1
	5000-9999	dwt	2,573	7	0	6,985	3,187	12.8	182	257	38	10.0	19.2	1.5	0.3	0.2	15.8	15.5
	10000-19999	dwt	1,116	0	0	13,629	5,464	14.2	189	273	30	11.6	16.8	2.9	0.8	0.2	13.9	13.7
	20000-+	dwt	783	0	0	34,710	9,052	15.1	194	285	32	12.1	9.2	4.6	0.8	0.2	14	13.8
Liquefied gas tanker	0-49999	cbm	979	1,134	10	7,938	2,334	14.0	191	92	38	11.9	43.8	2.3	0.4	1.1	13.5	13.3
	50000-99999	cbm	189	0	0	51,870	13,231	16.5	230	321	17	14.2	9.8	9.4	3.0	0.8	7.9	7.8
	100000-199999	cbm	297	0	0	79,101	29,153	19.5	287	340	3	15.2	11.4	25.7	4.5	0.9	30.4	28.8
	200000-+	cbm	45	0	0	121,311	36,751	19.3	265	359	2	17.1	10.9	32.5	11.7	1.7	6.5	6.4
Oil tanker	0-4999	dwt	1,600	5,344	633	2,995	992	11.4	139	23	17	9.2	75.9	0.6	0.4	0.7	18.8	18.6
	5000-9999	dwt	714	0	0	6,730	2,771	12.1	147	142	13	9.4	34.9	1.0	0.6	0.9	5.7	5.6
	10000-19999	dwt	234	0	0	14,601	4,579	13.0	141	178	33	10.1	25.8	1.6	1.0	1.4	2.9	2.9
	20000-59999	dwt	698	0	0	42,895	8,543	14.6	169	225	32	11.7	10.5	3.6	1.0	2.9	16.5	16.2
	60000-79999	dwt	398	0	0	72,420	11,972	14.9	191	284	58	12.0	7.1	5.5	1.0	3.0	12	11.8
	80000-119999	dwt	893	0	0	107,585	13,461	14.8	198	288	65	11.4	5.0	5.7	1.2	3.0	28.1	27.7
	120000-199999	dwt	489	0	0	155,384	17,857	15.2	220	308	53	11.4	4.1	7.9	1.8	3.6	20.6	20.3
	200000-+	dwt	613	0	0	306,655	27,367	15.6	247	340	10	12.0	2.7	14.5	1.7	3.2	37.7	37.1
Other liquids tankers	0-999	dwt	17	194	64	2,099	816	9.8	93	43	64	7.6	2,241.8	0.2	0.6	2.1	1	1.0
	1000-+	dwt	31	68	0	9,986	2,219	14.0	164	62	23	12.0	98.0	3.9	0.9	1.5	0.7	0.7
Ferry-pax only	0-299°	gt	509	4,381	1,453	2,335	1,219	20.4	127	19	97	17.0	1,625.7	0.5	0.3	0.0	6.5	6.4
	300-999°	gt	533	0	0	102	3,339	26.8	131	57	74	17.9	1,130.5	0.9	0.3	0.0	2.1	2.0
	1000-1999°	gt	35	0	0	417	2,452	13.2	117	42	132	8.6	417.8	0.6	0.3	0.0	0.1	0.1

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	2000-+	gt	50	0	0	1,866	6,776	16.3	201	85	45	12.4	140.3	3.6	0.9	0.0	0.7	0.7
Cruise	0-1999	gt	83	161	64	1,593	861	12.4	103	54	100	8.6	2,943.6	0.1	0.5	2.1	1.3	1.3
	2000-9999	gt	86	0	0	984	3,502	14.0	177	140	37	9.8	330.6	0.7	0.8	1.6	0.8	0.8
	10000-59999	gt	102	0	0	4,017	19,081	19.2	215	231	57	13.8	145.4	5.2	6.4	1.3	4.2	4.1
	60000-99999	gt	92	0	0	8,243	51,843	21.9	263	273	100	15.3	148.2	16.1	20.2	0.9	10.8	10.7
	100000-149999	gt	49	0	0	10,956	69,705	21.4	259	289	77	16.4	133.4	25.4	19.8	0.9	7.2	7.1
	150000-+	gt	6	0	0	13,692	83,552	22.1	290	333	43	16.4	128.3	30.4	19.7	0.7	1	0.9
Ferry-RoPax	0-1999°	gt	778	667	365	926	1,476	12.9	147	12	98	10.2	539.1	0.7	0.2	0.5	4.7	4.6
	2000-4999	gt	329	0	0	829	5,654	17.6	148	78	95	12.9	262.3	1.9	0.6	0.5	3.1	3.0
	5000-9999	gt	196	0	0	1,752	13,529	22.7	156	100	94	15.4	231.7	4.3	1.2	0.4	3.7	3.6
	10000-19999	gt	215	0	0	3,865	16,079	20.4	186	161	78	16.1	127.5	8.9	1.9	0.6	7.7	7.6
	20000-+	gt	278	0	0	6,449	28,048	22.6	199	204	152	17.4	112.1	15.3	3.3	0.5	16.9	16.6
Refrigerated bulk	0-1999	dwt	108	583	79	1,712	791	12.3	152	59	19	9.2	170.2	0.5	1.0	0.5	1.4	1.4
	2000-5999	dwt	247	0	0	3,886	3,176	14.7	160	304	20	11.5	78.0	1.4	2.1	0.4	3.1	3.1
	6000-9999	dwt	185	0	0	7,483	6,446	17.6	185	321	34	14.5	43.8	3.6	2.8	0.4	4	3.9
	10000-+	dwt	189	0	0	12,380	11,297	20.1	236	340	50	16.7	36.4	8.0	5.3	0.3	8.1	8.0
Ro-Ro	0-4999	dwt	523	583	354	1,294	1,714	11.3	130	89	24	8.8	221.1	0.8	0.9	0.5	5.6	5.5
	5000-9999	dwt	202	0	2	7,043	9,118	16.9	198	219	75	13.5	46.5	5.2	1.4	0.4	4.5	4.4
	10000-14999	dwt	134	0	0	12,117	15,062	19.3	215	278	136	15.1	37.0	8.8	1.9	0.5	4.7	4.7
	15000-+	dwt	86	0	0	26,133	19,160	19.0	199	297	138	15.3	22.9	11.4	1.8	0.5	3.7	3.7
Vehicle	0-29999	gt	169	6	0	5,316	7,451	17.4	221	187	69	14.2	54.6	5.3	0.9	0.4	3.5	3.5
	30000-49999	gt	233	0	0	13,906	11,511	19.3	264	313	35	14.9	21.1	7.6	1.0	0.3	6.5	6.4

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	50000-+	gt	416	0	0	21,372	14,826	19.9	274	314	44	15.7	16.9	10.5	0.9	0.2	15.3	15.1
Yacht	0-+°	gt	1,232	3,214	621	900	1,480	17.0	69	67	68	11.0	404.1	0.4	0.0	0.0	2.6	2.6
Service - tug	0-+°	gt	7,329	26,964	8,770	1,052	1,418	11.8	82	24	88	7.3	397.0	0.5	0.2	0.0	32.7	32.2
Miscellaneous - fishing	0-+°	gt	6,177	8,485	11,419	379	1,085	11.6	156	57	87	7.7	335.3	0.4	0.3	0.0	38.9	38.3
Offshore	0-+°	gt	4,159	6,365	796	6,387	2,401	13.4	87	37	121	8.7	149.9	0.8	0.5	0.0	20.6	20.2
Service - other	0-+°	gt	2,711	3,931	1,106	2,491	2,052	13.3	98	39	99	8.2	191.3	0.7	0.4	0.0	12.2	12.0
Miscellaneous - other	0-+°	gt	105	20	55	10,986	15,017	17.1	99	75	124	11.4	26.5	3.6	0.3	0.2	1.5	1.5

* Based on Type 1 and 2 vessels only.

° These ship types are classified ‘domestic’ in the vessel-based method to distinguish domestic from international emissions. All other ship types are considered international in that option

O.3 Detailed 2014 results

Table 77 - Detailed results for 2014 describing the fleet (international, domestic and fishing) analysed using the bottom-up method

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	659	512	73	4,200	1,932	11.7	178	71	25	9.7	27.5	1.1	0.3	0.1	3.8	3.7
	10000-34999	dwt	2,210	4	0	26,851	5,965	13.8	173	265	37	11.2	7.6	2.8	0.3	0.1	22.3	21.9
	35000-59999	dwt	3,364	0	0	49,574	8,291	14.3	181	275	26	11.4	5.4	3.7	0.4	0.2	46.4	45.7
	60000-99999	dwt	2,766	0	0	77,352	10,005	14.4	204	306	29	11.5	4.2	4.9	0.7	0.3	51.9	51.1
	100000-199999	dwt	1,282	0	0	167,792	16,611	14.5	242	339	13	11.1	2.7	8.8	0.7	0.3	39.4	38.8
	200000-+	dwt	396	0	0	251,615	20,498	14.6	241	341	4	11.7	2.4	12.1	0.7	0.3	16.3	16.1
Chemical tanker	0-4999	dwt	933	3,414	135	3,564	1,049	12.1	166	29	49	9.9	64.5	0.9	0.3	0.9	11.8	11.7
	5000-9999	dwt	794	22	0	7,327	3,139	13.0	178	214	46	10.6	29.3	1.6	0.8	0.7	8	7.9
	10000-19999	dwt	975	0	0	15,132	5,157	13.8	188	261	60	11.6	18.5	2.8	0.8	1.0	14.4	14.2
	20000-39999	dwt	581	0	0	32,628	8,503	14.7	201	287	74	12.2	11.5	4.8	1.2	1.3	13.4	13.1
	40000-+	dwt	975	0	0	48,386	9,283	14.6	196	277	58	12.1	8.3	4.8	1.2	1.3	22.5	22.2
Container	0-999	teu	888	69	1	8,764	5,778	16.3	196	207	46	12.4	24.2	2.9	0.7	0.3	11.2	11.0
	1000-1999	teu	1,277	0	0	19,321	12,198	19.0	206	277	28	13.7	17.7	5.2	1.5	0.4	29	28.6
	2000-2999	teu	672	0	0	35,069	21,514	21.4	221	295	21	14.1	11.0	7.8	1.5	0.5	21	20.7
	3000-4999	teu	970	0	0	53,211	35,273	23.2	249	292	34	14.9	10.3	13.2	2.4	0.5	49.1	48.3
	5000-7999	teu	618	0	0	74,244	52,887	24.6	256	300	32	15.6	9.6	19.6	2.4	0.5	44.1	43.5
	8000-11999	teu	477	0	0	108,988	61,438	24.4	254	310	35	15.9	8.0	23.7	2.9	0.6	41.1	40.4
	12000-14499	teu	160	0	0	150,392	66,882	24.0	260	318	30	15.9	6.5	27.4	3.3	0.6	15.8	15.6
	14500-19999	teu	36	0	0	178,947	64,038	21.2	210	331	40	15.8	4.9	16.0	3.5	0.9	2.3	2.3
	20000-+	teu	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
General cargo	0-4999	dwt	4,930	6,315	1,587	2,386	1,598	11.1	175	87	59	8.9	25.2	0.7	0.1	0.0	22.4	22.0
	5000-9999	dwt	2,497	6	0	6,992	3,167	12.8	179	253	38	10.0	19.4	1.4	0.3	0.2	15	14.8
	10000-19999	dwt	1,084	0	0	13,573	5,447	14.1	186	270	33	11.5	16.9	2.8	0.8	0.2	13.1	12.9
	20000-+	dwt	799	0	0	35,206	9,044	15.1	194	277	38	11.9	9.0	4.5	0.8	0.2	14	13.8

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Liquefied gas tanker	0-49999	cbm	1,003	1,224	10	8,190	2,278	14.0	178	94	39	11.9	46.8	2.2	0.4	1.2	14.1	13.9
	50000-99999	cbm	199	0	0	51,969	13,142	16.5	234	323	18	14.5	10.0	10.0	3.0	0.8	8.7	8.5
	100000-199999	cbm	328	0	0	79,996	29,752	19.5	279	333	4	14.8	10.7	22.8	4.5	1.0	30.7	28.9
	200000-+	cbm	45	0	0	121,311	36,751	19.3	260	355	1	16.9	10.5	30.9	11.7	1.7	6.3	6.2
Oil tanker	0-4999	dwt	1,672	5,852	642	3,354	994	11.4	130	24	15	9.2	82.5	0.6	0.4	0.7	20.8	20.6
	5000-9999	dwt	718	0	0	6,737	2,767	12.1	133	141	12	9.5	36.8	0.9	0.6	0.9	5.6	5.5
	10000-19999	dwt	228	0	0	14,563	4,575	13.0	143	179	32	10.0	25.8	1.6	1.0	1.4	2.9	2.8
	20000-59999	dwt	679	0	0	43,072	8,557	14.6	164	226	34	11.5	10.7	3.4	1.0	3.0	15.9	15.7
	60000-79999	dwt	404	0	0	72,419	11,948	14.9	190	286	53	11.8	7.1	5.3	1.0	3.1	12	11.9
	80000-119999	dwt	888	0	0	107,830	13,481	14.8	193	290	63	11.3	5.1	5.4	1.2	3.3	27.9	27.5
	120000-199999	dwt	496	0	0	155,424	17,843	15.2	216	306	46	11.4	4.1	7.7	1.8	3.6	20.5	20.2
	200000-+	dwt	614	0	0	307,626	27,509	15.6	248	340	9	11.8	2.6	14.0	1.7	3.2	36.6	36.1
Other liquids tankers	0-999	dwt	21	277	65	1,051	747	9.8	93	37	62	8.2	1,875.2	0.1	0.6	2.0	1.2	1.2
	1000-+	dwt	29	60	0	12,921	2,393	13.8	167	67	22	12.3	93.3	4.2	0.9	1.5	0.7	0.7
Ferry-pax only	0-299°	gt	551	5,227	1,443	2,194	1,245	20.1	121	16	102	16.3	1,681.0	0.5	0.3	0.0	7.3	7.2
	300-999°	gt	550	0	0	105	3,352	26.7	125	61	75	17.6	1,212.8	0.9	0.3	0.0	2.2	2.1
	1000-1999°	gt	36	0	0	418	2,453	13.5	118	38	123	9.4	394.8	0.6	0.3	0.0	0.1	0.1
	2000-+	gt	50	0	0	1,881	6,835	16.3	195	78	38	12.4	128.5	3.5	0.9	0.0	0.7	0.7
Cruise	0-1999	gt	84	175	66	1,465	931	12.5	113	59	107	8.5	2,886.7	0.1	0.4	2.1	1.3	1.3
	2000-9999	gt	91	0	0	941	3,375	13.8	175	135	46	9.7	375.7	0.7	0.8	1.6	0.9	0.9
	10000-59999	gt	103	0	0	3,975	19,083	19.1	206	238	69	13.6	154.6	4.9	6.4	1.4	4.1	4.1
	60000-99999	gt	93	0	0	8,239	51,771	21.9	263	276	104	15.0	148.7	15.0	20.2	0.9	10.6	10.5
	100000-149999	gt	52	0	0	10,999	69,517	21.4	261	285	85	16.0	132.4	24.5	19.8	0.9	7.4	7.3
	150000-+	gt	7	0	0	13,450	80,016	22.1	263	331	58	16.4	126.4	27.3	19.7	0.9	1.1	1.0
Ferry-RoPax	0-1999°	gt	849	934	356	1,076	1,451	13.0	147	11	95	10.1	561.6	0.7	0.2	0.5	5.2	5.1
	2000-4999	gt	349	0	0	829	5,691	17.6	154	66	90	12.6	267.5	2.0	0.6	0.5	3.3	3.3
	5000-9999	gt	200	0	0	1,784	12,975	22.4	147	89	95	15.3	248.6	4.0	1.2	0.5	3.6	3.5
	10000-19999	gt	213	0	0	3,854	16,392	20.5	185	144	80	16.3	132.1	9.1	1.9	0.6	7.8	7.7

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	20000-+	gt	274	0	0	6,365	28,185	22.6	203	207	151	17.4	110.3	15.6	3.3	0.5	16.9	16.6
Refrigerated bulk	0-1999	dwt	105	664	80	3,077	889	12.2	137	29	18	9.5	168.9	0.4	1.0	0.5	1.5	1.5
	2000-5999	dwt	247	0	0	3,876	3,159	14.6	157	299	20	11.4	73.6	1.3	2.1	0.4	3	3.0
	6000-9999	dwt	181	0	0	7,496	6,428	17.6	186	324	29	14.5	43.8	3.6	2.8	0.4	3.9	3.8
	10000-+	dwt	186	0	0	12,391	11,301	20.1	230	343	56	16.5	36.3	7.5	5.3	0.3	7.7	7.6
Ro-Ro	0-4999	dwt	551	666	368	1,297	1,842	11.2	128	77	23	8.6	225.2	0.7	0.9	0.5	6	5.9
	5000-9999	dwt	191	0	2	6,975	9,185	17.0	194	211	81	13.8	45.4	5.5	1.4	0.4	4.4	4.3
	10000-14999	dwt	129	0	0	12,142	15,483	19.5	206	275	137	15.1	38.0	8.5	1.9	0.5	4.5	4.4
	15000-+	dwt	84	0	0	25,830	18,991	19.0	206	292	160	15.1	22.2	11.7	1.8	0.5	3.7	3.7
Vehicle	0-29999	gt	167	8	0	5,305	7,450	17.5	219	188	68	14.0	54.7	5.1	0.9	0.4	3.4	3.3
	30000-49999	gt	228	0	0	13,862	11,539	19.3	261	309	36	14.7	20.8	7.3	1.0	0.3	6.2	6.1
	50000-+	gt	436	0	0	21,286	14,742	19.9	271	313	46	15.6	16.5	10.0	0.9	0.2	15.5	15.2
Yacht	0-+°	gt	1,324	3,891	611	788	1,415	16.8	71	61	71	11.1	424.3	0.4	0.0	0.0	3.2	3.1
Service - tug	0-+°	gt	8,018	32,011	9,073	1,045	1,363	11.8	79	23	83	7.2	420.1	0.4	0.2	0.0	34.9	34.3
Miscellaneous - fishing	0-+°	gt	6,690	12,021	11,289	453	1,046	11.7	156	52	83	7.8	330.3	0.4	0.3	0.0	40.8	40.2
Offshore	0-+°	gt	4,633	7,710	807	5,605	2,402	13.5	81	35	122	8.7	154.2	0.8	0.5	0.0	22.8	22.4
Service - other	0-+°	gt	2,838	4,630	1,130	2,738	1,964	13.4	93	36	97	8.2	207.3	0.7	0.4	0.0	12.6	12.4
Miscellaneous - other	0-+°	gt	118	7	52	12,669	20,127	18.0	81	77	161	11.4	32.0	3.1	0.3	0.2	1.5	1.5

* Based on Type 1 and 2 vessels only.

° These ship types are classified ‘domestic’ in the vessel-based method to distinguish domestic from international emissions. All other ship types are considered international in that option

0.4 Detailed 2015 results

Table 78 - Detailed results for 2015 describing the fleet (international, domestic and fishing) analysed using the bottom-up method.

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	679	547	73	4,237	2,028	11.7	167	70	22	9.6	28.1	1.0	0.3	0.1	3.8	3.7
	10000-34999	dwt	2,210	3	0	26,992	5,965	13.8	171	263	36	11.2	7.5	2.7	0.3	0.1	22.1	21.7
	35000-59999	dwt	3,431	0	0	49,450	8,228	14.3	180	276	24	11.5	5.5	3.7	0.4	0.2	47.3	46.5
	60000-99999	dwt	3,068	0	0	76,676	9,889	14.4	202	302	25	11.5	4.2	4.8	0.7	0.4	56.5	55.6
	100000-199999	dwt	1,333	0	0	168,285	16,590	14.5	236	337	11	11.0	2.7	8.4	0.7	0.3	39.3	38.7
	200000-+	dwt	428	0	0	249,629	20,286	14.6	247	341	3	11.8	2.4	12.5	0.7	0.3	18.3	18.0
Chemical tanker	0-4999	dwt	930	3,414	136	3,478	1,059	12.2	167	29	50	9.9	65.8	0.9	0.3	0.9	12.8	12.7
	5000-9999	dwt	796	12	0	7,307	3,154	12.9	184	230	45	10.6	29.1	1.7	0.8	0.7	8.1	8.0
	10000-19999	dwt	995	0	0	15,226	5,150	13.8	186	261	59	11.7	18.7	2.9	0.8	1.0	14.9	14.6
	20000-39999	dwt	620	0	0	32,814	8,397	14.7	197	282	72	12.3	11.8	4.8	1.2	1.3	14.3	14.1
	40000-+	dwt	1,084	0	0	48,423	9,115	14.6	195	279	55	12.1	8.2	4.8	1.2	1.3	25.2	24.8
Container	0-999	teu	866	82	1	8,616	5,633	16.2	193	198	43	12.2	24.3	2.8	0.7	0.4	10.6	10.4
	1000-1999	teu	1,285	0	0	19,245	12,160	19.0	208	277	27	13.6	17.5	5.3	1.5	0.4	29.3	28.9
	2000-2999	teu	670	0	0	34,875	21,341	21.3	221	290	22	14.0	11.1	7.5	1.5	0.5	20.4	20.1
	3000-4999	teu	928	0	0	53,017	35,082	23.2	253	288	33	14.8	10.1	13.1	2.4	0.5	46.6	45.9
	5000-7999	teu	621	0	0	74,235	52,646	24.6	257	294	37	15.4	9.5	18.8	2.5	0.5	42.7	42.1
	8000-11999	teu	545	0	0	109,374	59,597	24.2	244	311	35	15.7	7.8	21.7	2.9	0.6	43.5	42.8
	12000-14499	teu	176	0	0	149,965	65,348	24.0	253	309	35	16.0	6.5	26.8	3.3	0.6	17.1	16.8
	14500-19999	teu	64	0	0	182,365	61,829	20.3	210	320	44	16.9	5.6	22.2	3.6	0.8	5.4	5.3
	20000-+	teu	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
General cargo	0-4999	dwt	4,945	5,970	1,555	2,274	1,630	11.1	169	87	56	8.9	25.6	0.7	0.1	0.0	21.7	21.3
	5000-9999	dwt	2,410	20	0	6,983	3,142	12.8	176	253	38	9.9	19.3	1.4	0.3	0.2	14.2	14.0
	10000-19999	dwt	1,066	0	0	13,500	5,406	14.1	185	276	35	11.6	17.0	2.8	0.8	0.2	13.1	12.9
	20000-+	dwt	807	0	0	35,842	9,093	15.1	195	278	38	12.1	8.9	4.6	0.8	0.2	14.3	14.1

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Liquefied gas tanker	0-49999	cbm	1,023	1,158	11	7,586	2,365	14.0	175	99	40	12.0	45.7	2.2	0.4	1.3	14.7	14.5
	50000-99999	cbm	230	0	0	52,327	12,949	16.5	228	324	18	14.7	10.0	9.7	3.0	0.9	9.8	9.7
	100000-199999	cbm	350	0	0	80,966	30,101	19.4	242	332	4	14.7	11.0	19.7	4.4	1.2	29.5	27.5
	200000-+	cbm	45	0	0	121,311	36,751	19.3	254	356	2	16.7	10.5	29.3	11.7	1.7	6.1	6.0
Oil tanker	0-4999	dwt	1,694	5,523	642	3,325	1,028	11.4	130	23	15	9.1	86.2	0.6	0.4	0.7	21.9	21.6
	5000-9999	dwt	711	0	0	6,732	2,771	12.1	139	140	10	9.4	37.1	1.0	0.6	0.9	5.7	5.6
	10000-19999	dwt	227	0	0	14,618	4,524	12.9	139	187	28	9.9	26.2	1.5	1.0	1.4	2.8	2.7
	20000-59999	dwt	660	0	0	43,198	8,619	14.6	165	225	29	11.6	10.9	3.5	1.0	3.1	15.8	15.6
	60000-79999	dwt	400	0	0	72,595	11,986	14.9	187	288	50	12.0	7.4	5.6	1.0	3.1	12.1	12.0
	80000-119999	dwt	900	0	0	108,205	13,509	14.8	189	293	63	11.5	5.4	5.7	1.2	3.4	29.4	29.0
	120000-199999	dwt	499	0	0	155,462	17,851	15.2	211	310	43	11.7	4.3	8.1	1.9	4.0	22.1	21.8
	200000-+	dwt	628	0	0	307,504	27,439	15.6	243	339	8	12.4	2.8	15.7	1.8	3.4	41.3	40.6
Other liquids tankers	0-999	dwt	23	306	62	1,210	750	9.8	79	30	47	7.5	1,716.1	0.1	0.6	2.1	1.3	1.3
	1000-+	dwt	29	55	0	11,134	2,547	13.7	172	74	27	12.1	112.9	4.3	0.9	1.5	0.7	0.7
Ferry-pax only	0-299°	gt	591	5,919	1,423	2,830	1,240	19.8	119	15	106	15.4	1,686.2	0.4	0.3	0.0	7.3	7.2
	300-999°	gt	590	0	0	100	3,294	26.5	127	57	69	18.0	1,301.5	1.0	0.3	0.0	2.5	2.4
	1000-1999°	gt	44	0	0	440	2,434	13.7	110	30	108	9.5	371.4	0.5	0.3	0.0	0.1	0.1
	2000-+	gt	52	0	0	1,875	6,844	16.3	191	75	40	12.7	140.3	3.6	0.9	0.0	0.7	0.7
Cruise	0-1999	gt	92	205	62	1,765	980	12.3	109	42	94	8.3	2,985.9	0.1	0.4	2.1	1.3	1.3
	2000-9999	gt	92	0	0	896	3,330	13.7	159	146	60	9.7	420.0	0.6	0.8	1.7	0.9	0.9
	10000-59999	gt	99	0	0	3,934	19,086	19.0	213	231	68	13.5	151.4	5.1	6.4	1.3	4	3.9
	60000-99999	gt	95	0	0	8,249	51,688	21.8	253	276	93	15.2	155.1	15.5	20.3	1.0	11.1	10.9
	100000-149999	gt	54	0	0	10,927	69,142	21.3	263	290	85	15.9	138.6	24.8	20.0	0.9	7.8	7.7
	150000-+	gt	9	0	0	13,094	77,301	22.1	251	330	70	16.4	119.7	24.8	19.8	1.0	1.3	1.3
Ferry-RoPax	0-1999°	gt	896	984	360	1,270	1,455	13.2	141	12	94	10.0	571.5	0.7	0.2	0.5	5.4	5.3
	2000-4999	gt	355	0	0	836	5,751	17.6	150	61	91	12.3	280.4	1.8	0.6	0.5	3.3	3.2
	5000-9999	gt	210	0	0	1,847	12,690	22.2	142	92	93	15.3	253.4	4.1	1.2	0.5	3.9	3.8
	10000-19999	gt	216	0	0	3,857	15,846	20.3	168	146	85	16.1	144.5	8.3	1.9	0.6	7.4	7.3

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	20000-+	gt	275	0	0	6,382	28,202	22.6	200	205	149	17.4	112.4	15.5	3.3	0.5	16.9	16.6
Refrigerated bulk	0-1999	dwt	95	693	82	1,774	911	12.2	155	31	23	9.3	158.5	0.5	1.0	0.5	1.7	1.7
	2000-5999	dwt	232	0	0	3,960	3,205	14.7	149	301	21	11.4	73.9	1.3	2.1	0.5	2.8	2.8
	6000-9999	dwt	181	0	0	7,465	6,354	17.5	179	326	21	14.2	45.1	3.3	2.8	0.4	3.7	3.7
	10000-+	dwt	179	0	0	12,431	11,241	20.1	230	342	48	16.5	36.4	7.6	5.3	0.3	7.5	7.4
Ro-Ro	0-4999	dwt	595	732	377	1,277	1,785	11.2	125	72	23	8.6	242.9	0.7	0.9	0.5	6.4	6.3
	5000-9999	dwt	189	0	2	7,030	9,448	17.3	193	207	86	14.1	47.5	5.8	1.4	0.4	4.6	4.5
	10000-14999	dwt	125	0	0	12,118	15,669	19.5	223	271	137	15.2	39.2	9.5	1.9	0.5	4.7	4.6
	15000-+	dwt	86	0	0	27,284	19,536	19.2	205	300	151	15.3	21.9	11.7	1.8	0.5	3.8	3.8
Vehicle	0-29999	gt	165	8	0	5,224	7,425	17.4	212	183	67	14.0	54.7	4.9	0.9	0.4	3.3	3.2
	30000-49999	gt	225	0	0	13,852	11,551	19.3	255	305	36	14.8	21.3	7.3	1.0	0.3	6.1	6.0
	50000-+	gt	451	0	0	21,144	14,646	19.9	273	308	46	15.6	16.6	10.3	0.9	0.2	16.4	16.2
Yacht	0-+°	gt	1,431	3,995	600	1,138	1,427	16.8	65	61	67	11.2	448.0	0.4	0.0	0.0	3.5	3.5
Service - tug	0-+°	gt	8,473	31,193	9,124	1,072	1,410	11.9	75	24	80	7.1	451.2	0.4	0.2	0.0	35.8	35.3
Miscellaneous - fishing	0-+°	gt	7,484	12,163	10,971	436	1,058	11.7	155	53	81	7.7	332.3	0.4	0.3	0.0	42.4	41.7
Offshore	0-+°	gt	4,799	7,362	798	5,287	2,538	13.6	76	37	118	8.6	167.4	0.6	0.5	0.0	21.8	21.4
Service - other	0-+°	gt	2,972	4,321	1,134	2,511	2,058	13.5	91	39	92	8.5	226.3	0.7	0.4	0.0	13.4	13.2
Miscellaneous - other	0-+°	gt	125	20	54	12,100	17,815	18.0	87	78	149	11.1	33.2	2.8	0.3	0.2	1.5	1.5

* Based on Type 1 and 2 vessels only.

° These ship types are classified ‘domestic’ in the vessel-based method to distinguish domestic from international emissions. All other ship types are considered international in that option

O.5 Detailed 2016 results

Table 79 - Detailed results for 2016 describing the fleet (international, domestic and fishing) analysed using the bottom-up method

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	682	535	70	4,263	1,987	11.8	167	72	21	9.6	27.2	1.0	0.3	0.1	3.7	3.7
	10000-34999	dwt	2,151	0	0	27,094	5,961	13.8	173	263	34	11.2	7.5	2.8	0.3	0.1	21.7	21.4
	35000-59999	dwt	3,448	0	0	49,543	8,208	14.3	180	278	23	11.5	5.5	3.7	0.4	0.2	47.5	46.8
	60000-99999	dwt	3,262	0	0	76,270	9,806	14.4	207	304	25	11.6	4.2	4.9	0.7	0.3	61.3	60.4
	100000-199999	dwt	1,323	0	0	169,151	16,630	14.5	243	335	10	11.1	2.7	8.7	0.7	0.3	40.3	39.6
	200000-+	dwt	468	0	0	246,600	20,008	14.6	246	333	3	11.9	2.4	12.8	0.7	0.3	20.4	20.1
Chemical tanker	0-4999	dwt	981	3,792	134	3,707	1,030	12.2	162	26	48	9.9	68.8	0.9	0.3	0.9	13.6	13.4
	5000-9999	dwt	798	16	0	7,285	3,135	12.9	183	236	46	10.6	29.2	1.7	0.8	0.7	8.2	8.0
	10000-19999	dwt	1,018	0	0	15,288	5,141	13.8	187	263	57	11.7	18.5	2.9	0.8	1.0	15.2	15.0
	20000-39999	dwt	664	0	0	32,701	8,261	14.7	197	287	69	12.5	11.9	4.9	1.2	1.3	15.5	15.3
	40000-+	dwt	1,180	0	0	48,543	8,999	14.6	195	278	54	12.3	8.2	5.0	1.2	1.3	27.9	27.5
Container	0-999	teu	857	109	1	8,605	5,509	16.1	191	185	42	12.2	24.3	2.7	0.7	0.4	10.4	10.3
	1000-1999	teu	1,293	0	0	19,154	12,119	19.0	206	277	28	13.7	17.6	5.2	1.5	0.4	29.4	29.0
	2000-2999	teu	677	0	0	34,681	21,010	21.2	214	287	21	14.1	11.5	7.6	1.5	0.6	20.8	20.5
	3000-4999	teu	906	0	0	53,007	35,133	23.2	242	287	31	14.8	10.4	12.6	2.4	0.5	44.4	43.7
	5000-7999	teu	618	0	0	74,280	52,597	24.6	246	292	32	15.5	9.6	18.1	2.5	0.6	41.3	40.7
	8000-11999	teu	582	0	0	109,836	58,665	24.0	249	307	32	16.1	8.1	23.9	2.9	0.6	50.6	49.8
	12000-14499	teu	187	0	0	149,826	64,498	23.9	251	308	35	16.3	6.7	28.5	3.3	0.6	19.2	18.9
	14500-19999	teu	81	0	0	183,338	61,417	20.0	241	315	50	17.1	5.9	27.9	3.6	0.7	8.3	8.1
	20000-+	teu	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
General cargo	0-4999	dwt	4,957	6,147	1,539	2,252	1,604	11.1	169	84	55	8.9	25.6	0.7	0.1	0.0	21.4	21.1
	5000-9999	dwt	2,381	9	0	6,979	3,146	12.8	177	252	39	9.8	19.2	1.4	0.3	0.2	13.9	13.7

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	10000-19999	dwt	1,075	0	0	13,477	5,347	14.0	188	277	38	11.6	17.1	2.9	0.8	0.2	13.5	13.2
	20000-+	dwt	820	0	0	36,023	9,150	15.0	198	281	37	12.1	8.8	4.7	0.8	0.2	14.9	14.7
Liquefied gas tanker	0-49999	cbm	1,042	1,189	11	8,104	2,414	14.1	178	99	41	12.0	43.6	2.3	0.4	1.2	15.2	14.9
	50000-99999	cbm	279	0	0	52,736	12,838	16.4	231	330	19	14.5	9.8	9.6	3.0	0.8	11.8	11.6
	100000-199999	cbm	362	0	0	82,024	30,762	19.2	248	333	5	14.5	10.7	19.7	4.4	1.1	30.9	28.5
	200000-+	cbm	46	0	0	121,977	36,735	19.2	229	353	3	16.1	10.7	24.4	11.8	1.8	5.5	5.4
Oil tanker	0-4999	dwt	1,715	5,714	648	3,235	1,010	11.4	128	21	15	9.1	89.1	0.6	0.4	0.7	22.2	21.9
	5000-9999	dwt	731	0	0	6,735	2,755	12.0	138	141	10	9.3	37.2	0.9	0.6	0.9	5.7	5.6
	10000-19999	dwt	231	0	0	14,662	4,529	13.0	132	166	21	10.1	27.6	1.5	1.0	1.4	2.8	2.8
	20000-59999	dwt	647	0	0	43,352	8,742	14.6	161	224	29	11.6	11.0	3.5	1.0	3.1	15.6	15.3
	60000-79999	dwt	412	0	0	72,703	11,930	14.9	192	289	46	12.2	7.1	5.9	1.0	3.0	12.8	12.6
	80000-119999	dwt	952	0	0	108,433	13,397	14.8	188	293	65	11.6	5.4	5.7	1.2	3.4	30.9	30.5
	120000-199999	dwt	529	0	0	155,550	17,716	15.2	207	312	42	11.8	4.4	8.2	1.9	4.0	23.6	23.3
	200000-+	dwt	680	0	0	307,677	27,298	15.6	239	340	10	12.5	2.9	15.9	1.8	3.6	45.9	45.2
Other liquids tankers	0-999	dwt	22	288	63	1,229	686	9.7	87	30	48	7.6	1,513.3	0.2	0.7	2.1	1.2	1.2
	1000-+	dwt	25	26	0	12,262	3,654	14.2	193	109	34	12.4	95.2	5.1	0.9	1.4	0.6	0.6
Ferry-pax only	0-299°	gt	615	6,893	1,405	3,130	1,224	19.8	119	12	112	15.5	1,826.8	0.4	0.3	0.0	7.7	7.5
	300-999°	gt	608	0	0	100	3,248	26.3	128	45	71	18.7	1,284.2	1.1	0.3	0.0	2.7	2.6
	1000-1999°	gt	47	0	0	412	2,492	13.8	124	34	93	9.1	362.5	0.6	0.3	0.0	0.1	0.1
	2000-+	gt	52	0	0	1,886	6,836	16.4	183	79	37	12.9	184.0	3.7	0.9	0.0	0.8	0.7
Cruise	0-1999	gt	91	237	61	1,956	890	12.4	109	45	103	8.3	2,931.7	0.1	0.4	2.2	1.4	1.4
	2000-9999	gt	96	0	0	863	3,243	13.7	162	145	62	9.5	486.7	0.6	0.8	1.7	0.9	0.9
	10000-59999	gt	101	0	0	4,043	19,339	19.0	210	225	62	13.7	154.2	5.2	6.4	1.4	4.1	4.1
	60000-99999	gt	96	0	0	8,245	51,620	21.8	257	273	92	15.2	154.5	15.9	20.4	1.0	11.3	11.1
	100000-149999	gt	55	0	0	11,015	68,779	21.3	259	297	87	16.2	133.7	25.8	20.0	1.0	8.1	8.0
	150000-+	gt	12	0	0	13,788	76,626	22.3	256	338	63	16.0	112.2	24.3	20.0	1.0	1.7	1.7

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Ferry-RoPax	0-1999°	gt	957	1,177	348	1,504	1,452	13.0	139	10	94	9.9	599.9	0.7	0.2	0.5	5.7	5.6
	2000-4999	gt	375	0	0	851	5,656	17.4	149	69	90	12.3	273.4	1.8	0.6	0.5	3.5	3.4
	5000-9999	gt	211	0	0	1,838	12,788	22.2	141	80	92	14.9	248.2	4.0	1.2	0.5	3.8	3.7
	10000-19999	gt	216	0	0	3,901	15,882	20.3	177	139	84	15.9	135.4	8.3	1.9	0.6	7.4	7.3
	20000-+	gt	278	0	0	6,367	28,244	22.6	206	199	146	17.4	113.0	16.1	3.3	0.5	17.6	17.3
Refrigerated bulk	0-1999	dwt	92	787	82	2,152	878	12.1	151	34	26	9.3	171.0	0.5	1.0	0.5	1.7	1.6
	2000-5999	dwt	227	0	0	3,964	3,201	14.7	139	301	25	11.5	74.4	1.2	2.1	0.5	2.7	2.7
	6000-9999	dwt	181	0	0	7,468	6,347	17.5	155	328	27	14.2	49.8	2.9	2.8	0.5	3.5	3.5
	10000-+	dwt	175	0	0	12,456	11,323	20.1	230	344	49	16.4	36.5	7.6	5.3	0.3	7.3	7.2
Ro-Ro	0-4999	dwt	607	793	382	1,258	1,853	11.2	118	59	23	8.6	259.2	0.7	0.9	0.5	6.6	6.5
	5000-9999	dwt	190	0	2	7,033	9,455	17.3	198	198	87	14.2	47.9	6.1	1.4	0.4	4.8	4.7
	10000-14999	dwt	125	0	0	12,152	15,785	19.5	222	267	137	15.6	39.3	10.2	1.9	0.5	5	4.9
	15000-+	dwt	86	0	0	28,544	19,632	19.1	212	296	138	15.0	17.5	11.4	1.8	0.5	3.7	3.7
Vehicle	0-29999	gt	167	8	0	5,264	7,314	17.4	210	176	63	13.9	54.3	4.8	0.9	0.4	3.2	3.2
	30000-49999	gt	221	0	0	13,687	11,559	19.3	240	304	31	14.7	21.9	6.8	1.0	0.3	5.7	5.6
	50000-+	gt	464	0	0	21,061	14,592	19.9	273	306	46	15.6	16.6	10.2	0.9	0.2	16.8	16.5
Yacht	0-+°	gt	1,514	4,758	583	974	1,348	16.8	66	53	72	11.0	453.1	0.4	0.0	0.0	3.6	3.6
Service - tug	0-+°	gt	8,645	37,435	9,022	1,050	1,302	11.9	73	21	81	7.0	481.2	0.4	0.2	0.0	36.2	35.6
Miscellaneous - fishing	0-+°	gt	8,436	14,025	10,105	462	1,032	11.7	161	46	94	7.6	360.9	0.4	0.3	0.0	44.1	43.4
Offshore	0-+°	gt	4,477	7,954	825	5,325	2,411	13.8	70	34	115	8.6	189.2	0.6	0.5	0.0	19.9	19.6
Service - other	0-+°	gt	3,010	5,048	1,120	2,521	1,954	13.5	88	34	90	8.4	233.5	0.7	0.4	0.0	13.3	13.1
Miscellaneous - other	0-+°	gt	126	30	53	11,935	17,079	18.2	86	119	154	11.3	34.0	2.8	0.3	0.2	1.5	1.5

* Based on Type 1 and 2 vessels only. ° These ship types are classified 'domestic' in the vessel-based method to distinguish domestic from international emissions. All other ship types are considered international in that option

0.6 Detailed 2017 results

Table 80 - Detailed results for 2017 describing the fleet (international, domestic and fishing) analysed using the bottom-up method.

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	697	659	69	4,230	1,752	11.8	180	65	20	9.6	25.8	1.1	0.3	0.1	4	4.0
	10000-34999	dwt	2,073	0	0	27,153	5,947	13.8	181	256	34	11.1	7.4	2.9	0.3	0.1	21.5	21.2
	35000-59999	dwt	3,437	0	0	49,511	8,192	14.3	186	272	24	11.4	5.4	3.8	0.4	0.2	47.9	47.2
	60000-99999	dwt	3,332	0	0	76,161	9,763	14.4	218	304	28	11.5	4.1	5.1	0.7	0.3	64.3	63.4
	100000-199999	dwt	1,260	0	0	169,505	16,706	14.5	255	334	11	11.3	2.7	9.5	0.7	0.2	41.6	41.0
	200000-+	dwt	492	0	0	246,204	19,925	14.6	257	333	2	11.9	2.4	13.2	0.7	0.2	21.9	21.6
Chemical tanker	0-4999	dwt	1,030	4,607	129	3,615	981	12.2	173	22	44	9.8	64.4	0.9	0.3	0.8	15	14.8
	5000-9999	dwt	820	15	0	7,289	3,123	12.9	186	221	47	10.5	28.5	1.7	0.8	0.7	8.3	8.1
	10000-19999	dwt	1,045	0	0	15,290	5,120	13.8	195	253	56	11.6	17.7	2.9	0.8	1.0	15.5	15.2
	20000-39999	dwt	690	0	0	32,613	8,154	14.7	201	282	60	12.3	11.3	4.8	1.2	1.3	15.8	15.6
	40000-+	dwt	1,241	0	0	48,716	8,947	14.6	203	277	56	12.1	7.8	4.9	1.2	1.2	28.6	28.2
Container	0-999	teu	864	132	1	8,514	5,324	16.1	198	173	43	12.1	23.9	2.8	0.7	0.3	10.6	10.4
	1000-1999	teu	1,303	0	0	19,141	12,093	19.0	214	272	30	13.6	17.2	5.3	1.5	0.4	30	29.5
	2000-2999	teu	661	0	0	34,767	20,851	21.2	226	274	22	14.2	11.2	8.2	1.5	0.5	21.4	21.1
	3000-4999	teu	854	0	0	52,598	34,782	23.2	244	278	28	14.7	10.4	12.6	2.4	0.5	41.8	41.1
	5000-7999	teu	582	0	0	74,512	52,548	24.6	252	284	38	15.9	10.1	20.4	2.4	0.6	43.1	42.5
	8000-11999	teu	609	0	0	110,376	58,143	24.0	256	305	36	16.4	8.3	25.9	2.9	0.6	56.7	55.8
	12000-14499	teu	204	0	0	149,472	62,923	23.8	258	308	31	16.4	6.8	29.5	3.3	0.6	21.5	21.2
	14500-19999	teu	95	0	0	181,175	60,532	20.1	246	313	52	16.8	5.7	28.3	3.7	0.6	9.8	9.7
	20000-+	teu	19	0	0	192,050	60,681	20.4	191	329	16	15.2	5.2	12.8	3.4	1.0	1	1.0
General cargo	0-4999	dwt	4,917	6,609	1,508	2,190	1,427	11.1	174	75	54	8.9	25.3	0.7	0.1	0.0	22.3	21.9
	5000-9999	dwt	2,319	0	0	6,971	3,146	12.8	180	245	41	9.9	18.9	1.4	0.3	0.2	13.7	13.5
	10000-19999	dwt	1,074	0	0	13,488	5,323	14.0	196	274	36	11.5	16.7	2.9	0.8	0.2	13.5	13.3
	20000-+	dwt	812	0	0	36,516	9,225	15.0	201	278	38	12.0	8.6	4.7	0.8	0.2	14.7	14.5

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Liquefied gas tanker	0-49999	cbm	1,093	1,539	11	8,829	2,244	14.1	189	88	40	11.9	39.5	2.3	0.4	1.1	16.1	15.8
	50000-99999	cbm	301	0	0	52,939	12,828	16.4	231	324	21	14.3	9.5	9.3	2.9	0.8	12.4	12.2
	100000-199999	cbm	395	0	0	82,910	30,955	19.2	261	337	6	14.7	10.5	21.2	4.4	1.1	35.8	32.7
	200000-+	cbm	46	0	0	121,977	36,735	19.2	246	358	4	15.9	10.1	25.0	11.7	1.8	5.6	5.5
Oil tanker	0-4999	dwt	1,754	7,042	646	3,156	936	11.4	138	19	13	9.0	80.4	0.6	0.4	0.7	24.5	24.1
	5000-9999	dwt	759	0	0	6,765	2,754	12.1	143	136	11	9.2	35.9	0.9	0.6	0.8	5.8	5.7
	10000-19999	dwt	233	0	0	14,692	4,516	12.9	146	163	21	9.9	24.3	1.6	0.9	1.3	2.9	2.8
	20000-59999	dwt	646	0	0	43,358	8,866	14.6	167	208	26	11.5	10.6	3.6	1.0	2.8	15.2	14.9
	60000-79999	dwt	424	0	0	72,717	11,880	14.9	199	289	42	11.9	6.8	5.7	1.0	2.9	12.7	12.6
	80000-119999	dwt	1,005	0	0	108,757	13,316	14.8	195	293	63	11.4	5.1	5.6	1.2	3.2	31.8	31.4
	120000-199999	dwt	581	0	0	155,718	17,470	15.1	212	313	40	11.6	4.3	8.1	1.9	3.8	25.3	24.9
	200000-+	dwt	729	0	0	307,496	27,141	15.6	249	342	11	12.1	2.7	15.3	1.7	3.2	46.6	45.9
Other liquids tankers	0-999	dwt	23	374	65	1,871	758	9.6	90	29	33	7.8	1,555.5	0.2	0.7	2.1	1.4	1.4
	1000-+	dwt	27	63	0	12,066	2,366	13.8	188	55	30	11.6	99.5	4.7	0.9	1.3	0.7	0.7
Ferry-pax only	0-299°	gt	638	8,074	1,407	3,995	1,144	19.4	139	11	107	15.1	1,456.8	0.4	0.3	0.0	8.1	8.0
	300-999°	gt	648	0	0	102	3,172	26.0	145	50	68	16.8	1,046.0	0.8	0.3	0.0	2.3	2.3
	1000-1999°	gt	46	0	0	390	2,538	14.0	135	30	87	9.3	293.1	0.6	0.3	0.0	0.1	0.1
	2000-+	gt	56	0	0	1,719	6,364	15.9	177	80	42	12.5	194.9	3.1	0.9	0.0	0.7	0.7
Cruise	0-1999	gt	100	363	59	2,418	896	12.6	97	33	84	8.4	3,196.8	0.1	0.4	2.2	1.5	1.5
	2000-9999	gt	105	0	0	858	3,270	13.8	154	118	59	9.5	500.6	0.6	0.8	1.7	1	1.0
	10000-59999	gt	96	0	0	4,021	19,491	19.2	214	230	63	13.7	151.9	5.3	6.4	1.3	3.9	3.9
	60000-99999	gt	94	0	0	8,177	51,107	21.8	261	271	92	15.3	152.3	16.1	20.3	0.9	11.1	10.9
	100000-149999	gt	57	0	0	11,004	68,219	21.2	262	291	88	16.1	135.4	25.5	20.0	0.9	8.4	8.2
	150000-+	gt	15	0	0	13,701	74,579	22.3	257	301	48	15.7	112.8	23.4	20.0	1.1	2.1	2.1
Ferry-RoPax	0-1999°	gt	1,014	1,405	351	1,800	1,382	12.9	150	9	92	9.5	497.8	0.6	0.2	0.5	5.7	5.7
	2000-4999	gt	386	0	0	843	5,612	17.3	158	52	90	12.0	268.5	1.9	0.6	0.5	3.5	3.5
	5000-9999	gt	220	0	0	1,886	12,356	21.9	152	85	96	14.5	226.1	3.8	1.2	0.5	3.9	3.8
	10000-19999	gt	229	0	0	3,927	15,887	20.3	187	125	79	15.6	125.9	8.4	1.9	0.6	7.9	7.7

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	20000-+	gt	276	0	0	6,373	28,292	22.6	223	197	144	17.1	104.2	16.7	3.3	0.5	17.9	17.6
Refrigerated bulk	0-1999	dwt	94	1,067	78	2,121	799	12.0	159	34	24	9.2	171.9	0.5	1.0	0.4	1.9	1.9
	2000-5999	dwt	225	0	0	3,996	3,245	14.8	148	290	24	11.2	73.2	1.2	2.1	0.5	2.7	2.7
	6000-9999	dwt	178	0	0	7,485	6,334	17.5	153	316	21	14.0	49.6	2.7	2.8	0.5	3.4	3.3
	10000-+	dwt	174	0	0	12,506	11,423	20.1	215	338	47	16.3	37.7	7.0	5.3	0.3	6.9	6.8
Ro-Ro	0-4999	dwt	637	1,130	384	1,399	1,597	11.2	128	45	22	8.4	241.9	0.7	0.9	0.5	6.9	6.8
	5000-9999	dwt	200	0	2	6,993	9,830	17.5	203	185	78	14.3	50.1	6.3	1.5	0.4	5.2	5.1
	10000-14999	dwt	131	0	0	12,118	15,712	19.5	231	260	139	15.3	38.6	10.4	1.9	0.4	5.3	5.2
	15000-+	dwt	88	0	0	28,121	19,487	19.1	214	295	146	15.1	19.3	11.7	1.8	0.5	3.9	3.8
Vehicle	0-29999	gt	171	4	0	5,271	7,365	17.3	220	178	60	13.8	51.7	4.9	0.9	0.4	3.4	3.3
	30000-49999	gt	201	0	0	13,673	11,747	19.4	251	298	36	14.9	21.7	7.2	1.0	0.3	5.4	5.3
	50000-+	gt	480	0	0	21,035	14,551	19.9	277	305	46	15.6	16.6	10.5	0.9	0.2	17.7	17.4
Yacht	0-+°	gt	1,593	7,177	553	1,162	1,128	16.8	76	41	71	10.8	418.3	0.4	0.0	0.0	4.6	4.5
Service - tug	0-+°	gt	8,769	55,381	8,918	1,139	1,095	11.9	77	15	80	6.8	456.1	0.4	0.2	0.0	40.1	39.4
Miscellaneous - fishing	0-+°	gt	8,986	15,662	9,904	497	997	11.7	164	44	92	7.6	312.9	0.3	0.3	0.0	40.5	39.8
Offshore	0-+°	gt	4,290	11,182	838	4,901	2,039	13.9	75	26	110	8.5	168.1	0.6	0.5	0.0	20.2	19.9
Service - other	0-+°	gt	3,121	7,594	1,135	2,761	1,660	13.5	93	27	87	8.2	217.5	0.6	0.4	0.0	14	13.8
Miscellaneous - other	0-+°	gt	124	53	56	11,192	13,841	17.7	89	72	140	11.5	28.3	2.2	0.3	0.2	1.2	1.2

* Based on type 1 and 2 vessels only.

° These ship types are classified 'domestic' in the vessel-based method to distinguish domestic from international emissions. All other ship types are considered international in that option

0.7 Detailed 2018 results

Table 81 - Detailed results for 2018 describing the fleet (international, domestic and fishing) analysed using the bottom-up method

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Bulk carrier	0-9999	dwt	696	680	70	4,271	1,796	11.8	178	56	19	9.3	25.5	1.0	0.3	0.1	3.8	3.7
	10000-34999	dwt	2,014	0	0	27,303	5,941	13.8	177	255	34	11.0	7.3	2.8	0.3	0.1	20.3	20.0
	35000-59999	dwt	3,391	0	0	49,487	8,177	14.3	184	266	25	11.4	5.4	3.7	0.4	0.2	46.4	45.7
	60000-99999	dwt	3,409	0	0	76,147	9,748	14.4	214	302	30	11.4	4.1	4.9	0.7	0.3	63.9	63.0
	100000-199999	dwt	1,242	0	0	169,868	16,741	14.5	252	334	13	11.2	2.7	9.2	0.7	0.2	39.6	39.0
	200000-+	dwt	516	0	0	251,667	20,094	14.6	258	336	3	11.8	2.3	12.7	0.7	0.2	22.3	22.0
Chemical tanker	0-4999	dwt	1,032	4,908	127	4,080	987	12.2	168	21	46	9.6	65.7	0.8	0.3	0.9	15.0	14.8
	5000-9999	dwt	844	18	0	7,276	3,109	12.9	185	217	50	10.3	28.7	1.6	0.8	0.7	8.2	8.1
	10000-19999	dwt	1,088	0	0	15,324	5,101	13.8	190	249	57	11.4	17.9	2.7	0.8	1.0	15.6	15.3
	20000-39999	dwt	706	0	0	32,492	8,107	14.7	202	280	63	12.1	11.1	4.5	1.2	1.3	15.6	15.3
	40000-+	dwt	1,289	0	0	48,796	8,929	14.6	201	274	55	11.9	7.7	4.7	1.2	1.2	28.7	28.2
Container	0-999	teu	861	165	1	8,438	5,077	16.0	196	163	43	11.8	23.9	2.6	0.7	0.4	10.2	10.0
	1000-1999	teu	1,271	0	0	19,051	12,083	19.0	210	270	30	13.4	17.2	5.1	1.5	0.4	28.5	28.0
	2000-2999	teu	668	0	0	34,894	20,630	21.1	220	275	24	14.2	11.4	7.9	1.5	0.6	21.2	20.9
	3000-4999	teu	815	0	0	52,372	34,559	23.1	246	271	29	14.7	10.3	12.7	2.4	0.5	40.1	39.4
	5000-7999	teu	561	0	0	74,661	52,566	24.6	258	280	39	15.7	9.8	20.3	2.4	0.5	41.3	40.7
	8000-11999	teu	623	0	0	110,782	57,901	23.9	261	301	38	16.3	8.3	26.4	2.9	0.5	58.8	57.9
	12000-14499	teu	227	0	0	149,023	61,231	23.8	246	297	33	16.3	6.8	27.2	3.3	0.6	22.3	22.0
	14500-19999	teu	101	0	0	179,871	60,202	20.2	250	309	51	16.5	5.4	26.7	3.7	0.6	9.9	9.7
	20000-+	teu	44	0	0	195,615	60,210	20.3	210	292	43	16.3	5.3	21.0	3.6	0.9	3.5	3.5
General cargo	0-4999	dwt	4,880	6,926	1,490	2,104	1,454	11.1	170	71	55	8.8	24.3	0.6	0.1	0.0	19.2	18.9
	5000-9999	dwt	2,245	0	0	6,985	3,150	12.7	176	238	44	9.8	19.1	1.4	0.3	0.2	13.0	12.8
	10000-19999	dwt	1,054	0	0	13,423	5,280	14.0	192	267	39	11.4	16.8	2.8	0.8	0.2	12.9	12.7
	20000-+	dwt	793	0	0	36,980	9,189	15.0	197	269	38	11.9	8.5	4.5	0.8	0.2	14.0	13.7

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
Liquefied gas tanker	0-49999	cbm	1,085	1,589	11	8,603	2,236	14.2	190	87	42	11.7	38.0	2.4	0.4	1.1	16.1	15.8
	50000-99999	cbm	308	0	0	52,974	12,832	16.4	229	324	22	14.1	9.3	8.9	3.0	0.8	12.3	12.1
	100000-199999	cbm	436	0	0	83,661	30,996	19.0	271	339	8	14.9	10.3	22.2	4.4	1.0	41.3	37.5
	200000-+	cbm	46	0	0	121,977	36,735	19.2	252	364	5	16.0	10.3	26.3	11.7	1.9	5.8	5.7
Oil tanker	0-4999	dwt	1,734	7,310	648	3,158	966	11.4	135	17	14	8.7	79.5	0.5	0.4	0.7	23.5	23.2
	5000-9999	dwt	779	0	0	6,789	2,761	12.1	142	136	11	9.1	36.7	0.9	0.6	0.9	6.0	5.9
	10000-19999	dwt	235	0	0	14,733	4,417	12.9	136	149	18	9.8	24.3	1.4	0.9	1.4	2.8	2.8
	20000-59999	dwt	615	0	0	43,750	8,975	14.6	166	202	26	11.2	10.6	3.4	1.0	2.8	14.0	13.8
	60000-79999	dwt	429	0	0	72,826	11,837	14.8	194	278	45	11.6	6.7	5.2	1.0	2.8	12.2	12.1
	80000-119999	dwt	1,029	0	0	109,262	13,319	14.8	195	289	61	11.2	4.9	5.4	1.2	3.1	31.5	31.1
	120000-199999	dwt	597	0	0	155,878	17,446	15.1	220	313	44	11.4	4.1	8.0	1.8	3.5	25.1	24.7
	200000-+	dwt	755	0	0	307,866	27,159	15.5	252	342	10	11.9	2.6	14.5	1.7	3.1	46.0	45.3
Other liquids tankers	0-999	dwt	26	443	64	3,450	687	9.6	98	8	30	7.5	1,577.8	0.1	0.6	2.1	1.5	1.5
	1000-+	dwt	27	79	0	10,813	2,034	13.6	207	59	37	11.6	82.9	4.8	0.9	1.2	0.7	0.7
Ferry-pax only	0-299°	gt	663	8,607	1,410	4,034	1,152	19.3	162	11	104	14.1	1,280.2	0.4	0.3	0.0	8.6	8.4
	300-999°	gt	666	0	0	102	3,182	26.2	161	53	70	14.7	926.9	0.7	0.3	0.0	2.1	2.1
	1000-1999°	gt	51	0	0	354	2,623	14.5	135	38	88	9.3	314.0	0.6	0.3	0.0	0.1	0.1
	2000-+	gt	55	0	0	1,730	6,539	16.2	199	77	28	12.4	169.0	3.5	0.9	0.0	0.8	0.8
Cruise	0-1999	gt	126	641	45	3,115	911	12.7	93	17	74	8.1	3,770.5	0.1	0.4	2.2	1.7	1.7
	2000-9999	gt	110	0	0	867	3,232	13.8	148	109	63	9.2	513.4	0.5	0.8	1.8	1.1	1.1
	10000-59999	gt	105	0	0	4,018	19,378	19.0	206	232	63	13.4	147.3	5.0	6.4	1.4	4.3	4.2
	60000-99999	gt	98	0	0	8,249	51,518	21.8	256	272	94	15.3	155.2	16.1	20.3	1.0	11.6	11.4
	100000-149999	gt	61	0	0	10,935	67,456	21.3	250	295	96	16.0	140.5	24.4	20.0	1.0	8.8	8.6
	150000-+	gt	21	0	0	13,499	73,442	22.0	236	301	58	16.4	109.6	23.2	19.8	1.2	2.9	2.9
Ferry-RoPax	0-1999°	gt	1,040	1,474	340	2,720	1,383	13.0	165	9	95	9.0	458.1	0.6	0.2	0.5	5.7	5.6
	2000-4999	gt	400	0	0	832	5,668	17.4	167	64	94	11.4	257.3	1.8	0.6	0.4	3.5	3.5
	5000-9999	gt	227	0	0	1,891	12,024	21.6	155	83	88	13.2	205.0	3.2	1.2	0.5	3.5	3.4
	10000-19999	gt	231	0	0	3,952	15,780	20.3	190	124	80	15.1	123.0	7.9	1.9	0.6	7.6	7.5

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea *	Avg. days international *	Avg. days in SECA *	Avg. SOG at sea *	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4									Main	Aux.	Boiler		
	20000-+	gt	282	0	0	6,364	28,255	22.6	219	203	145	16.5	105.1	15.2	3.3	0.5	17.1	16.7
Refrigerated bulk	0-1999	dwt	93	1,201	77	2,409	793	12.1	147	29	22	9.1	175.8	0.4	1.0	0.5	1.9	1.9
	2000-5999	dwt	213	0	0	3,986	3,223	14.7	149	284	24	11.1	76.1	1.2	2.1	0.5	2.6	2.5
	6000-9999	dwt	182	0	0	7,476	6,206	17.4	150	313	16	13.6	48.2	2.6	2.8	0.5	3.4	3.3
	10000-+	dwt	157	0	0	12,612	11,505	20.2	218	340	51	16.3	37.1	7.1	5.3	0.3	6.3	6.2
Ro-Ro	0-4999	dwt	615	1,175	384	1,406	1,618	11.2	129	56	24	8.1	226.2	0.7	0.9	0.5	6.8	6.7
	5000-9999	dwt	200	0	2	6,955	9,909	17.6	201	183	73	14.2	50.7	6.1	1.4	0.4	5.0	4.9
	10000-14999	dwt	135	0	0	12,101	15,939	19.6	218	264	137	15.5	39.3	10.0	1.9	0.5	5.3	5.2
	15000-+	dwt	89	0	0	27,488	19,505	19.1	199	299	171	15.2	22.4	11.1	1.8	0.5	3.8	3.7
Vehicle	0-29999	gt	168	7	0	5,151	7,264	17.3	213	167	63	13.6	53.9	4.6	0.9	0.4	3.2	3.1
	30000-49999	gt	189	0	0	13,571	11,831	19.4	254	297	36	14.7	21.8	7.1	1.0	0.3	5.0	4.9
	50000-+	gt	487	0	0	20,947	14,588	19.9	281	309	47	15.5	16.4	10.4	0.9	0.2	17.8	17.5
Yacht	0-+°	gt	1,665	7,914	542	1,077	1,116	16.7	78	36	64	10.7	405.8	0.4	0.0	0.0	4.9	4.9
Service - tug	0-+°	gt	8,805	58,478	8,983	1,218	1,086	11.9	80	14	82	6.6	422.7	0.3	0.2	0.0	41.0	40.3
Miscellaneous - fishing	0-+°	gt	9,140	17,583	9,807	468	983	11.7	164	42	89	7.5	304.3	0.3	0.3	0.0	40.7	40.0
Offshore	0-+°	gt	4,322	11,696	875	4,765	2,010	13.9	80	25	111	8.5	152.8	0.6	0.5	0.0	20.9	20.5
Service - other	0-+°	gt	3,157	8,104	1,158	2,496	1,620	13.6	96	25	90	8.1	205.3	0.6	0.4	0.0	14.3	14.1
Miscellaneous - other	0-+°	gt	138	55	56	11,496	15,301	18.2	102	70	154	10.7	31.6	2.1	0.4	0.2	1.3	1.3

* Based on type 1 and 2 vessels only.

° These ship types are classified 'domestic' in the vessel-based method to distinguish domestic from international emissions. All other ship types are considered international in that option

O.8 Detailed species-specific results

Table 82 - Bottom-up CO_2 emissions estimates (million tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	848	837	836	859	894	929	919
	Domestic navigation	76	82	88	90	89	95	97
	Fishing	38	38	40	42	43	40	40
2	International shipping	701	684	681	700	727	746	740
	Domestic navigation	223	235	243	249	256	278	276
	Fishing	38	38	40	42	43	40	40
	Total bottom-up estimate	962	957	964	991	1,026	1,064	1,056

Table 83 - Bottom-up CH_4 emissions estimates (tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	59,083	66,117	76,379	81,143	98,968	124,351	147,849
	Domestic navigation	3,054	3,405	4,419	3,714	3,733	3,793	5,104
	Fishing	641	651	683	711	743	680	685
2	International shipping	54,732	60,882	69,001	73,794	91,852	115,878	139,800
	Domestic navigation	7,405	8,640	11,797	11,063	10,849	12,265	13,154
	Fishing	641	651	683	711	743	680	685
	Total bottom-up estimate	62,778	70,173	81,481	85,569	103,444	128,824	153,639

Table 84 - Bottom-up N_2O emissions estimates (tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	46,551	45,942	45,935	47,346	49,344	51,397	50,871
	Domestic navigation	4,360	4,744	5,158	5,273	5,246	5,619	5,776
	Fishing	2,230	2,272	2,385	2,481	2,579	2,388	2,409
2	International shipping	38,615	37,716	37,666	38,806	40,396	41,506	41,222
	Domestic navigation	12,296	12,970	13,427	13,814	14,195	15,510	15,425
	Fishing	2,230	2,272	2,385	2,481	2,579	2,388	2,409
	Total bottom-up estimate	53,141	52,958	53,478	55,101	57,169	59,405	59,056

Table 85 - Bottom-up SO_x emissions estimates (thousand tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	10,765	10,072	10,086	10,010	11,055	11,553	11,358
	Domestic navigation	153	142	141	104	106	108	98
	Fishing	39	37	38	27	29	27	24
2	International shipping	9,145	8,549	8,576	8,563	9,455	9,781	9,626
	Domestic navigation	1,772	1,666	1,652	1,552	1,706	1,880	1,829
	Fishing	39	37	38	27	29	27	24
	Total bottom-up estimate	10,956	10,252	10,265	10,142	11,190	11,687	11,480

Table 86 - Bottom-up NO_x emissions estimates (thousand tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	19,662	18,931	18,594	19,192	19,945	20,700	20,163
	Domestic navigation	1,496	1,585	1,699	1,716	1,692	1,787	1,810
	Fishing	755	763	797	830	866	782	781
2	International shipping	16,860	16,114	15,858	16,363	16,992	17,414	17,056
	Domestic navigation	4,298	4,403	4,434	4,544	4,644	5,073	4,918
	Fishing	755	763	797	830	866	782	781
	Total bottom-up estimate	**21,912**	**21,280**	**21,089**	**21,737**	**22,502**	**23,269**	**22,754**

Table 87 - Bottom-up PM10 emissions estimates (thousand tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	1,660	1,584	1,580	1,556	1,678	1,753	1,727
	Domestic navigation	37	37	39	35	35	37	36
	Fishing	13	13	14	14	14	13	13
2	International shipping	1,418	1,349	1,349	1,336	1,440	1,488	1,468
	Domestic navigation	279	272	270	255	273	302	295
	Fishing	13	13	14	14	14	13	13
	Total bottom-up estimate	**1,710**	**1,635**	**1,633**	**1,604**	**1,727**	**1,803**	**1,776**

Table 88 - Bottom-up $PM_{2.5}$ emissions estimates (thousand tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	1,527	1,458	1,454	1,431	1,544	1,613	1,589
	Domestic navigation	34	34	36	32	32	34	33
	Fishing	12	12	13	12	13	12	12
2	International shipping	1,304	1,241	1,241	1,229	1,325	1,369	1,351
	Domestic navigation	257	250	249	235	251	278	271
	Fishing	12	12	13	12	13	12	12
	Total bottom-up estimate	**1,573**	**1,504**	**1,502**	**1,476**	**1,589**	**1,658**	**1,634**

Table 89 - Bottom-up CO emissions estimates (thousand tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	742	730	729	755	791	832	829
	Domestic navigation	68	73	80	81	81	87	89
	Fishing	34	35	36	38	40	36	36
2	International shipping	628	613	613	634	664	690	692
	Domestic navigation	183	191	197	202	207	229	226
	Fishing	34	35	36	38	40	36	36
	Total bottom-up estimate	**844**	**838**	**846**	**874**	**911**	**955**	**954**

Table 90 - Bottom-up VOC emissions estimates (thousand tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	790	773	768	796	833	872	861
	Domestic navigation	63	68	74	75	74	80	82
	Fishing	31	31	33	34	36	32	32
2	International shipping	674	655	653	677	707	730	725
	Domestic navigation	179	186	190	195	200	222	218
	Fishing	31	31	33	34	36	32	32
	Total bottom-up estimate	**884**	**872**	**875**	**905**	**942**	**984**	**976**

Table 91 - Bottom-up BC emissions estimates (tonnes)

	Fleet sector	2012	2013	2014	2015	2016	2017	2018
1	International shipping	73,226	74,008	75,086	74,659	76,967	79,411	79,374
	Domestic navigation	10,111	11,284	12,263	12,717	12,733	14,129	14,788
	Fishing	5,594	5,760	6,046	6,219	6,422	6,159	6,226
2	International shipping	58,923	59,097	59,802	59,298	60,805	61,868	61,622
	Domestic navigation	24,413	26,195	27,546	28,077	28,895	31,673	32,540
	Fishing	5,594	5,760	6,046	6,219	6,422	6,159	6,226
	Total bottom-up estimate	**88,931**	**91,051**	**93,395**	**93,595**	**96,123**	**99,699**	**100,389**

P EU MRV 2018 Validation Statistics

This appendix provides more insight into the validation undertaken against the EU MRV dataset for 2018 on a vessel type and size basis. All of these plots have been obtained following the filtering and corrections as described in Section 2.7.1.

In the boxplots provided, the black solid box represents the 25-75% interquartile range including the median, the black dashed lines represent the whiskers reaching to the minimum and maximum values and the red dashed line represents the mean value. Outliers have been omitted for clarity. The numbers above the x axis represent the sample size for the particular vessel size.

The metrics presented include primary variables such as sailing time, cargo and distance sailed as well as derived metrics:

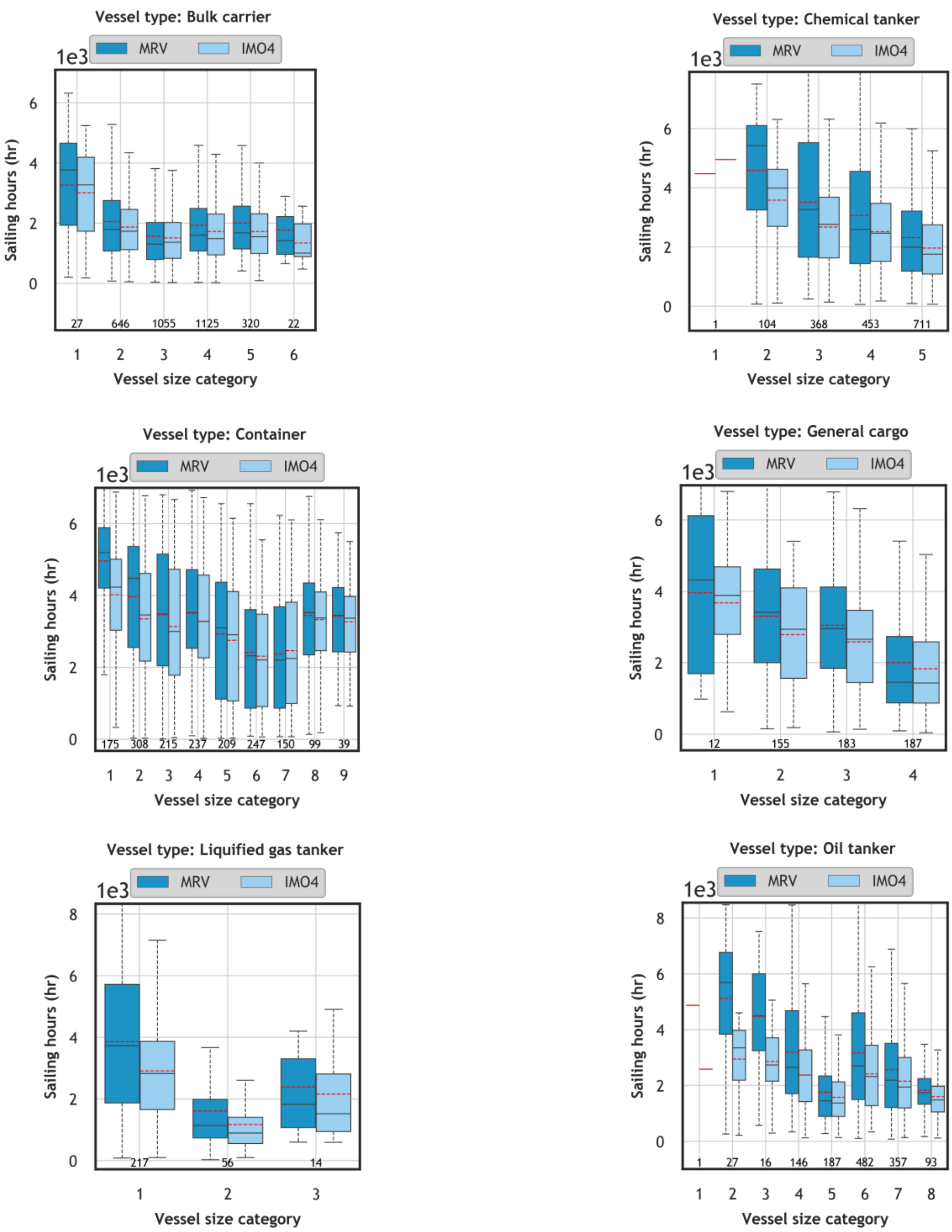
- temporal carbon intensity (gCO_2/hr);
- distance carbon intensity (gCO_2/nm);
- AER (gCO_2/DWTnm);
- EEOI (gCO_2/tnm).

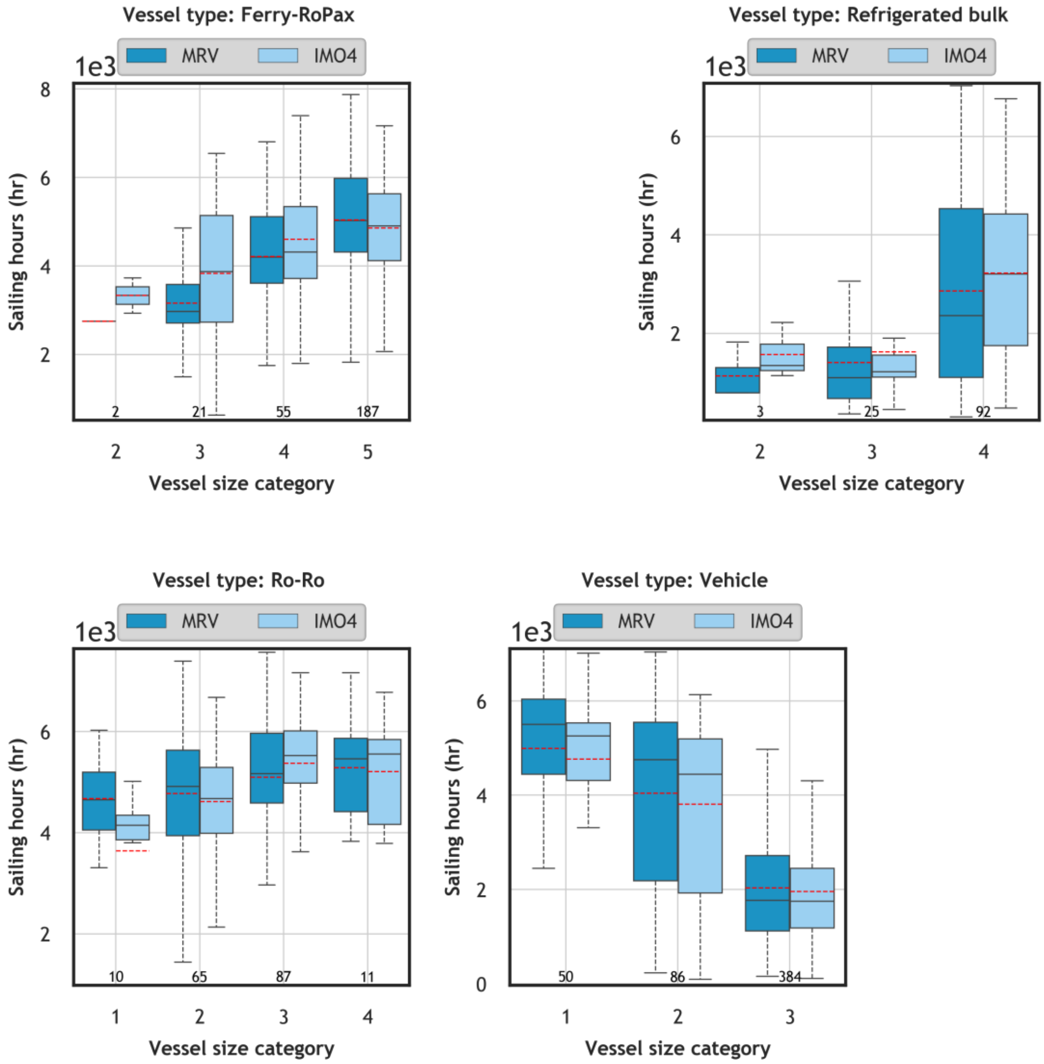
Vessel types with less than ten vessels have been omitted as the sample size is judged not to be representative.

P.1 Sailing hours

As discussed in Section 2.7.1 the definition of what falls under the purview of the MRV regulation is different to what is considered in the BU model leading to an underestimation of sailing time captured. The variation is captured by the similar whiskers in both datasets.

Figure 70 - Box plot sailing hours comparison by vessel type and size



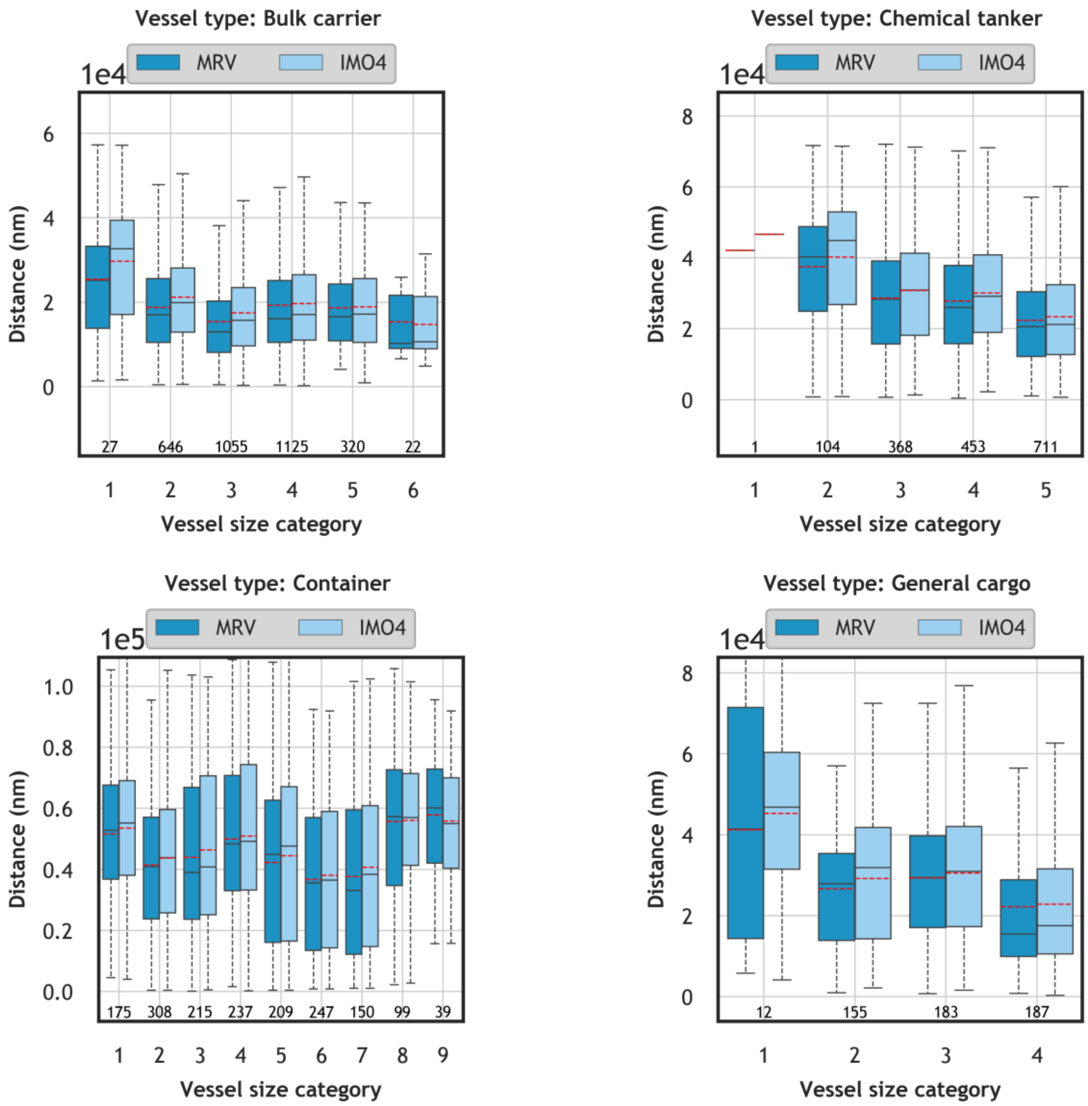


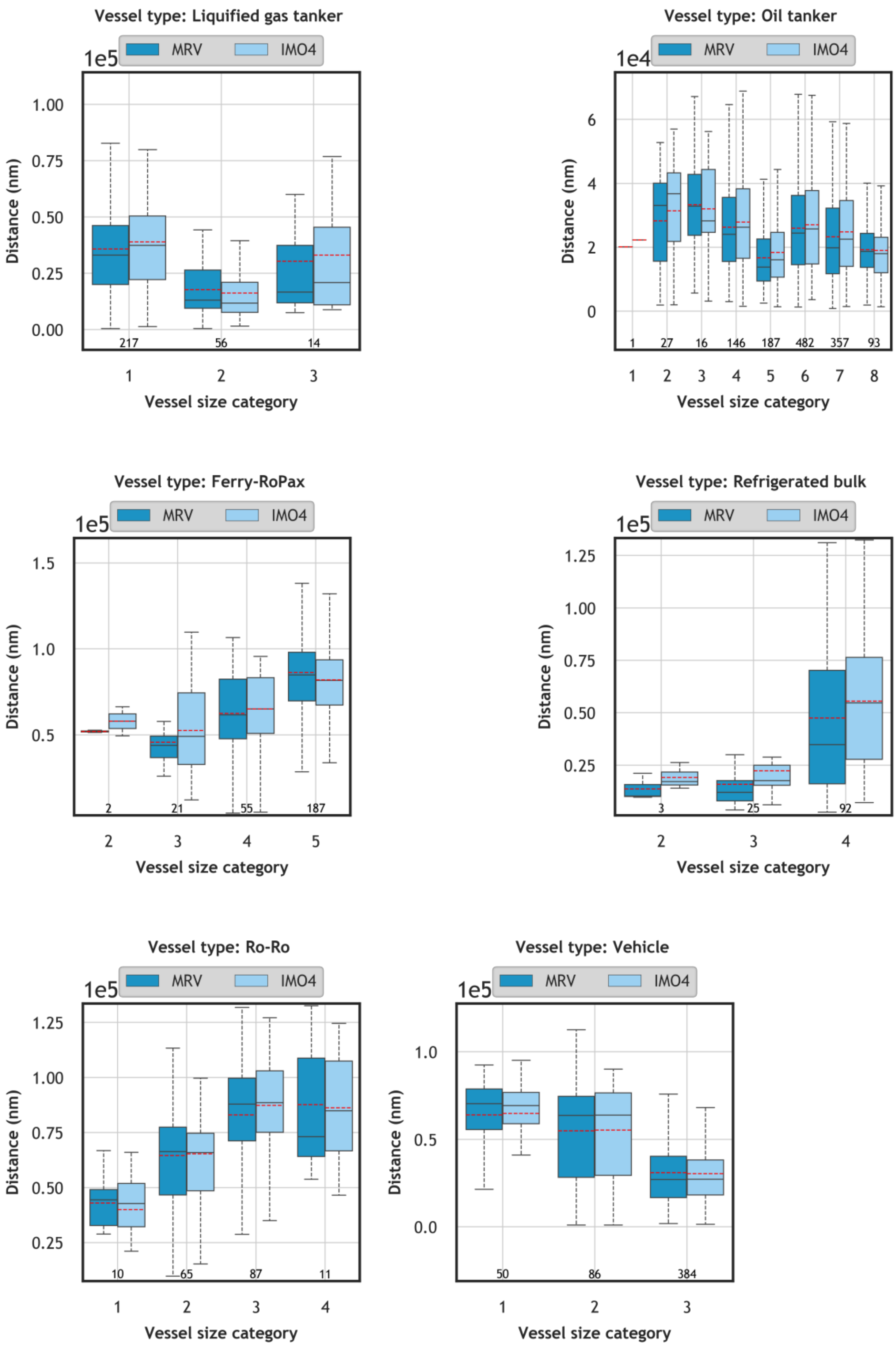
Vessel type: Ferry-RoPax
MRV
IMO4
1e3
Sailing hours (hr)
8
6
4
2
2
21
55
187
2
3
4
5
Vessel size category
Vessel type: Refrigerated bulk
MRV
IMO4
1e3
Sailing hours (hr)
6
4
2
3
25
92
2
3
4
Vessel size category
Vessel type: Ro-Ro
MRV
IMO4
1e3
Sailing hours (hr)
6
4
2
10
65
87
11
1
2
3
4
Vessel size category
Vessel type: Vehicle
MRV
IMO4
1e3
Sailing hours (hr)
6
4
2
0
50
86
384
1
2
3
Vessel size category

P.2 Distance sailed

The cargo estimate from the MRV dataset was derived from the submitted EEOI value (gCO_2/hr) and sailing hours (hr). Distance sailed is systematically overestimated to a small degree for most vessel types, as can be seen form the medians in the boxplots below. This is associated with the overestimation in sailing hours as more distance is accounted for in the bottom-up model. The variation indicated by the whiskers is consistent along both datasets.

Figure 71 - Box plot distance sailed comparison by vessel type and size

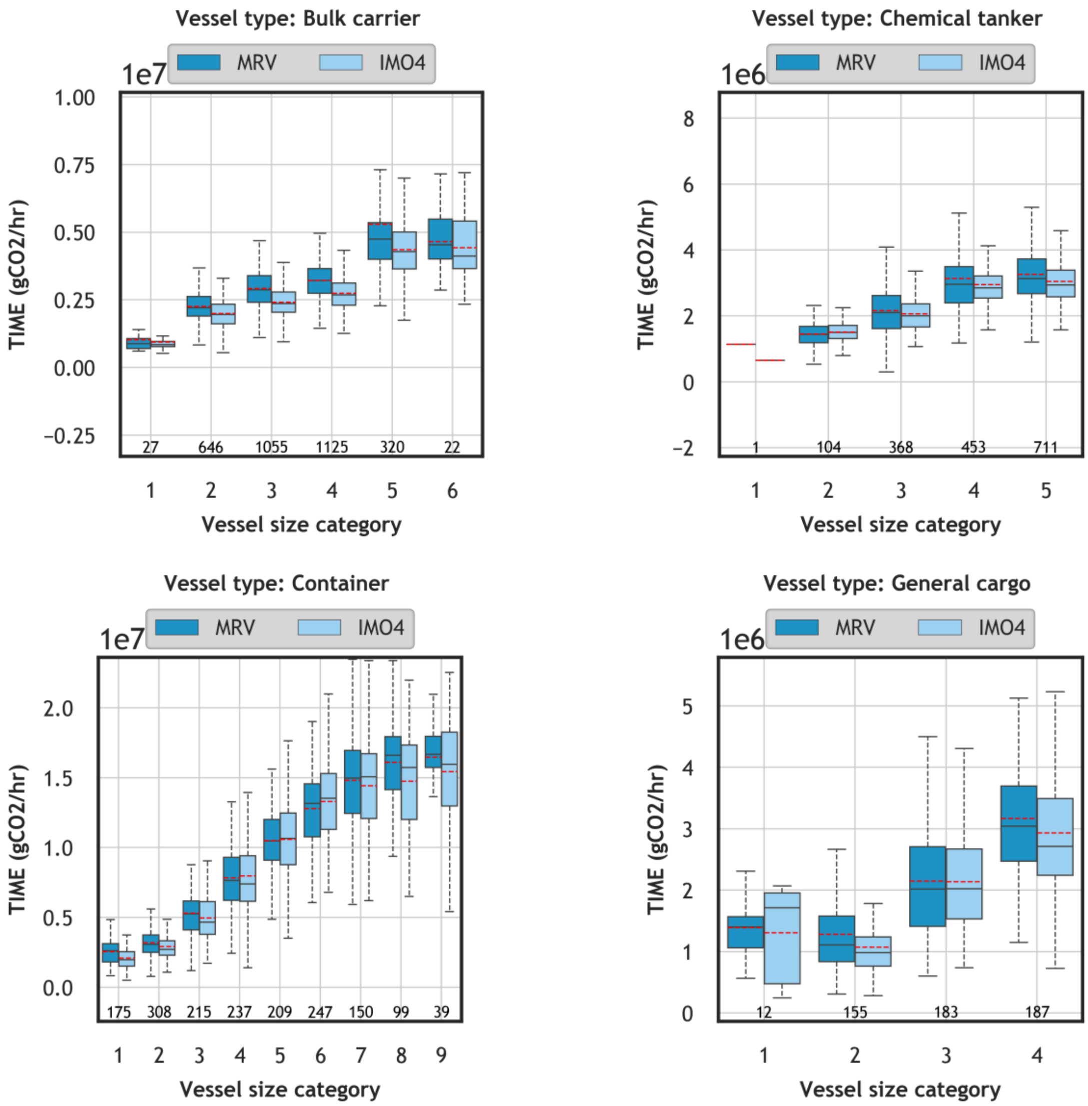


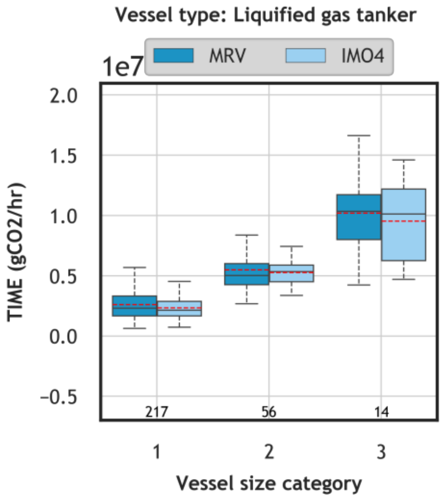

Vessel type: Liquified gas tanker
MRV
IMO4
1e5
Distance (nm)
1.00
0.75
0.50
0.25
0.00
217
56
14
1
2
3
Vessel size category
Vessel type: Oil tanker
MRV
IMO4
1e4
Distance (nm)
6
4
2
0
1
27
16
146
187
482
357
93
1
2
3
4
5
6
7
8
Vessel size category
Vessel type: Ferry-RoPax
MRV
IMO4
1e5
Distance (nm)
1.5
1.0
0.5
2
21
55
187
2
3
4
5
Vessel size category
Vessel type: Refrigerated bulk
MRV
IMO4
1e5
Distance (nm)
1.25
1.00
0.75
0.50
0.25
3
25
92
2
3
4
Vessel size category
Vessel type: Ro-Ro
MRV
IMO4
1e5
Distance (nm)
1.25
1.00
0.75
0.50
0.25
10
65
87
11
1
2
3
4
Vessel size category
Vessel type: Vehicle
MRV
IMO4
1e5
Distance (nm)
1.0
0.5
0.0
50
86
384
1
2
3
Vessel size category

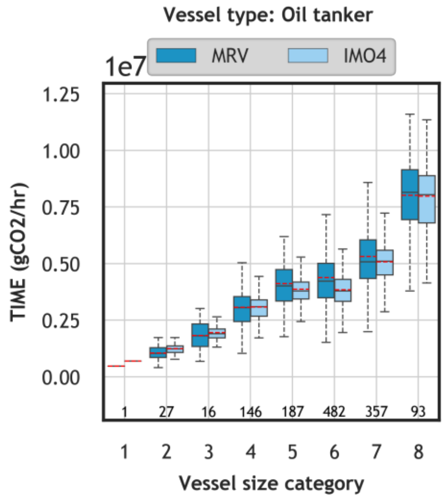
P.3 Temporal carbon intensity

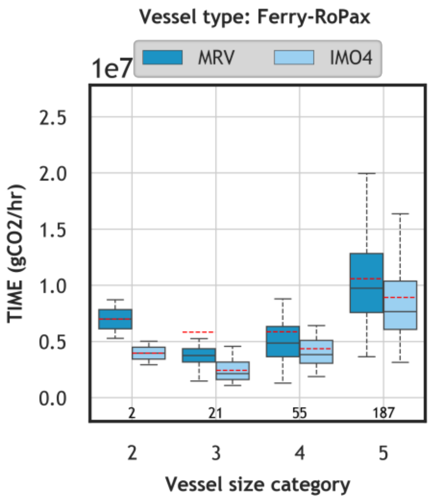
The temporal carbon intensity provided in the MRV dataset was compared to the same metric derived from the bottom-up dataset. The overestimation in sailing hours is reflected in an underestimate in temporal carbon intensity with the variability being also carried through.

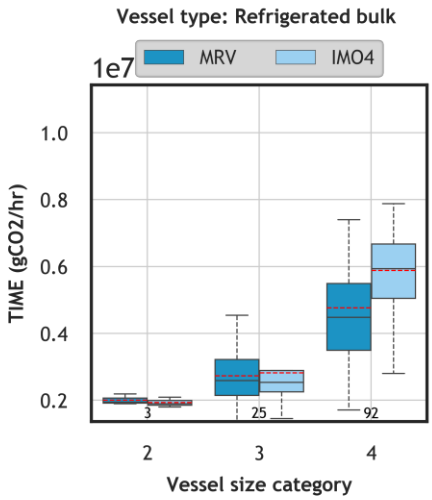
Figure 72 - Box plot temporal carbon intensity comparison by vessel type and size

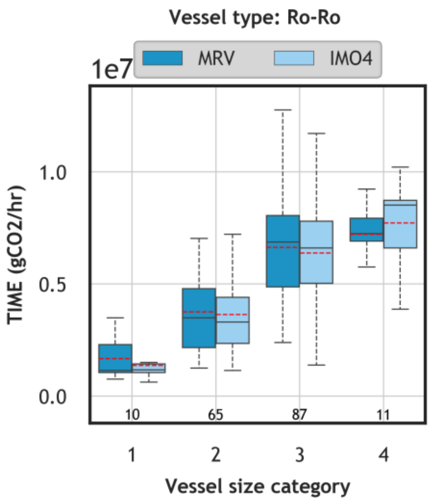


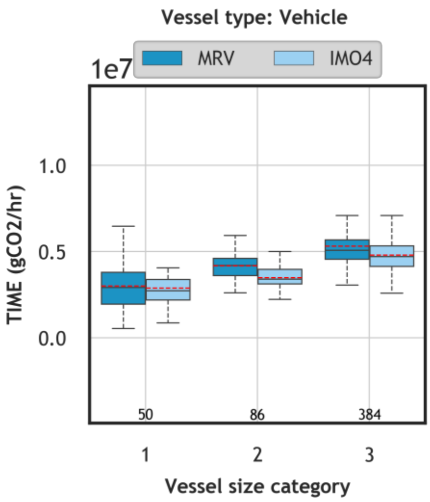

Vessel type: Liquified gas tanker
MRV
IMO4
1e7
2.0
1.5
1.0
0.5
0.0
−0.5
TIME (gCO2/hr)
217
56
14
1
2
3
Vessel size category


Vessel type: Oil tanker
MRV
IMO4
1e7
1.25
1.00
0.75
0.50
0.25
0.00
TIME (gCO2/hr)
1
27
16
146
187
482
357
93
1
2
3
4
5
6
7
8
Vessel size category


Vessel type: Ferry-RoPax
MRV
IMO4
1e7
2.5
2.0
1.5
1.0
0.5
0.0
TIME (gCO2/hr)
2
21
55
187
2
3
4
5
Vessel size category


Vessel type: Refrigerated bulk
MRV
IMO4
1e7
1.0
0.8
0.6
0.4
0.2
TIME (gCO2/hr)
3
25
92
2
3
4
Vessel size category

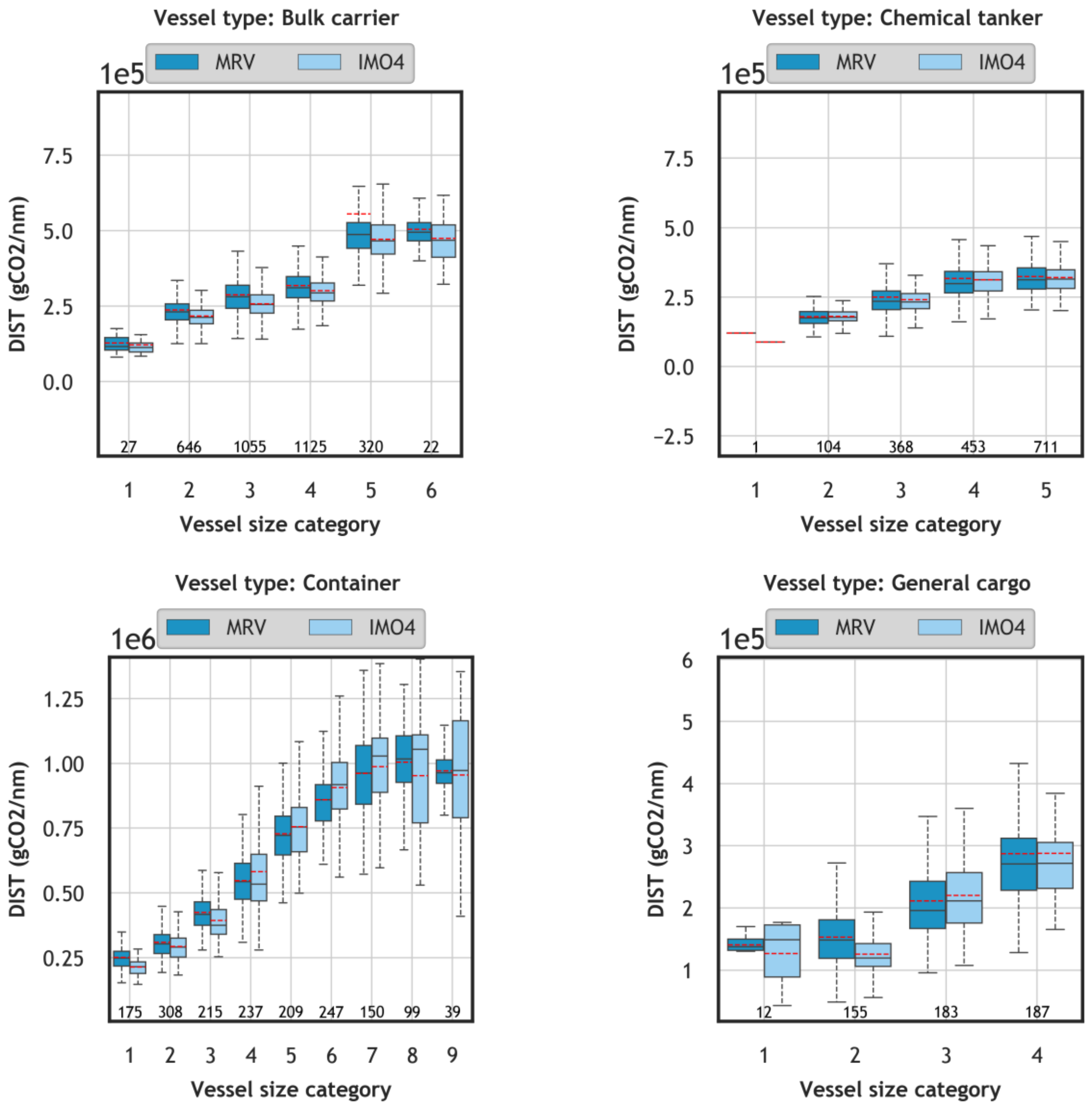

Vessel type: Ro-Ro
MRV
IMO4
1e7
1.0
0.5
0.0
TIME (gCO2/hr)
10
65
87
11
1
2
3
4
Vessel size category

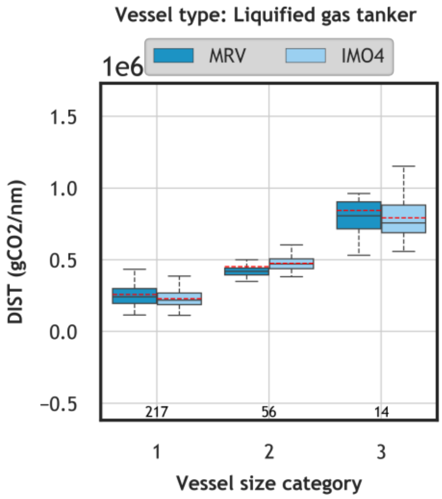

Vessel type: Vehicle
MRV
IMO4
1e7
1.0
0.5
0.0
TIME (gCO2/hr)
50
86
384
1
2
3
Vessel size category

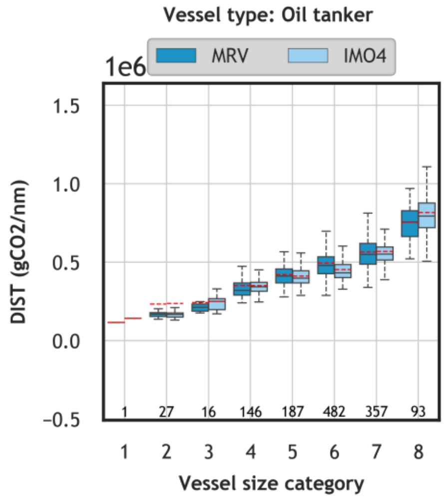
P.4 Distance carbon intensity

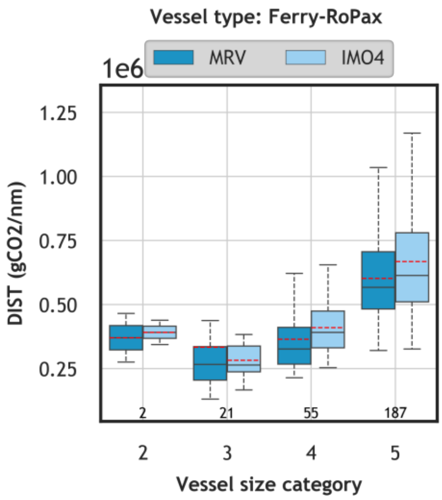
The temporal carbon intensity provided in the MRV dataset was compared to the same metric derived from the bottom-up dataset.

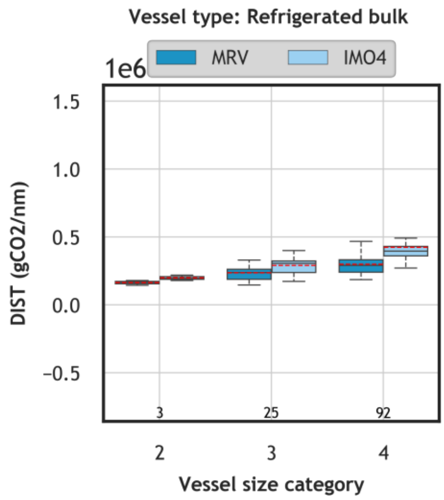
Figure 73 - Box plot distance carbon intensity comparison by vessel type and size

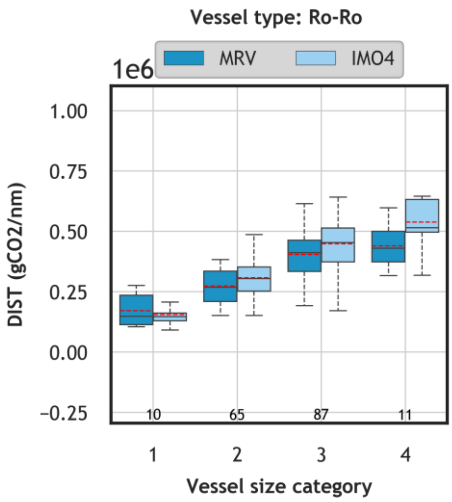


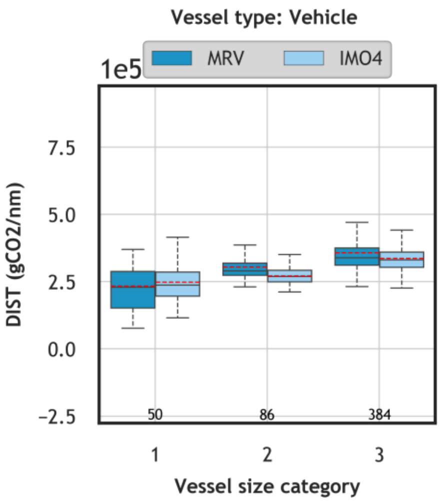

Vessel type: Liquified gas tanker
MRV
IMO4
1e6
1.5
1.0
0.5
0.0
−0.5
DIST (gCO2/nm)
217
56
14
1
2
3
Vessel size category


Vessel type: Oil tanker
MRV
IMO4
1e6
1.5
1.0
0.5
0.0
−0.5
DIST (gCO2/nm)
1
27
16
146
187
482
357
93
1
2
3
4
5
6
7
8
Vessel size category


Vessel type: Ferry-RoPax
MRV
IMO4
1e6
1.25
1.00
0.75
0.50
0.25
DIST (gCO2/nm)
2
21
55
187
2
3
4
5
Vessel size category


Vessel type: Refrigerated bulk
MRV
IMO4
1e6
1.5
1.0
0.5
0.0
−0.5
DIST (gCO2/nm)
3
25
92
2
3
4
Vessel size category

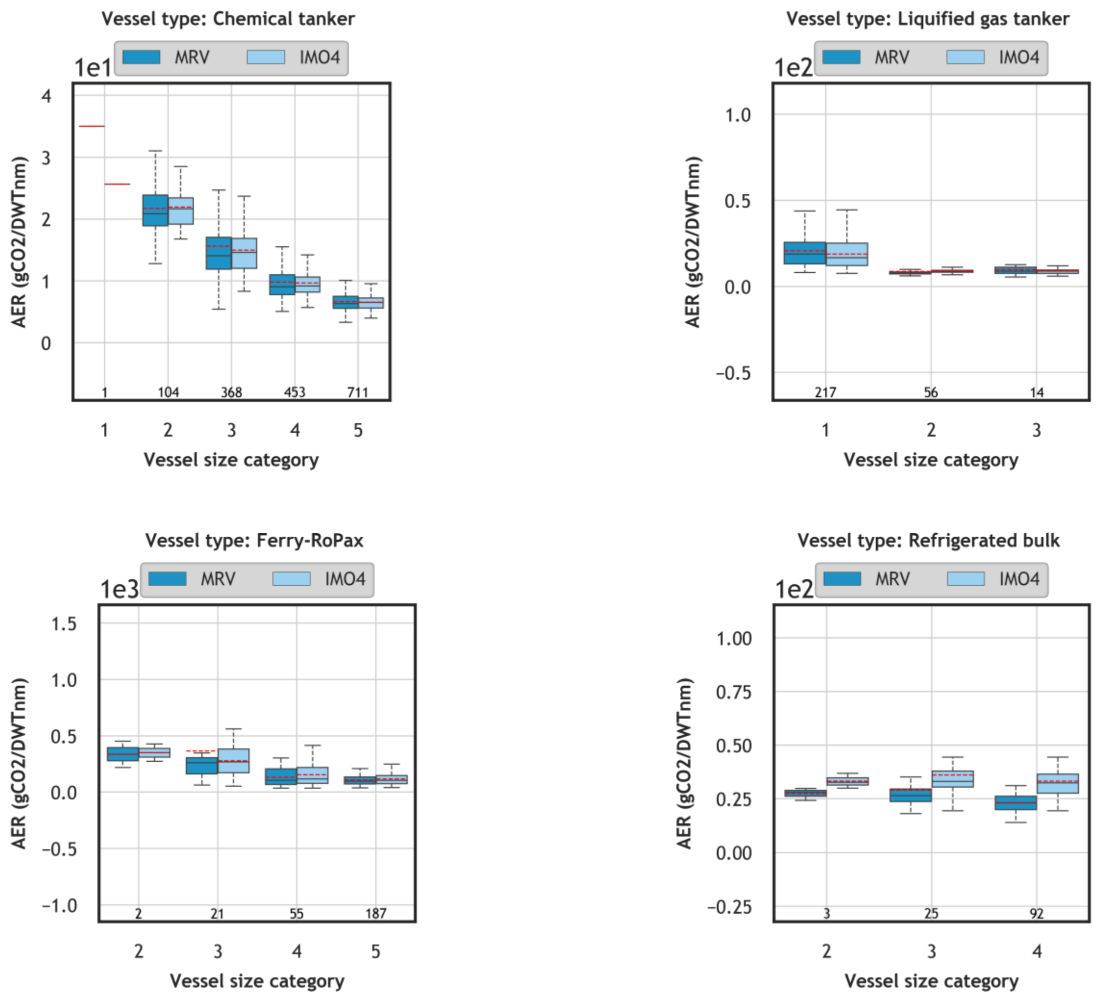

Vessel type: Ro-Ro
MRV
IMO4
1e6
1.00
0.75
0.50
0.25
0.00
−0.25
DIST (gCO2/nm)
10
65
87
11
1
2
3
4
Vessel size category

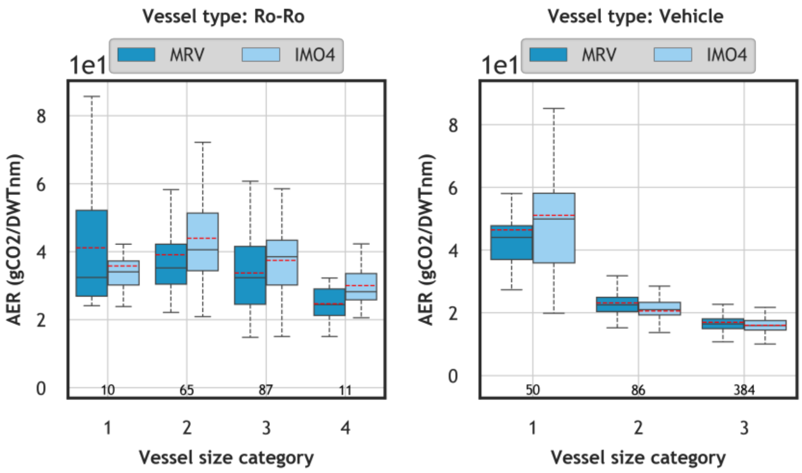

Vessel type: Vehicle
MRV
IMO4
1e5
7.5
5.0
2.5
0.0
−2.5
DIST (gCO2/nm)
50
86
384
1
2
3
Vessel size category

P.5 AER (gCO_2/DWTnm)

The AER provided in the MRV dataset was compared to the same metric derived from the bottom-up dataset.

Figure 74 - Box plot AER comparison by vessel type and size

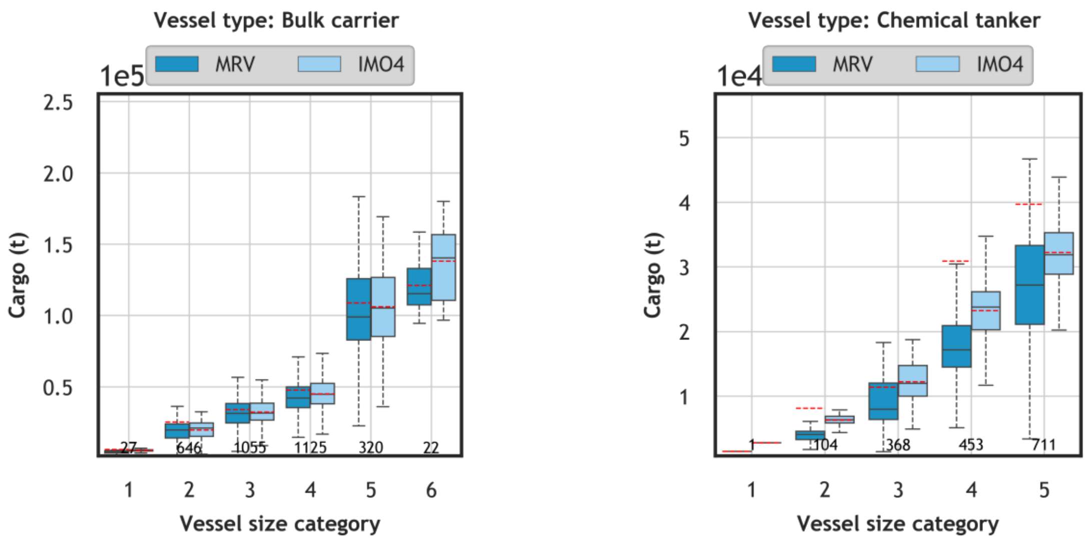


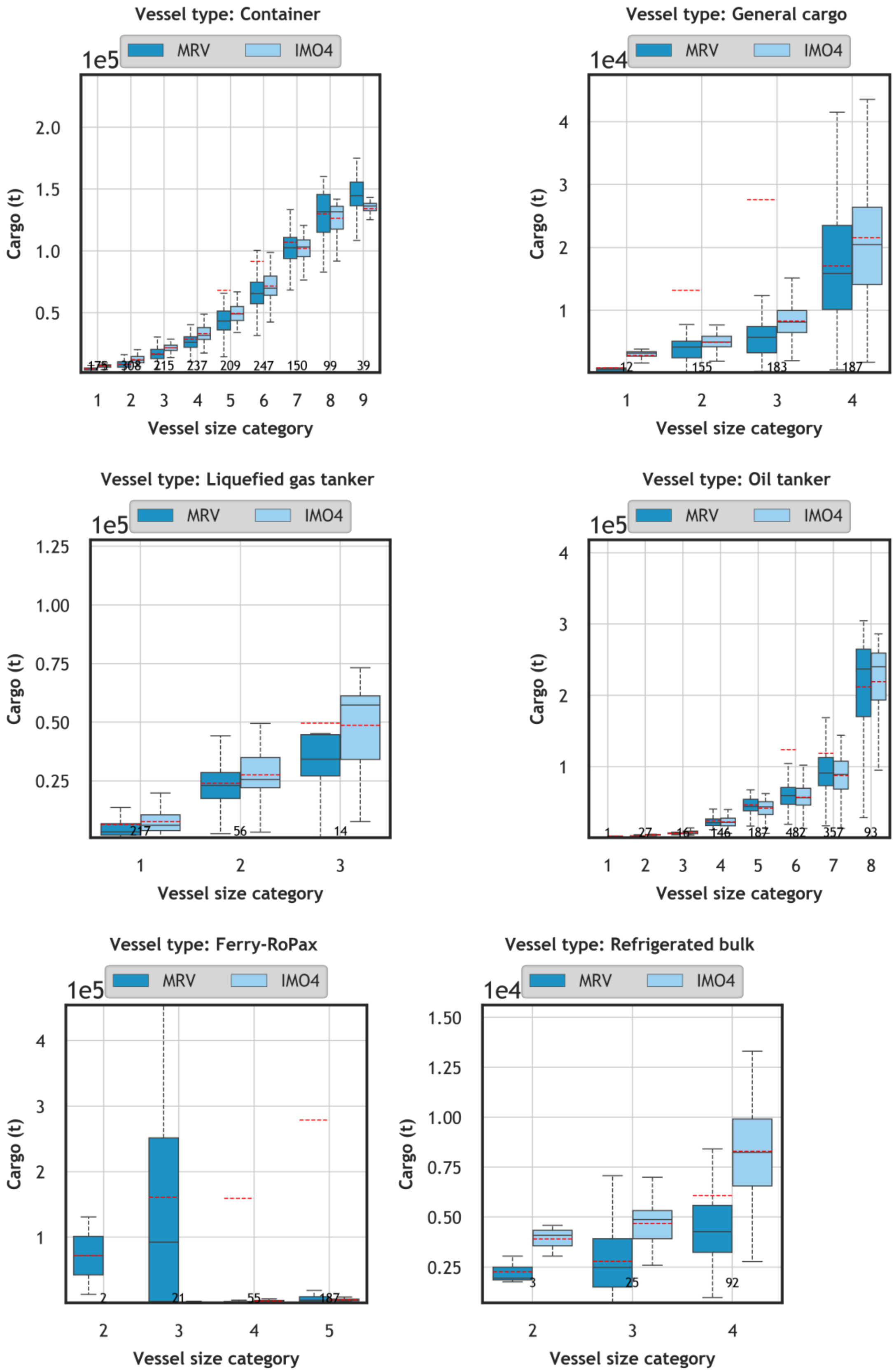


P.6 Cargo masses

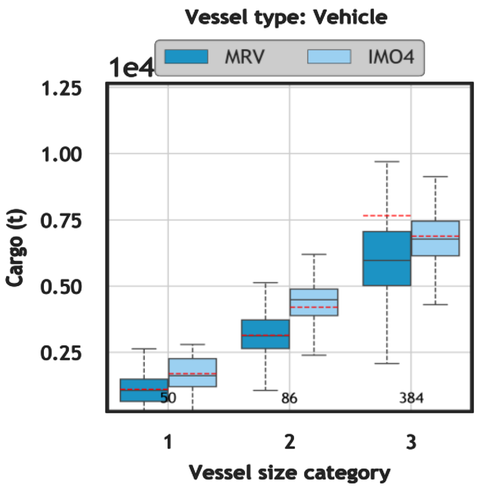
The cargo estimate from the MRV dataset was derived from the submitted EEOI value (gCO_2/tnm) and distance carbon intensity (gCO_2/nm). Not all vessels had an associated distance-based carbon intensity, implying the dataset for cargo validation is smaller. Cargo is systematically overestimated for most vessel types as can be seen form the medians in the boxplots below.

Figure 75 - Box plot cargo masses estimate comparison by vessel type and size

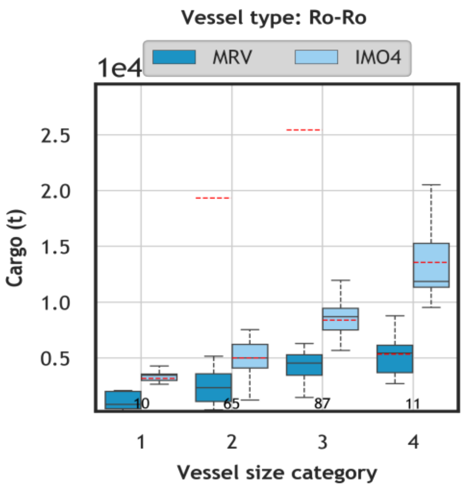




Vessel type: Container
MRV
IMO4
1e5
Cargo (t)
2.0
1.5
1.0
0.5
175
308
215
237
209
247
150
99
39
1 2 3 4 5 6 7 8 9
Vessel size category
Vessel type: General cargo
MRV
IMO4
1e4
Cargo (t)
4
3
2
1
12
155
183
187
1 2 3 4
Vessel size category
Vessel type: Liquefied gas tanker
MRV
IMO4
1e5
Cargo (t)
1.25
1.00
0.75
0.50
0.25
217
56
14
1 2 3
Vessel size category
Vessel type: Oil tanker
MRV
IMO4
1e5
Cargo (t)
4
3
2
1
1
27
16
146
187
482
357
93
1 2 3 4 5 6 7 8
Vessel size category
Vessel type: Ferry-RoPax
MRV
IMO4
1e5
Cargo (t)
4
3
2
1
2
21
55
187
2 3 4 5
Vessel size category
Vessel type: Refrigerated bulk
MRV
IMO4
1e4
Cargo (t)
1.50
1.25
1.00
0.75
0.50
0.25
3
25
92
2 3 4
Vessel size category



Vessel type: Vehicle
MRV
IMO4
1e4
1.25
1.00
0.75
0.50
0.25
Cargo (t)
50
86
384
1
2
3
Vessel size category

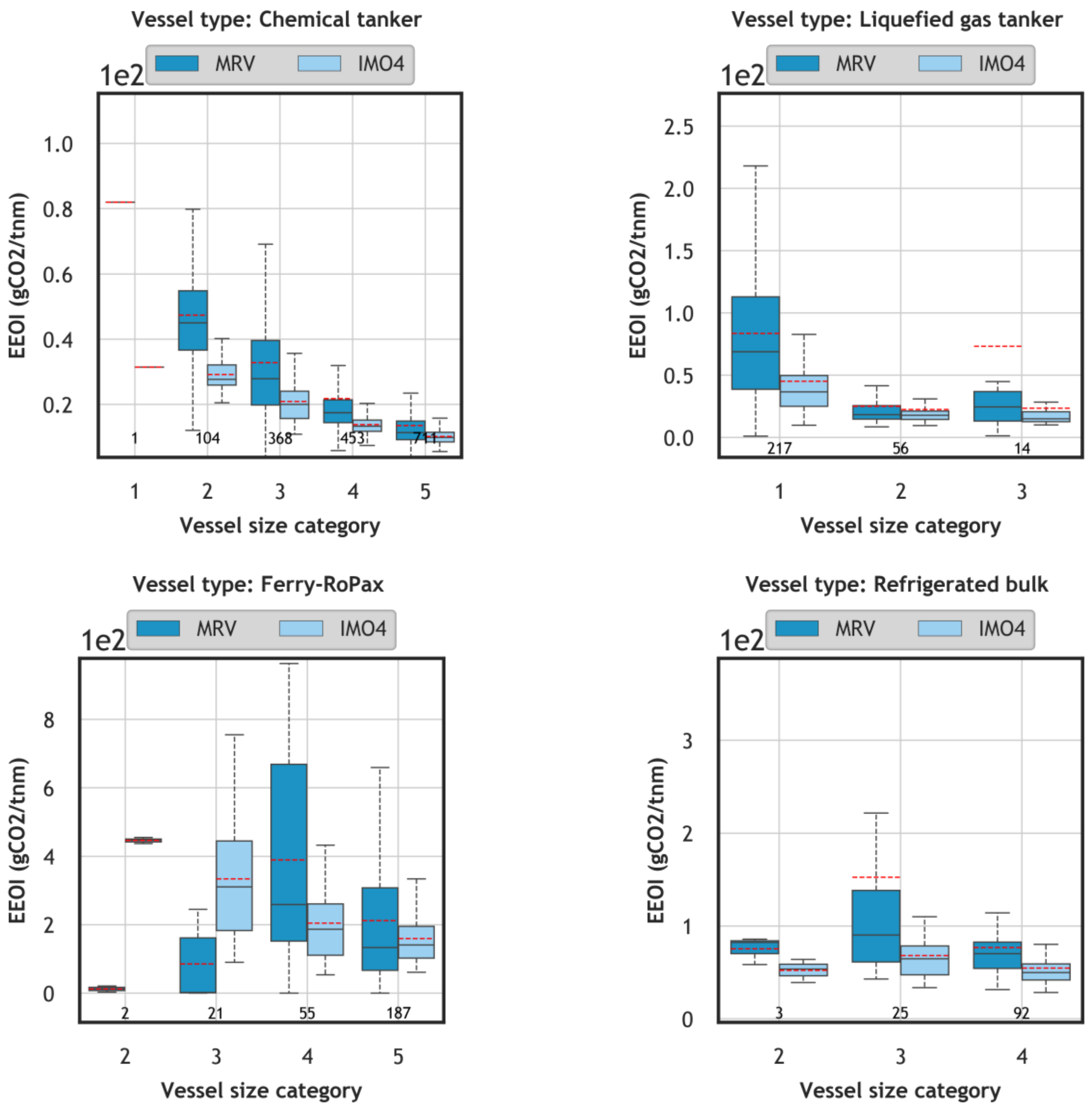


Vessel type: Ro-Ro
MRV
IMO4
1e4
2.5
2.0
1.5
1.0
0.5
Cargo (t)
10
65
87
11
1
2
3
4
Vessel size category

P.7 EEOI (gCO_2/tnm)

The EEOI provided in the MRV dataset was compared to the same metric derived from the bottom-up dataset.

Figure 76 - Box plot EEOI comparison by vessel type and size



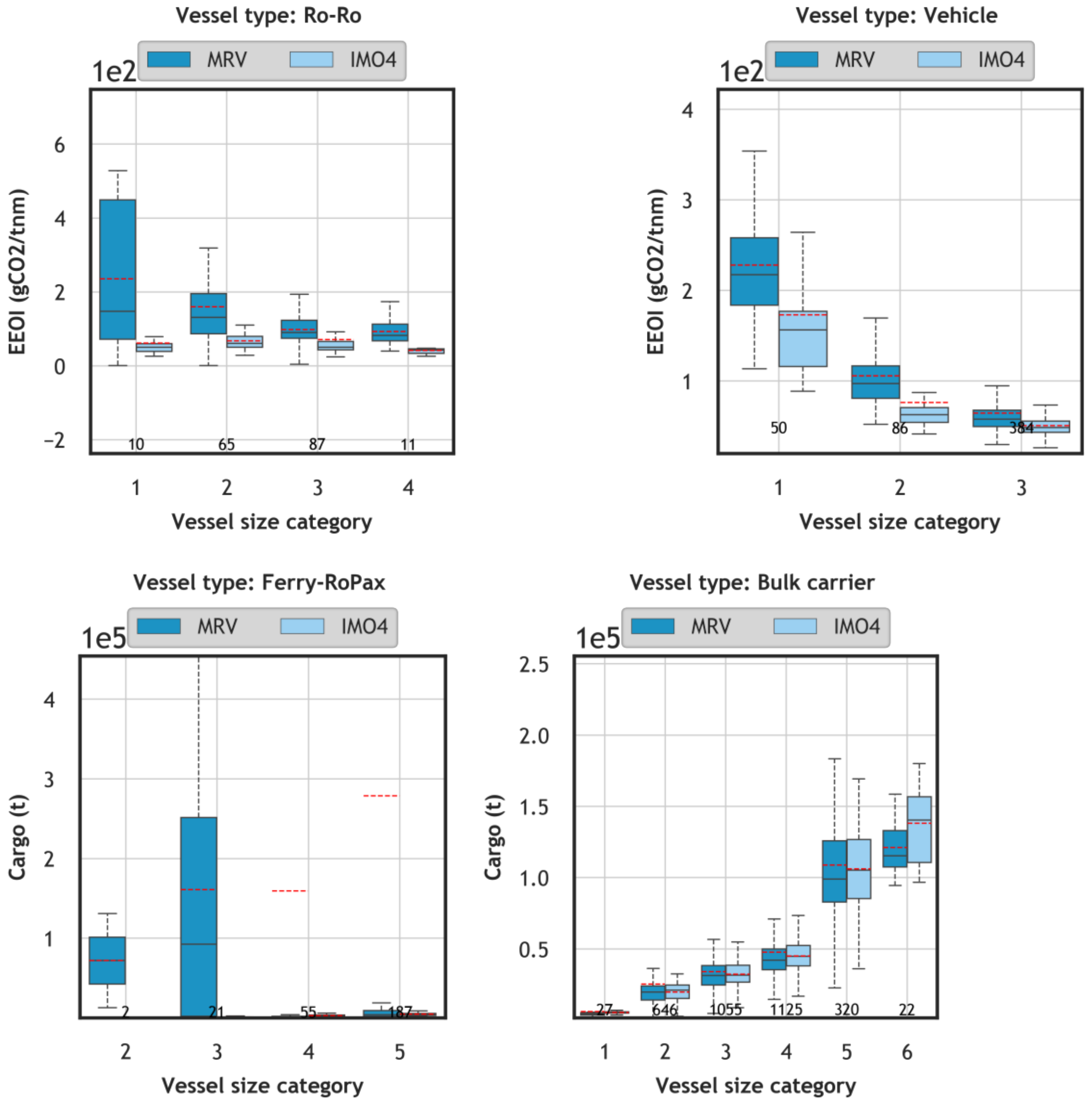

Vessel type: Ro-Ro
MRV
IMO4
1e2
EEOI (gCO2/tnm)
6
4
2
0
−2
10
65
87
11
1
2
3
4
Vessel size category
Vessel type: Vehicle
MRV
IMO4
1e2
EEOI (gCO2/tnm)
4
3
2
1
50
86
384
1
2
3
Vessel size category
Vessel type: Ferry-RoPax
MRV
IMO4
1e5
Cargo (t)
4
3
2
1
2
21
55
187
2
3
4
5
Vessel size category
Vessel type: Bulk carrier
MRV
IMO4
1e5
Cargo (t)
2.5
2.0
1.5
1.0
0.5
27
646
1055
1125
320
22
1
2
3
4
5
6
Vessel size category

Table 92 - MRV summary statistics per vessel type and size

Size Bin	Type bin	Ship Type	Size Range	Unit	# Vessels MRV	Total CO_2 MRV (t)	Total CO_2 IMO4 (t)	% difference	Weighting by CO_2
1	1	Bulk carrier	0-9999	dwt	27	94204.3	102020.6675	8%	7,816
2	1	Bulk carrier	10000-34999	dwt	646	2795282.4	2986985.688	7%	191,703
3	1	Bulk carrier	35000-59999	dwt	1055	4517195.8	4739227.76	5%	222,032
4	1	Bulk carrier	60000-99999	dwt	1125	6886865.4	6805661.414	-1%	-81,204
5	1	Bulk carrier	100000-199999	dwt	320	3218903.0	2860800.415	-12%	-358,103
6	1	Bulk carrier	200000-+	dwt	22	180771.1	161492.1422	-11%	-19,279
1	3	Chemical tanker	0-4999	dwt	1	5088.2	4162.067766	-20%	-926
2	3	Chemical tanker	5000-9999	dwt	104	696822.8	759707.863	9%	62,885
3	3	Chemical tanker	10000-19999	dwt	368	2521631.7	2754029.05	9%	232,397
4	3	Chemical tanker	20000-39999	dwt	453	3926938.3	4341748.571	10%	414,810
5	3	Chemical tanker	40000-+	dwt	711	5113072.5	5369126.038	5%	256,054
1	4	Container	0-999	teu	175	2214971.4	2063407.4	-7%	-151,564
2	4	Container	1000-1999	teu	308	3900008.9	4019867.5	3%	119,859
3	4	Container	2000-2999	teu	215	4110865.8	4118895.7	0%	8,030
4	4	Container	3000-4999	teu	237	6673616.4	7262018.1	8%	588,402
5	4	Container	5000-7999	teu	209	6417566.7	7089015.3	10%	671,449
6	4	Container	8000-11999	teu	247	7943337.8	8815796.4	10%	872,459
7	4	Container	12000-14499	teu	150	5349252.9	6026328.9	12%	677,076
8	4	Container	14500-19999	teu	99	5450362.8	5499931.4	1%	49,569
9	4	Container	20000-+	teu	39	2179397.1	2096993.5	-4%	-82,404
1	5	General cargo	0-4999	dwt	12	74679.6	79429.2	6%	4,750
2	5	General cargo	5000-9999	dwt	155	614963.2	593876.0	-3%	-21,087
3	5	General cargo	10000-19999	dwt	183	1114713.7	1237207.5	10%	122,494
4	5	General cargo	20000-+	dwt	187	1224109.8	1284105.5	5%	59,996
1	6	Liquefied gas tanker	0-49999	cbm	217	1926564.7	1946346.8	1%	19,782
2	6	Liquefied gas tanker	50000-99999	cbm	56	471980.2	433604.4	-8%	-38,376
3	6	Liquefied gas tanker	100000-199999	cbm	14	327238.6	367797.5	12%	40,559
1	7	Oil tanker	0-4999	dwt	1	2317.9	3201.6	32%	884
2	7	Oil tanker	5000-9999	dwt	27	136149.7	149293.5	9%	13,144

Size Bin	Type bin	Ship Type	Size Range	Unit	# Vessels MRV	Total CO_2 MRV (t)	Total CO_2 IMO4 (t)	% difference	Weighting by CO_2
3	7	Oil tanker	10000-19999	dwt	16	115837.1	124090.2	7%	8,253
4	7	Oil tanker	20000-59999	dwt	146	1333122.3	1424303.9	7%	91,182
5	7	Oil tanker	60000-79999	dwt	187	1268544.8	1416349.8	11%	147,805
6	7	Oil tanker	80000-119999	dwt	482	6167187.8	5911738.2	-4%	-255,450
7	7	Oil tanker	120000-199999	dwt	357	4604224.6	5015617.9	9%	411,393
8	7	Oil tanker	200000-+	dwt	93	1364228.7	1461410.6	7%	97,182
2	8	Other liquids tankers	1000-+	dwt	10	176323.7	215082.7	20%	38,759
2	10	Cruise	2000-9999	gt	6	47669.9	44722.7	-6%	-2,947
3	10	Cruise	10000-59999	gt	65	1446116.6	1294070.5	-11%	-152,046
4	10	Cruise	60000-99999	gt	52	2777165.5	3118279.7	12%	341,114
5	10	Cruise	100000-149999	gt	24	1800168.6	1906630.8	6%	106,462
6	10	Cruise	150000-+	gt	8	452410.0	568407.4	23%	115,997
2	11	Ferry-RoPax	2000-4999	gt	2	38446.1	46325.4	19%	7,879
3	11	Ferry-RoPax	5000-9999	gt	21	314445.9	303891.7	-3%	-10,554
4	11	Ferry-RoPax	10000-19999	gt	55	1243320.8	1478599.0	17%	235,278
5	11	Ferry-RoPax	20000-+	gt	187	9852966.7	10528552.6	7%	675,586
2	12	Refrigerated bulk	2000-5999	dwt	3	6750.0	11682.5	54%	4,932
3	12	Refrigerated bulk	6000-9999	dwt	25	91443.5	164743.8	57%	73,300
4	12	Refrigerated bulk	10000-+	dwt	92	1423901.1	2142702.5	40%	718,801
1	13	Ro-Ro	0-4999	dwt	10	77133.4	66859.2	-14%	-10,274
2	13	Ro-Ro	5000-9999	dwt	65	1203734.0	1374602.6	13%	170,869
3	13	Ro-Ro	10000-14999	dwt	84	2827060.1	3355539.0	17%	528,479
4	13	Ro-Ro	15000-+	dwt	11	419428.8	512121.4	20%	92,693
1	14	Vehicle	0-29999	gt	50	756554.8	840018.1	10%	83,463
2	14	Vehicle	30000-49999	gt	85	1414916.9	1257531.9	-12%	-157,385
3	14	Vehicle	50000-+	gt	383	4091307.8	3969181.9	-3%	-122,126
1	16	Service - tug	0-+	gt	2	19560.3	15620.0	-22%	-3,940
1	18	Offshore	0-+	gt	1	480.9	6140.4	171%	5,660
1	19	Service - other	0-+	gt	4	24310.1	30443.5	22%	6,133
						118,924,102	**125,645,226**	**5.5%**	**5.5%**

Q Updated Marginal Abatement Cost Curves

At MEPC74, the Committee approved the terms of reference of the Fourth IMO GHG Study, one of which states “Updated Marginal Abatement Cost Curves (MACCs) taking into account recent technology and economic trends in shipping should be developed as a technical information for reference”.

To this end, this annex aims to update the MACCs of GHG emission reduction at 2030 and 2050, taking into account recent developments on both energy saving technologies (for better transport efficiency of each ship) and use of alternative fuel (reducing the conversion factor per energy inputs).

Q.1 Screening for potential GHG abatement technologies

Q.1.1 Methodology and screening results

This study updated the MACCs for 2030 and 2050, taking into account recent developments and actual implementation of more energy-saving technologies, possible use of alternative fuels and speed reduction.

We examined scientific and engineering literatures, e.g. by IMarEST (2011) [1], CE Delft (2012) [2], JSTRA/NMRI (2011) [3], Eide et al. (2011) [4], GloMEEP (2015) [5], JSTRA/NMRI (2018) [6], and UMAS/CE Delft et al. (2019) [7], which conducted investigation of CO_2 emission reduction potentials and costs of technologies including new abatement technologies. We also took into account recent scientific papers on use of alternative fuels. Some kinds of new technologies are being developed faster for land-based use than for shipping. For instance, as for fuel cells, we examined literatures including one related to land-based use.

Through the investigation, 47 technologies were identified. Then we excluded some of these technologies for the reasons of duplications. Because of insufficient information when used onboard, we could not include some other potential technologies. We excluded some of operational abatement options, such as Shaft power meter (performance monitoring), Fuel consumption meter (performance monitoring), Weather routeing and Autopilot upgrade/adjustment, because the actual reduction is varied by individual operation.

As a result, 44 technologies were screened out. The screened technologies consist of four types: (1) 23 of energy-saving technologies, (2) 4 of use of renewable energy (e.g. wind engine, solar panels), (3) 16 of use of alternative fuels (e.g. LNG, hydrogen, ammonia) and (4) speed reduction.

Q.1.2 Definitions and sources of abatement technologies

The definitions of the 44 abatement technologies selected in Section Q.1.1 were determined based on the literatures. The information on costs and GHG emission reduction potential of the technologies was extracted from the literatures. Table 93 lists the 44 technologies.

Table 93 - Selected abatement technologies

Categories	No.	Abatement technologies	References
(1) Energy-saving technologies	1	Main Engine Tuning	[1]
	2	Common-rail	[1]
	3	Electronic engine control	[5]
	4	Frequency converters	[5]
	5	Speed control of pumps and fans	[1]
	6	Steam plant operation improvements	[5]
	7	Waste heat recovery	[1], [5]
	8	Exhaust gas boilers on auxiliary engines	[5]
	9	Propeller-rudder upgrade	[1]
	10	Propeller upgrade (nozzle, tip winglet)	[1]
	11	Propeller boss cap fins	[1]
	12	Contra-rotating propeller	[5]
	13	Propeller performance monitoring	[1]
	14	Propeller polishing	[1]
	15	Air lubrication	[1], [5]
	16	Low-friction hull coating	[1], [5], [8]-[11]
	17	Hull performance monitoring	[12]
	18	Hull brushing	[12], [13]
	19	Hull hydro-blasting	[12]
	20	Dry-dock full blast	[12]
	21	Optimization water flow hull openings	[1]
	22	Super light ship	[14]
	23	Reduced auxiliary power demand (low energy lighting etc.)	[1], [5]
(2) Use of renewable energy	24	Towing kite	[1], [5]
	25	Wind power (fixed sails or wings)	[5]
	26	Wind engines (Flettner rotor)	[1]
	27	Solar panels	[1], [5]
(3) Use of alternative fuels	28	LNG + internal combustion engine (ICE)	[15]-[29]
	29	LNG + fuel cells (FC)	[27], [28], [30]-[35]
	30	Methanol + internal combustion engine (ICE)	[19], [22], [23], [25]-[28], [39]-[41]
	31	Ethanol + internal combustion engine (ICE)	[42]
	32	Hydrogen + internal combustion engine (ICE)	[24], [25], [27], [28]
	33	Hydrogen + fuel cells (FC)	[22], [24]-[28], [30]-[36]
	34	Ammonia + internal combustion engine (ICE)	[24], [27], [28], [37], [38]
	35	Ammonia + fuel cells (FC)	[24], [27], [28], [31]-[35], [37]
	36	Synthetic methane + internal combustion engine (ICE)	[15]-[29] ,[54]
	37	Synthetic methane + fuel cells (FC)	[27], [28], [30]-[35]
	38	Biomass methane + internal combustion engine (ICE)	[15]-[29], [54]
	39	Biomass methane + fuel cells (FC)	[27], [28], [30]-[35]
	40	Synthetic methanol + internal combustion engine (ICE)	[19], [22], [23], [25]-[28], [39]-[41] [54]
	41	Biomass methanol + internal combustion engine (ICE)	[19], [22], [23], [25]-[28], [39]-[41], [54]
	42	Synthetic ethanol + internal combustion engine (ICE)	[42], [54]
	43	Biomass ethanol + internal combustion engine (ICE)	[43], [44]
(4) Speed reduction	44	Speed reduction by 10%	[1], [45]-[51]

Q.2 Estimation of costs and GHG emission reduction potential for the screened technologies

Q.2.1 Methodology for estimating costs and GHG emission reduction potential for the screened technologies

For calculating MACs, it is necessary to prepare the fact sheets in which information on costs, GHG emission reduction potential, etc. are compiled. For the estimation of CAPEX (Capital Expenditure), OPEX (Operational Expenditure) and annual CO_2 emission reduction potential (expressed as percentage), the medians of these values were used. For establishing the fact sheets, some extrapolated data were taken into account.

Although there are five greenhouse gases other than CO_2, for MAC calculation, only fuel consumption, i.e. CO_2 emissions were counted, except for methane slip described in subsection of Q.2.7.

Q.2.2 Applicability

Some abatement technologies are subject to technological limitation in their installation depending on ship type and size. The applicability of an abatement technology means to what type and size of a ship it could be applicable in 2030/2050.

The applicability was indicated not only in the Second IMO GHG Study but also in IMarEST (2011) [1], GloMEEP (2015) [5], and Frontier Economics, UMAS and CE Delft (2019) [7], etc. We set the applicability as wide as possible, as listed on Table 94 based on those literatures and manufacturers' opinions. Many of abatement technologies have no technological limitation and can be applied to all ships.

Q.2.3 Expected lifetime

Expected lifetime of respective technology means an interval up to the replacement or renewal, and is an important value related to both costs and CO_2 emission reduction potential for each technology.

We set the expected lifetime of technologies as listed on Table 94 taking into account research of the Second IMO GHG Study and IMarEST (2011) [1].

The standard ship lifetime is set at 25 years, and therefore the expected lifetime of most of technologies is set as 25 years. On the other hand, it means that the technologies which have the expected lifetime of less than 25 years shown in the table are re-installed or maintained at its intervals.

Table 94 - Applicability and expected lifetime for abatement technologies

	Name of technology	Category of Maturity	Applicability of technologies	Expected lifetime (year)
No.1	Main Engine Tuning	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.2	Common-rail	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.3	Electronic engine control	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.4	Frequency converters	1:Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.5	Speed control of pumps and fans	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.6	Steam plant operation improvements	1: Matured and available on the market for > 5 years	All sizes of Chemical tanker and Oil tanker only.	25
No.7	Waste heat recovery	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.8	Exhaust gas boilers on auxiliary engines	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.9	Propeller-rudder upgrade	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (10 years intervals in average)
No.10	Propeller upgrade (nozzle, tip winglet)	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (10 years intervals in average)
No.11	Propeller boss cap fins	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (10 years intervals in average)
No.12	Contra-rotating propeller	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.13	Propeller performance monitoring	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (1 year intervals in average)
No.14	Propeller polishing	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (1 year intervals in average)
No.15	Air lubrication	2: Matured and available on the market for =< 5 years	All types and all ship sizes of new ships.	25
No.16	Low-friction hull coating	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (5 years intervals in average)
No.17	Hull performance monitoring	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (5 years intervals in average)
No.18	Hull brushing	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (5 years intervals in average)
No.19	Hull hydro-blasting	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25 (5 years intervals in average)
No.20	Dry-dock full blast	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	15

	Name of technology	Category of Maturity	Applicability of technologies	Expected lifetime (year)
No.21	Optimization water flow hull openings	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.22	Super light ship	3: Evolving, with some units available	New & Ferry-pax, Ferry-RoPax, Ro-Ro	25
No.23	Reduced auxiliary power demand (low energy lighting etc.)	1: Matured and available on the market for > 5 years	All ship types and all ship sizes.	25
No.24	Towing kite	3: Evolving, with some units available	All new ship types and all ship sizes.	25
No.25	Wind power (fixed sails or wings)	3: Evolving, with some units available	New & other than Container and Liquefied gas tanker and all ship sizes.	25
No.26	Wind engine (Flettner rotor)	1: Matured and available on the market for > 5 years	New & Bulk carrier > 59,999 dwt and Oil tanker > 59,999 dwt.	25
No.27	Solar panels	3: Evolving, with some units available	Bulk carrier > 59,999 dwt, Chemical tanker, General Cargo > 9,999 dwt, Oil tanker, Other liquids tankers, Cruise > 59,999 grt, Ferry-RoPax, Ro-Ro, Vehicle.	25
No.28	LNG + ICE	3: Evolving, with some units available	All ship types and all ship sizes.	25
No.29	LNG + FC	4: Evolving	All ship types and all ship sizes.	25
No.30	Methanol + ICE	3: Evolving, with some units available	All ship types and all ship sizes.	25
No.31	Ethanol + ICE	4: Evolving	All ship types and all ship sizes.	25
No.32	Hydrogen + ICE	4: Evolving	All ship types and all ship sizes.	25
No.33	Hydrogen + FC	4: Evolving	All ship types and all ship sizes.	25
No.34	Ammonia + ICE	4: Evolving	All ship types and all ship sizes.	25
No.35	Ammonia + FC	4: Evolving	All ship types and all ship sizes.	25
No.36	Synthetic methane + ICE	4: Evolving	All ship types and all ship sizes.	25
No.37	Synthetic methane + FC	4: Evolving	All ship types and all ship sizes.	25
No.38	Biomass methane + ICE	4: Evolving	All ship types and all ship sizes.	25
No.39	Biomass methane + FC	4: Evolving	All ship types and all ship sizes.	25
No.40	Synthetic methanol + ICE	4: Evolving	All ship types and all ship sizes.	25

	Name of technology	Category of Maturity	Applicability of technologies	Expected lifetime (year)
No.41	Biomass methanol + ICE	4: Evolving	All ship types and all ship sizes.	25
No.42	Synthetic ethanol + ICE	4: Evolving	All ship types and all ship sizes.	25
No.43	Biomass ethanol + ICE	4: Evolving	All ship types and all ship sizes.	25
No.44	Speed reduction by 10%	1: Matured and available on the market for > 5 years	Ships other than Ferry-pax only, Cruise, Ferry-RoPax, Ro-Ro and Vehicle.	25

Q.2.4 General description of fact sheets

The fact sheets were prepared for respective 44 technologies. CAPEX (USD/ships), OPEX (USD/ships/year) and CO_2 emission reduction potential (%) are assessed and established by ship type/size bins. We also assessed the applicability of the technologies to new ships and/or to existing ships (Retrofit).

The CAPEX means the incremental capital cost, such as purchasing cost for additional equipment and installation compared to conventional technology at the base year 2018. Future CAPEXs of several technologies are discounted by applying learning curves as described in A3.1.5.

The OPEX means the annual incremental operation and maintenance cost. We assumed that the OPEX for use of alternative fuel is generally the same as that of conventional fuel. Therefore, the OPEX of the alternative fuel is assumed to be zero.

Q.2.5 Extrapolation for CAPEX/OPEX

The both CAPEX and OPEX can generally be calculated based on data from the literatures, which only include data for typical ship type/size. Therefore, it is necessary to extrapolate from the available data. We used either of the methods to extrapolate by regression analysis with ship size (dwt) or main engine output (kW) as shown in Table 95.

Table 95 - Methods of extrapolation for abatement options

Extrapolation by ship size, dwt	Extrapolation by main engine output, kW
No.14 Propeller polishing	No.1 Main Engine Tuning
No.15 Air lubrication	No.2 Common-rail
No.16 Low-friction hull coating	No.3 Electronic engine control
No.17 Hull performance monitoring	No.4 Frequency converters
No.18 Hull brushing	No.5 Speed control of pumps and fans
No.19 Hull hydro-blasting	No.7 Waste heat recovery
No.20 Dry-dock full blast	No.8 Exhaust gas boilers on auxiliary engines
No.21 Optimization water flow hull openings	No.9 Propeller-rudder upgrade
No.22 Super light ship	No.10 Propeller upgrade (nozzle, tip winglet)
No.24 Towing kite	No.11 Propeller boss cap fins
	No.12 Contra-rotating propeller
	No.13 Propeller performance monitoring
	No.23 Reduced auxiliary power demand (low energy lighting, etc.)

Extrapolation by ship size, dwt	Extrapolation by main engine output, kW
	No.25 Wind power (fixed sails or wings)
	No.28-29 LNG+ICE or FC
	No.30 Methanol + ICE
	No.31 Ethanol + ICE
	No.32-33 Hydrogen + ICE or FC
	No.34-35 Ammonia + ICE or FC
	No.36-37 Synthetic methane + ICE or FC
	No.38-39 Biomass methane + ICE or FC
	No.40 Synthetic methanol + ICE
	No.41 Biomass methanol + ICE
	No.42 Synthetic ethanol + ICE
	No.43 Biomass ethanol + ICE

Q.2.6 Evaluation for speed reduction

Speed reduction is known as technology having a higher CO_2 reduction potential. It is important to recognize the actual effectiveness and the problems, including the costs.

We assumed 10% speed reduction from 2018, while in the Second GHG Study 10% reduction from 2007 was assumed.

Fuel Oil Consumption, FOC per hour (tonne/hr) of a main engine is proportional to the cube of the speed. Thus, the total FOC (tonne) of the engine during a navigation is proportional to the square of the ship speed, although FOC of auxiliary engines and a boiler are assumed constant. We set the ratio of CO_2 emissions of an auxiliary engine and a boiler to those of a main engine based on data in 2018 mentioned in the result of Table 31 in Section 2.5.3.

In addition, speed reduction of a ship could often cause incremental CAPEX, due to additional ships to keep the total annual transport amount as fleet.

Based upon the above-mentioned conditions, the incremental cost caused by the additional ships can be calculated. For MAC calculation, we assumed that in the base case, additional ships are newly built so as to keep 50% of the total freight transport volume. The CAPEX and the OPEX were calculated by using these values.

Q.2.7 Emission reduction potential for use of alternative fuel

GHG emission reduction potential for LNG

It is known that methane slip occurs in using LNG fueled engines. The global warming potential of methane is 28 according to the IPCC Fifth Assessment Report (AR5). To this end, we estimated the GHG emission reduction cancelled by the amount of methane slip expressed as CO_2 equivalent.

As a result of review of literature on several types of LNG fueled engines, we estimated 10% CO_2 emission reduction cancelled by the methane slip, which is the central value of the engine types using LNG. . Although it is recognized that there are still uncertainties about the amount of methane slip that can be mitigated with the future development of technology by 2050, for the purpose of calculation emission projections the GHG emission from engines using methane as a fuel was set at 0 (zero).

Emission reduction potential for use of alternative fuels

At present, neither hydrogen fueled engines nor ammonia fueled engines applicable to ships of larger size have been developed yet. These kinds of engines are expected to use inflammable oil fuel as pilot fuel the same as LNG fueled engines. With regard to hydrogen and ammonia, CO_2 is not emitted from these engines by combustion but is emitted when Marine Diesel Oil (MDO) is used as pilot fuel to maintain good diesel combustion with worse self-ignition properties.

We expected hydrogen fueled engine not to be the spark ignition type, i.e. Otto type but to be the direct injection type, i.e. Diesel type, because the latter could be easily enlarged. By assuming that the proportion of pilot fuel used in hydrogen fueled engines is similar to that in LNG fueled engines, CO_2 emission reduction potential for hydrogen fueled engines is set at 95% for 2030. As for ammonia fueled engines, MAN B&W [38] stated that the pilot fuel account for around 5% of the total heat input energy. Thus, CO_2 emission reduction potential for ammonia fueled engines is also set at 95% for 2030. By 2050, biofuels or synthetic fuels can be used as pilot fuel. Thus, the GHG emission reduction potential of these kinds of engine at 2050 was set at 100% in the MAC calculation.

Q.3 Updating MACCs among the technologies based on GHG emission reduction scenarios from the baseline at 2030 and 2050

Q.3.1 Methodology

Principle formulae

We used the methodology mentioned in IMarEST (2011) [1] for calculating MACs. Based on IMarEST (2011), we modeled the cost function of installing CO_2 abatement technologies as formula A3.1. IMarEST (2011) considered the opportunity cost related to the loss of service time and/or of spaces due to the installation of the technology, but we did not consider the opportunity cost in formula 3.1.

$$C_j = K_j + S_j - E_j \qquad \text{(formula 3.1)}$$

where,

C_j : the change of annual cost of the technology, j (USD/year);
K_j : the annualized CAPEX (USD/year);
S_j : the incremental operating costs related to the use of the technology (USD/year); and
E_j : the fuel expenditure savings from the technology (USD/year).

All K_j, S_j and E_j are expressed as nominal monetary values, without applying any discount rate.

The annualized CAPEX, K_j means payment corresponding to yearly installment. We annualized the nominal monetary value of CAPEX using a capital recovery factor (CRF). CRF converts a nominal monetary value into equally distributed annual payments over a specified time, at a specified interest rate, as described in formula 3.2.

$$K_j = CAPEX_j \times CRF = CAPEX_j \times \frac{i}{1-(1+i)^{-nj}} \qquad \text{(formula 3.2)}$$

Where:

$CAPEX_j$: the nominal monetary value of CAPEX of technology j (USD/year);
CRF : the capital recovery factor;
i : interest rate; and
n_j : the lifetime of the technology j

n_j is the lifetime of the technology, which may be the remaining lifetime of the ship or the interval of maintenance, etc.

Ej is the fuel expenditure savings from the technology, which is a product of the price of fuel and the saving of fuel as described in formula 3.3 for the technologies other than use of alternative fuels. *Ej* for the use of alternative fuels can be expressed as formula 3.4.

$$E_j = \alpha_j \times F \times P \quad \text{(formula 3.3)}$$
$$E_j = \alpha_j \times F \times (P - P_{alt} \times \beta/\beta_{alt}) \quad \text{(formula 3.4)}$$

Where:
α_j : the fuel reduction rate of technology j;
F : the pre-installation or original fuel consumption for a ship (fuel tonne);
P : the conventional fuel price (USD/tonne);
P_{alt} : the alternative fuel price (USD/tonne);
β: the low heating value of conventional fuel (joule/tonne); and
β_{alt}: the low heating value of alternative fuels (joule/tonne)

α_j represents the product of the maximum fuel reduction rate and the rate of ships adopting the technology after 2018 to all ships in 2030/2050. In Scenario 1, the latter rate is 0.54 for 2030 and 1.0 for 2050. For 2050, a_j corresponds to the maximum fuel reduction rate for the technology. α_j is calculated by formula 3.5.

$$\alpha_j = \gamma_j \times \delta \quad \text{(formula 3.5)}$$

Where:
γ_j : the maximum fuel reduction rate of technology j;
δ : the rate of ships adopting the technology after 2018 year to all ships in 2030/2050

δ is determined by the penetration rate defined in Q.3.3.

The cost efficiency, MAC of given technology is therefore determined in formula 3.6.

$$MAC_j = \frac{C_j}{\alpha_j \times CF \times F} = \frac{K_j + S_j - E_j}{\alpha_j \times CF \times F} \quad \text{(formula 3.6)}$$

Where:
MAC_j : cost efficiency of given technology j (USD/tonne-CO_2);
CF : non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content (3.1144 tonne-CO_2/tonne-Fuel).

For costs and CO_2 abatement potential, the results of 2030 and 2050 are not either obtained by analysis on a year-to-year basis or taking into account continuity.

Base year and year subject to calculation

For MAC calculation, we set 2018 as the base year and 2030 and 2050 as the year subject to calculation.

Interest rate

Interest rate is usually determined on a commercial basis, and on the other hand, some experts indicated that a higher discount rate should be used on socioeconomic basis. Interest rate was assumed at 4% for MAC calculation in the Second IMO GHG study and 10% in IMarEST [1]. Taking into account recent decline in actual market interest rates, we set interest rate at 4% in following calculations.

Future fuel costs

We set the future fuel costs as indicated in the main part of this report, by referencing the literatures such as IMarEST (2011) [1], Frontier Economics (2019) [7], IMO documents related to methanol (2016) [41], ECOFYS (2019) [53], and CE Delft (2020) [54]. We used the reference price of Very Low Sulphur Fuel Oil (VLSFO), which will be used as HFO in 2030 and 2050.

Applying learning curves to the future CAPEX

Costs for several abatement technologies will decrease as time goes. Particularly, costs for technologies in developing stage, e.g. fuel cells, have been decreasing considerably. The literature by UMAS and CE Delft provides learning curve for estimating costs for maritime technologies [5].

The learning curves for the abatement technologies are as shown in Table 96. In the table, cost reduction means the reduction rate of the CAPEX at 2030 or 2050 of the technologies to that at 2018. The CAPEX of the other technologies which are not listed on the table is assumed to be constant.

Table 96 - Learning curves for abatement technologies

Classification	Cost reduction		Applied technologies	
	2030	2050		
Moderate cost reduction	20%	30%	No.7	Waste heat recovery
			No.12	Contra-rotating propeller
			No.15	Air lubrication
			No.24	Towing kite
			No.25	Wind power (fixed sail or wings)
			No.26	Wind engines (Flettner rotor)
			No.27	Solar panels
			No.30	Methanol + ICE
			No.31	Ethanol + ICE
			No.32	Hydrogen + ICE
			No.34	Ammonia + ICE
			No.40	Synthetic methanol + ICE
			No.41	Biomass methanol + ICE
			No.42	Synthetic ethanol + ICE
			No.43	Biomass ethanol + ICE
High cost reduction	50%	60%	No.29	LNG+FC
			No.33	Hydrogen + FC
			No.35	Ammonia + FC
			No.37	Synthetic methane + FC
			No.39	Biomass methane + FC

Q.3.2 Grouping of technologies

Outline of grouping

The Second IMO GHG Study set 10 groups among 25 technologies. In this update, we rearranged these groups and added several technologies related to natural energy and use of alternative fuels taking into account IMarEST (2011) [1] and MADDOX (2012) [13] and then set 16 technology groups as shown in main part of this report.

In order to set up MACCs, we grouped the 44 abatement technologies. The groups were chosen such that technologies in different groups do not exclude each other and that technologies in the same group are not to be installed or used on the same ship.

For example, Group 11 "Wind power" consists of three technologies exploiting wind energy surrounding ships, and therefore it is not appropriate to use more than one technology of the group at the same time and only one technology is chosen from a technology group.

And for MAC and CO_2 emission reduction potential of each group in the calculation, the medians of those values of the technologies in the group were used as a representative value of the group.

Method for use of alternative fuels

Taking into account the nature of alternative fuels, we calculated by dividing the group into 2 subgroups. Group 15A as alternative fuel contains carbon (i.e. conversion factor, Cf, is more than zero) and Group 15B as alternative fuel contains no carbon or may be regarded as carbon neutral fuel.
CO_2 emission reduction of use of alternative fuel can be calculated simply by the sum of respective CO_2 emission reduction, the same as that of wind power and abatement technologies related to engine thermal efficiency.

Method for technologies related to propulsion efficiency

In the MAC calculation, the technologies in Groups 5, 1, 7, 8, 9, 10 and 16 are related to propulsion efficiency. CO_2 emission reduction of abatement technologies related to propulsion efficiency needs to be evaluated not based on the sum of the CO_2 emission reduction of respective technologies but based on the product of CO_2 abatement potential of the technologies. After MAC calculation of respective groups, the CO_2 emission reduction is recalculated based on the above-mentioned method.

Q.3.3 Penetration

For calculating MACs, the number of ships adopting abatement technologies after the base year needs to be specified. Penetration is defined as the rate of the number of ships adopting respective technology to all ships. The potential capacity to implement each technology would be considered as the difference between the expected penetration in the year subject to calculation and the base year.

MADDOX (2012) [13] conducted a quantitative investigation on the penetration rates for individual technologies. We set the penetration rates at 2018 as listed on a table in the main part of this report mainly based on this literature and partly referring to World Fleet Register (WFR), online vessel database provided by Clarkson Research Services Limited, UK [52], etc.

MADDOX (2012) indicated that it is difficult to determine future penetration based on only technologies and the costs. It also indicated that implementation barriers are likely to impede penetration in the future. For example, with regard to implementation barriers, IMarEST (2011) [1] described not only technological barriers, but also institutional barriers, split incentive, and financial barriers, as well as methods to overcome these barriers. This paper also states that it is difficult to quantify the implementation barriers because of uncertainties.

Thus, we provided two scenarios with different penetration rates that are listed in Table 69 of the main part of this report.

Q.4 Sensitivity analysis on of MACCs

In this chapter, we described the results of sensitivity analysis using Scenario 1.

Q.4.1 Sensitivity analysis for fuel costs

Since fuel costs are greatly affected by social situations, fuel costs have large uncertainty and it is difficult to quantify the change of the costs. We conducted sensitivity analysis to investigate such uncertainties.

Table 97 shows the results of sensitivity analysis by changing the conventional fuel (VLSFO) price in 2030, at 375 USD, halved price and doubled price in Scenario 1. In the 375 USD of the conventional fuel price, 36% of CO_2 emission reduction by cost-effective technologies can be achieved, and if the price rises to 750 USD, 80% of CO_2 emission reduction by cost-effective technologies can be achieved, also if the price decreases to 188 USD, 25% of CO_2 emission reduction by cost-effective technologies can be achieved. Whichever of 375 USD, 750 USD or 188 USD the conventional fuel price may be, the MACs are positive on, Group 15A “Use of alternative fuel with carbons”, Group 15B “Use of alternative fuel without carbons” and Group 14 “Solar panels”.

Table 98 show the results of the same sensitivity analysis on the conventional fuel price in 2050 as that in 2030. In Scenario 1 for 2050, cost-effective CO_2 emission reduction accounts for 13% at the 375 USD of the conventional fuel price. In case of the 750 USD, 26% of CO_2 emission reduction by cost-effective technologies can be achieved. Furthermore, in case of 188 USD, 10% of CO_2 emission reduction by cost-effective technologies can be achieved.

Table 97 - Cost efficiency and abatement potential in 2030 (interest rate: 4%, Change of conventional fuel price from base price: -50%/0%/+100%)

Code	Technology group	Conventional fuel price (% change from base price)			CO_2 abatement potential (%)
		-50%	0%	+100%	
		MAC (USD/tonne-CO_2)			
Group 10	Optimization water flow hull openings	-57	-119	-243	1.64%
Group 3	Steam plant improvements	-49	-111	-235	1.30%
Group 6	Propeller maintenance	-40	-102	-226	2.20%
Group 9	Hull maintenance	-30	-92	-216	2.22%
Group 12	Reduced auxiliary power usage	1	-61	-185	0.40%
Group 8	Hull coating	9	-53	-176	1.48%
Group 2	Auxiliary systems	21	-41	-165	0.87%
Group 1	Main engine improvements	27	-35	-159	0.25%
Group 13	Wind power	68	6	-118	0.89%

Code	Technology group	Conventional fuel price (% change from base price)			CO_2 abatement potential (%)
		-50%	0%	+100%	
		MAC (USD/tonne-CO_2)			
Group 16	Speed reduction	79	17	-107	7.38%
Group 5	Propeller improvements	83	21	-103	1.40%
Group 11	Super light ship	116	54	-70	0.28%
Group 4	Waste heat recovery	131	69	-54	1.68%
Group 7	Air lubrication	167	105	-19	1.35%
Group 15A	Use of alternative fuel with carbons	320	258	134	5.54%
Group 15B	Use of alternative fuel without carbons	478	416	292	0.10%
Group 14	Solar panels	1,248	1,186	1,062	0.18%

Table 98 - Cost efficiency and abatement potential in 2050 (interest rate: 4%, Change of conventional fuel price from base price: -50%/0%/+100%)

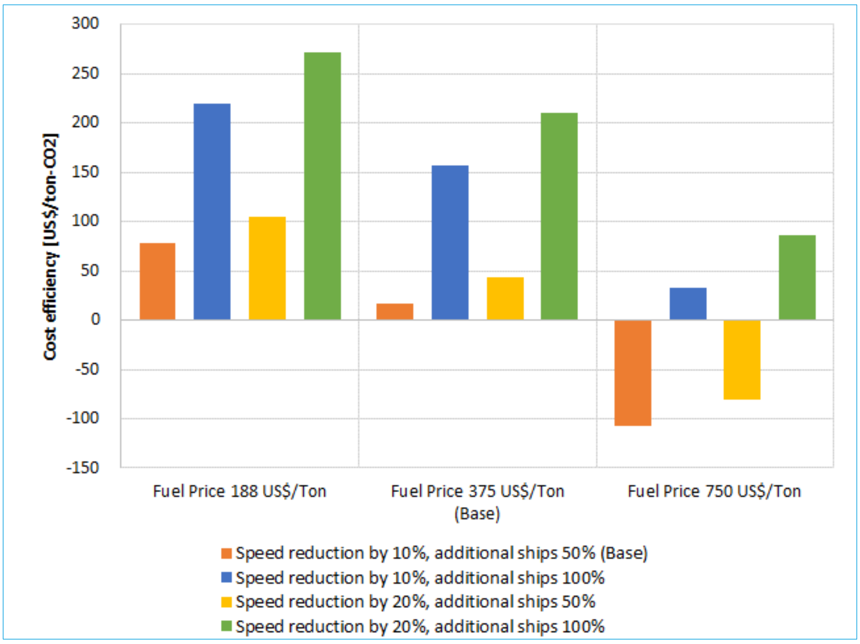
Code	Technology group	Conventional fuel price (% change from base price)			CO_2 abatement potential (%)
		-50%	0%	+100%	
		MAC (USD/tonne -CO_2)			
Group 10	Optimization water flow hull openings	-57	-119	-243	3.00%
Group 3	Steam plant improvements	-49	-111	-235	2.13%
Group 6	Propeller maintenance	-40	-102	-226	3.95%
Group 9	Hull maintenance	-29	-91	-215	3.90%
Group 12	Reduced auxiliary power usage	3	-59	-183	0.71%
Group 8	Hull coating	12	-50	-174	2.55%
Group 2	Auxiliary systems	23	-39	-163	1.59%
Group 1	Main engine improvements	28	-34	-158	0.45%
Group 13	Wind power	64	2	-122	1.66%
Group 16	Speed reduction	72	10	-113	7.54%
Group 5	Propeller improvements	80	18	-106	2.40%
Group 11	Super light ship	116	54	-70	0.39%
Group 4	Waste heat recovery	116	54	-70	3.09%
Group 7	Air lubrication	155	93	-31	2.26%
Group 15B	Use of alternative fuel without carbons	478	416	292	64.08%
Group 14	Solar panels	1,110	1,048	924	0.30%
Group 15A	Use of alternative fuel with carbons	-	-	-	-

Q.4.2 Sensitivity analysis on the MAC of speed reduction

It was confirmed that CO_2 abatement potential of speed reduction indicates higher values as described in the main part of this report. And the results of sensitivity analysis for speed reduction were shown in the report.

Figure 77 and Table 99 show the results of sensitivity analysis for speed reduction rate in 2030, and speed reduction by 20% is compared to Speed reduction by 10%. In our model, by increasing the speed reduction from 10 to 20%, 1.7 times CO_2 reductions can be achieved with this technology. On the other hand, the marginal abatement cost increases by 2.6 times in the base setting.

Figure 77 - Sensitivity analysis of speed reduction in 2030



* The percentage which additional ships account for means the ratio between the number of newly built ships and the number of additional ships to keep the total freight transport volume.

Table 99 - Cost efficiency and abatement potential in 2030 (Speed reduction by 10%/20%, lifetime: 25 years, price of fuel oil: 375 USD/tonne)

Code	Technology group	MAC (USD/tonne-CO_2)	CO_2 abatement potential (%)
Group 16	Speed reduction by 10%	17	7.38%
Group 16	Speed reduction by 20%	43	12.60%

Q.5 MAC calculation by introduction of NPV

Q.5.1 General description of NPV

For the MAC calculation in Chapter Q.3, the investment cost of an abatement technology per year is calculated as an annuity so that it remains constant over the lifetime of the technology. For example, the cost corresponds to the loan per year to be paid at a fixed rate for 25 years. This calculation method is hereinafter referred to as “capital recovery method”. In this case, the MACs for 25-year period containing 2030 are basically identical with those for 25-year period containing 2050 in a ship type and size. This means that it is not possible to identify when an abatement technology is adopted.

However, as a matter of fact, the penetration of a technology changes every year and a kind of adopted technologies alters with the change of the penetration. This can be estimated by introduction of the concept of net present value (NPV).

Under the concept of NPV, in considering the profitability of CO_2 abatement technologies, firstly it is deemed that the farther in the future, the more expenditure and income should be discounted. Based upon this point of view, we calculated MACs by altering the sum of costs and the benefits used in this chapter to NPV, taking into account discount rate. The methodology and discussed results of MAC calculation by introduction of NPV is described in this chapter.

Q.5.2 Formulae of MAC and NPV

MAC of NPV is calculated by formula 5.1 and NPV in formula 5.1 is calculated by formulae 5.2 and 5.3.

$$MAC_{y,j} = \frac{NPV_{y,j}/(y-b)}{\alpha_j \times CF \times F_y} \quad \text{(formula 5.1)}$$

$MAC_{y,j}$: Marginal abatement cost (USD/tonne-CO_2) of technology j in the year, y
α_j : the fuel reduction rate of technology j;
F_y : the pre-installation or original fuel consumption for a ship (tonne-Fuel/year);
CF : Non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content (3.1144 tonne-CO_2/tonne-Fuel); and
b : the base year (2018).

$$NPV_{y,j} = C_{b,j} + \frac{C_{b+1,j}}{(1+r)} + \frac{C_{b+2,j}}{(1+r)^2} + \cdots + \frac{C_{y,j}}{(1+r)^{y-b}} \quad \text{(formula 5.2)}$$

$$C_y = L_{y,j}K_j + S_{y,j} - E_{y,j} \quad \text{(formula 5.3)}$$

r : discount rate (%)
$C_{y,j}$: the cost implementing the technology j in the year y, i.e. investment cost, other operating cost, and decline in cost by reduction of fuel cost (USD/year);
$L_{y,j}$: learning rate in the year y(%)
K_j : the CAPEX in 2018 (USD/year); if the expected lifetime of an abatement technology, *li* (refer to Section Q.2.3), is less than 25 years, the CAPEX is included in the year *Yr+li* under the condition that *Yr+li<Yt* is true, where *Yr* is the year of introduction of the technology, *Yt* is the year subject to MAC calculation, and *i* is an integer of 0 or more;
$S_{y,j}$: the incremental operating cost related to the use of the technology in the year y (USD/year); and
$E_{y,j}$: the fuel expenditure savings from the technology in the year y (USD/year).

Q.5.3 Number of ships for MAC calculation with NPV

For MAC calculation with NPV, if the number of ships by age can be obtained at a year, more accurate calculation could be performed. However, the number of ships to be actually obtained is only the number of new ships and existing ships at the year. Thus, we used the following formula with penetration rate, *P*, to count the number of ships that is effective for calculation of costs and CO_2 emission reduction.

$$M_{y,j} = \sum_{k=b+1}^{y} (N_k P_{k,j} - N_{k-1} P_{k-1,j}) \quad \text{(formula 5.4)}$$

$M_{y,j}$: the number of ship implemented with technology j in the year y

N_k : the number of ship in the year *k*; and
$P_{k,j}$: the penetration rate of technology *j* in the year *k*.

Under Scenario 1, the penetration rate of Group 15A declines after 2030. Thereby the number of ships with any technology in Group 15A decreases, and thus it is assumed that the decline in number is compensated by ships with any technology in Group 15B.

Q.5.4 Results of MAC calculation with NPV

As an example of MAC calculation, we described the result of calculation with NPV based on the assumptions of Scenario 1. Scenario 1 is for maximizing CO_2 abatement potentials.

Since NPV is calculated at each year, the continuity of MACs can be investigated. And the impact on introduction process of respective technologies can be evaluated.

Figure 78 shows respective MACCs at 2030 and 2050. Table 100 shows MAC and CO_2 abatement potential with NPV at 2030 and 2050, respectively. In the figure and the table, CO_2 abatement potential is based on baseline CO_2 emissions at 2030 and 2050.

In Table 100, technologies are arranged in order from smallest to largest value of MACs at 2030. Some groups are listed in the different order on the table.

Figure 79 shows time-series variation of MAC and CO_2 abatement potential of representative abatement technologies. From penetration setting in Table 69 of the main part of this report, it is found that the penetration of use of alternative fuel without carbons increases rapidly from 2030. The time-series variation of MACs in Figure 79 sufficiently indicates a feature of the penetration of the alternative fuel without carbons.

Table 100 - Cost efficiency and abatement potential in 2030 and 2050 with NPV (Scenario 1)

Group	Technology	2030		2050	
		MAC (USD/tonne - CO_2)	CO_2 abatement potential (%)	MAC (USD/tonne - CO_2)	CO_2 abatement potential (%)
Group 3	Steam plant improvements	-28.0	1.30%	-25.3	2.13%
Group 10	Optimization water flow hull openings	-27.1	1.64%	-25.6	3.00%
Group 6	Propeller maintenance	-26.0	2.20%	-23.1	3.95%
Group 9	Hull maintenance	-21.9	2.22%	-20.2	3.90%
Group 8	Hull coating	-5.9	1.48%	-14.3	2.55%
Group 12	Reduced auxiliary power demand	27.6	0.40%	-9.9	0.71%
Group 13	Wind power	36.5	0.89%	4.2	1.66%
Group 2	Auxiliary systems	42.4	0.87%	-4.4	1.59%
Group 1	Main engine improvements	42.5	0.25%	-2.6	0.45%
Group 5	Propeller improvements	54.1	1.40%	5.6	2.40%
Group 16	Speed reduction by 10%	60.3	7.38%	6.7	7.54%
Group 7	Air lubrication	108.0	1.35%	29.1	2.26%
Group 4	Waste heat recovery	123.3	1.68%	22.6	3.09%
Group 15B	Use of alternative fuel without carbons	126.6	0.10%	46.4	64.08%
Group 11	Super light ship	135.3	0.28%	20.2	0.39%
Group 15A	Use of alternative fuel with carbons	156.9	5.54%	---	---
Group 14	Solar panels	631.4	0.18%	241.5	0.30%

Figure 78 - Marginal abatement cost curve in 2030 and 2050 with NPV (Scenario 1, Calculation result of Group 14 "Solar panels" is out of graph.)

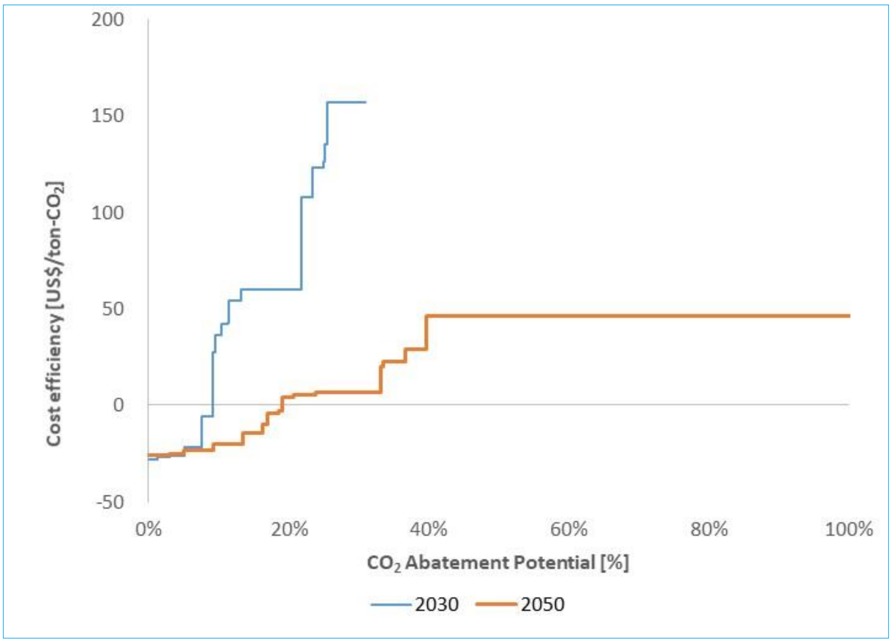
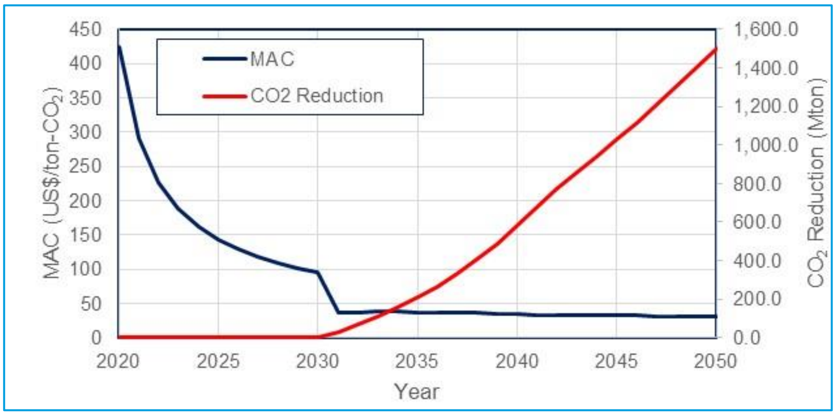


Figure 79 - Time-series variation of MAC and CO_2 abatement potential of representative abatement technologies (No.32 Hydrogen + ICE)



Q.6 QA/QC for updated MACCs

Q.6.1 Comparison between the MACs in this study and that in the Second IMO GHG study

We compared the updated MACs with those reported in the Second IMO GHG Study. For the Second IMO GHG Study, 4 patterns of MACs are shown for each technologies.

In some technologies, the updated MAC has decrease dramatically from that of the Second IMO GHG study. For instance, MAC of Main Engine Tuning in the Second IMO GHG Study is 160

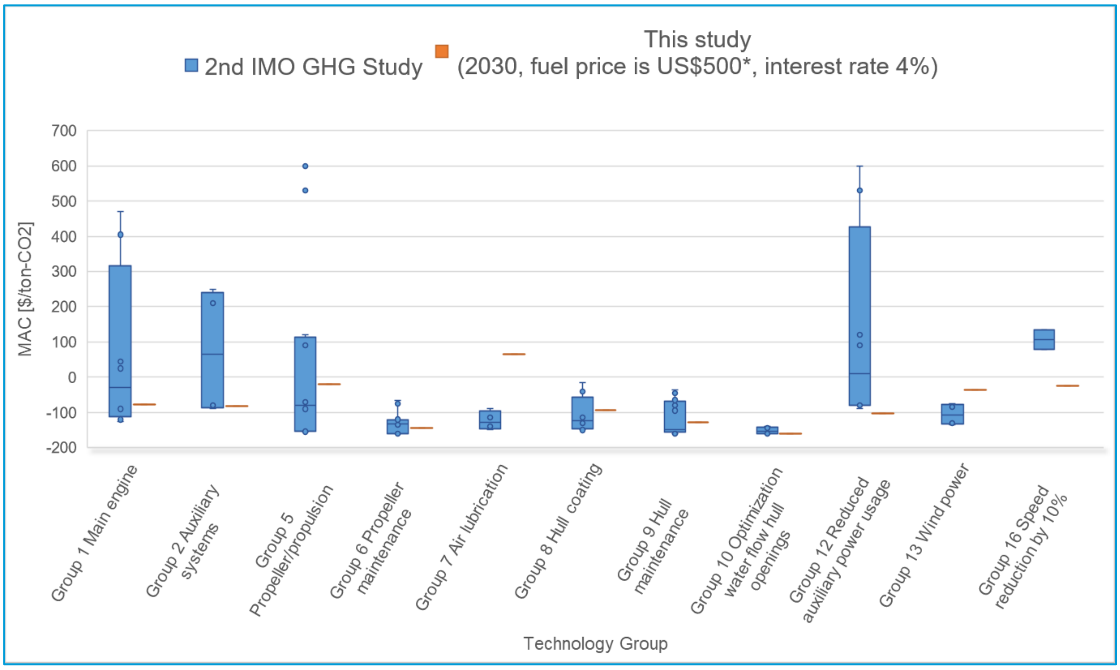
USD/tonne-CO2, which is a median of 4 MACs; 470, 405, -85, -90 USD/tonne-CO_2. On the other hand, the MAC in this study has only one pattern, which indicated -76.5 USD/tonne-CO2. The MAC in this study is within a range of these MACs.

On the other hands, the MAC of some abatement technologies is outside the range between the maximum and the minimum values in the Second IMO GHG Study. Regarding Air lubrication and Towing kite, their CO_2 emission reduction in this study were assumed to be lower than in the Second IMO GHG Study with less uncertainties of data through review of the latest literatures.

Since the MAC of each of groups is expressed a median of respective MACs of individual technologies belong to the group. For the reference, Figure 80 shows the MACs of 11 groups which exist both in the Second IMO GHG study and this study. MACs of more than half of the 11 groups are in the range of MACs in the Second IMO GHG Study. For instance, the updated MAC for the group of Air lubrication is higher than maximum MAC reported in the second GHG study because of the less CO2 abatement potential according to the updated information through review of the latest literatures. We consider that in both cases less uncertaintieis is expected in this update with the same reasons. Therefore, we concluded that the updating MACs are performed with an appropiate QA/QC.

However, with respect to the groups which we could not assess by the method mentioned above, there are potential uncertainties remained, particurary the future cost of the alternative fuel belonging to group 15B could varied significantly according to the balancies between supply and demands on land.

Figure 80 - Comparison of MACs between groups



* The fuel price is set at USD500 to compare with the Second GHG Study.

Q.6.2 Comparison between the methodologies of NPV and capital recovery method

We conducted MAC calculation with NPV based on the assumptions of Scenario 1. We compared the calculation results with those using capital recovery method. Table A6.1 shows MAC and CO_2 abatement potential respectively with NPV and capital recovery method at 2050. In the table, CO_2 abatement potential is based on baseline CO_2 emissions at 2050.

In the table, it is confirmed that CO_2 abatement potential with NPV is almost the same as that with capital recovery method due to the same penetration. This indicates that for obtaining CO_2 abatement potential, there is no difference between NPV and capital recovery method.

On the other hand, the absolute value of MAC with NPV is much smaller than that with capital recovery method. For technologies with large absolute value of MACs, based on the concept that the farther in the future, the more expenditure and income should be discounted, MACs with NPV are approximately 20 to 40% of those with capital recovery method.

For technologies with large absolute value of MACs, respective values calculated with NPV and capital recovery method are listed almost in the same order on the table. However, some respective values calculated with NPV and capital recovery method, i.e. those values of Groups 5 and 12, are listed in the different order on the table.

These results represent the difference in the characteristics of the calculation methods. To evaluate the cost efficiency or the CO_2 abatement potential, a general tendency for the values calculated with capital recovery method and NPV was confirmed, and thus their uncertainties were mitigated by comparing these methods. However, it is deemed that some values differ depending on the CAPEX, the OPEX, and years of depreciation, and thus respective methods need to be selected taking into account their characteristics.

Table 101 - Cost efficiency and abatement potential in 2050 with NPV and capital recovery method (Scenario 1)

Group	Technology	NPV		Capital Recovery Method	
		MAC (USD/tonne-CO_2)	CO_2 abatement potential (%)	MAC (USD/tonne-CO_2)	CO_2 abatement potential (%)
Group 10	Optimization water flow hull openings	-25.6	3.00%	-119.2	3.00%
Group 3	Steam plant improvements	-25.3	2.13%	-111.1	2.13%
Group 6	Propeller maintenance	-23.1	3.95%	-102.0	3.95%
Group 9	Hull maintenance	-20.2	3.90%	-91.2	3.90%
Group 8	Hull coating	-14.3	2.55%	-50.5	2.55%
Group 12	Reduced auxiliary power demand	-9.9	0.71%	-59.4	0.71%
Group 2	Auxiliary systems	-4.4	1.59%	-39.2	1.59%
Group 1	Main engine improvements	-2.6	0.45%	-33.6	0.45%
Group 13	Wind power	4.2	1.66%	1.5	1.66%
Group 5	Propeller improvements	5.6	2.40%	17.8	2.40%
Group 16	Speed reduction by 10%	6.7	7.54%	10.5	7.54%
Group 11	Super light ship	20.2	0.39%	53.7	0.39%
Group 4	Waste heat recovery	22.6	3.09%	54.1	3.09%
Group 7	Air lubrication	29.1	2.26%	92.7	2.26%
Group 15B	Use of alternative fuel without carbons	46.4	64.08%	415.7	64.08%
Group 14	Solar panels	241.5	0.30%	1048.2	0.30%

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Appendix: Definitions of abatement technologies

No.1, Main Engine Tuning

The main engine tuning is optimization of combustion parameters related to fuel consumption of main engines. The most commonly used load ranges have to be determined and then the main engine is optimized for operation at that load. This technology requires a different engine mapping and entails changes in cam profiles and injection timing. This technology can reduce overall fuel consumption, although there may be a penalty in fuel use under seldomly used full load operations.

No.2, Common-rail

Common-rail system is a controlled fuel injection system in which high-pressure fuel generated by a pump is stored in a common-rail (accumulator) and the start and end of fuel injection are determined by controlling an injector. Fuel can be injected with the optimized timing, quantity, and injection pattern according to the engine load.

No.3, Electronic engine control

Recent electronic engine control technologies particularly for large marine diesel engines replace the function of the mechanical camshaft of conventional engines with hydraulic control and optimize fuel injection and exhaust valve timing. By optimizing fuel injection parameters according to the engine load, the fuel efficiency characteristics can be improved.

No.4, Frequency converters

Frequency converters are equipped to regulate frequency in order to adapt the motor load to the actual need at all times. Converter technology is widely used as energy-saving technology in AC motors, e.g. for land-based industrial use. Then the total energy consumed by all the electrical motors on-board can be reduced.

No.5, Speed control of pumps and fans

Many pumps and fans are used on ships. Conventional pumps and fans without speed control constantly circulate a certain amount of cooling water and air to cool engines and other machinery. By controlling speed of pumps and fans automatically, an appropriate amount of water or air can be circulated, which contributes to reduction of power consumption on board.

No.6, Steam plant operation improvements

For ships that use boilers for cargo handling and propulsion, fuel consumption of boilers can be reduced by reducing the steam consumption, monitoring and tuning the boiler performance, and improving the operation of the boiler, such as optimal cargo heating. This technology is valid for oil tankers and chemical tankers with boilers for cargo handling and for liquefied gas tankers with boilers (steam turbine) for propulsion, due to large FOCs in these ship types. In case of ship types using only a little steam, since this technology has small estimated CO_2 reduction, the technology is deemed not applicable in practical even if technically applicable.

No.7, Waste heat recovery

Waste heat recovery is generally the system for generating steam by waste heat from engines and thereby driving steam turbines for generation of electricity, resulting in reduction of fuel consumption of auxiliary engines.

No.8, Exhaust gas boilers on auxiliary engines

This technology recovers the heat of exhaust gas from an auxiliary diesel engine by using a boiler to generate steam or hot water. By making effective use of this technology, the fuel consumption of oil-fired boilers can be reduced.

No.9, Propeller-rudder upgrade

Rudder is a part of propulsion system. Propeller-rudder upgrade is an improvement of propeller performance by changing the rudder profile and propeller. An integrated propeller rudder design with a rudder bulb can reduce the drag of the rudder.

No.10, Propeller upgrade (nozzle, tip winglet)

Propeller upgrade is an improvement of propeller performance by changing nozzle, tip and winglet.

No.11, Propeller boss cap fins

The propeller boss cap fin is a specially designed fins attached to propeller boss cap so that the hub vortex is eliminated and energy can be recovered from the rotating flow around the boss.

No.12, Contra-rotating propeller

Contra-rotating propeller is a propulsion device that coaxially arranges two propellers rotating in the opposite directions. By recovering the rotational energy component generated by the front propeller with the rear propeller, higher efficiency can be achieved. Although this technology has developed before 2000 and it is obvious that energy saving effects can be obtained, its penetration rate at present is not so high.

No.13, Propeller performance monitoring

The propeller performance monitoring is to monitor the propeller performance on a regular basis and to plan appropriate maintenance treatment. The method to monitor the propeller performance is, for example, to place a shaft power meter in a propeller shaft and thereby monitor the deterioration of the required power to reach a certain speed.

No.14, Propeller polishing

Propeller surfaces can be cleaned to reduce roughness and the accumulation of organic materials. Smooth propeller blades improve the efficiency of the propeller. Propeller polishing is done in port while the ship is at the dock or at anchor with mechanical devices controlled by a diver.

No.15, Air lubrication

By covering hull surface in contact with water with air bubbles, frictional resistance can be reduced. In practice, air babbles are injected from the bottom part of a ship to reduce the frictional resistance of the ship. Reduction of frictional resistance can result in a CO_2

reduction effect. A ship with a shallow draft and a wide flat bottom shape can easily be covered with air bubbles.

No.16, Low-friction hull coating

Hull coating is a paint for reducing friction resistance of a ship which occurs between the surface of the painting on hull surface and seawater by preventing marine organisms from fouling the hull, and is used to protect steel hull from corrosion. By reducing friction resistance of a ship, engine power to achieve the same speed can be reduced and thereby CO_2 emissions can also be reduced. Various paint makers have been developing and commercializing new technologies for hull coating such as new biocides (e.g., silyl-acrylates) and self-polishing silicone types. Their CO_2 reduction effect differs depending on the hull shape and operational conditions of a ship.

No.17, Hull performance monitoring

This technology is to monitor the hull performance on regular basis and to plan appropriate maintenance treatment.

No.18, Hull brushing

Hull brushing is to remove marine organisms fouling the hull in order to maintain the smoothness of the hull and thereby reduce friction resistance of the ship. This brushing can result in decreasing engine power to achieve the same speed and thereby can also reduce CO_2 emissions. This should be done on a regular basis or when monitoring of the hull gives an indication that it is needed. Hull brushing is performed while the ship is at anchor or, when allowed, at the dock. Hull brushing is done with a mechanical device that scrubs the surface of the hull and with divers. Regular hull brushing is assumed to be carried out not only during dry-docking but also when a ship is in service. Regarding in-water hull cleaning, the necessity and the adverse effect have been discussed at IMO.

No.19, Hull hydro-blasting

Hull hydro-blasting is a one way of hull cleaning in hydro-blasting, a highly pressured stream of water is used to remove old paint, chemicals, or buildup without damaging original surface.

No.20, Dry-dock full blast

Dry-dock full blast is one way of hull cleaning to remove abrasive material in full area of the surface of the hull during a dry-docking.

No.21, Optimization water flow hull openings

This technology is optimization of hull opening so that the water flow disturbances from hull openings can be reduced by installing scallops or grids (e.g. side thruster).

No.22, Super light ship

Super light ship is technology using light hull materials for shipbuilding such as aluminum or fiber reinforced polymer (FRP) composite. Ships with this technology could achieve more pay load and/or lower fuel consumption than conventional steel ships of the same size.

No.23, Reduced auxiliary power demand (low energy lighting etc.)

There are many different ways to reduce the power demand on-board, i.e. the use of less electricity and heat efficient lighting, the use of energy efficient heating, ventilation and air condition, according to the actual need. Use of energy efficient lighting equipment such as low energy halogen lamps, fluorescent tubes and LED (Light Emitting Diode) in combination with electronically controlled systems for dimming, automatic shut off, etc. is continuously developed as the focus on energy and environment. The new technology has been applied only to a limited extent to the shipping industry and normal design does not include low energy lighting.

No.24, Towing kite

Towing kite is a kite which is attached to the bow of a ship to substitute wind energy for a part of the engine power of the ship. The kite works from wind power which is transferred to the ship and results in less engine power needed to move the ship. This technology requires sufficient space on the upper deck for the its storage and expansion installation.

No.25, Wind power (fixed sails or wings)

This technology exploits wind energy for propulsion, which is proportional to the cube of wind speed. Various types of wind power technologies such as flexible and rigid sails have been developed. Wind propulsion is a promising GHG abatement technology from the viewpoint of direct use of renewable energy. However, since the performance of wind propulsion depends on wind condition, wind propulsion needs to be combined with engine propulsion to maintain punctuality of the ship. Accordingly, this technology is expected to be used not as major propulsion energy but as supplementary one. Wind propulsion is a well-developed technology and thus is likely to start to be introduced early, but the introduction would be limited to some types of ship due to not only high initial cost and difficulty of sail handling during cargo handling but also restriction of upper deck structure and cargo handling equipment. This technology requires enough space on the upper deck for the installation.

No.26, Wind engines (Flettner rotor)

A Flettner rotor is a spinning vertical rotor that generates wind power irrespective of its direction. The rotor is driven by a motor to create a propulsive force acting in a perpendicular direction to that of the wind as a result of the Magnus effect. This technology is applied only to ships which can ensure enough space on the upper deck for the installation, because the size of the equipment is very large.

No.27, Solar panels

This technology is a technology which converts energy of sunlight to electricity by means of solar panels on-board.

No.28, LNG+ICE

This technology uses LNG as fuel in internal combustion engines (ICE). The ICE is assumed to be a reciprocating engine, not a gas-turbine engine. The same is applied to the technology for ICE thereafter. In this study, it is assumed that this technology uses Otto cycle or Diesel cycle type. It is known that methane slip occurs in some types of ICE, the part of CO_2 emission reduction potential could be canceled by methane slip. This technology is already commercially available and is installed for hundreds of ships.

No.29, LNG+FC

This technology uses LNG as fuel in fuel cells (FC). Regarding use of fuel cells, the propulsion system should be motor-driven by electrical power. However, since it is difficult to estimate the incremental cost compared to conventional driven system, we calculated the CAPEX by applying a median of CAPEX from various types of propulsion systems, including motor-driven system. Fuel cells using LNG requires a reforming device which produces hydrogen from methane. This technology is commercially available for land-based facilities.

No.30, Methanol + ICE

This technology uses methanol (CH_3OH) as fuel in internal combustion engines. This technology can be applied to only a few ships. Methanol is assumed to be produced from fossil fuel such as natural gas.

No.31, Ethanol + ICE

This technology uses ethanol (C_2H_5OH) as alternative fuel in internal combustion engines. Since combustion proparties of ethanol is not so different from methanol, ethanol engine can be made based on the technology for methanol engines.

No.32, Hydrogen + ICE

This technology uses hydrogen (H_2) as fuel in internal combustion engines. Large-size hydrogen engines have not been developed yet. These engines are expected to use inflammable oil fuel as pilot fuel in order to control the appropreate timing of hydrogen combustion.

No.33, Hydrogen + FC

This technology uses hydrogen as alternative fuel in fuel cells. This technology is commercially available for some of automobiles. But marine application is not so matured and this technology is still in demonstration stage. Regarding use of fuel cells, use of the propulsion system by electrical power is like No.29.

No.34, Ammonia + ICE

This technology uses ammonia (NH_3) as fuel in internal combustion engines. Large-size ammonia engines have not been developed yet. These engines are expected to use inflammable oil fuel as pilot fuel in order to appropriately control the timing of ammonia fuel combustion.

No.35, Ammonia + FC

This technology uses ammonia as alternative fuel in fuel cells. This technology has not been established yet and is being developed mainly for land-based use. Regarding use of fuel cells, use of the reforming device and the propulsion system by electrical power are like No.29.

No.36, Synthetic methane + ICE

This technology uses the same engines and auxiliaries as those for No.28. Therefore, no changes either in CAPEX or OPEX for maitenance. The fuel used in No.28 is switched to synthesized methane instead of Liquified Natural Gas. If carbon for the synthesis is separated from combustion/atmospheric gas, then the methane as products can be classified as “carbon-free fuel”. In this case, we assume that pilot fuel also will be switched to “carbon-free diesel fuel”, and, also assume that methane slip will be fully mitigated. Therefore, CO_2 emission reduction potential of this technology can reach to 100%. Future price of synthetic methane is assumed, taking into account the process shown above. The supply of synthetic fuel including synthetic methane is still quite limited at present.

No.37, Synthetic methane + FC

This technology is the same as No.29, except for the difference in production method of the fuel as described in No. 36.

No.38, Biomass methane + ICE

This technology is the same as No.28, except for the difference in production method of the fuel. This technology is based on the premise that all biomass origin energy can be classified as carbon neutral. The supply of biomass fuel including biomass methane is still quite limited at present.

No.39, Biomass methane + FC

This technology is the same as No.29, except for the difference in production method of the fuel. This technology is based on the premise that all biomass origin energy can be classified as carbon neutral.

No.40, Synthetic methanol + ICE

This technology is the same as No.30, except for the difference in production method of the fuel as described in No.36.

No.41, Biomass methanol + ICE

This technology is the same as No.30, except for the difference in production method of the fuel. This technology is based on the premise that all biomass origin energy can be classified as carbon neutral.

No.42, Synthetic ethanol + ICE

This technology is the same as No.31, except for the difference in production method of the fuel as described in No.36.

No.43, Biomass ethanol + ICE

This technology is the same as No.31, except for the difference in production method of the fuel. This technology is based on the premise that all biomass origin energy can be classified as carbon neutral.

No.44, Speed reduction by 10%

This technology intends to save fuel consumption during navigation under a speed reduction. Speed of a ship is utilized for evaluating CO_2 emission reduction affected by actual fuel consumption. It should be noted that owing to a dispersion in actual speed of ships, even if the type and size of the ships are the same, there is a range of dispersion also in the CO_2 reduction effect.
We estimated CO_2 reduction effect created by 10% of speed reduction compared to 2018 as the base year.

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