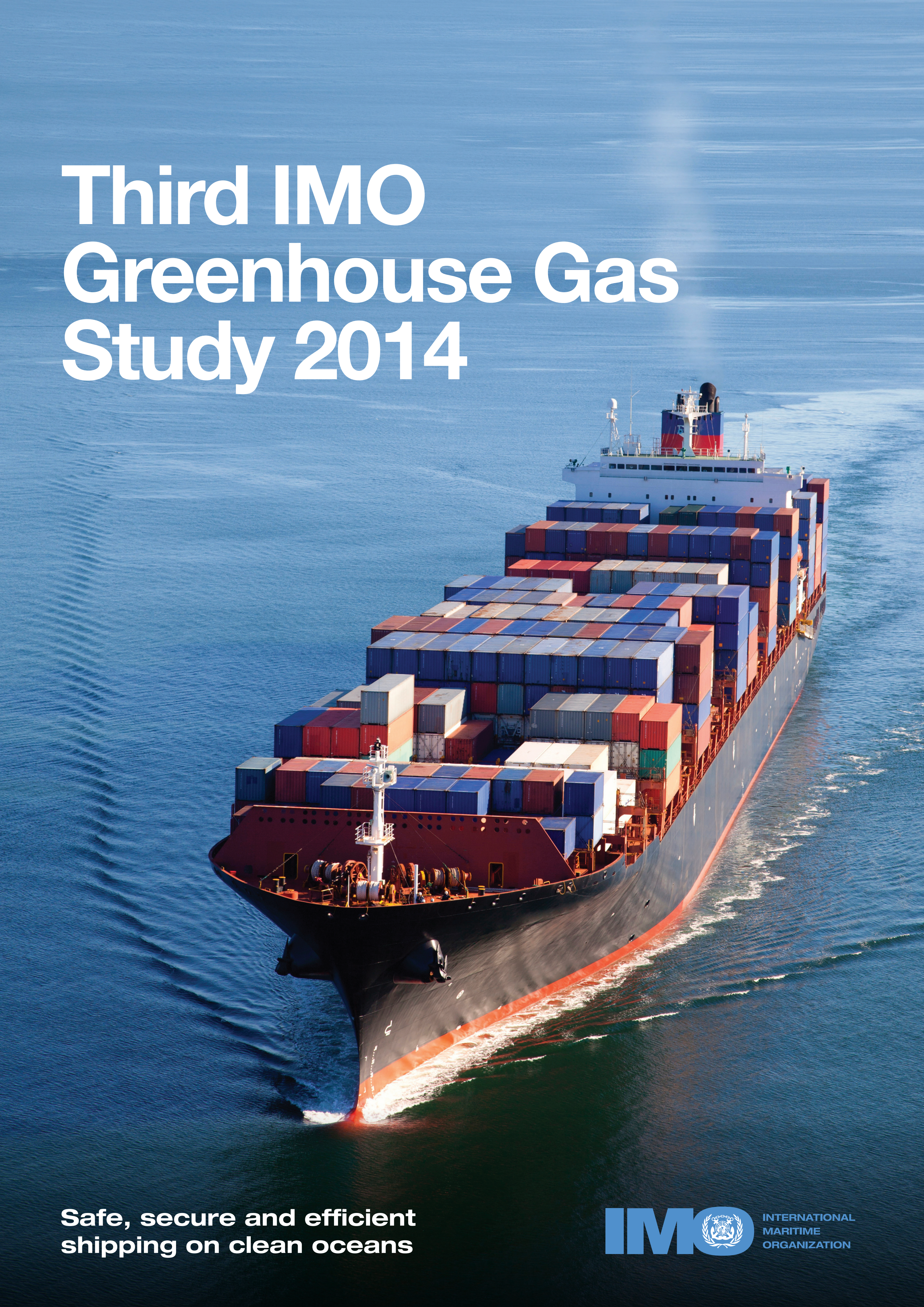

Third IMO Greenhouse Gas Study 2014

Safe, secure and efficient
shipping on clean oceans

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Third IMO GHG Study 2014

Executive Summary and
Final Report

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Foreword by the Secretary-General, Mr Koji Sekimizu

In recognition of the magnitude of the climate change challenge and the importance of global action to address it, we, at IMO, for some time now, have been energetically pursuing the development and implementation of measures to address greenhouse gas (GHG) emissions from international shipping.

According to current estimates presented in this Third IMO GHG Study 2014, international shipping emitted 796 million tonnes of CO_2 in 2012, which accounts for no more than about 2.2% of the total emission volume for that year. By contrast, in 2007, before the global economic downturn, international shipping is estimated to have emitted 885 million tonnes of CO_2, which represented 2.8% of the global emissions of CO_2 for that year. These percentages are all the more significant when considering that shipping is the principal carrier of world trade, carrying as much as 90% by volume and therefore providing a vital service to global economic development and prosperity.

In 2011, IMO adopted a suite of technical and operational measures which together provide an energy-efficiency framework for ships. These mandatory measures entered into force as a 'package' on 1 January 2013, under Annex VI of the International Convention for the Prevention of Pollution from Ships (the MARPOL Convention). These measures address ship types responsible for approximately 85% of CO_2 emissions from international shipping and, together, they represent the first-ever, mandatory global regime for CO_2 emission reduction in an entire industry sector.

Without reference to the findings of this Third IMO GHG Study 2014, it would be extremely difficult for IMO to demonstrate the steady and ongoing improvement in ships' energy efficiencies resulting from the global introduction of the mandatory technical and operational measures. Furthermore, the study findings demonstrate that IMO is best placed, as the competent global regulatory body, to continue to develop both an authoritative and robust greenhouse gas emissions control regime that is relevant for international shipping while also matching overall expectations for climate change abatement.

That said, the mid-range forecasted scenarios presented in this Third IMO GHG Study 2014 show that, by 2050, CO_2 emissions from international shipping could grow by between 50% and 250%, depending on future economic growth and energy developments. Therefore, if we are to succeed in further enhancing the sector's energy efficiency, which is already the most energy-efficient mode of mass transport of cargo, the international community must deliver realistic and pragmatic solutions, both from a technical standpoint and a political perspective. I believe that 2015 will be a crucial year for progress on difficult and complex matters in the world's climate change negotiations, culminating in the international conference to be convened in Paris in December 2015, which should identify the way forward for all sectors. IMO will bring the findings of the Study to the attention of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) and I am confident that, in the light of the progress made by the Organization, both in gathering relevant information and in supporting implementation of the package of mandatory technical and operational measures, we have a positive message to convey to the global community.

The Study constitutes, without any doubt, a significant scientific work. It was undertaken on a global scale by a consortium of world-renowned scientific experts under the auspices of IMO, and I would like to congratulate all the experts involved for the comprehensive and rigorous research work they carried out.

On behalf of the Organization, I also applaud and extend my wholehearted thanks to the Steering Committee of twenty IMO Member Governments for their dedication and support in overseeing this important Study for the Organization, that is, Belgium, Brazil, Canada, Chile, China, Finland, India, Islamic Republic of Iran, Japan, Malaysia, the Marshall Islands, the Netherlands, Nigeria, Norway, the Republic of Korea, the Russian Federation, South Africa, Uganda, the United Kingdom and the United States. I would also like to express profound appreciation to the Governments of Australia, Denmark, Finland, Germany, Japan, the Netherlands, Norway, Sweden and the United Kingdom and to the European Commission for their financial contributions, without which the Study would not have been possible.

I trust that the Third IMO GHG Study 2014 will become the paramount reference for the Organization's Marine Environment Protection Committee as it continues its consideration of further appropriate measures as part of a robust regime to regulate international shipping emissions at the global level.

Contents

Preface

This study of greenhouse gas emissions from ships (hereafter the Third IMO GHG Study 2014) was commissioned as an update of the International Maritime Organization's (IMO) Second IMO GHG Study 2009. The updated study has been prepared on behalf of IMO by an international consortium led by the University College London (UCL) Energy Institute. The Third IMO GHG Study 2014 was carried out in partnership with the organizations and individuals listed below.

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The consortium thanks the Steering Committee of the Third IMO GHG Study 2014 for its helpful review and comments.

The consortium acknowledges and thanks the following organizations for their invaluable data contributions to this study: exactEarth, IHS Maritime, Marine Traffic, Carbon Positive, Kystverket, Gerabulk, V.Ships and Shell. In the course of its efforts, the consortium gratefully received input and comments from the International Energy Agency (IEA), the International Association of Independent Tanker Owners (INTERTANKO), the International Chamber of Shipping (ICS), the World Shipping Council (WSC), the Port of Los Angeles, the Port of Long Beach, the Port Authority of New York & New Jersey, the Environmental Protection Department of the HKSAR Government and the Marine Department of the HKSAR Government.

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Approval of the Third IMO GHG Study 2014

The Marine Environment Protection Committee, at its sixty-seventh session (October 2014), approved the Third IMO GHG Study 2014.

Consortium members:

OPRF
Ocean Policy Research Foundation

UCL ENERGY INSTITUTE

STARCREST CONSULTING GROUP, LLC
ENVIRONMENTAL MANAGEMENT
AIR QUALITY • CLIMATE • SUSTAINABILITY

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FINNISH METEOROLOGICAL INSTITUTE

τScientific

思匯
CIVIC EXCHANGE

CE Delft

exactEarth

EVI
Sustainable Solutions for the Environment

Data partners:

KYSTVERKET

IHS Fairplay

Marine Traffic

StarBulk

V.Ships

GEARBULK

ALMI TANKERS S.A.
Committed to operational integrity

KYLA SHIPPING

IMAREM

GASLOG

List of abbreviations and acronyms

AIS	Automatic Identification System
AR5	Fifth Assessment Report of IPCC
BAU	business as usual
BSFC	brake-specific fuel consumption
DG ENV	Directorate-General for the Environment (European Commission)
DOE	Department of Energy (US)
dwt	deadweight tonnage
ECA	emission control area
EEDI	Energy Efficiency Design Index
EEZ	Exclusive Economic Zone
EF	emissions factor
EIA	Energy Information Administration
EPA	(US) Environmental Protection Agency
FCF	fuel correction factors
FPSO	floating production storage and offloading
GDP	gross domestic product
GHG	greenhouse gas
gt	gross tonnage
GWP	global warming potential (GWP100 represents the 100-year GWP)
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	heavy fuel oil
HSD	high-speed diesel (engine)
IAM	integrated assessment models
IEA	International Energy Agency
IFO	intermediate fuel oil
IHSF	IHS Fairplay
IMarEST	Institute of Marine Engineering, Science and Technology
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LNG	liquefied natural gas
LRIT	long-range identification and tracking (of ships)
MACCs	marginal abatement cost curves
MCR	maximum continuous revolution
MDO	marine diesel oil

MEPC	Marine Environment Protection Committee (IMO)
MGO	marine gas oil
MMSI	Maritime Mobile Service Identity
MSD	medium-speed diesel (engine)
nmi	nautical mile
NMVOC	non-methane volatile organic compounds
PFC	perfluorocarbon
PM	particulate matter
QA	quality assurance
QC	quality control
RCP	representative concentration pathways
S-AIS	Satellite-based Automatic Identification System
SEEMP	Ship Energy Efficiency Management Plan
SFOC	specific fuel oil consumption
SSD	slow-speed diesel (engine)
SSP	shared socioeconomic pathway
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOC	volatile organic compounds

Key definitions

International shipping: shipping between ports of different countries, as opposed to domestic shipping. International shipping excludes military and fishing vessels. By this definition, the same ship may frequently be engaged in both international and domestic shipping operations. This is consistent with the IPCC 2006 Guidelines (Second IMO GHG Study 2009).

International marine bunker fuel: "[…] fuel quantities delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is also excluded and included in residential, services and agriculture" (IEA website: http://www.iea.org/aboutus/glossary/i/).

Domestic shipping: shipping between ports of the same country, as opposed to international shipping. Domestic shipping excludes military and fishing vessels. By this definition, the same ship may frequently be engaged in both international and domestic shipping operations. This definition is consistent with the IPCC 2006 Guidelines (Second IMO GHG Study 2009).

Domestic navigation fuel: fuel delivered to vessels of all flags not engaged in international navigation (see the definition for international marine bunker fuel above). The domestic/international split should be determined on the basis of port of departure and port of arrival and not by the flag or nationality of the ship. Note that this may include journeys of considerable length between two ports in the same country (e.g. San Francisco to Honolulu). Fuel used for ocean, coastal and inland fishing and military consumption is excluded (http://www.iea.org/media/training/presentations/statisticsmarch/StatisticsofNonOECDCountries.pdf).

Fishing fuel: fuel used for inland, coastal and deep-sea fishing. It covers fuel delivered to ships of all flags that have refuelled in the country (including international fishing) as well as energy used in the fishing industry (ISIC Division 03). Before 2007, fishing was included with agriculture/forestry and this may continue to be the case for some countries (http://www.iea.org/media/training/presentations/statisticsmarch/StatisticsofNonOECDCountries.pdf).

Tonne: a metric system unit of mass equal to 1,000 kilograms (2,204.6 pounds) or 1 megagram (1 Mg). To avoid confusion with the smaller "short ton" and the slightly larger "long ton", the tonne is also known as a "metric ton"; in this report, the tonne is distinguished by its spelling.

Ton: a non-metric unit of mass considered to represent 907 kilograms (2,000 pounds), also sometimes called "short ton". In the United Kingdom the ton is defined as 1016 kilograms (2,240 pounds), also called "long ton". In this report, ton is used to imply "short ton" (907 kg) where the source cited used this term, and in calculations based on these sources (e.g. Section 2.1.3 on refrigerants, halogenated hydrocarbons and other non-combustion emissions).

List of figures

Page

Page

Annex Figures

Page

Page

List of tables

Page

Annex Tables

Page

Executive Summary

Key findings from the Third IMO GHG Study 2014

1 Shipping emissions during the period 2007–2012 and their significance relative to other anthropogenic emissions

1.1 For the year 2012, total shipping emissions were approximately 938 million tonnes CO_2 and 961 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping emissions for 2012 are estimated to be 796 million tonnes CO_2 and 816 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping accounts for approximately 2.2% and 2.1% of global CO_2 and GHG emissions on a CO_2 equivalent (CO_2e) basis, respectively. Table 1 presents the full time series of shipping CO_2 and CO_2e emissions compared with global total CO_2 and CO_2e emissions.

For the period 2007–2012, on average, shipping accounted for approximately 3.1% of annual global CO_2 and approximately 2.8% of annual GHGs on a CO_2e basis using 100-year global warming potential conversions from the IPCC Fifth Asssessment Report (AR5). A multi-year average estimate for all shipping using bottom-up totals for 2007–2012 is 1,015 million tonnes CO_2 and 1,036 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping accounts for approximately 2.6% and 2.4% of CO_2 and GHGs on a CO_2e basis, respectively. A multi-year average estimate for international shipping using bottom-up totals for 2007–2012 is 846 million tonnes CO_2 and 866 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. These multi-year CO_2 and CO_2e comparisons are similar to, but slightly smaller than, the 3.3% and 2.7% of global CO_2 emissions reported by the Second IMO GHG Study 2009 for total shipping and international shipping in the year 2007, respectively.

Table 1 – *a) Shipping CO_2 emissions compared with global CO_2 (values in million tonnes CO_2); and b) Shipping GHGs (in CO_2e) compared with global GHGs (values in million tonnes CO_2e)*

Third IMO GHG Study 2014 CO_2

Year	Global CO_2[1]	Total shipping	% of global	International shipping	% of global
2007	31,409	1,100	3.5%	885	2.8%
2008	32,204	1,135	3.5%	921	2.9%
2009	32,047	978	3.1%	855	2.7%
2010	33,612	915	2.7%	771	2.3%
2011	34,723	1,022	2.9%	850	2.4%
2012	35,640	938	2.6%	796	2.2%
Average	33,273	1,015	3.1%	846	2.6%

Third IMO GHG Study 2014 CO_2e

Year	Global CO_2e[2]	Total shipping	% of global	International shipping	% of global
2007	34,881	1,121	3.2%	903	2.6%
2008	35,677	1,157	3.2%	940	2.6%
2009	35,519	998	2.8%	873	2.5%
2010	37,085	935	2.5%	790	2.1%
2011	38,196	1,045	2.7%	871	2.3%
2012	39,113	961	2.5%	816	2.1%
Average	36,745	1,036	2.8%	866	2.4%

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[1] Global comparator represents CO_2 from fossil fuel consumption and cement production, converted from Tg C y^{-1} to million metric tonnes CO_2. Sources: Boden et al. 2013 for years 2007–2010; Peters et al. 2013 for years 2011–2012, as referenced in IPCC (2013).

[2] Global comparator represents N_2O from fossil fuels consumption and cement production. Source: IPCC (2013, Table 6.9).

1.2 This study estimates multi-year (2007–2012) average annual totals of 20.9 million and 11.3 million tonnes for NO_x (as NO_2) and SO_x (as SO_2) from all shipping, respectively (corresponding to 6.3 million and 5.6 million tonnes converted to elemental weights for nitrogen and sulphur respectively). NO_x and SO_x play indirect roles in tropospheric ozone formation and indirect aerosol warming at regional scales. Annually, international shipping is estimated to produce approximately 18.6 million and 10.6 million tonnes of NO_x (as NO_2) and SO_x (as SO_2) respectively; this converts to totals of 5.6 million and 5.3 million tonnes of NO_x and SO_x respectively (as elemental nitrogen and sulphur respectively). Global NO_x and SO_x emissions from all shipping represent about 15% and 13% of global NO_x and SO_x from anthropogenic sources reported in the IPCC Fifth Assessment Report (AR5), respectively; international shipping NO_x and SO_x represent approximately 13% and 12% of global NO_x and SO_x totals respectively.

1.3 Over the period 2007–2012, average annual fuel consumption ranged between approximately 247 million and 325 million tonnes of fuel consumed by all ships within this study, reflecting top-down and bottom-up methods respectively. Of that total, international shipping fuel consumption ranged on average between approximately 201 million and 272 million tonnes per year, depending on whether consumption was defined as fuel allocated to international voyages (top-down) or fuel used by ships engaged in international shipping (bottom-up), respectively.

1.4 Correlated with fuel consumption, CO_2 emissions from shipping are estimated to range between approximately 739 million and 795 million tonnes per year in top-down results, and to range between approximately 915 million and 1135 million tonnes per year in bottom-up results. Both the top-down and the bottom-up methods indicate limited growth in energy and CO_2 emissions from ships during 2007–2012, as suggested both by the IEA data and the bottom-up model. Nitrous oxide (N_2O) emission patterns over 2007–2012 are similar to the fuel consumption and CO_2 patterns, while methane (CH_4) emissions from ships increased due to increased activity associated with the transport of gaseous cargoes by liquefied gas tankers, particularly over 2009–2012.

1.5 International shipping CO_2 estimates range between approximately 596 million and 649 million tonnes calculated from top-down fuel statistics, and between approximately 771 million and 921 million tonnes according to bottom-up results. International shipping is the dominant source of the total shipping emissions of other GHGs: nitrous oxide (N_2O) emissions from international shipping account for the majority (approximately 85%) of total shipping N_2O emissions, and methane (CH_4) emissions from international ships account for nearly all (approximately 99%) of total shipping emissions of CH_4.

1.6 Refrigerant and air conditioning gas releases account for the majority of HFC (and HCFC) emissions from ships. For older vessels, HCFCs (R-22) are still in service, whereas new vessels use HFCs (R134a/R404a). Use of SF_6 and PFCs in ships is documented as rarely used in large enough quantities to be significant and is not estimated in this report.

1.7 Refrigerant and air conditioning gas releases from shipping contribute an additional 15 million tons (range 10.8 million–19.1 million tons) in CO_2 equivalent emissions. Inclusion of reefer container refrigerant emissions yields 13.5 million tons (low) and 21.8 million tons (high) of CO_2 emissions.

1.8 Combustion emissions of SO_x, NO_x, PM, CO and NMVOCs are also correlated with fuel consumption patterns, with some variability according to properties of combustion across engine types, fuel properties, etc., which affect emissions substances differently.

2 Resolution, quality and uncertainty of the emissions inventories

2.1 The bottom-up method used in this study applies a similar approach to the Second IMO GHG Study 2009 in order to estimate emissions from activity. However, instead of analysis carried out using ship type, size and annual average activity, calculations of activity, fuel consumption (per engine) and emissions (per GHG and pollutant substances) are performed for each in-service ship during each hour of each of the years 2007–2012, before aggregation to find the totals of each fleet and then of total shipping (international, domestic and fishing) and international shipping. This removes any uncertainty attributable to the use of average values and represents a substantial improvement in the resolution of shipping activity, energy demand and emissions data.

2.2 This study clearly demonstrates the confidence that can be placed in the detailed findings of the bottom-up method of analysis through both quality analysis and uncertainty analysis. Quality analysis includes rigorous testing of bottom-up results against noon reports and LRIT data. Uncertainty analysis quantifies, for the first time, the uncertainties in the top-down and the bottom-up estimates.

2.3 These analyses show that high-quality inventories of shipping emissions can be produced through the analysis of AIS data using models. Furthermore, the advancement in the state-of-the-art methods used in this study provides insight and produces new knowledge and understanding of the drivers of emissions within subsectors of shipping (ships of common type and size).

2.4 The quality analysis shows that the availability of improved data (particularly AIS data) since 2010 has enabled the uncertainty of inventory estimates to be reduced (relative to previous years' estimates). However, uncertainties remain, particularly in the estimation of the total number of active ships and the allocation of ships or ship voyages between domestic and international shipping.

2.5 For both the top-down and the bottom-up inventory estimates in this study, the uncertainties relative to the best estimate are not symmetrical (the likelihood of an overestimate is not the same as that of an underestimate). The top-down estimate is most likely to be an underestimate (for both total shipping and international shipping), for reasons discussed in the main report. The bottom-up uncertainty analysis shows that while the best estimate is higher than top-down totals, uncertainty is more likely to lower estimated values from the best estimate (again, for both total shipping and international shipping).

2.6 There is an overlap between the estimated uncertainty ranges of the bottom-up and the top-down estimates of fuel consumption in each year and for both total shipping and international shipping. This provides evidence that the discrepancy between the top-down and the bottom-up best estimate value is resolvable through the respective methods' uncertainties.

2.7 Estimates of CO_2 emissions from the top-down and bottom-up methods converge over the period of the study as the source data of both methods improve in quality. This provides increased confidence in the quality of the methodologies and indicates the importance of improved AIS coverage from the increased use of satellite and shore-based receivers to the accuracy of the bottom-up method.

2.8 All previous IMO GHG studies have preferred activity-based (bottom-up) inventories. In accordance with IPCC guidance, the statements from the MEPC Expert Workshop and the Second IMO GHG Study 2009, the Third IMO GHG Study 2014 consortium specifies the bottom-up best estimate as the consensus estimate for all years' emissions for GHGs and all pollutants.

3 Comparison of the inventories calculated in this study with the inventories of the Second IMO GHG Study 2009

3.1 Best estimates for 2007 fuel use and CO_2 emissions in this study agree with the "consensus estimates" of the Second IMO GHG Study 2009 as they are within approximately 5% and approximately 4%, respectively.

3.2 Differences with the Second IMO GHG Study 2009 can be attributed to improved activity data, better precision of individual vessel estimation and aggregation and updated knowledge of technology, emissions rates and vessel conditions. Quantification of uncertainties enables a fuller comparison of this study with previous work and future studies.

3.3 The estimates in this study of non-CO_2 GHGs and some air pollutant substances differ substantially from the 2009 results for the common year 2007. This study produces higher estimates of CH_4 and N_2O than the earlier study, higher by 43% and 40% respectively (approximate values). The new study estimates lower emissions of SO_x (approximately 30% lower) and approximately 40% of the CO emissions estimated in the 2009 study.

3.4 Estimates for NO_x, PM and NMVOC in both studies are similar for 2007, within 10%, 11% and 3% respectively (approximate values).

4 Fuel use trends and drivers in fuel use (2007–2012), in specific ship types

4.1 The total fuel consumption of shipping is dominated by three ship types: oil tankers, container ships and bulk carriers. Consistently for all ship types, the main engines (propulsion) are the dominant fuel consumers.

4.2 Allocating top-down fuel consumption to international shipping can be done explicitly, according to definitions for international marine bunkers. Allocating bottom-up fuel consumption to international shipping required application of a heuristic approach. The Third IMO GHG Study 2014 used qualitative information from AIS to designate larger passenger ferries (both passenger-only pax ferries and vehicle-and-passenger ro-pax ferries) as international cargo transport vessels. Both methods are unable to fully evaluate global domestic fuel consumption.

4.3 The three most significant sectors of the shipping industry from a CO_2 perspective (oil tankers, container ships and bulk carriers) have experienced different trends over the period of this study (2007–2012). All three contain latent emissions increases (suppressed by slow steaming and historically low activity and productivity) that could return to activity levels that create emissions increases if the market dynamics that informed those trends revert to their previous levels.

4.4 Fleet activity during the period 2007–2012 demonstrates widespread adoption of slow steaming. The average reduction in at-sea speed relative to design speed was 12% and the average reduction in daily fuel consumption was 27%. Many ship type and size categories exceeded this average. Reductions in daily fuel consumption in some oil tanker size categories was approximately 50% and some container-ship size categories reduced energy use by more than 70%. Generally, smaller ship size categories operated without significant change over the period, also evidenced by more consistent fuel consumption and voyage speeds.

4.5 A reduction in speed and the associated reduction in fuel consumption do not relate to an equivalent percentage increase in efficiency, because a greater number of ships (or more days at sea) are required to do the same amount of transport work.

5 Future scenarios (2012–2050)

5.1 Maritime CO_2 emissions are projected to increase significantly in the coming decades. Depending on future economic and energy developments, this study's BAU scenarios project an increase by 50% to 250% in the period to 2050. Further action on efficiency and emissions can mitigate the emissions growth, although all scenarios but one project emissions in 2050 to be higher than in 2012.

5.2 Among the different cargo categories, demand for transport of unitized cargoes is projected to increase most rapidly in all scenarios.

5.3 Emissions projections demonstrate that improvements in efficiency are important in mitigating emissions increase. However, even modelled improvements with the greatest energy savings could not yield a downward trend. Compared to regulatory or market-driven improvements in efficiency, changes in the fuel mix have a limited impact on GHG emissions, assuming that fossil fuels remain dominant.

5.4 Most other emissions increase in parallel with CO_2 and fuel, with some notable exceptions. Methane emissions are projected to increase rapidly (albeit from a low base) as the share of LNG in the fuel mix increases. Emissions of nitrogen oxides increase at a lower rate than CO_2 emissions as a result of Tier II and Tier III engines entering the fleet. Emissions of particulate matter show an absolute decrease until 2020, and sulphurous oxides continue to decline through to 2050, mainly because of MARPOL Annex VI requirements on the sulphur content of fuels.

Aim and objective of the study

This study provides IMO with a multi-year inventory and future scenarios for GHG and non-GHG emissions from ships. The context for this work is:

- The IMO committees and their members require access to up-to-date information to support working groups and policy decision-making. Five years have passed since the publication of the previous study (Second IMO GHG Study 2009), which estimated emissions for 2007 and provided scenarios from 2007 to 2050. Furthermore, IPCC has updated its analysis of future scenarios for the global economy in its AR5 (2013), including mitigation scenarios. IMO policy developments, including MARPOL Annex VI amendments for EEDI and SEEMP, have also occurred since the 2009 study was undertaken. In this context, the Third IMO GHG Study 2014 updates the previous work by producing yearly inventories since 2007.
- Other studies published since the Second IMO GHG Study 2009 have indicated that one impact of the global financial crisis may have been to modify previously reported trends, both in demand for shipping and in the intensity of shipping emissions. This could produce significantly different recent-year

emissions than the previously forecasted scenarios, and may modify the long-run projections for 2050 ship emissions. In this context, the Third IMO GHG Study 2014 provides new projections informed by important economic and technological changes since 2007.

- Since 2009, greater geographical coverage achieved via satellite technology/AIS receivers has improved the quality of data available to characterize shipping activity beyond the state of practice used in the Second IMO GHG Study 2009. These new data make possible more detailed methods that can substantially improve the quality of bottom-up inventory estimates. Additionally, improved understanding of marine fuel (bunker) statistics reported by nations has identified, but not quantified, potential uncertainties in the accuracy of top-down inventory estimates from fuel sales to ships. Improved bottom-up estimates can reconcile better the discrepancies between top-down and bottom-up emissions observed in previous studies (including the Second IMO GHG Study 2009). In this context, the Third IMO GHG Study 2014 represents the most detailed and comprehensive global inventory of shipping emissions to date.

The scope and design of the Third IMO GHG Study 2014 responds directly to specific directives from the IMO Secretariat that derived from the IMO Expert Workshop (2013) recommendations with regard to activity-based (bottom-up) ship emissions estimation. These recommendations were:

- to consider direct vessel observations to the greatest extent possible;
- to use vessel-specific activity and technical details in a bottom-up inventory model;
- to use "to the best extent possible" actual vessel speed to obtain engine loads.

The IMO Expert Workshop recognized that "bottom-up estimates are far more detailed and are generally based on ship activity levels by calculating the fuel consumption and emissions from individual ship movements" and that "a more sophisticated bottom-up approach to develop emission estimates on a ship-by-ship basis" would "require significant data to be inputted and may require additional time […] to complete".

Structure of the study and scope of work

The Third IMO GHG Study 2014 report follows the structure of the terms of reference for the work, which comprise three main sections:

Section 1: Inventories of CO_2 emissions from international shipping 2007–2012

This section deploys both a top-down (2007–2011) and a bottom-up (2007–2012) analysis of CO_2 emissions from international shipping. The inventories are analysed and discussed with respect to the quality of methods and data and to uncertainty of results. The discrepancies between the bottom-up and top-down inventories are discussed. The Third IMO GHG Study 2014 inventory for 2007 is compared to the Second IMO GHG Study 2009 inventory for the same year.

Section 2: Inventories of emissions of GHGs and other relevant substances from international shipping 2007–2012

This section applies the top-down (2007–2011) and bottom-up (2007–2012) analysis from Section 1 in combination with data describing the emissions factors and calculations inventories for non-CO_2 GHGs – methane (CH_4), nitrous oxide (N_2O), HFCs and sulphur hexafluoride (SF_6) – and relevant substances – oxides of sulphur (SOx), oxides of nitrogen (NO_x), particulate matter (PM), carbon monoxide (CO) and NMVOCs. The quality of methods and data and uncertainty of the inventory results are discussed, and comparisons are made between the top-down and bottom-up estimates in the Third IMO GHG Study 2014 and the results of the Second IMO GHG Study 2009.

Section 3: Scenarios for shipping emissions 2012–2050

This section develops scenarios for future emissions for all GHGs and other relevant substances investigated in Sections 1 and 2. Results reflect the incorporation of new base scenarios used in GHG projections for non-shipping sectors and method advances, and incorporate fleet activity and emissions insights emerging from the 2007–2012 estimates. Drivers of emissions trajectories are evaluated and sources of uncertainty in the scenarios are discussed.

Summary of Section 1: Inventories of CO_2 emissions from international shipping 2007–2012

2012 fuel consumption and CO_2 emissions by ship type

Figure 1 presents the CO_2 emissions by ship type for 2012, calculated using the bottom-up method. Equivalent ship-type-specific results cannot be presented for the top-down method because the reported marine fuel sales statistics are only available in three categories: international, domestic and fishing.

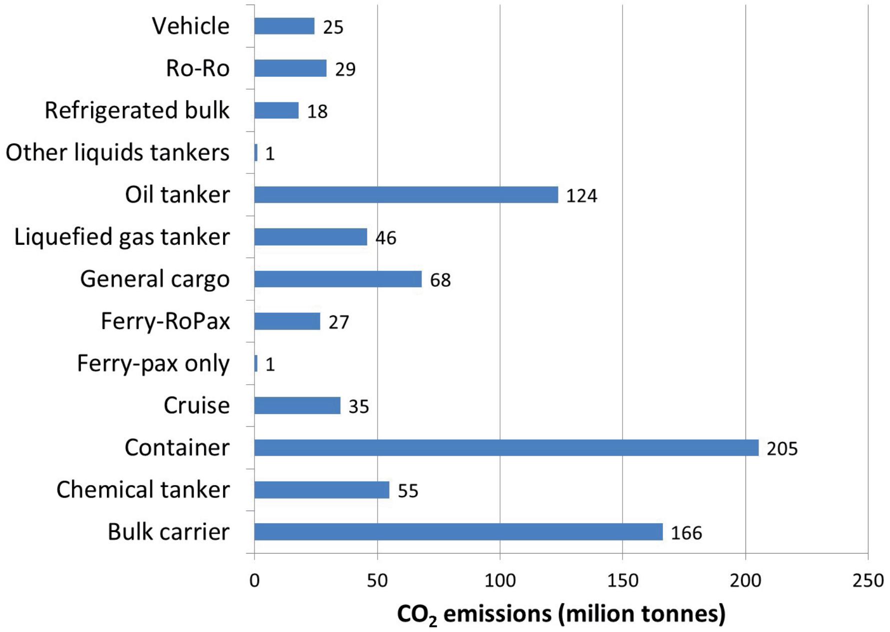


Figure 1: *Bottom-up CO_2 emissions from international shipping by ship type 2012*

Figure 2 shows the relative fuel consumption among vessel types in 2012 (both international and domestic shipping), estimated using the bottom-up method. The figure also identifies the relative fuel consumption of the main engine (predominantly for propulsion purposes), auxiliary engine (normally for electricity generation) and the boilers (for steam generation). The total shipping fuel consumption is shown in 2012 to be dominated by three ship types: oil tankers, bulk carriers and container ships. In each of those ship types, the main engine consumes the majority of the fuel.

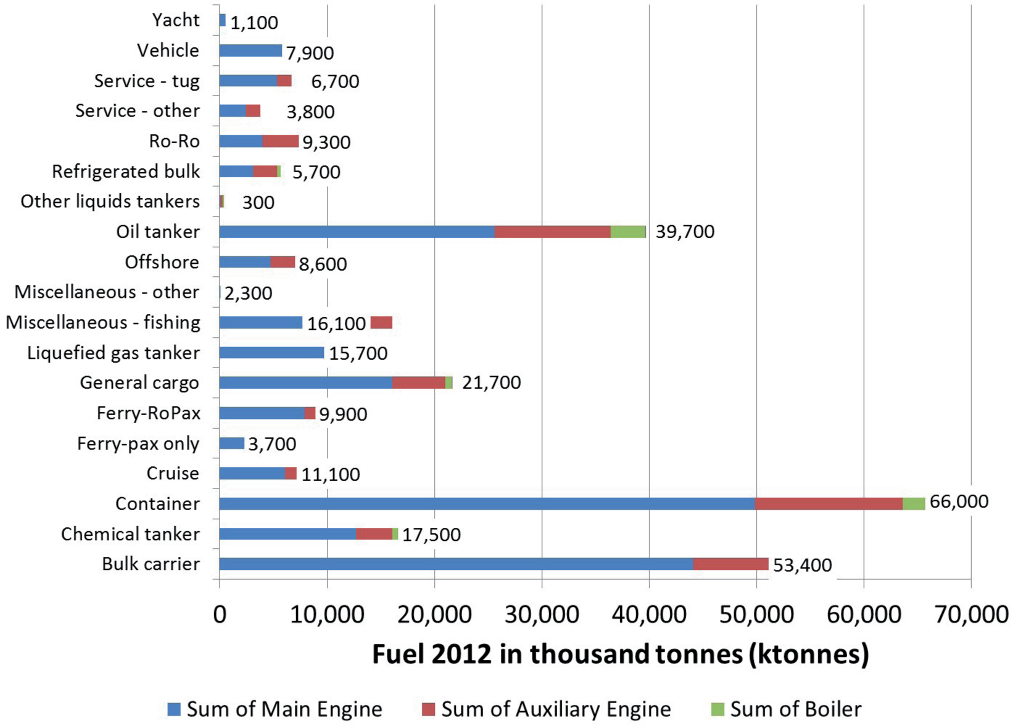


Figure 2: *Summary graph of annual fuel consumption broken down by ship type and machinery component (main, auxiliary and boiler) 2012*

2007–2012 fuel consumption by bottom-up and top-down methods: Third IMO GHG Study 2014 and Second IMO GHG Study 2009

Figure 3 shows the year-on-year trends for the total CO_2 emissions of each ship type, as estimated using the bottom-up method. Figure 4 and Figure 5 show the associated total fuel consumption estimates for all years of the study, from both the top-down and bottom-up methods. The total CO_2 emissions aggregated to the lowest level of detail in the top-down analysis (international, domestic and fishing) are presented in Table 2 and Table 3.

Figure 3 presents results from the Third IMO GHG Study 2014 (all years). Figure 4 presents results from both the Third IMO GHG Study 2014 (all years) and the Second IMO GHG Study 2009 (2007 results only). The comparison of the estimates in 2007 shows that using both the top-down and the bottom-up analysis methods, the results of the Third IMO GHG Study 2014 for the total fuel inventory and the international shipping estimate are in close agreement with the findings from the Second IMO GHG Study 2009. Further analysis and discussion of the comparison between the two studies is undertaken in Section 1.6 of this report.

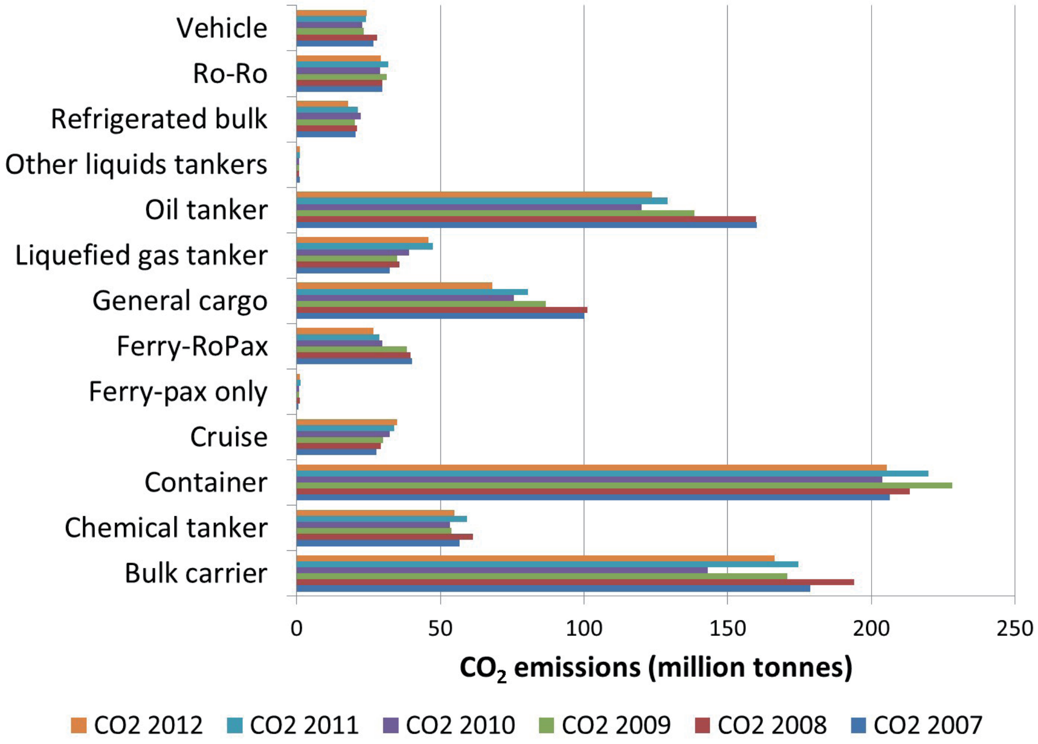


Figure 3: *CO_2 emissions by ship type (international shipping only) calculated using the bottom-up method for all years (2007–2012)*

In Figure 4 the vertical bar attached to the total fuel consumption estimate for each year and each method represents the uncertainty in the estimates. For the bottom-up method, this error bar is derived from a Monte Carlo simulation of the most important input parameters to the calculation. The most important sources of uncertainty in the bottom-up method results are the number of days a ship spends at sea per year (attributable to incomplete AIS coverage of a ship's activity) and the number of ships that are active (in service) in a given year (attributable to the discrepancy between the difference between the number of ships observed in the AIS data and the number of ships described as in service in the IHSF database). The top-down estimates are also uncertain, including observed discrepancies between global imports and exports of fuel oil and distillate oil, observed transfer discrepancies among fuel products that can be blended into marine fuels, and potential for misallocation of fuels between sectors of shipping (international, domestic and fishing). Neither the top-down nor the bottom-up uncertainties are symmetric, showing that uncertainty in the top-down best estimate is more likely to increase the estimate of fuel consumption from the best estimate, and that uncertainty in the bottom-up best-estimate value is more likely to lower estimated values from the best estimate.

Differences between the bottom-up and the top-down best-estimate values in this study are consistent with the differences observed in the Second IMO GHG Study 2009. This convergence of best estimates is important because, in conjunction with the quality (Section 1.4) and uncertainty (Section 1.5) analyses, it provides evidence that increasing confidence can be placed in both analytical approaches.

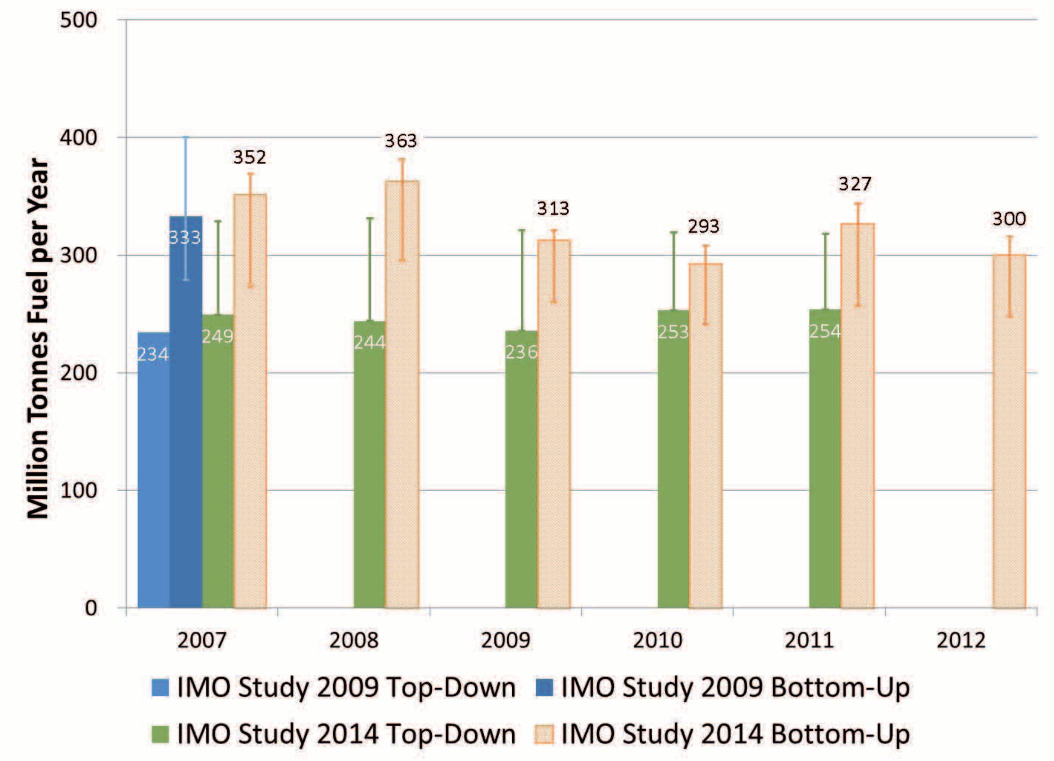


Figure 4: *Summary graph of annual fuel use by all ships, estimated using the top-down and bottom-up methods, showing Second IMO GHG Study 2009 estimates and uncertainty ranges*

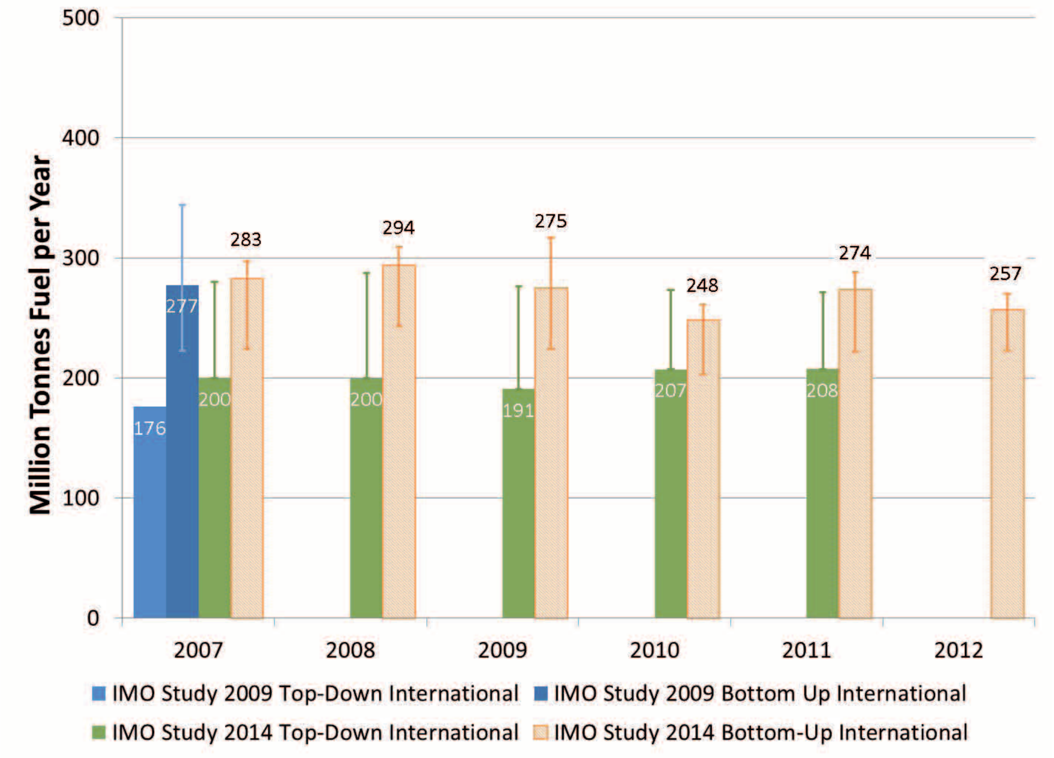


Figure 5: *Summary graph of annual fuel use by international shipping, estimated using the top-down and bottom-up methods, showing Second IMO GHG Study 2009 estimates and uncertainty ranges*

Table 2 – *International, domestic and fishing CO_2 emissions 2007–2011, using top-down method*

Marine sector	Fuel type	2007	2008	2009	2010	2011
International shipping	HFO	542.1	551.2	516.6	557.1	554.0
	MDO	83.4	72.8	79.8	90.4	94.9
	LNG	0.0	0.0	0.0	0.0	0.0
Top-down international total	**All**	**625.5**	**624.0**	**596.4**	**647.5**	**648.9**
Domestic navigation	HFO	62.0	44.2	47.6	44.5	39.5
	MDO	72.8	76.6	75.7	82.4	87.8
	LNG	0.1	0.1	0.1	0.1	0.2
Top-down domestic total	**All**	**134.9**	**121.0**	**123.4**	**127.1**	**127.6**
Fishing	HFO	3.4	3.4	3.1	2.5	2.5
	MDO	17.3	15.7	16.0	16.7	16.4
	LNG	0.1	0.1	0.1	0.1	0.1
Top-down fishing total	**All**	**20.8**	**19.2**	**19.3**	**19.2**	**19.0**
Total CO_2 emissions		**781.2**	**764.1**	**739.1**	**793.8**	**795.4**

Table 3 – *International, domestic and fishing CO_2 emissions 2007–2012, using bottom-up method*

Marine sector	Fuel type	2007	2008	2009	2010	2011	2012
International shipping	HFO	773.8	802.7	736.6	650.6	716.9	667.9
	MDO	97.2	102.9	104.2	102.2	109.8	105.2
	LNG	13.9	15.4	14.2	18.6	22.8	22.6
Bottom-up international total	**All**	**884.9**	**920.9**	**855.1**	**771.4**	**849.5**	**795.7**
Domestic navigation	HFO	53.8	57.4	32.5	45.1	61.7	39.9
	MDO	142.7	138.8	80.1	88.2	98.1	91.6
	LNG	0	0	0	0	0	0
Bottom-up domestic total	**All**	**196.5**	**196.2**	**112.6**	**133.3**	**159.7**	**131.4**
Fishing	HFO	1.6	1.5	0.9	0.8	1.4	1.1
	MDO	17.0	16.4	9.3	9.2	10.9	9.9
	LNG	0	0	0	0	0	0
Bottom-up fishing total	**All**	**18.6**	**18.0**	**10.2**	**10.0**	**12.3**	**11.0**
Total CO_2 emissions		**1,100.1**	**1,135.1**	**977.9**	**914.7**	**1,021.6**	**938.1**

The fuel split between residual (HFO) and distillate (MDO) for the top-down approach is explicit in the fuel sales statistics from IEA. However, the HFO/MDO allocation for the bottom-up inventory could not be finalized without considering the top-down sales insights. This is because the engine-specific data available through IHSF are too sparse, incomplete or ambiguous with respect to fuel type for large numbers of main engines and nearly all auxiliary engines on vessels. QA/QC analysis with regard to fuel type assignment in the bottom-up model was performed using top-down statistics as a guide, along with fuel allocation information from the Second IMO GHG Study 2009. This iteration was important in order to finalize the QA/QC on fuel-determined pollutant emissions (primarily SO_x) and resulted in slight QA/QC adjustments for other emissions.

In addition to the uncertainties behind the total shipping emissions and fuel type allocations in each year, both methods contain separate but important uncertainty about the allocation of fuel consumption and emissions to international and domestic shipping. Where international shipping is defined as shipping between ports of different countries, and one tank of fuel is used for multiple voyages, there is an intrinsic shortcoming in the top-down method. More specifically, fuel can be sold to a ship engaged in both domestic and international voyages but only one identifier (international or domestic) can be assigned to the report of fuel sold. Using the bottom-up method, while location information is available, the AIS coverage is not consistently high enough to be able to resolve voyage-by-voyage detail. Section 1.2 discusses possible alternative approaches to the classification of international and domestic fuel consumption using the bottom up method and the selection of definition according to ship type and size category.

Particular care must be taken when interpreting the domestic fuel consumption and emissions estimates from both the top-down and the bottom-up methods. Depending on where the fuel for domestic shipping and fishing is bought, it may or may not be adequately captured in the IEA marine bunkers. For example, inland or leisure and fishing vessels may purchase fuel at locations where fuel is also sold to other sectors of the economy and therefore it may be misallocated. In the bottom-up method, fuel consumption is only included for ships that appear in the IHSF database (and have an IMO number). While this should cover all international shipping, many domestic vessels (inland, fishing or cabotage) may not be included in this database. An indication of the number of vessels excluded from the bottom-up method was obtained from the count of MMSI numbers observed on the AIS for which no match with the IHSF database was obtained. The implications of this count for both the bottom-up and top-down analyses are discussed in Section 1.4.

2007–2012 trends in CO_2 emissions and drivers of emissions

Figure 6, Figure 7 and Figure 8 present indexed time series of the total CO_2 emissions during the period studied for three ship types: oil tankers, container ships and bulk carriers (all in-service ships). The figures also present several key drivers of CO_2 emissions that can be used to decompose the fleet, activity and CO_2 emission trends, estimated using the bottom-up method. All trends are indexed to their values in 2007. Despite rising transport demand in all three fleets, each fleet's total emissions are shown either to remain approximately constant or to decrease slightly.

The contrast between the three plots in Figures 6–8 shows that these three sectors of the shipping industry have experienced different changes over the period 2007–2012. The oil tanker sector has reduced its emissions by a total of 20%. During the same period the dry bulk and container ship sectors also saw absolute emissions reductions but by smaller amounts. All ship types experienced similar reductions in average annual fuel consumption but differences in the number of ships in service, which explains the difference in fleet total CO_2 emissions trends. The reduction in average days at sea during the period studied is greatest in the dry bulk fleet, while the container ship fleet has seen a slight increase. Consistent with the results presented in Table 4, container ships adopted slow steaming more than any other ship type. So, over the same period of time, similar reductions in average fuel consumption per ship have come about through different combinations of slow steaming and days at sea.

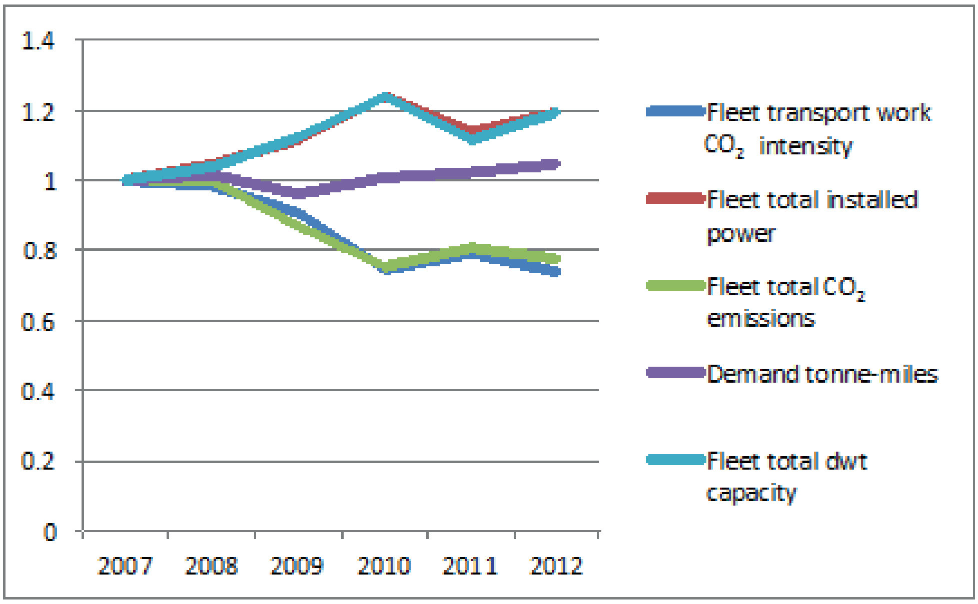


Figure 6: *Time series for trends in emissions and drivers of emissions in the oil tanker fleet 2007–2012. All trends are indexed to their values in 2007*

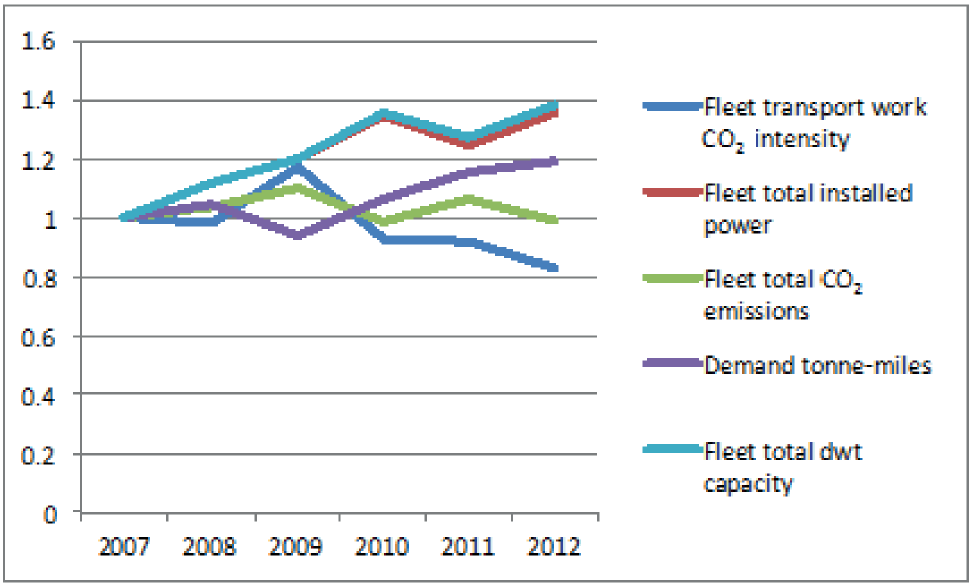


Figure 7: *Time series for trends in emissions and drivers of emissions in the container ship fleet 2007–2012. All trends are indexed to their values in 2007*

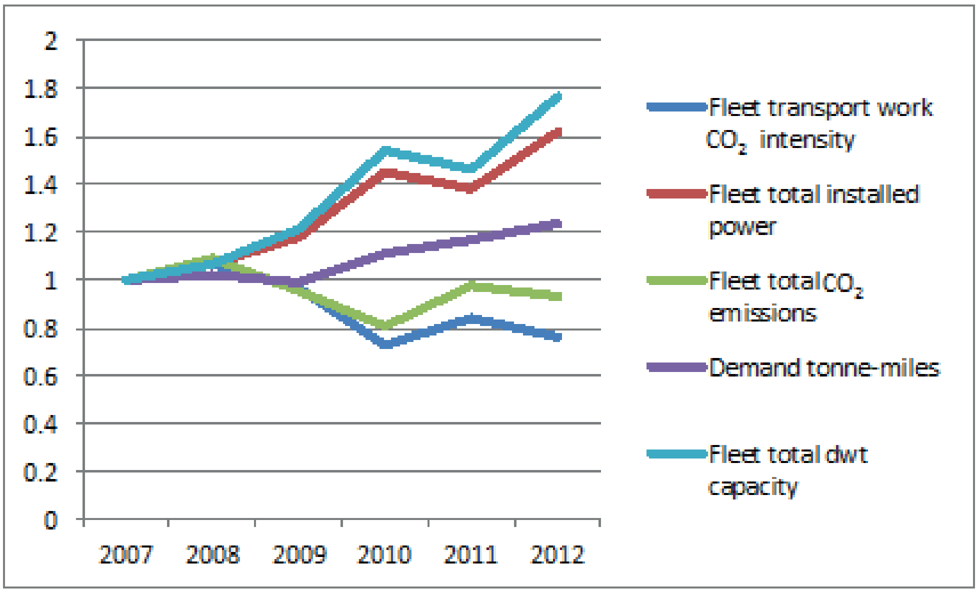


Figure 8: *Time series for trends in emissions and drivers of emissions in the bulk carrier fleet 2007–2012. All trends are indexed to their values in 2007*

Note: Further data on historical trends and relationship between transport supply and demand can be found in the Second IMO GHG Study 2009.

The bottom-up method constructs the calculations of ship type and size totals from calculations for the fuel consumption of each individual in-service ship in the fleet. The method allows quantification of both the variability within a fleet and the influence of slow steaming. Across all ship types and sizes, the average ratio of operating speed to design speed was 0.85 in 2007 and 0.75 in 2012. In relative terms, ships have slowed down in line with the reported widespread adoption of slow steaming, which began after the financial crisis. The consequence of this observed slow steaming is a reduction in daily fuel consumption of approximately 27%, expressed as an average across all ship types and sizes. However, that average value belies the significant operational changes that have occurred in certain ship type and size categories. Table 4 describes, for three of the ship types studied, the ratio between slow steaming percentage (average at-sea operating speed expressed as a percentage of design speed), the average at-sea main engine load factor (a percentage of the total installed power produced by the main engine) and the average at-sea main engine daily fuel consumption. Many of the larger ship sizes in all three categories are estimated to have experienced reductions in daily fuel consumption in excess of the average value for all shipping of 27%.

Table 4 also shows that the ships with the highest design speeds (container ships) have adopted the greatest levels of slow steaming (in many cases operating at average speeds that are 60–70% of their design speeds), relative to oil tankers and bulk carriers. Referring back to Figure 8, it can be seen that for bulk carriers, the observed trend in slow steaming is not concurrent with the technical specifications of the ships remaining constant. For example, the largest bulk carriers (200,000+ dwt capacity) saw increases in average size (dwt capacity) as well as increased installed power (from an average of 18.9 MW to 22.2 MW), as a result of a large number of new ships entering the fleet over the period studied. (The fleet grew from 102 ships in 2007 to 294 ships in 2012.)

The analysis of trends in speed and days at sea is consistent with the findings in Section 3 that the global fleet is currently at or near the historic low in terms of productivity (transport work per unit of capacity). The consequence is that these (and many other) sectors of the shipping industry represent latent emissions increases, because the fundamentals (number of ships in service) have seen upward trends that have been offset as economic pressures act to reduce productivity (which in turn reduces emissions intensity). Whether and when the latent emissions may appear is uncertain, as it depends on the future market dynamics of the industry. However, the risk is high that the fleet could encounter conditions favouring the conversion of latent emissions to actual emissions; this could mean that shipping reverts to the trajectory estimated in the Second IMO GHG Study 2009. This upward potential is quantified as part of sensitivity analysis in Section 3.

A reduction in speed and the associated reduction in fuel consumption do not relate to an equivalent percentage increase in efficiency, because a greater number of ships (or more days at sea) are required to do the same amount of transport work. This relationship is discussed in greater detail in Section 3.

Table 4 – *Relationship between slow steaming, engine load factor (power output) and fuel consumption for 2007 and 2012*

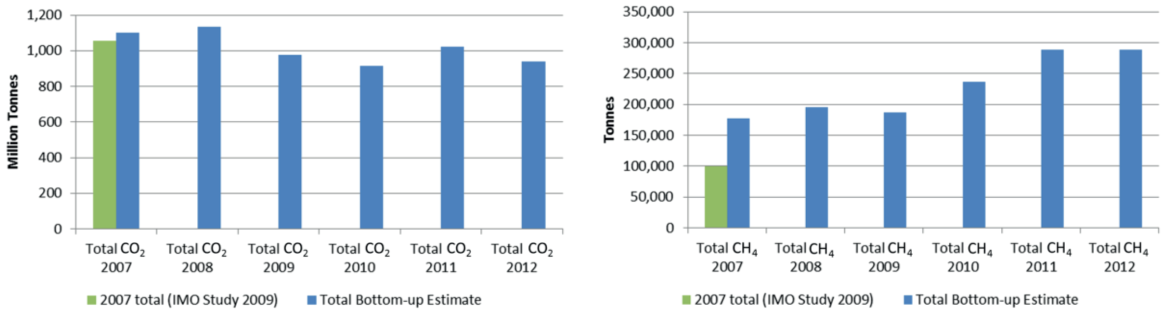
Ship type	Size category	Units	2007			2012			% change in average at-sea tonnes per day (tpd) 2007–2012
			Ratio of average at-sea speed to design speed	Average at-sea main engine load factor (% MCR)	At-sea consumption in tonnes per day (tpd)	Ratio of average at-sea speed to design speed	Average at-sea main engine load factor (% MCR)	At-sea consumption in tonnes per day (tpd)	
Bulk carrier	0–9,999	dwt	0.92	92%	7.0	0.84	70%	5.5	–24%
	10,000–34,999		0.86	68%	22.2	0.82	59%	17.6	–23%
	35,000–59,999		0.88	73%	29.0	0.82	58%	23.4	–21%
	60,000–99,999		0.90	78%	37.7	0.83	60%	28.8	–27%
	100,000–199,999		0.89	77%	55.5	0.81	57%	42.3	–27%
	200,000–+		0.82	66%	51.2	0.84	62%	56.3	10%
Container	0–999	TEU	0.82	62%	17.5	0.77	52%	14.4	–19%
	1,000–1,999		0.80	58%	33.8	0.73	45%	26.0	–26%
	2,000–2,999		0.80	58%	55.9	0.70	39%	38.5	–37%
	3,000–4,999		0.80	59%	90.4	0.68	36%	58.7	–42%
	5,000–7,999		0.82	63%	151.7	0.65	32%	79.3	–63%
	8,000–11,999		0.85	69%	200.0	0.65	32%	95.6	–71%
	12,000–14,500		0.84	67%	231.7	0.66	34%	107.8	–73%
	14,500–+		–	–	–	0.60	28%	100.0	–
Oil tanker	0–4,999	dwt	0.89	85%	5.1	0.80	67%	4.3	–18%
	5,000–9,999		0.83	64%	9.2	0.75	49%	7.1	–26%
	10,000–19,999		0.81	61%	15.3	0.76	49%	10.8	–34%
	20,000–59,999		0.87	72%	28.8	0.80	55%	22.2	–26%
	60,000–79,999		0.91	83%	45.0	0.81	57%	31.4	–35%
	80,000–119,999		0.91	81%	49.2	0.78	51%	31.5	–44%
	120,000–199,999		0.92	83%	65.4	0.77	49%	39.4	–50%
	200,000–+		0.95	90%	103.2	0.80	54%	65.2	–45%

Summary of Section 2: Inventories of emissions of GHGs and other relevant substances from international shipping 2007–2012

All data are calculated using the bottom-up method and the results of this study are compared with the Second IMO GHG Study 2009 results in Figure 9 (all shipping). Figure 10 (international, domestic and fishing) presents the time series of GHGs and other relevant substance emissions over the period of this study (2007–2012). Calculations performed using the top-down method are presented in Section 2.3.

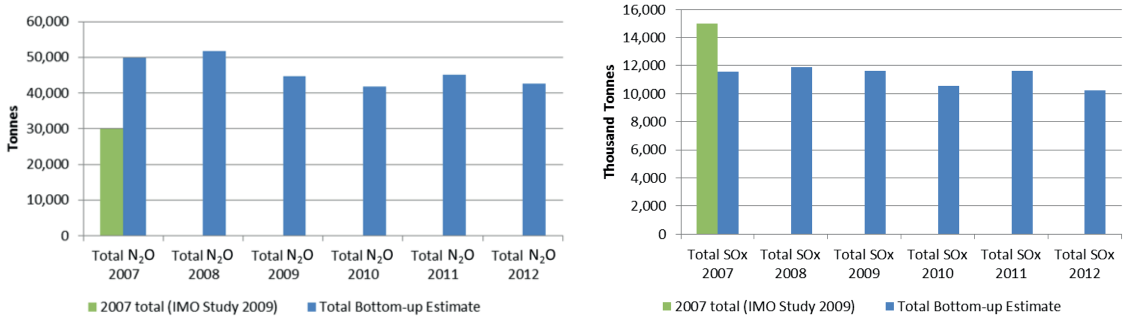
The trends are generally well correlated with the time series trend of CO_2 emissions totals, which is in turn well correlated to fuel consumption. A notable exception is the trend in CH_4 emissions, which is dominated by the increase in LNG fuel consumption in the LNG tanker fleet (related to increases in fleet size and activity) during the years 2007–2012.

Agreements with the Second IMO GHG Study 2009 estimates are generally good, although there are some differences, predominantly related to the emissions factors used in the respective studies and how they have been applied. The Second IMO GHG Study 2009 estimated CH_4 emissions from engine combustion to be approximately 100,000 tonnes in the year 2007.



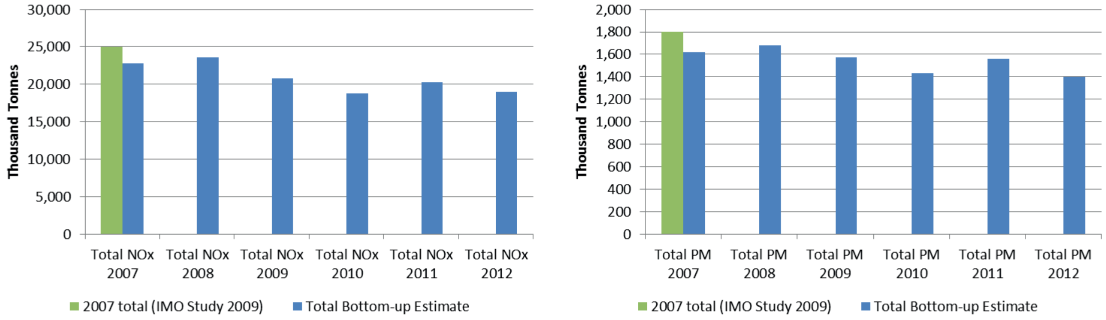
a. CO_2

b. CH_4



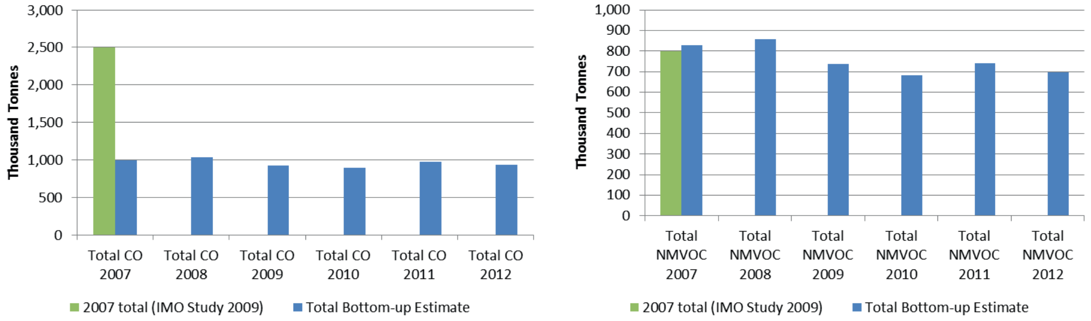
c. N_2O

d. SO_x



e. NO_x

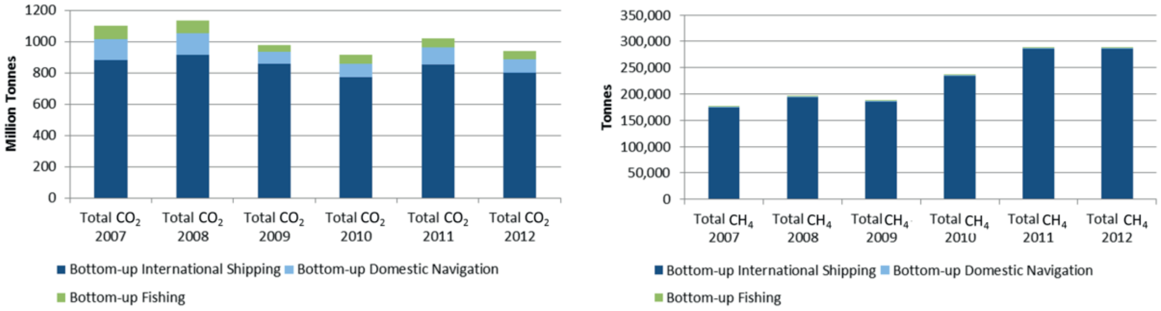
f. PM



g. CO

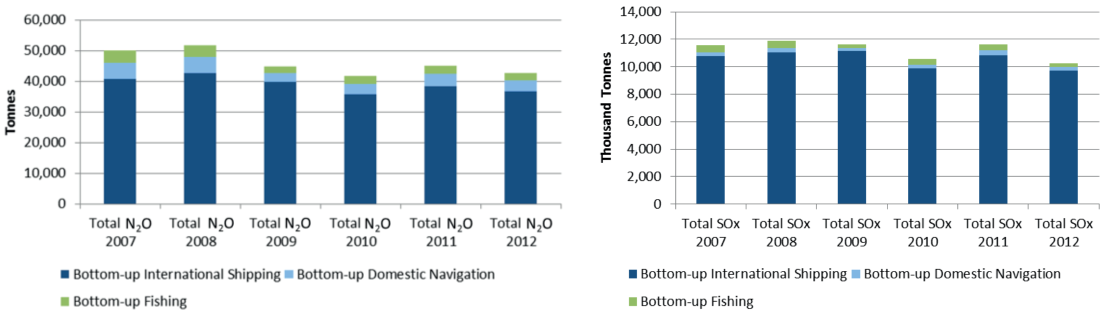
h. NMVOC

Figure 9: *Time series of bottom-up results for GHGs and other substances (all shipping). The green bar represents the Second IMO GHG Study 2009 estimate*



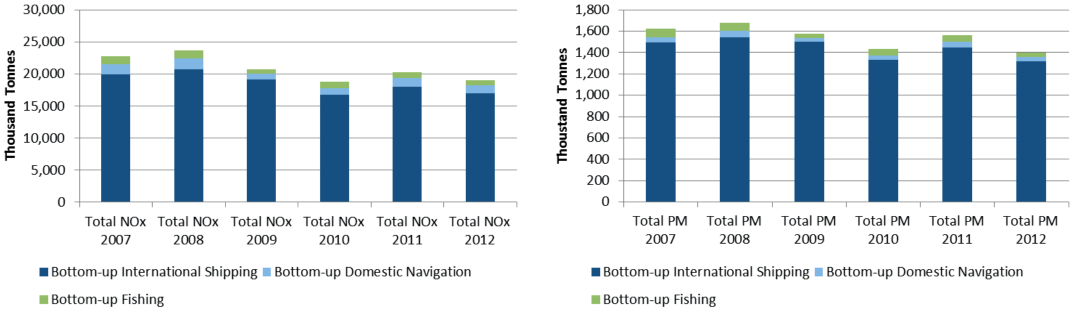
a. CO_2

b. CH_4



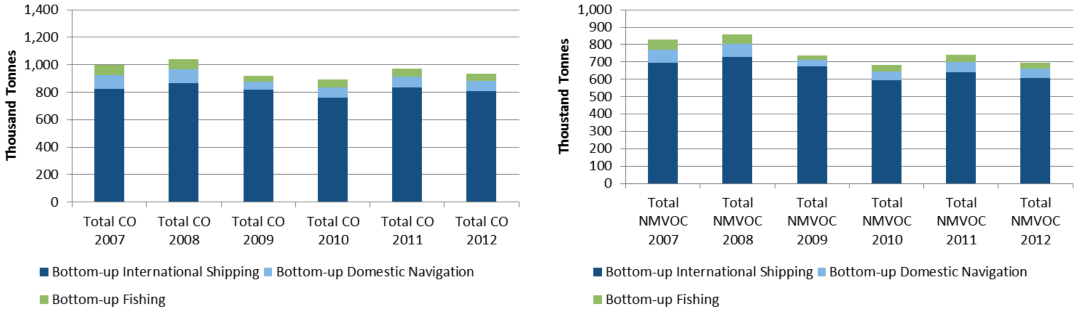
c. N_2O

d. SO_x



e. NO_x

f. PM



g. CO

h. NMVOC

Figure 10: *Time series of bottom-up results for GHGs and other substances (international shipping, domestic navigation and fishing)*

Summary of Section 3: Scenarios for shipping emissions 2012–2050

Shipping projection scenarios are based on the Representative Concentration Pathways (RCPs) for future demand of coal and oil transport and Shared Socioeconomic Pathways (SSPs) for future economic growth. SSPs have been combined with RCPs to develop four internally consistent scenarios of maritime transport demand. These are BAU scenarios, in the sense that they assume that the current policies on the energy efficiency and emissions of ships remain in force, and that no increased stringencies or additional policies will be introduced. In line with common practice in climate research and assessment, there are multiple BAU scenarios to reflect the inherent uncertainty in projecting economic growth, demographics and the development of technology.

In addition, for each of the BAU scenarios, this study developed three policy scenarios that have increased action on either energy efficiency or emissions or both. Hence, there are two fuel-mix/ECA scenarios: one keeps the share of fuel used in ECAs constant over time and has a slow penetration of LNG in the fuel mix; the other projects a doubling of the amount of fuel used in ECAs and has a higher share of LNG in the fuel mix. Moreover, two efficiency trajectories are modelled: the first assumes an ongoing effort to increase the fuel efficiency of new and existing ships, resulting in a 60% improvement over the 2012 fleet average by 2050; the second assumes a 40% improvement by 2050. In total, emissions are projected for 16 scenarios.

Maritime transport demand projections

The projections of demand for international maritime transport show a rapid increase in demand for unitized cargo transport, as it is strongly coupled to GDP and statistical analyses show no sign of demand saturation. The increase is largest in the SSP that projects the largest increase of global GDP (SSP5) and relatively more modest in the SSP with the lowest increase (SSP3). Non-coal dry bulk is a more mature market where an increase in GDP results in a modest increase in transport demand.

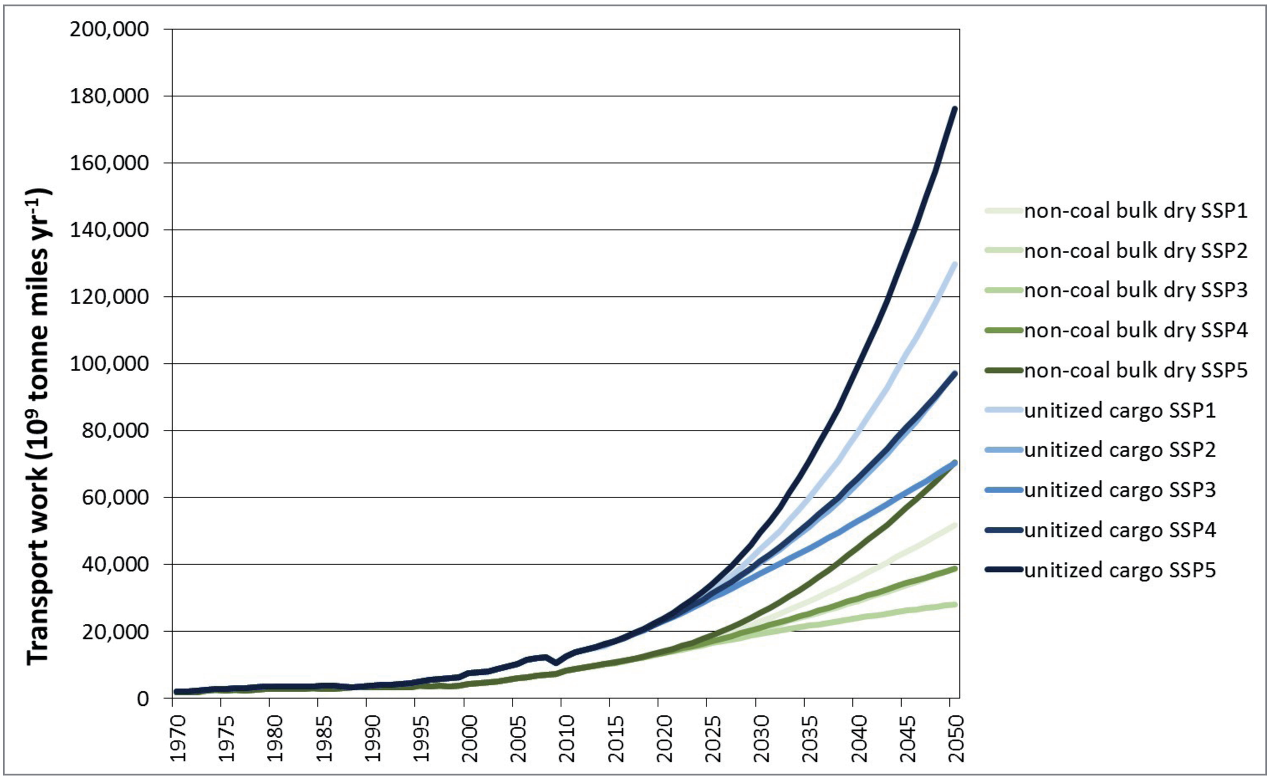


Figure 11: *Historical data to 2012 on global transport work for non-coal combined bulk dry cargoes and other dry cargoes (billion tonne-miles) coupled to projections driven by GDPs from SSP1 through to SSP5 by 2050*

Demand for coal and oil transport has historically been strongly linked to GDP. However, because of climate policies resulting in a global energy transition, the correlation may break down. Energy transport demand projections are based on projections of energy demand in the RCPs. The demand for transport of fossil fuels is projected to decrease in RCPs that result in modest global average temperature increases (e.g. RCP2.6) and to continue to increase in RCPs that result in significant global warming (e.g. RCP8.5).

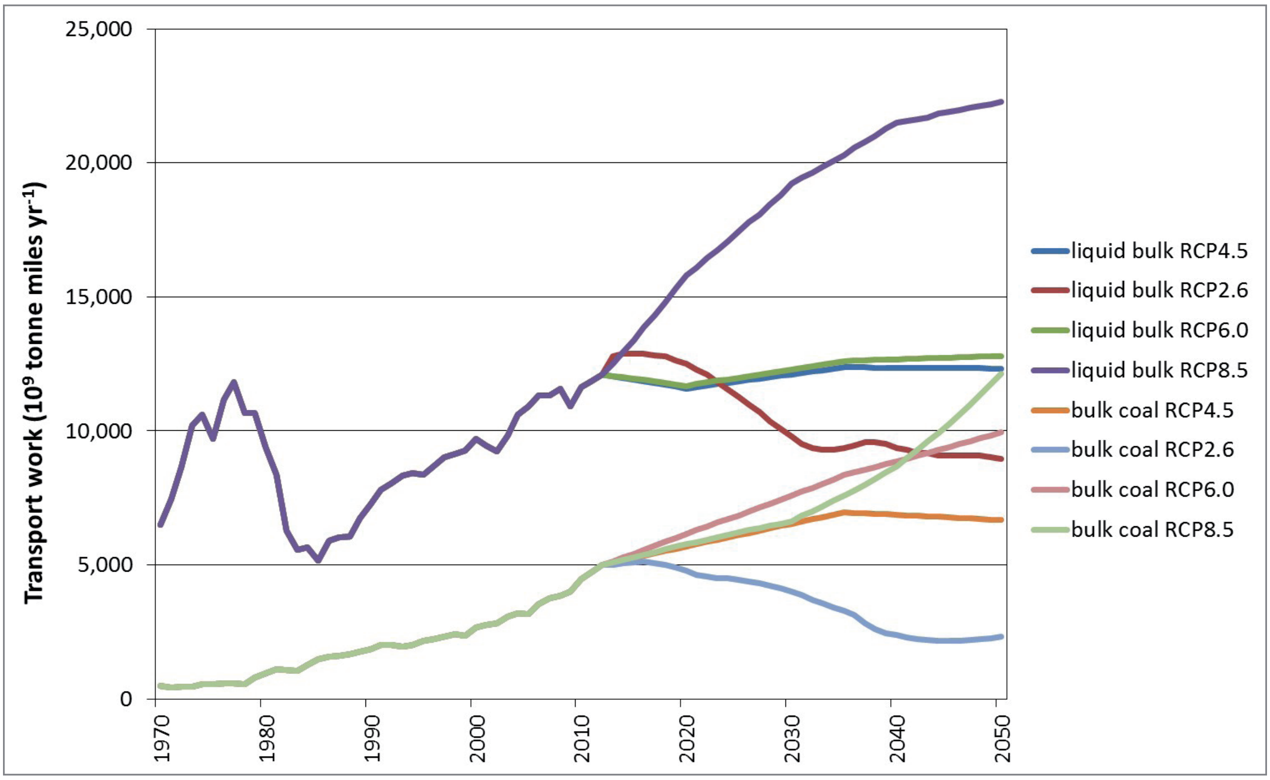


Figure 12: *Historical data to 2012 on global transport work for ship-transported coal and liquid fossil fuels (billion tonne-miles) coupled to projections of coal and energy demand driven by RCPs 2.6, 4.5, 6.0 and 8.5 by 2050*

Maritime emissions projections

Maritime CO_2 emissions are projected to increase significantly. Depending on future economic and energy developments, our four BAU scenarios project an increase of between 50% and 250% in the period up to 2050 (see Figure 13). Further action on efficiency and emissions could mitigate emissions growth, although all but one scenarios project emissions in 2050 to be higher than in 2012, as shown in Figure 14.

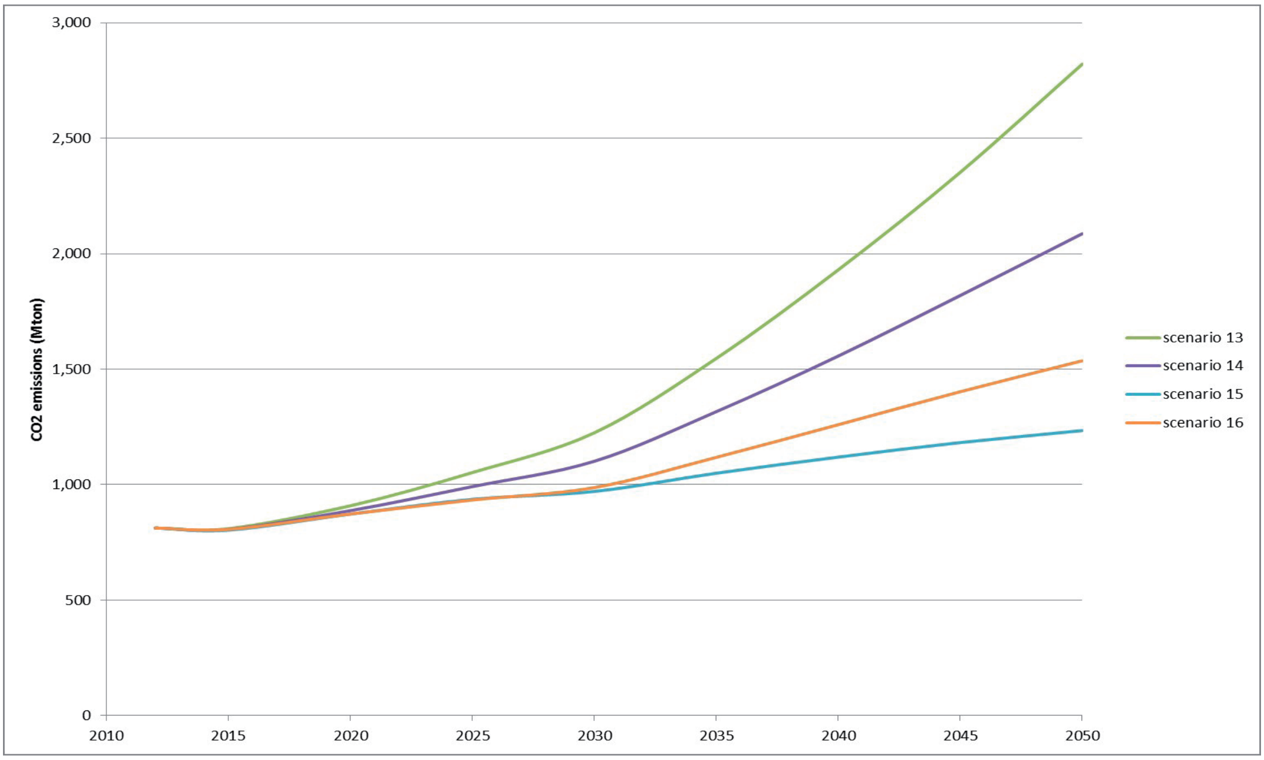


Figure 13: *BAU projections of CO_2 emissions from international maritime transport 2012–2050*

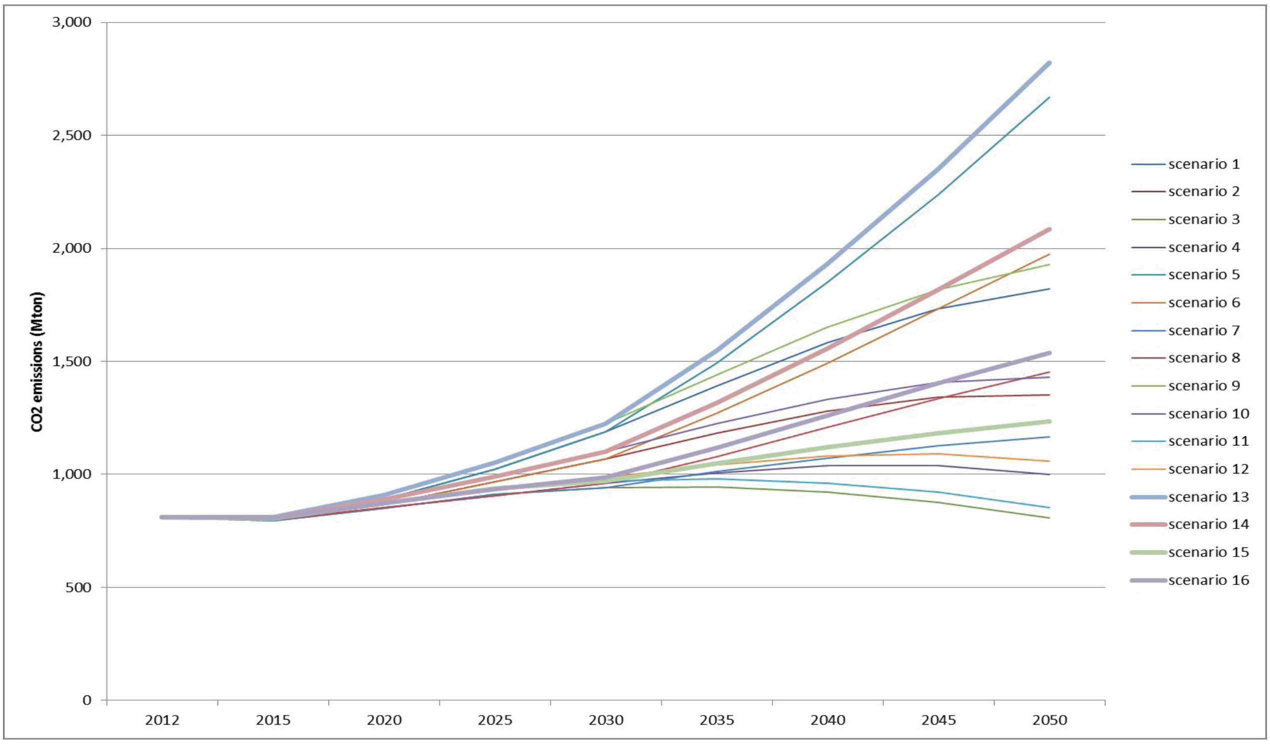


Figure 14: *Projections of CO_2 emissions from international maritime transport. Bold lines are BAU scenarios. Thin lines represent either greater efficiency improvement than BAU or additional emissions controls or both*

Figure 15 shows the impact of market-driven or regulatory improvements in efficiency contrasted with scenarios that have a larger share of LNG in the fuel mix. These four emissions projections are based on the same transport demand projections. The two lower projections assume an efficiency improvement of 60% instead of 40% over 2012 fleet average levels in 2050. The first and third projections have a 25% share of LNG in the fuel mix in 2050 instead of 8%. Under these assumptions, improvements in efficiency have a larger impact on emissions trajectories than changes in the fuel mix.

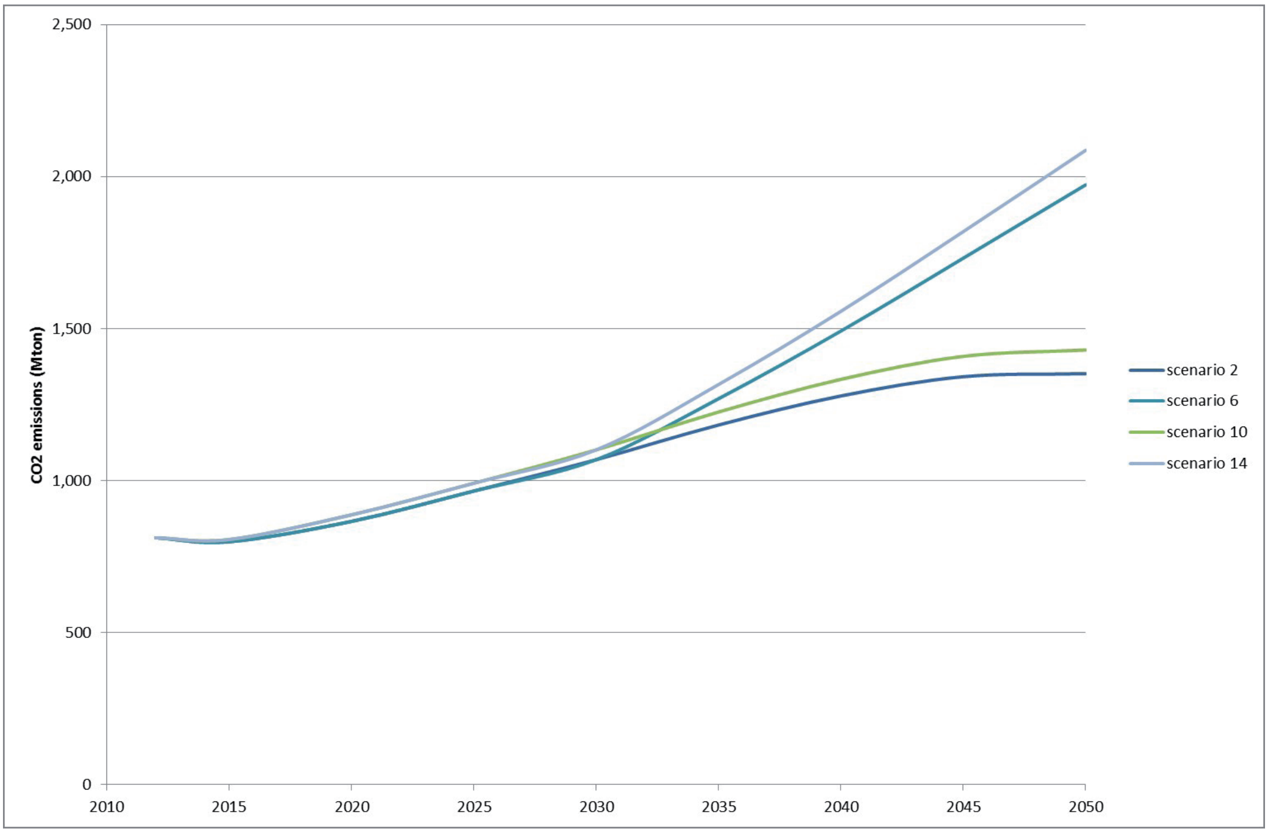


Figure 15: *Projections of CO_2 emissions from international maritime transport under the same demand projections. Larger improvements in efficiency have a higher impact on CO_2 emissions than a larger share of LNG in the fuel mix*

Table 5 shows the projection of the emissions of other substances. For each year, the median (minimum–maximum) emissions are expressed as a share of their 2012 emissions. Most emissions increase in parallel with CO_2 and fuel, with some notable exceptions. Methane emissions are projected to increase rapidly (albeit from a very low base) as the share of LNG in the fuel mix increases. Emissions of sulphurous oxides, nitrogen oxides and particulate matter increase at a lower rate than CO_2 emissions. This is driven by MARPOL Annex VI requirements on the sulphur content of fuels (which also impact PM emissions) and the NO_x technical code. In scenarios that assume an increase in the share of fuel used in ECAs, the impact of these regulations is stronger.

Table 5 – *Summary of the scenarios for future emissions from international shipping, GHGs and other relevant substances*

		Scenario	2012	2020	2050
			index (2012 = 100)	**index (2012 = 100)**	**index (2012 = 100)**
Greenhouse gases	CO_2	low LNG	100	108 (107 – 112)	183 (105 – 347)
		high LNG	100	106 (105 – 109)	173 (99 – 328)
	CH_4	low LNG	100	1.600 (1.600 – 1.700)	10.500 (6.000 – 20.000)
		high LNG	100	7.550 (7.500 – 7.900)	32.000 (19.000 – 61.000)
	N_2O	low LNG	100	108 (107 – 112)	181 (104 – 345)
		high LNG	100	105 (104 – 109)	168 (97 – 319)
	HFC		100	106 (105 – 108)	173 (109 – 302)
	PFC		–	–	–
	SF_6		–	–	–
Other relevant substances	NO_x	constant ECA	100	107 (106 – 110)	161 (93 – 306)
		more ECAs	100	99 (98 – 103)	130 (75 – 247)
	SO_x	constant ECA	100	64 (63 – 66)	30 (17 – 56)
		more ECAs	100	55 (54 – 57)	19 (11 – 37)
	PM	constant ECA	100	77 (76 – 79)	84 (48 – 159)
		more ECAs	100	65 (64 – 67)	56 (32 – 107)
	NMVOC	constant ECA	100	108 (107 – 112)	183 (105 – 348)
		more ECAs	100	106 (105 – 110)	175 (101 – 333)
	CO	constant ECA	100	112 (111 – 115)	206 (119 – 392)
		more ECAs	100	123 (122 – 127)	246 (142 – 468)

Note: Emissions of PFC and SF_6 from international shipping are insignificant.

Summary of the data and methods used (Sections 1, 2 and 3)

Key assumptions and method details

Assumptions are made in Sections 1, 2 and 3 for the best-estimate international shipping inventories and scenarios. The assumptions are chosen on the basis of their transparency and connection to high-quality, peer-reviewed sources. Further justification for each of these assumptions is presented and discussed in greater detail in Sections 1.4 and 2.4. The testing of key assumptions consistently demonstrates that they are of high quality. The uncertainty analysis in Section 1.5 examines variations in the key assumptions, in order to quantify the consequences for the inventories. For future scenarios, assumptions are also tested through the deployment of multiple scenarios to illustrate the sensitivities of trajectories of emissions to different assumptions. Key assumptions made are that:

- the IEA data on marine fuel sales are representative of shipping's fuel consumption;
- in 2007 and 2008, the number of days that a ship spends at sea per year can be approximated by the associated ship-type- and size-specific days at sea given in the Second IMO GHG Study 2009 (for the year 2007);
- in 2009, the number of days that a ship spends at sea per year can be approximated by a representative sample of LRIT data (approximately 10% of the global fleet);
- in 2010–2012, the annual days at sea can be derived from a combined satellite and shore-based AIS database;
- in all years, the time spent at different speeds can be estimated from AIS observations of ship activity, even when only shore-based AIS data are available (2007–2009);
- in all years, the total number of active ships is represented by any ship defined as in service in the IHSF database;

- ships observed in the AIS data that cannot be matched or identified in the IHSF data must be involved in domestic shipping only;
- combinations of RCPs and SSPs can be used to derive scenarios for future transport demand of shipping; and
- technologies that could conceivably reduce ship combustion emissions to zero (for GHGs and other substances) will either not be available or not be deployed cost-effectively in the next 40 years on both new and existing ships.

Inventory estimation methods overview (Sections 1 and 2)

Top-down and bottom-up methods provide two different and independent analysis tools for estimating shipping emissions. Both methods are used in this study.

The top-down estimate mainly used data on marine bunker sales (divided into international, domestic and fishing sales) from IEA. Data availability for 2007–2011 enabled top-down analysis of annual emissions for these years. In addition to the marine bunker fuel sales data, historical IEA statistics were used to understand and quantify the potential for misallocation in the statistics resulting in either under- or overestimations of marine energy use and emissions.

The bottom-up estimate combined the global fleet technical data (from IHSF) with fleet activity data derived from AIS observations. Estimates for individual ships in the IHSF database were aggregated by vessel category to provide statistics describing activity, energy use and emissions for all ships for each of the years 2007–2012. For each ship and each hour of that ship's operation in a year, the bottom-up model relates speed and draught to fuel consumption using equations similar to those deployed in the Second IMO GHG Study 2009 and the wider naval architecture and marine engineering literature. Until the Third IMO GHG Study 2014, vessel activity information was obtained from shore-based AIS receivers with limited temporal and geographical coverage (typically a range of approximately 50nmi) and this information informed general fleet category activity assumptions and average values. With low coverage comes high uncertainty about estimated activity and, therefore, uncertainty in estimated emissions. To address these methodological shortcomings and maximize the quality of the bottom-up method, the Third IMO GHG Study 2014 has accessed the most globally representative set of vessel activity observations by combining AIS data from a variety of providers (both shore-based and satellite-received data), shown in Figure 16.

The AIS data used in this study provide information for the bottom-up model describing a ship's identity and its hourly variations in speed, draught and location over the course of a year.

This work advances the activity-based modelling of global shipping by improving geographical and temporal observation of ship activity, especially for recent years.

Table 6 – *AIS observation statistics of the fleet identified in the IHSF database as in service in 2007 and 2012*

	Total in-service ships	Average % of in-service ships observed on AIS (all ship types)	Average % of the hours in the year that each ship is observed on AIS (all ship types)
2007	51,818	76%	42%
2012	56,317	83%	71%

In terms of both space and time, the AIS data coverage is not consistent year-on-year during the period studied (2007–2012). For the first three years (2007–2009), no satellite AIS data were available, only AIS data from shore-based stations. This difference can be seen by contrasting the first (2007) and last (2012) years' AIS data sets, as depicted for their geographical coverage in Figure 16. Table 6 describes the observation statistics (averages) for the different ship types. These data cannot reveal the related high variability in observation depending on ship type and size. Larger oceangoing ships are observed very poorly in 2007 (10–15% of the hours of the year) and these observations are biased towards the coastal region when the ships are either moving slowly as they approach or leave ports, at anchor or at berth. Further details and implications of this coverage for the estimate of shipping activity are discussed in greater detail in Sections 1.2, 1.4 and 1.5.

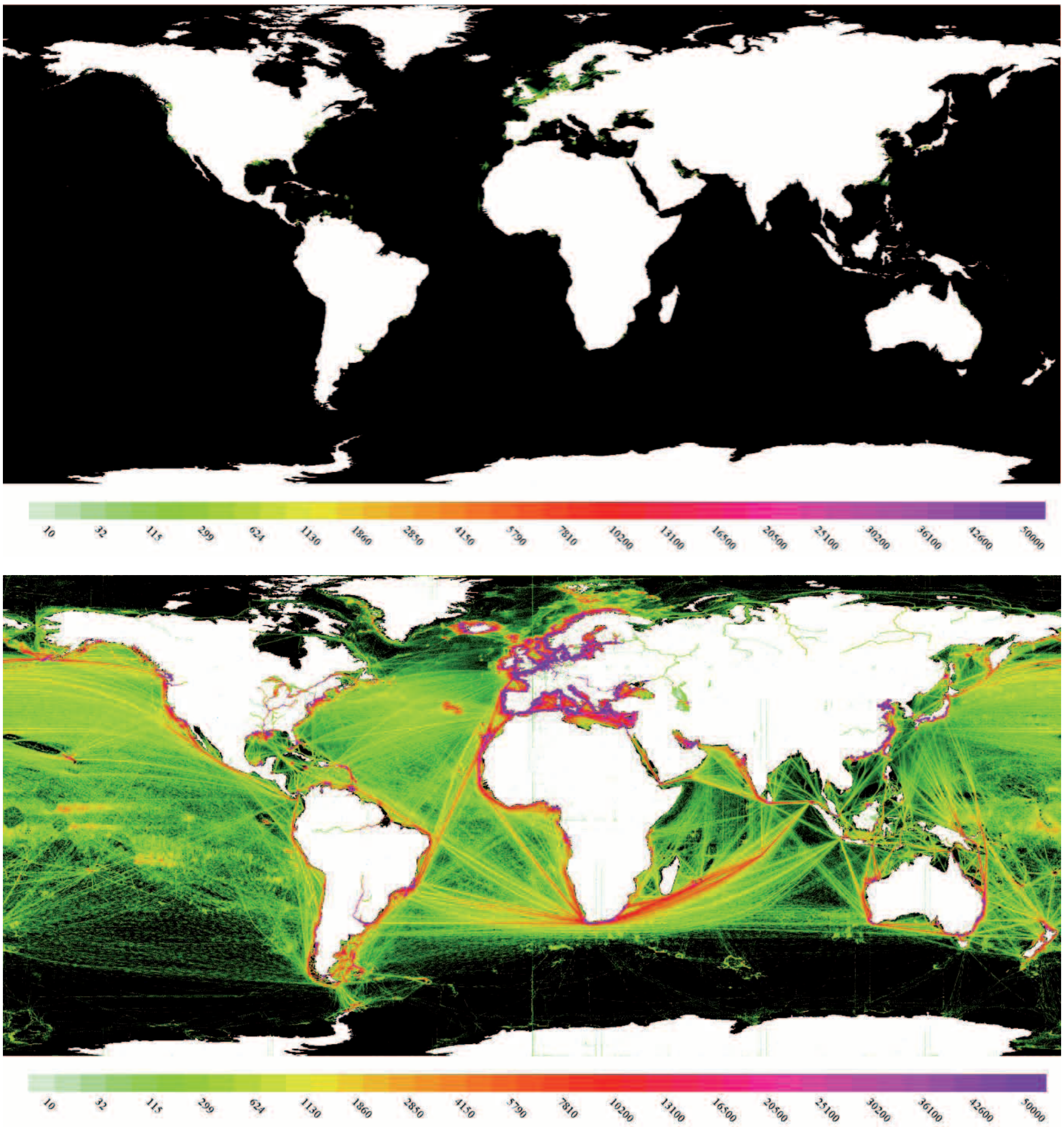


Figure 16: *Geographical coverage in 2007 (top) and 2012 (bottom), coloured according to the intensity of messages received per unit area. This is a composite of both vessel activity and geographical coverage; intensity is not solely indicative of vessel activity*

AIS coverage, even in the best year, cannot obtain readings of vessel activity 100% of the time. This can be due to disruption to satellite or shore-based reception of AIS messages, the nature of the satellite orbits and interruption of a ship's AIS transponder's operation. For the time periods when a ship is not observed on AIS, algorithms are deployed to estimate the unobserved activity. For 2010, 2011 and 2012, those algorithms deploy heuristics developed from the observed fleet. However, with the low level of coverage in 2007, 2008 and 2009, the consortium had to use methods similar to previous studies that combined sparse AIS-derived speed and vessel activity characteristics with days-at-sea assumptions. These assumptions were based on the Second IMO GHG Study 2009 expert judgements. Conservatively, the number of total days at sea is held constant for all three years (2007–2009) as no alternative, more reliable, source of data exists for these years.

Given the best available data, and by minimizing the amount of unobserved activity, uncertainties in both the top-down and the bottom-up estimates of fuel consumption can be more directly quantified than previous global ship inventories. For the bottom-up method, this study investigates these uncertainties in two ways:

1 The modelled activity and fuel consumption are validated against two independent data sources (Section 1.4):

  a LRIT data were obtained for approximately 8,000 ships and four years (2009–2012) and used to validate both the observed and unobserved estimates of the time that a ship spends in different modes (at sea, in port), as well as its speeds.

b Noon report data were collected for 470 ships for the period 2007–2012 (data for all ships were available in 2012, with fewer ships' data available in earlier years). The data were used to validate both the observed and unobserved activity estimates and the associated fuel consumption.

2 The comparison between the modelled data and the validation data samples enabled the uncertainty in the model to be broken down and discussed in detail. An analysis was undertaken to quantify the different uncertainties and their influence on the accuracy of the estimation of a ship's emissions in a given hour and a given year, and the emissions of a fleet of similar ships in a given year.

Figure 17 presents the comparison of bottom-up and noon report data used in the validation process of 2012 analysis (further plots and years of data are included in Section 1.4). For each comparison, a ship is identified by its IMO number in the two data sets so that the corresponding quarterly noon report and bottom-up model output can be matched. The red line represents an ideal match (equal values) between the bottom-up and noon-report outputs, the solid black line the best fit through the data and the dotted black lines the 95% confidence bounds on the best fit. The "x" symbols represent individual ships, coloured according to the ship type category as listed in the legend.

The comparative analysis demonstrates that there is a consistent and robust agreement between the bottom-up method and the noon report data at three important stages of the modelling:

1 The average at-sea speed plot demonstrates that, in combination with high coverage AIS data, the extrapolation algorithm estimates key activity parameters (e.g. speed) with high reliability.

2 The average daily fuel consumption plot demonstrates the reliability of the marine engineering and naval architecture relationships and assumptions used in the model to convert activity into power and fuel consumption.

3 The total quarterly fuel consumption plot demonstrates that the activity data (including days at sea) and the engineering assumptions combine to produce generally reliable estimates of total fuel consumption. The underestimate in the daily fuel consumption of the largest container ships can also be seen in this total quarterly fuel consumption.

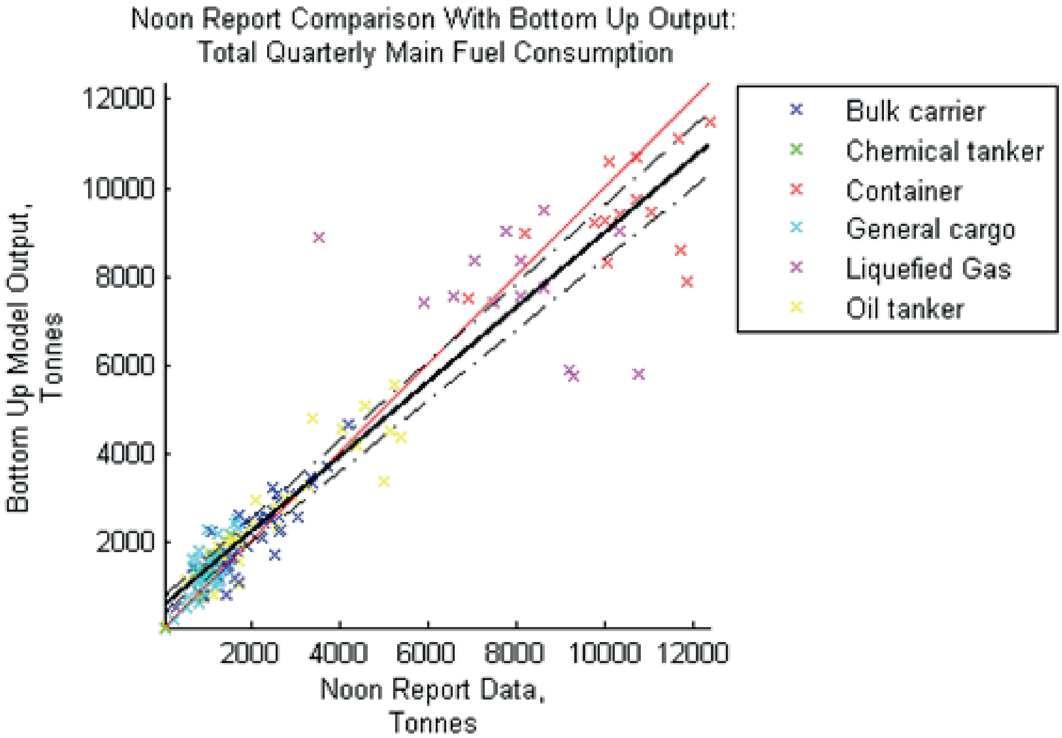


Figure 17: *Total noon-reported quarterly fuel consumption of the main engine, compared with the bottom-up estimate over each quarter of 2012, with a filter to select only days with high reliability observations of the ship for 75% of the time or more*

Scenario estimation method overview (Section 3)

The consortium developed emissions projections by modelling the international maritime transport demand and allocating it to ships, projecting regulation- and market-driven energy efficiency changes for each ship. These are combined with fuel-mix scenarios and projections for the amount of fuel used by international maritime transport. For most emissions, the energy demand is then multiplied by an emissions factor to arrive at an emissions projection.

The basis for the transport demand projections is a combination of RCPs and SSPs that have been developed for IPCC. The RCPs contain detailed projections about energy sources, which is relevant for fossil-fuel transport projections. The SSPs contain long-term projections of demographic and economic trends, which are relevant for the projections of demand for transport of non-energy cargoes. RCPs and SSPs are widely used across the climate community.

The long-term projections are combined with a statistical analysis of historical relationships between changes in transport demand, economic growth and fossil-fuel consumption.

The energy efficiency improvement projections are part regulation-driven, part market-driven. The relevant regulations are EEDI for new ships and SEEMP for all ships. Market driven efficiency improvements have been calculated using MACCs.

1

Inventories of CO_2 emissions from international shipping 2007–2012

1.1 Top-down CO_2 inventory calculation method

1.1.1 Introduction

Section 1.1 provides a top-down estimate of emissions from shipping for the period 2007–2012. This task also provides a comparison of this update with the methods used in the Second IMO GHG Study 2009. The top-down approach is based on statistical data derived from fuel delivery reports to internationally registered vessels. The top-down approach also considers allocation to domestic and international shipping, as reported in national statistics.

Calculations of emissions using top-down fuel consumption estimates are presented. For CO_2, these estimates use CO_2 emissions factors consistent with those used in the bottom-up calculations in Section 1.2. Specifically, the top-down inventory uses the CO_2 emissions factors reported in Section 2.2.7. For marine fuel oil (HFO), this study uses 3.114 grams CO_2 per gram fuel; for marine gas oil (MDO), this study uses 3.206 grams CO_2 per gram fuel; and for natural gas (LNG), this study uses 2.75 grams CO_2 per gram fuel.

1.1.2 Methods for review of IEA data

The World Energy Statistics published by IEA are used both in the Second IMO GHG Study 2009 and this study. Both studies reviewed several years of IEA data, mainly as a quality assurance measure, but IEA statistics provided the main top-down comparator with bottom-up results in that study.

The Second IMO GHG Study 2009 used IEA data for 1971–2005 (2007 edition). Two types of oil product (fuel oil and gas/diesel) and three sectors (international marine bunkers, domestic navigation and fishing) were reported, and the study subsequently projected those data for 2007 using tonne-miles transported.

For this study, the consortium reviewed data from IEA (2013) for all available years. Figure 18 shows the long-run statistics for total marine consumption of energy products (international, domestic and fishing) over the period 2007–2011. IEA statistics for international marine bunkers, domestic navigation and fishing data were specifically examined for the fuels known to be most used by ships: fuel oil (residual), gas diesel oil, motor gasoline, lubricants, non-specified fuel and natural gas fuel.

IEA statistics indicate that marine bunker consumption volumes of motor gasoline, lubricants, non-specified fuel and natural gas are very small. Each of these features has less than 0.10% of fuel oil consumption as international marine bunkers. Considering domestic and international marine fuels together, only motor gasoline is reported at quantities equivalent to more than 1% of fuel oil used by ships. No natural gas is reported as international marine bunkers consumption in IEA (2013), but a small quantity of natural gas is reported for domestic navigation and fishing.

Other energy products are used in shipping, such as a small amount of primary solid biofuels (domestic and fishing) and heat and electricity (exclusively in fishing). Given that the statistics identify none of these fuels as used in international shipping, and given their very small volumes, these fuels were determined to be outside the scope of this study. Comparison of top-down statistics is therefore limited to fuel oil (HFO), gas diesel oil (MDO) and natural gas (LNG).

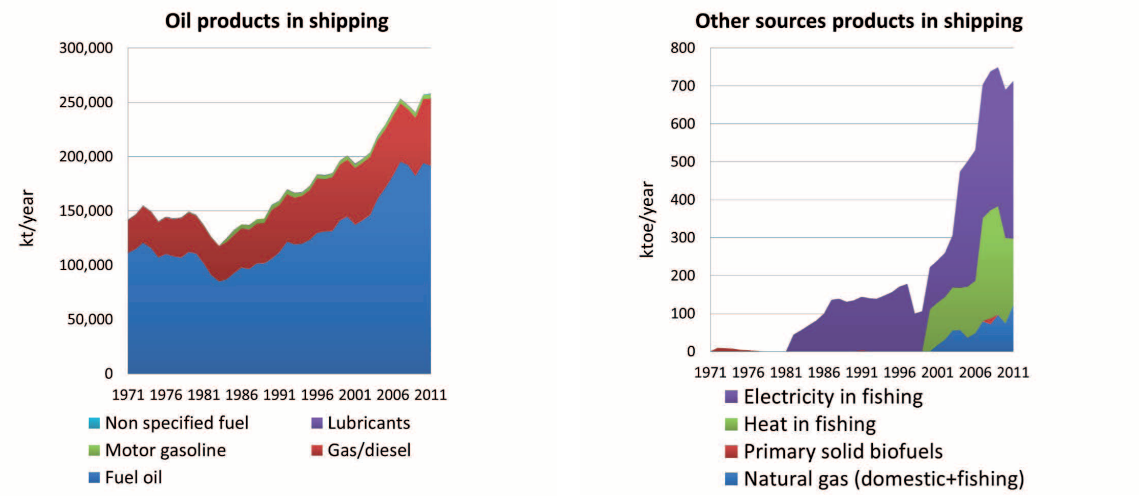


Figure 18: *Oil products and products from other sources used in shipping (international, domestic and fishing) 1971–2011*

There are significant gaps in the IEA (2013) data for 2012, at the time of this analysis. For example, international navigation fuel sales were available for only 29 countries, representing less than 20% of total sales in 2011 (see Table 7). IEA acknowledges that recent data are based on mini-questionnaires from OECD nations and supply data for non-OECD nations; 2012 marine fuel statistics will be updated in future editions (IEA 2013). The IMO Secretariat scope specifies that the Third IMO GHG Study 2014 should compute annual emissions "as far as statistical data are available". Given the incomplete data, this work therefore excludes year 2012 from this top-down analysis.

Table 7 – *Comparison of 2011 and 2012 marine fuels reporting to IEA*

	2011		**2012**	
Nations reporting	**Fuel oil (ktonnes)**	**Gas/diesel (ktonnes)**	**Fuel oil (ktonnes)**	**Gas/diesel (ktonnes)**
29 reporting nations in 2012 (Australia, Belgium, Canada, Chile, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Korea [Republic of], Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States)	74,833	16,479	70,359	17,532
Other 98 nations reporting in 2011	102,658	12,655		
Percentage of 2011 fuel reported by 29 nations reporting in 2012	**42%**	**57%**		

1.1.3 Top-down fuel consumption results

This section presents the Third IMO GHG Study 2014 top-down results for the period of 2007–2011.

Review of Second IMO GHG Study 2009 top-down estimates

The consortium reviewed the Second IMO GHG Study 2009 results, including updates based on current versions of IEA statistics. Table 8 presents a summary of the information reported in the Second IMO GHG Study 2009 (from appendix 1, Tables A1–17), with updated information from the IEA (2013) World Energy Statistics.

It is important to note that top-down information reported in the Second IMO GHG Study 2009 is not definitive. First, the estimated value for 2007 (derived from 2005 using a tonne-miles adjustment in the Second IMO GHG Study 2009) can be compared with the IEA value reported in today's World Energy Statistics. The 2007 IEA value is approximately 9% greater than the estimated 2007 value in the Second IMO GHG Study 2009. Second, IEA updated the 2005 reported value with an amended total for all marine fuels that is approximately 5% greater than the published IEA data used in the Second IMO GHG Study 2009. Most of that difference results from amended statistics for domestic navigation and fishing, with IEA statistics updates for marine fuels that are less than 2% of the values reported in the 2009 study. Lastly, the IEA statistics explicitly designate whether the fuel data aggregate was originally allocated to vessels identified as international shipping, domestic shipping or fishing. These categories are defined by IEA and described in the Key Definitions section of this report. IEA definitions are consistent with the IPCC 2006 Guidelines.

Table 8 – *Comparison of Second IMO GHG Study 2009 top-down ship fuel consumption data (million tonnes)*

		Second IMO GHG Study 2009		**Current IEA**			
Marine sector	**Fuel type**	**2005**	**2007**	**2004**	**2005**	**2006**	**2007**
International marine bunkers	HFO	150	159	144	153	164	174
	MDO	26	27	28	26	27	26
International total		**176**	**186**	**172**	**179**	**191**	**200**
Domestic navigation	HFO	13	14	17	17	18	20
	MDO	20	21	20	21	22	23
Domestic total		**33**	**35**	**37**	**38**	**40**	**43**
Fishing	HFO	0	1	1	1	1	1
	MDO	5	6	6	7	6	5
Fishing total		**5**	**7**	**7**	**8**	**7**	**6**
Total		214	228	216	225	238	249
				% difference from Second IMO GHG Study 2009			
					5%		9%

Top-down results for the period 2007–2011

Fuel statistics allocated to international shipping, domestic navigation and fishing are presented in Figures 19–21 and Table 9. Figure 19 shows a generally flat trend in fuel oil consumption statistics since 2007 for each shipping category (fishing, international navigation and domestic navigation). Similarly, Figure 20 shows a generally increasing trend for gas/diesel while Figure 21 shows an increasing trend in natural gas sales in domestic shipping and interannual variation in natural gas sales to fishing vessels.

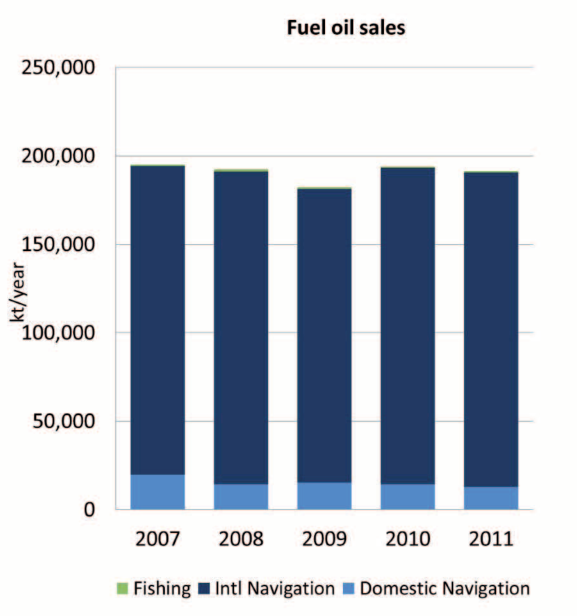


Figure 19: *IEA fuel oil sales in shipping 2007–2011*

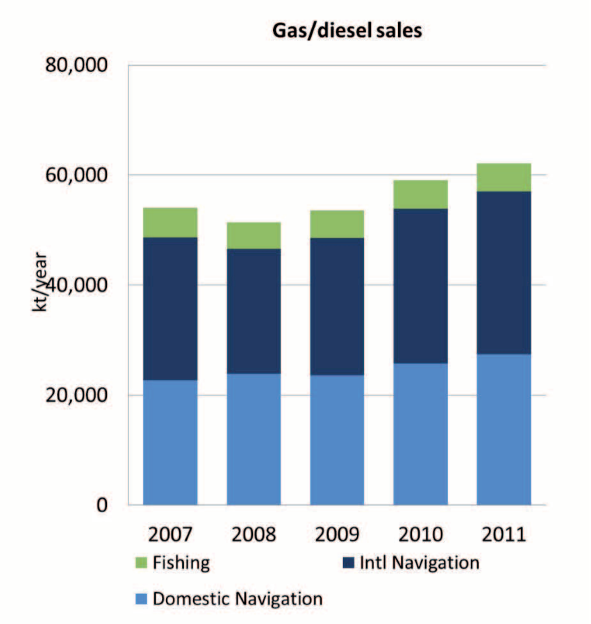


Figure 20: *IEA gas/diesel sales in shipping 2007–2011*

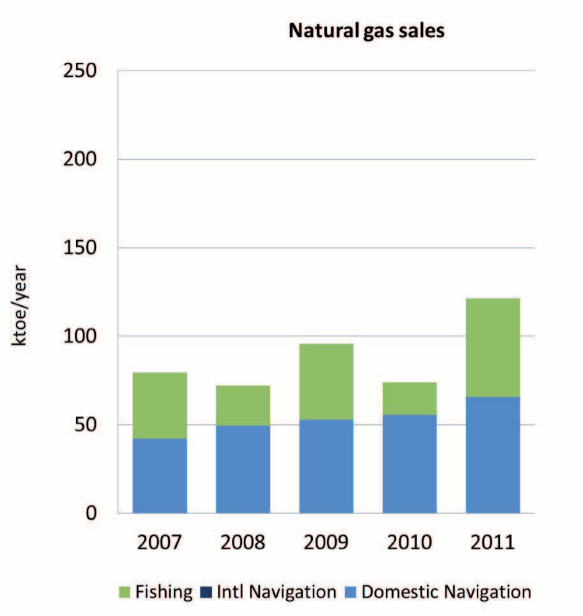


Figure 21: *IEA natural gas sales in shipping 2007–2011*

The IEA statistics explicitly designate fuel to ships as either international or domestic navigation, while fishing vessel fuel statistics group international and domestic fishing activities together from 2007. The allocation of total marine fuels provided to ships depends upon the data quality aggregated by IEA from national fuel reports and ancillary statistical sources. (Issues of data quality and uncertainty in IEA statistics are addressed in Sections 1.4 and 1.5.) For completeness, this section reports the top-down allocation provided in the IEA statistics for all three marine fuel designations.

Table 9 reports a summary of IEA data of the fuels most used in shipping over the three different categories in million tonnes, where natural gas data were converted to tonnes oil equivalent using IEA unit conversions (1 TJ = 0.0238845897 ktoe).

Table 9 – *Summary of IEA fuel sales data in shipping (million tonnes)*

Marine sector	Fuel type	2007	2008	2009	2010	2011
International marine bunkers	HFO	174.1	177.0	165.9	178.9	177.9
	MDO	26.0	22.7	24.9	28.2	29.6
	LNG	0	0	0	0	0
International total		**200.1**	**199.7**	**190.8**	**207.1**	**207.5**
Domestic navigation	HFO	19.9	14.2	15.3	14.3	12.7
	MDO	22.7	23.9	23.6	25.7	27.4
	LNG	0.04	0.05	0.05	0.05	0.07
Domestic total		**42.64**	**38.15**	**38.95**	**40.05**	**40.17**
Fishing	HFO	1.1	1.1	1.0	0.8	0.8
	MDO	5.4	4.9	5.0	5.2	5.1
	LNG	0.04	0.02	0.04	0.02	0.05
Fishing total		**6.54**	**6.02**	**6.04**	**6.02**	**5.95**
Total		249.28	243.87	235.79	253.17	253.62

The time series for top-down fuel inventories reveals some correlation, which may be interpreted as a response to the economic conditions (lower fuel consumption). The consortium evaluated the top-down consumption data trends for international marine fuel oil and the world GDP trends as reported by the World Bank's World Development Indicators. "World Development Indicators (WDI) is the primary World Bank collection of development indicators, compiled from officially recognized international sources. It presents the most current and accurate global development data available, and includes national, regional and global estimates" (World Bank, November 2013).

Figure 22 illustrates this correlation graphically and shows the correlation coefficient for 2000–2012 to be very high (96.5%). This trend also shows correlation with the start of economic recovery in 2009. The divergence between fuel oil consumption and GDP trends since 2010 could be a function of three factors:

1 energy efficiency measures adopted by shipping in response to price;

2 fuel-switching to gas diesel or natural gas fuels;

3 a lag in shipping activity change compared to world GDP change.

Further time series and additional analysis beyond the scope of this study would be required to evaluate post-recession changes further.

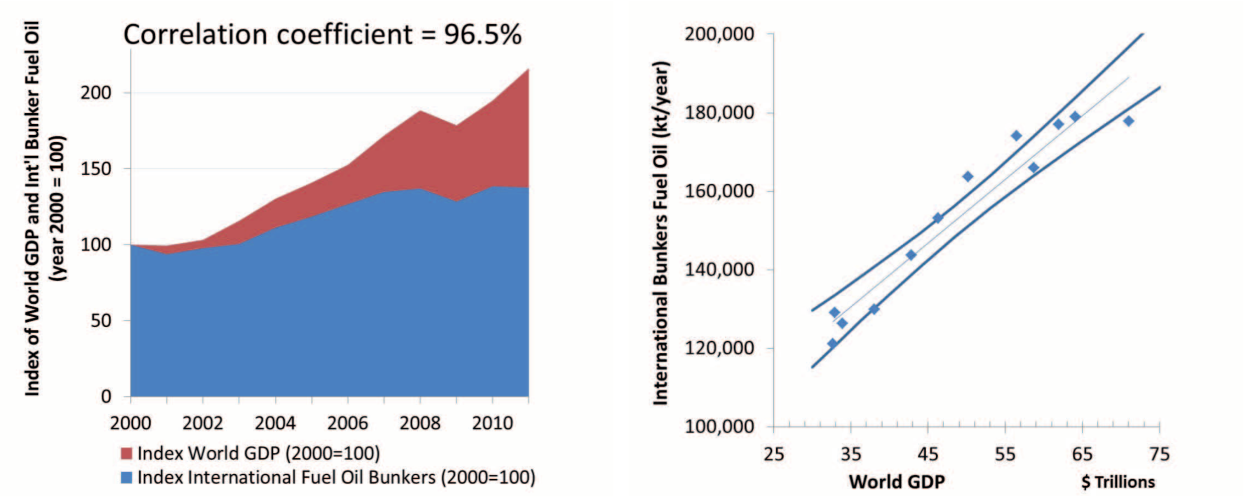


Figure 22: *Correlation between world GDP and international bunker fuel oil during the recession*

1.2 Bottom-up CO_2 inventory calculation method

The bottom-up method derives estimates of emissions from data sources describing shipping activity. The primary source of vessel activity used is the AIS data, which describe, among other things, a ship's identity, position, speed and draught at a given time-stamp. The data are transmitted by the ship with a broadcast frequency of one message every six seconds. The data are received by shore-based stations, satellites and other ships and the consortium acquired access to a number of shore-based station and satellite receiver archives. These were used to build time histories of shipping activity, which could be used, in conjunction with ship specifications, to calculate the time histories of fuel consumption and emissions. Calculations were carried out for every individual ship identified as in service in the IHSF database and for every hour of the year.

1.2.1 Overall bottom-up approach

The bottom-up method is split into two stages:

1 initial estimation of observed per-ship activity, energy consumption and emissions;

2 estimation of per-ship activity and associated energy consumption and emissions for ships not observed in the AIS database.

The first stage is performed only on ships that appear coincidentally in both the IHSF and AIS databases. The second stage is performed for all ships listed as "in service/commission" within the IHSF database and uses estimated activity for similar ships in stage 1, in combination with IHSF technical specifications to estimate power requirements, fuel consumption and emissions. The total energy consumption and emissions for a fleet of similar ships is then found by summing the calculations for each ship, estimated either at stage 1 or stage 2. The total shipping emissions are then found by summing across all ship type and size categories. International shipping emissions are estimated by defining which ship type and size categories are involved in international shipping.

Figure 23 is a diagram of the flow of data through the processes and calculation stages that make up the bottom-up method.

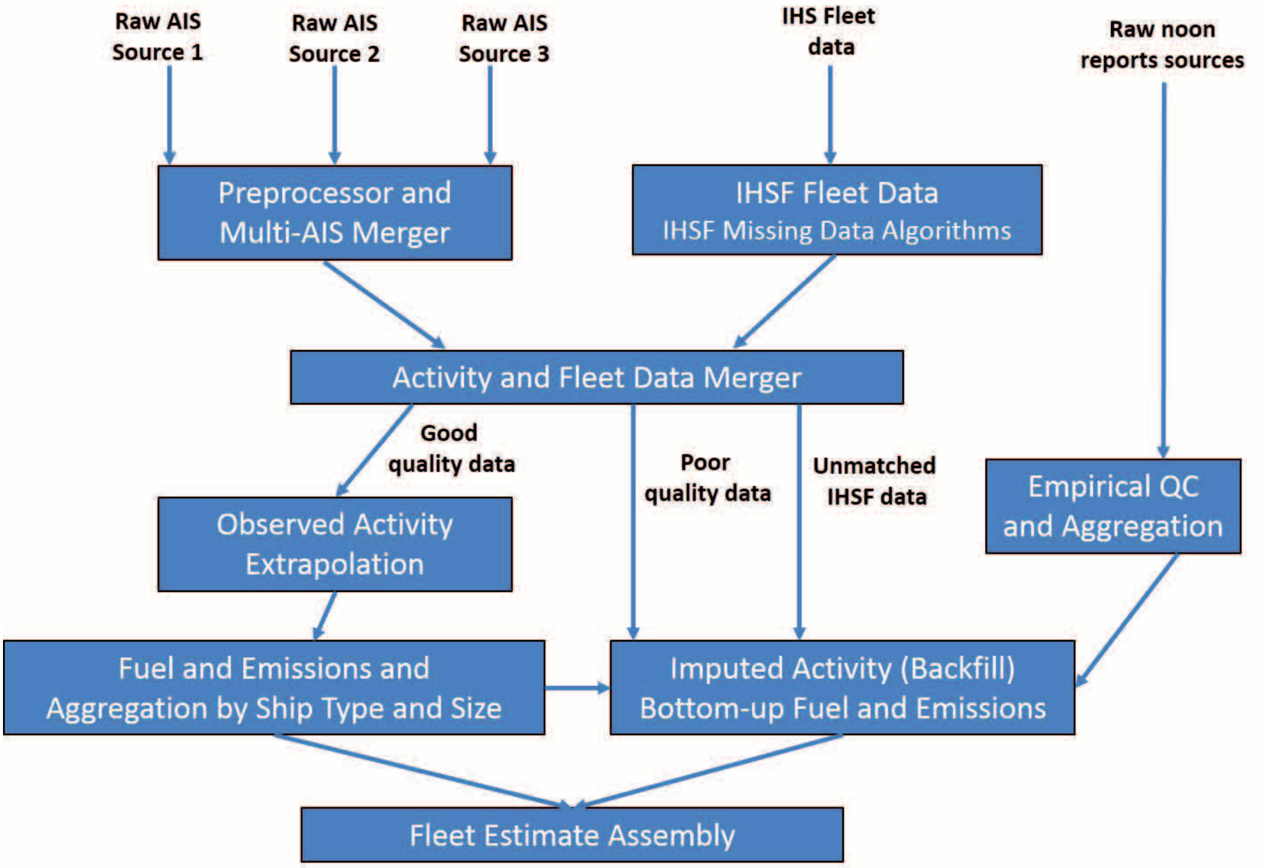


Figure 23: *Data assembly and method for Sections 1.2 and 2.2*

1.2.2 Summary of data and method input revisions

Data

Access to increasingly detailed data on ships' activity was enabled by the advent of S-AIS, which began providing significant coverage in 2010. These data enable the specifics of any ship's operation to be identified on an hourly basis, or even more frequently if required. S-AIS allows greater fidelity in the calculation of the fleet's aggregate operational characteristics. For the first time in global inventory calculations, the activity of specific individual ships (e.g. actual vessel speed over ground) and consequent engine load and emissions can be considered as a component of an overall inventory calculation. In the Second IMO GHG Study 2009, a limited sample of terrestrial AIS data was used to calculate ship activity parameters (speeds, days at sea, etc.). In that study, ship activity could only be observed for a subset of the fleet and only within approximately 50 nmi of available shore-based receivers (only partial coverage of coastal regions), which left the activity of vessels in the open ocean unobserved. In this study, the consortium brings together a number of data sets from both terrestrial and satellite receiver operators and merges the data to provide extensive spatial and temporal coverage of shipping activity observations. A visualization of the merged AIS data for 2012 is shown in Figure 24.

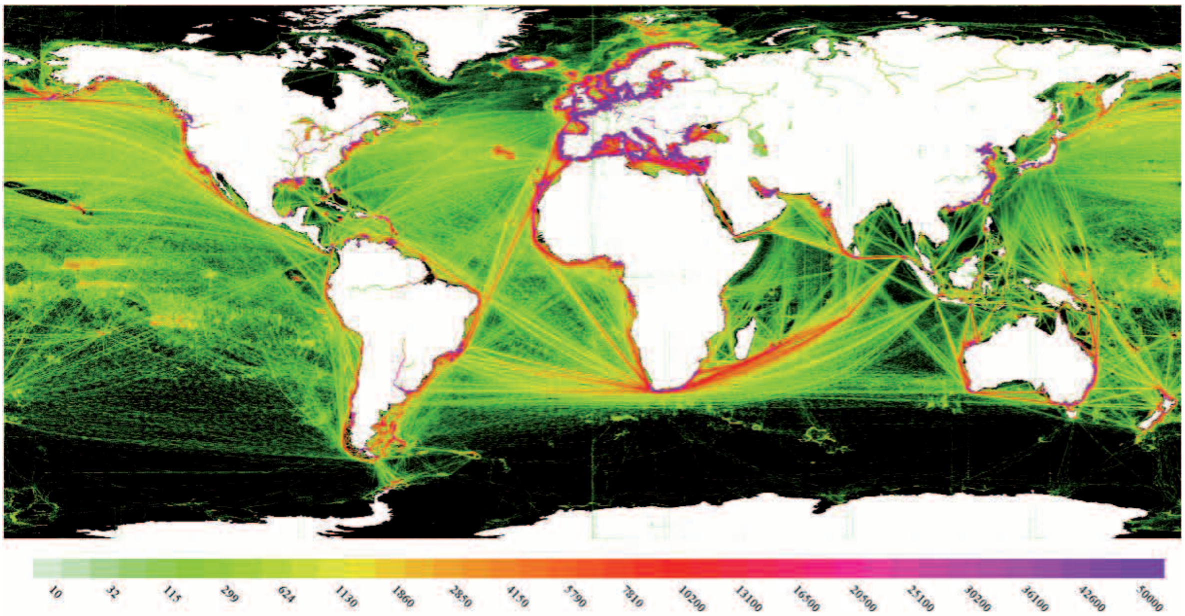


Figure 24: *Chart showing the coverage of one of the merged AIS data sets used in this study (2012, all sources, but no LRIT)*

Observations in the merged AIS data set of ship activity (speeds, time spent in modes) are compared to similar data derived from samples of the global fleet from LRIT. In all, data concerning approximately 8,000 ships were put together (see Section 1.4 for details). LRIT data were not used in the Second IMO GHG Study 2009. A visualization of the LRIT data for 2012 is shown in Figure 25. LRIT data are of lower temporal resolution than AIS data but provide higher reliability and therefore enable important quality checks for the AIS data set and the bottom-up calculations of average speeds and days at sea.

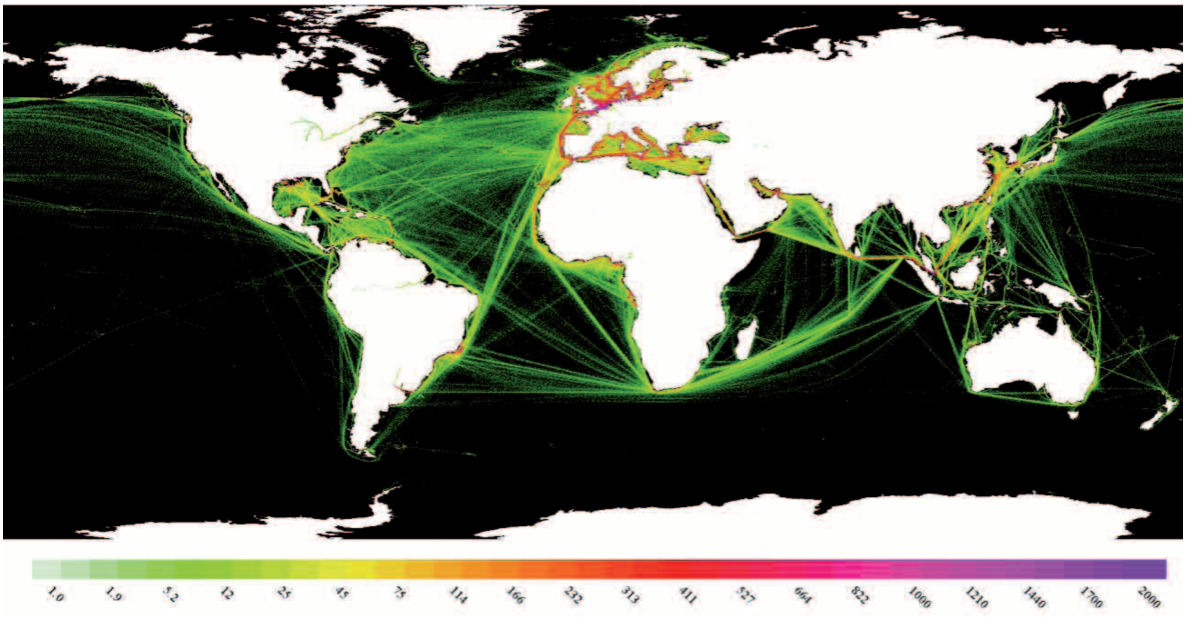


Figure 25: *Chart showing the coverage of one of the LRIT data sets used in this study (2012)*

The quality of the bottom-up model's activity and fuel consumption calculations was also checked against operators' fuel consumption data, contained in noon reports and fuel audits (see Section 1.4). No equivalent data were reportedly used in the Second IMO GHG Study 2009.

This study uses IHSF data to obtain the technical characteristics of individual ships. While IHSF data were used in the Second IMO GHG Study 2009, this study includes data on the status of a ship (in service, etc.). Ship status data are obtained on a quarterly basis, so that ships that are reportedly active for only part of the year are considered appropriately.

Method

The method developed by the consortium to conduct this study uses a comparable structure to the methodology of the Second IMO GHG Study 2009 for the collation of aggregate data on activity parameters, engine load and emissions. However, it is underpinned by analysis carried out at each calculation stage on a complete database of the global fleet (i.e. all calculations are performed at the level of the individual ship with aggregation of results only used for presentation purposes). This approach avoids the potential for asymmetry or data bias that might reduce fidelity and accuracy. This represents a substantial progression in the technology and practice of activity-based inventory methods for international shipping.

1.2.3 Aggregation of ship types and sizes

The algorithms used for vessel aggregation, developed by the consortium, build on aggregation methodologies for EEDI (taken from IMO MEPC.231(65), expanded for ship classes not included in EEDI) and divide vessels further into bins based on cargo capacity or ship size. The aggregations use definitions aligned as closely as possible with those used in the Second IMO GHG Study 2009. In some cases, however, this was not possible because the taxonomy used in the earlier study was not reported explicitly and because it did not always align with the EEDI categories. Aggregation uses IHSF Statcode3, Statcode5, and relevant capacity fields to group similar ships. IHSF organizes vessels into four types of ship:

- cargo-carrying;
- non-merchant;
- non-seagoing merchant;
- work vessels.

Most international shipping is represented by cargo-carrying transport ships, which are the primary focus of this study. However, the other classes are needed to compare the bottom-up estimate with the top-down estimate where both international and domestic voyages by oceangoing ships may be represented. The consortium subdivided cargo-carrying vessel types into 13 classes, the non-merchant ships and non-seagoing merchant ship types into two and one classes respectively, and the work vessel type into three classes. As shown in Table 10, a total of 19 classes are defined.

Table 10 – *IHSF vessel types and related vessel classes*

Vessel group	Vessel class
Cargo-carrying transport ships	1. Bulk carrier 2. Chemical tanker 3. Container 4. General cargo 5. Liquified gas tanker 6. Oil tanker 7. Other liquids tanker 8. Ferry – passengers (pax) only 9. Cruise 10. Ferry – roll-on/passengers (ro-pax) 11. Refrigerated cargo 12. Roll-on/roll-off (ro-ro) 13. Vehicle
Non-merchant ships	14. Yacht 15. Miscellaneous – fishing[1]
Non-seagoing merchant ships	16. Miscellaneous – other[2]
Work vessels	17. Service – tug 18. Offshore 19. Service – other

For each vessel class a capacity bin system was developed to further aggregate vessels by either their physical size or cargo-carrying capacity, based on the following metrics: deadweight tonnage (dwt); 20-foot equivalent units (TEU); cubic metres (cbm); gross tonnage (gt); or vehicle capacity (see Table 12). The capacity bins are the same for all vessels in a class. Wherever possible, bin sizes are aligned to the Second IMO GHG Study 2009, although there are some discrepancies due to differences in the class definitions. It should be noted that the Third IMO GHG Study 2014 provides higher resolution by class/subclass/capacity bin than the Second IMO GHG Study 2009. Further details of the approach used and the definitions applied can be found in Annex 1.

1.2.4 Estimating activity using AIS data

The primary purpose of AIS is to report the current location of vessels in order to avoid collisions. Under IMO regulations (SOLAS, chapter V), all vessels over 300 gt on international transport (IMO, 2002) are required to carry transmitters. AIS information is reported in different message types depending on the reporting entity (e.g. vessel, base station) and the nature of the message (i.e. dynamic or static). The messages of interest for this study are static and dynamic vessel messages (see ITU (2010) for further details of message types). Dynamic messages (types 1, 2 and 3) report more frequently and provide frequently changing information, such as location and speed. Static messages (types 5 and 24) contain voyage information, such as draught, destination and (importantly) the IMO number of the vessel. Static and dynamic messages are linked through the MMSI number, which is reported in both message types. These messages are collected through receivers on land (T-AIS) and through a satellite network (S-AIS). Due to temporal and spatial coverage issues, explained elsewhere (Smith et al. 2012; Second IMO GHG Study 2009), quality can be improved using a combination of these sources as they offer complementary spatial and temporal coverage.

The consortium used multiple data sources. Annex 1 describes the process adopted for the processing of the raw data to obtain hourly estimates of speed, draught and region of operation, and their merger into a single, combined data set for use in the bottom-up model. Information in message 18 transmitted from Class B transponders was not used to estimate activity and emissions.

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[1] misc. fishing vessels fall into the non-merchant ships and non-seagoing merchant ships categories.

[2] misc. other vessels fall into the non-seagoing merchant ships and work vessels categories.

1.2.5 Ship technical data

Ship technical data are required to estimate ship emissions in the bottom-up model. The primary source of technical data used for this study is the IHSF ship registry database. Ship technical data from the IHSF data sets used in this study include Statcode3, Statcode5, gt, dwt, length, beam, maximum draught, vessel speed, installed main engine power, engine revolutions per minute (RPM), various cargo capacity fields, date of build, keel laid date, propulsion type, number of screws, and main engine fuel consumption and stroke type. In addition to technical data, the IHSF data set includes a ship status field that indicates whether a ship is active, laid up, being built, etc. The consortium had access to quarterly IHSF data sets from 2007 through to 2012. Each year's specific data were used for the individual annual estimates.

It should be noted that the data sets do not provide complete coverage for all ships and all fields needed. In cases where data are missing, values are estimated either from interpolation or by referencing another publicly available data source. The details of the approach taken for the missing data and the technical and operational data themselves are discussed further in Section 1.4.3 and Annex 1.

For auxiliary engine operational profiles, neither IHSF nor the other vessel characteristic data services provide auxiliary engine use data by vessel mode. In the Second IMO GHG Study 2009, auxiliary loads were estimated by assuming the number and load of auxiliary engines operated by vessel type, and were based on the rated auxiliary engine power gauged from the limited data provided in IHS. To improve this approach, the consortium used Starcrest's Vessel Boarding Program (VBP) data, which had been collected at the Port of Los Angeles, the Port of Long Beach (Starcrest, 2013), the Port Authority of New York & New Jersey, the Port of Houston Authority, the Port of Seattle and the Port of Tacoma. The VBP data set includes over 1,200 vessels of various classes. For over 15 years, Starcrest has collected data on-board vessels specifically related to estimating emissions from ships and validating its models. Auxiliary loads (in kW) are recorded for at-berth, at-anchorage, manoeuvring and at-sea vessel modes. The vessel types boarded as part of VBP include bulk carriers, chemical tankers, cruise passenger ships, oil tankers, general cargo ships, container ships and refrigerated cargo ships.

For container and refrigerated cargo ships, vessel auxiliary engine and boiler loads (kW), by mode, were developed based on the VBP data set and averages by vessel type and bin size were used. This approach assumes that the vessels boarded are representative of the world fleet for the same classes.

For bulk carriers, chemical tankers, cruise passenger ships, oil tankers and general cargo ships, a hybrid approach was used combining VBP data, data collected from the Finnish Meteorological Institute (FMI) and the Second IMO GHG Study 2009 approach. The earlier study's approach was based on average auxiliary engine rating (kW), assumption of number of engines running expressed in operational days per year (if greater than 365, it was assumed that more than one engine was running), a single load factor for each vessel type, and capacity bins. A hybrid method was used for vessels boarded as part of VBP but this was not considered to be robust enough to use on its own. VBP data were used to inform and align the estimate of number of engines used and the ratios between various modes and to review the results for reasonableness.

For vessel classes not previously boarded by VBP, data collected by FMI (from engine manufacturers, classification societies and other sources) were used to determine the ratio between main engines and auxiliary engines. The number of engines assumed to be installed and running was derived from either the Second IMO GHG Study 2009 or professional judgement. This information was used for the various vessel types and bin sizes to develop vessel-weighted average auxiliary loads in kW. Consistent with the approach of the Second IMO GHG Study 2009, these loads are applied across all operational modes in this study.

LIke auxiliary engine loads, there is no commercial data source that provides information about auxiliary boiler loads by operational mode. Auxiliary boiler loads were developed using VBP data and the professional judgement of members of the consortium. Auxiliary boiler loads are typically reported in tons of fuel per day but these rates have been converted to kW (Starcrest, 2013). Boilers are used for various purposes on ships and their operational profile can change by mode.

Further details of the approach used to develop auxiliary engine and boiler loads by vessel type and mode can be found in Annex 1.

1.2.6 Sources and alignment/coverage of data sources

For the bottom-up method, calculations are performed on each individual ship's technical and activity data. For this, the consortium mainly used the IHSF database and AIS data sources and the majority of ships can be identified in each of these for a given year. However, during the method development, the consortium has recognized several ships for which a corresponding IHSF and activity data match does not occur (e.g. an IMO number is not reported or the MMSI number does not match). Treatment of ships in such categories can be summarized by the diagram presented in Figure 26, and is discussed below so that their contribution to global CO_2 emissions estimates can be better understood.

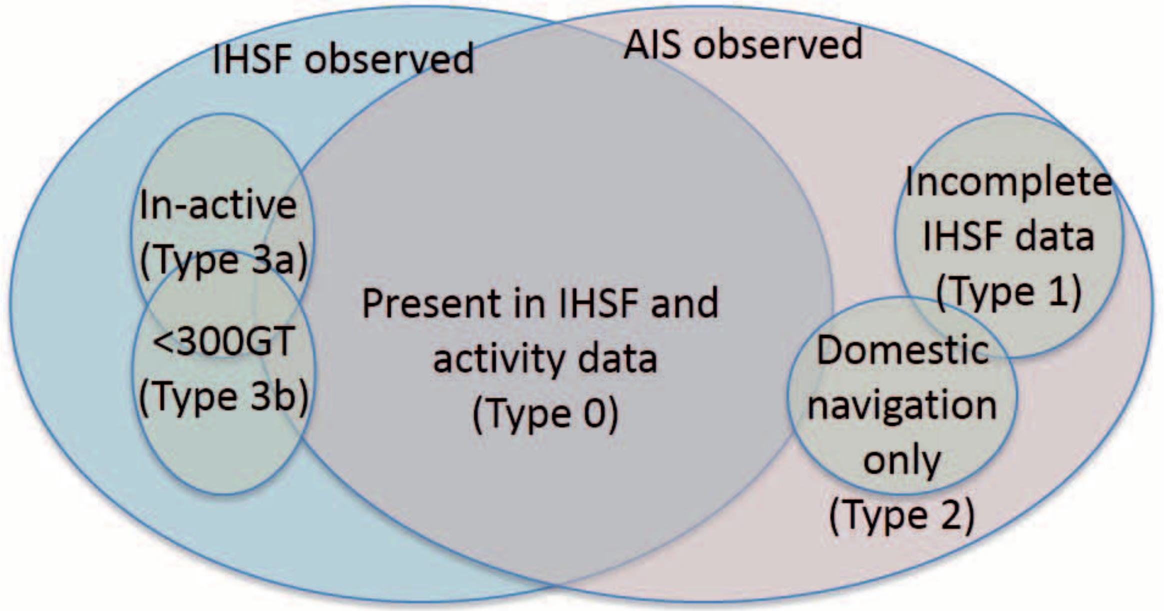

Figure 26: *Venn diagram describing the sets of ships observed in the two main data types used in the bottom-up method (IHSF and AIS)*

Type 1: IMO number is missing but MMSI number appears in both IHSF and activity data set

The SOLAS convention (chapter V) requires that all ships of >300 gt should install a class-A AIS transponder. Furthermore, ships of <300 gt are urged to install class-B AIS transponders voluntarily. The consortium recognized the MEPC request to calculate CO_2 emissions from all ships of >100 gt, therefore the consortium retrieved both class-A and class-B data for this purpose.

Each AIS transponder has an individual MMSI code. MMSI transponder data from non-ships (e.g. fixed structures, SAR aircraft) were excluded using message ID and the first three digits of the MMSI. Of the remaining ships, for which no IMO numbers are reported in the activity data, the match was carried out on MMSI number alone. However, this is not fully reliable because the record of MMSI numbers in the IHSF data set is imperfect.

Type 2: MMSI appears in the activity data set only

The consortium recognized that some ships appeared in the activity data set only and did not match any ships registered in the IHSF database. Three reasons could explain this mismatch:

1 erroneous or incomplete records in the IHSF database (e.g. incomplete list of MMSI numbers);

2 ships are operated only for domestic navigation purposes (in which case, the ships will be controlled under each individual administration and do not need to be registered in IHSF);

3 the AIS equipment has reverted back to default "factory settings" of IMO/MMSI numbers.[1]

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[1] See the Maritime and Coastguard Agency note MIN 298 (M+F): "AIS (Automatic Identification Systems) Operational Notification – Safety of Navigation. ACR/Nauticast AIS".

In some countries with cabotage, such as the United States, Japan and China, some ships may be employed in domestic navigation only and this could be consistent with explanation 2. As the bottom-up method will include both international and domestic fuel consumption and emissions (in order to assist in separating out international fuel consumption and emissions alone), this category of ships will have to be included in the method, but with high uncertainty because they cannot be given technical characteristics.

Type 3: ship appears in IHSF but cannot be identified in the activity data set

After the matching process, a number of ships may be identified in the IHSF database with no corresponding activity data. Explanations for this could be:

a the ships were not active or had their transponders turned off; e.g. FPSOs, barges, platforms and older ships awaiting scrapping;

b the ships may be less than 300 gt without any AIS installation.

If the ship was >300 gt, it was assumed to be inactive and omitted from the model. If the ship was <300 gt, it was assumed that its absence from the AIS data was because it did not have a transponder. In this case the vessel was assigned a typical activity model from similar identifiable ships.

Classifications for each type are summarized in Table 11. Category 0 includes ships that have no identification/matching issues. All of the other four categories require assumptions, which are studied in greater detail in Sections 1.4 and 1.5.

Table 11 – *Classification of ships in the bottom-up approach*

Type	Identified in activity data set	Identified in IHSF database	Reason for non-matching	Target for estimation
0	Yes	Yes		Yes
1	Yes	Yes on MMSI number	Incompletion in data	Yes
2	Yes	No	Ships are operated for domestic navigation only, therefore not registered in IHSF	Yes
3a	No	Yes	Ship is not active	No
3b	No	Yes	Ships of <300 gt and without any AIS transponder	Yes

1.2.7 Bottom-up fuel and emissions estimation

The bottom-up method combines activity data (derived from AIS and LRIT raw data sources) and technical data (derived from IHSF and a series of empirical data and assumptions derived from the literature).

The model is composed of a main programme that calls up a number of subroutines (as listed in Annex 1). Each ship has a total of 8,760 unique activity observations per year (8,784 in a leap year) and with approximately 100,000 ships included in a given year's fleet, the run time of the model is significant on conventional hardware.

The model can only perform calculations for ships for which both activity and IHSF activity data are available. Procedures for estimating the fuel demands and emissions of ships that are not matched are described in greater detail in Annex 1.

1.2.8 Classification of international and domestic fuel

Estimation of bottom-up fuel totals is performed without pre-identifying international versus domestic allocations, because bottom-up methods focus on characteristics of vessel activity, irrespective of ports of departure and arrival. Therefore, top-down allocations according to IEA and IPCC definitions cannot be directly extracted from bottom-up results without route identification. However, some approaches can produce estimates of the fraction of fuels reported in bottom-up totals that may represent a delineation of international shipping, domestic navigation and fishing. These approaches can be summarized as three allocation methods:

1 apply heuristic from T-D statistics as a ratio of international to total shipping;

2 assign fleet sectors to domestic service and subtract from fleet;

3 combine T-D heuristics and fleet sector information to match the vessel types most likely to serve domestic shipping (bottom-up) with expectations of total fraction likely to use domestic bunkers (top-down).

The Second IMO GHG Study 2009 used method 3, a combined application of the top-down heuristic and removal of some vessel types. However, the study noted significant uncertainties with this approach. Specifically, it assumed that ship activity was proportional to data on seaborne transport. The study noted that, over the course of a year's activity, a given vessel could be engaged in both international shipping and domestic navigation. "Since the [Second IMO GHG Study 2009] activity-based model cannot separate domestic shipping from international shipping, figures from bunker statistics for emissions from domestic shipping [were] used in the calculation of emissions from international shipping" (Second IMO GHG Study 2009, paragraph 3.17). This study explicitly removed fleet sectors associated with fishing, fixed offshore installations (production vessels) and domestic navigation relying on fuel totals reported in their top-down analysis based on IEA statistics.

The Third IMO GHG Study 2014 consortium chose not to apply allocation methods 1 or 3 and selected method 2, for several reasons. Method 1 requires a simplistic and arbitrary direct application of the top-down fuel ratios to bottom-up totals. The main disadvantage of method 1 is that it can be applied to the inventory total only; results cannot be tied to bottom-up insights within vessel categories. A related disadvantage is that the assumption may be untestable, preventing direct quality assurance or control and disabling any quantitative consideration of uncertainty.

Allocation method 3 requires subjective judgements to be imposed on the bottom-up data beyond a testable set of assumptions applied to vessel types. For example, the 2009 study imposed additional definitions of oceangoing and coastwise shipping, designating some fleet sectors like cruise passenger ships, service and fishing vessels and smaller ro-pax vessels as coastwise. However, that study did not reconcile or discuss whether the fuel totals allocated to coastwise vessels corresponded to an international versus domestic determination within its activity-based method. Moreover, an attempt to determine which shipping was coastwise, as opposed to transiting along a coastal route, was beyond scope of the study.

The Third IMO GHG Study 2014 applies allocation method 2 with information provided in AIS to support the bottom-up methodology. Based on general voyage behaviour, some ship types are likely to engage in international shipping more often than domestic navigation. These types include transport and larger ferry vessels, as listed in Table 12. This allocation, therefore, also identifies ship types that can be expected to engage mostly in domestic navigation, including non-transport vessels, such as offshore and service vessels, yachts and smaller regional ferry vessels (see Table 13). Results using allocation method 2 allow comparison between bottom-up and top-down allocation of international shipping and domestic navigation. As a caveat, method 2 might overestimate international shipping and could increase uncertainty, which is discussed in Sections 1.4 and 1.5.

Table 12 – *Summary of vessel types and sizes that can be expected to engage in international shipping*

Vessel type	Capacity bin	Capacity unit
Bulk carrier	0–9,999	dwt
	10,000–34,999	
	35,000–59999	
	60,000–99,999	
	100,000–199,999	
	200,000–+	
Chemical tanker	0–4,999	dwt
	5,000–9,999	
	10,000–19,999	
	20,000–+	
Container	0–999	TEU
	1,000–1,999	
	2,000–2,999	
	3,000–4,999	
	5,000–7,999	
	8,000–11,999	
	12,000–14,500	
	14,500–+	
Cruise	0–1,999	gt
	2,000–9,999	
	10,000–59,999	
	60,000–99,999	
	100,000–+	
Ferry – pax only	2,000–+	gt
Ferry – ro-pax	2,000–+	gt
General cargo	0–4,999	dwt
	5,000–9,999	
	10,000–+	
Liquefied gas tanker	0–49,999	cubic metres (cbm)
	50,000–199,999	
	200,000–+	
Oil tanker	0–4,999	dwt
	5,000–9,999	
	10,000–19,999	
	20,000–59,999	
	60,000–79,999	
	80,000–119,999	
	120,000–199,999	
	200,000–+	
Other liquids tankers	0–+	dwt
Refrigerated cargo	0–1,999	dwt
Ro-ro	0–4,999	gt
	5,000–+	
Vehicle	0–3,999	vehicles
	4,000–+	

Table 13 – *Summary of vessel types and sizes that can be expected to engage in domestic shipping*

Vessel type	Capacity bin	Capacity unit
Ferry: pax only	0–1,999	gt
Ferry: ro-pax	0–1,999	gt
Miscellaneous – fishing	All sizes	gt
Miscellaneous – other	All sizes	gt
Offshore	All sizes	gt
Service – other	All sizes	gt
Service – tug	All sizes	gt
Yacht	All sizes	gt

1.3 Inventories of CO_2 emissions calculated using both the top-down and bottom-up methods

1.3.1 CO_2 emissions and fuel consumption by ship type

Figure 27 presents CO_2 emissions by ship type, calculated using the bottom-up method. Equivalent ship-type-specific results cannot be presented for the top-down method because the reported marine fuel sales statistics are only available in three categories: international, domestic and fishing.

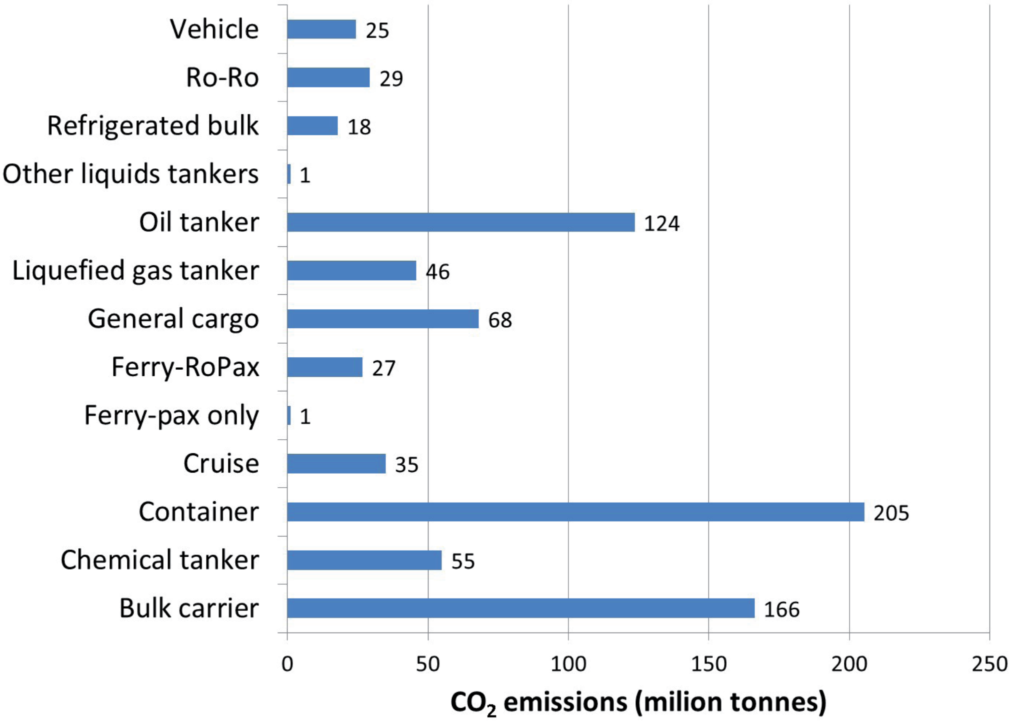

Figure 27: *Bottom-up CO_2 emissions from international shipping by ship type (2012)*

Figure 28 shows the relative fuel consumption among vessel types in 2012 (both international and domestic shipping), estimated using the bottom-up method. The figure also identifies relative fuel consumption between the main engine (predominantly propulsion), auxiliary engine (electricity generation) and boilers (steam generation). The total shipping fuel consumption is shown to be dominated by three ship types: oil tankers, bulk carriers and container ships. In each of these ship types, the main engine consumes the majority of the fuel. The same plots recreated for earlier years (2007–2011) are included in Annex 2.

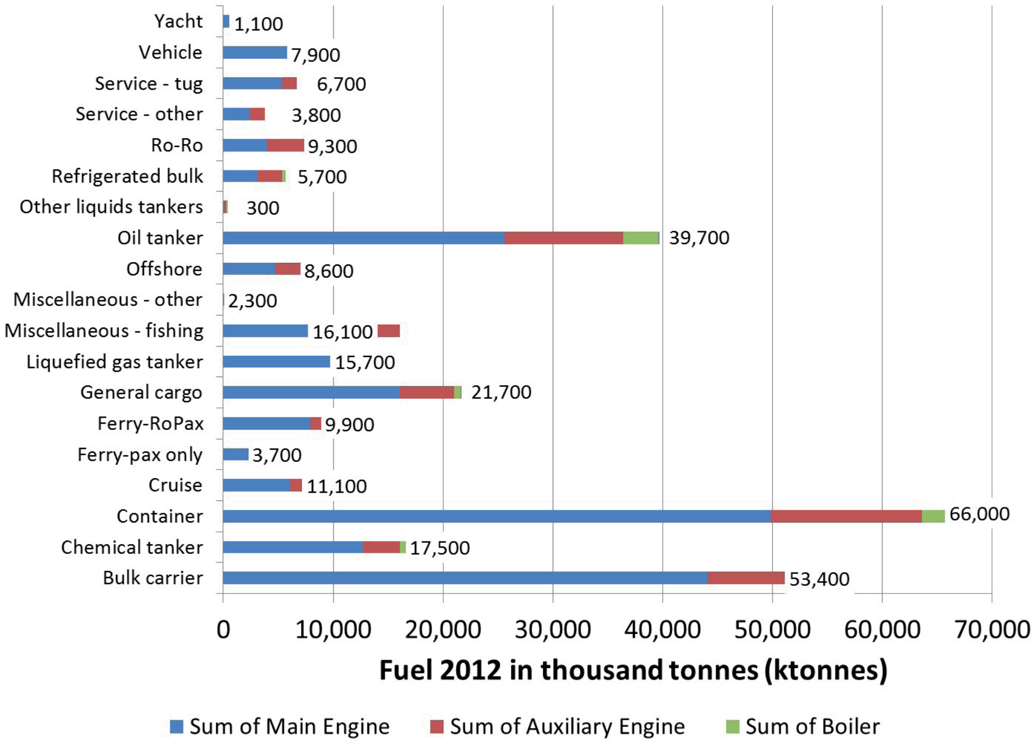

Figure 28: *Summary graph of annual fuel consumption (2012), broken down by ship type and machinery component (main, auxiliary and boiler)*

The detailed results for 2012, broken down by ship type and size category, are presented in Table 14. This table displays the differences between ship types and sizes; for example, differences in installed power, speeds (both design speed and operational speed) and as a result differences in fuel consumption. There are also important differences between the amounts (number of ships) in each of the ship type and size categories. When aggregated to a specific ship type, in sum, these explain the differences observed in Figure 27 and Figure 28, and the differences presented in the last column ("Total CO_2 emissions").

The table also displays information about the coverage of the fleet on AIS. The "IHSF" column under "Number active" lists the number of ships reported as being in service in the IHSF database for that year. The "AIS" column under "Number active" lists the number of ships that are observed in the AIS data at any point in time during the year. In general, the coverage of the in-service fleet on AIS is consistently high (e.g. 95% and above) for the larger ship sizes but less so for some smaller ship size categories (the smallest general cargo carriers in particular). This could be indicative of a number of issues:

- low quality in certain size and type categories of the IHSF database for maintaining information on a ship's status (in-service indication);
- low-quality AIS coverage for the smallest ship types;
- low compliance with SOLAS, chapter V (that ships above a certain size must fit an AIS transponder).

The discussion of quality of coverage is extended in Section 1.4.

Further tables listing the same specifics for the earlier years of the analysis are included in Annex 2.

Table 14 – *Tabular data for 2012 describing the fleet (international, domestic and fishing) analysed using the bottom-up method*

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Bulk carrier	0–9,999	dwt	1,216	670	0.55	3,341	1,640	11.6	167	9.4	0.9	0.5	0.1	5,550
	10,000–34,999	dwt	2,317	2,131	0.92	27,669	6,563	14.8	168	11.4	3.0	0.5	0.1	24,243
	35,000–59,999	dwt	3,065	2,897	0.95	52,222	9,022	15.3	173	11.8	4.0	0.7	0.1	44,116
	60,000–99,999	dwt	2,259	2,145	0.95	81,876	10,917	15.3	191	11.9	5.4	1.1	0.3	45,240
	100,000–199,999	dwt	1,246	1,169	0.94	176,506	17,330	15.3	202	11.7	8.5	1.1	0.2	36,340
	200,000–+	dwt	294	274	0.93	271,391	22,170	15.7	202	12.2	11.0	1.1	0.2	10,815
Chemical tanker	0–4,999	dwt	1,502	893	0.59	2,158	1,387	11.9	159	9.8	0.8	0.5	0.6	5,479
	5,000–9,999	dwt	922	863	0.94	7,497	3,292	13.4	169	10.6	1.6	0.6	0.4	7,199
	10,000–19,999	dwt	1,039	1,004	0.97	15,278	5,260	14.1	181	11.7	3.0	0.6	0.4	12,318
	20,000–+	dwt	1,472	1,419	0.96	42,605	9,297	15.0	183	12.3	5.0	1.4	0.4	30,027
Container	0–999	TEU	1,126	986	0.88	8,634	5,978	16.5	190	12.4	2.8	0.9	0.2	12,966
	1,000–1,999	TEU	1,306	1,275	0.98	20,436	12,578	19.5	200	13.9	5.2	2.2	0.4	31,015
	2,000–2,999	TEU	715	689	0.96	36,735	22,253	22.2	208	15.0	8.0	3.1	0.5	25,084
	3,000–4,999	TEU	968	923	0.95	54,160	36,549	24.1	236	16.1	13.9	3.9	0.6	53,737
	5,000–7,999	TEU	575	552	0.96	75,036	54,838	25.1	246	16.3	19.5	4.1	0.6	42,960
	8,000–11,999	TEU	331	325	0.98	108,650	67,676	25.5	256	16.3	24.4	4.5	0.7	30,052
	12,000–14,500	TEU	103	98	0.95	176,783	83,609	28.9	241	16.1	23.7	4.9	0.8	8,775
	14,500–+	TEU	8	7	0.88	158,038	80,697	25.0	251	14.8	25.3	6.1	1.1	806
General cargo	0–4,999	dwt	11,620	5,163	0.44	1,925	1,119	11.6	161	8.7	0.5	0.1	0.0	23,606
	5,000–9,999	dwt	2,894	2,491	0.86	7,339	3,320	13.6	166	10.1	1.4	0.4	0.1	16,949
	10,000–+	dwt	1,972	1,779	0.90	22,472	7,418	15.8	174	12.0	3.4	1.2	0.1	27,601
Liquefied gas tanker	0–49,999	cbm	1,104	923	0.84	6,676	3,815	14.2	180	11.9	2.4	0.6	0.4	11,271
	50,000–199,999	cbm	463	444	0.96	68,463	22,600	18.5	254	14.9	17.9	4.1	0.6	29,283
	200,000–+	cbm	45	43	0.96	121,285	37,358	19.3	277	16.9	33.5	4.0	1.0	5,406

Table 14 – *Tabular data for 2012 describing the fleet (international, domestic and fishing) analysed using the bottom-up method (continued)*

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Oil tanker	0–4,999	dwt	3,500	1,498	0.43	1,985	1,274	11.5	144	8.7	0.6	0.6	0.2	14,991
	5,000–9,999	dwt	664	577	0.87	6,777	2,846	12.6	147	9.1	1.1	1.0	0.3	4,630
	10,000–19,999	dwt	190	171	0.90	15,129	4,631	13.4	149	9.6	1.6	1.7	0.4	2,121
	20,000–59,999	dwt	659	624	0.95	43,763	8,625	14.8	164	11.7	3.7	2.0	0.6	12,627
	60,000–79,999	dwt	391	381	0.97	72,901	12,102	15.1	183	12.2	5.8	1.9	0.6	9,950
	80,000–119,999	dwt	917	890	0.97	109,259	13,813	15.3	186	11.6	5.9	2.6	0.8	25,769
	120,000–199,999	dwt	473	447	0.95	162,348	18,796	16.0	206	11.7	8.0	3.1	1.0	17,230
	200,000–+	dwt	601	577	0.96	313,396	27,685	16.0	233	12.5	15.3	3.6	1.1	36,296
Other liquids tankers	0–+	dwt	149	39	0.26	670	558	9.8	116	8.3	0.3	1.3	0.5	5,550
Ferry – pax only	0–1,999	gt	3,081	1,145	0.37	135	1,885	22.7	182	13.9	0.8	0.4	0.0	10,968
	2,000–+	gt	71	52	0.73	1,681	6,594	16.6	215	12.8	3.9	1.0	0.0	1,074
Cruise	0–1,999	gt	198	75	0.38	137	914	12.4	102	8.8	0.3	1.0	0.5	1,105
	2,000–9,999	gt	69	53	0.77	1,192	4,552	16.0	161	9.9	1.3	1.1	0.4	580
	10,000–59,999	gt	115	108	0.94	4,408	19,657	19.9	217	13.8	9.1	9.2	1.4	6,929
	60,000–99,999	gt	87	85	0.98	8,425	53,293	22.2	267	15.7	30.8	26.2	0.6	15,415
	100,000–+	gt	51	51	1.00	11,711	76,117	22.7	261	16.4	47.2	25.5	0.5	10,906
Ferry – ro-pax	0–1,999	gt	1,669	732	0.44	401	1,508	13.0	184	8.4	0.6	0.2	0.0	4,308
	2,000–+	gt	1,198	1,046	0.87	3,221	15,491	21.6	198	13.9	6.0	1.4	0.0	26,753
Refrigerated bulk	0–1,999	dwt	1,090	763	0.70	5,695	5,029	16.8	173	13.4	3.0	2.3	0.4	17,945
Ro-ro	0–4,999	dwt	1,330	513	0.39	1,031	1,482	10.7	146	8.8	1.1	2.5	0.3	15,948
	5,000–+	dwt	415	396	0.95	11,576	12,602	18.6	209	14.2	6.8	3.6	0.4	13,446
Vehicle	0–3,999	vehicle	279	261	0.94	9,052	9,084	18.3	222	14.2	5.4	1.6	0.3	6,200
	4,000–+	vehicle	558	515	0.92	19,721	14,216	20.1	269	15.5	9.0	1.4	0.2	18,302
Yacht	0–+	gt	1,750	1,110	0.63	171	2,846	16.5	66	10.7	0.4	0.5	0.0	3,482
Service – tug	0–+	gt	14,641	5,043	0.34	119	2,313	11.8	100	6.7	0.4	0.1	0.0	21,301

Table 14 – *Tabular data for 2012 describing the fleet (international, domestic and fishing) analysed using the bottom-up method (continued)*

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Miscellaneous – fishing	0–+	gt	22,130	4,510	0.20	181	956	11.5	164	7.4	0.4	0.4	0.0	50,959
Offshore	0–+	gt	6,480	5,082	0.78	1,716	4,711	13.8	106	8.0	0.7	0.6	0.0	27,397
Service – other	0–+	gt	3,423	2,816	0.82	2,319	3,177	12.8	116	7.9	0.7	0.4	0.0	11,988
Miscellaneous – other	0–+	gt	3,008	64	0.02	59	2,003	12.7	117	7.3	0.4	0.4	0.0	7,425

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* indicates the use of weighted averaging (weighted by days at sea for each individual ship).

Note: slight differences in Table 14 and Table 16 totals are due to rounding in values reported in the report. For 2012 the dfference is approximately 0.1%.

1.3.2 CO_2 and fuel consumption for multiple years 2007–2012

Figure 29 shows the year-on-year trends for the total CO_2 emissions of each ship type, as estimated using the bottom-up method. Figure 30 and Figure 31 show the associated total fuel consumption estimates for all years of the study, from both the top-down and bottom-up methods. The total CO_2 emissions aggregated to the lowest level of detail in the top-down analysis (international, domestic and fishing) are presented in Table 15 and Table 16.

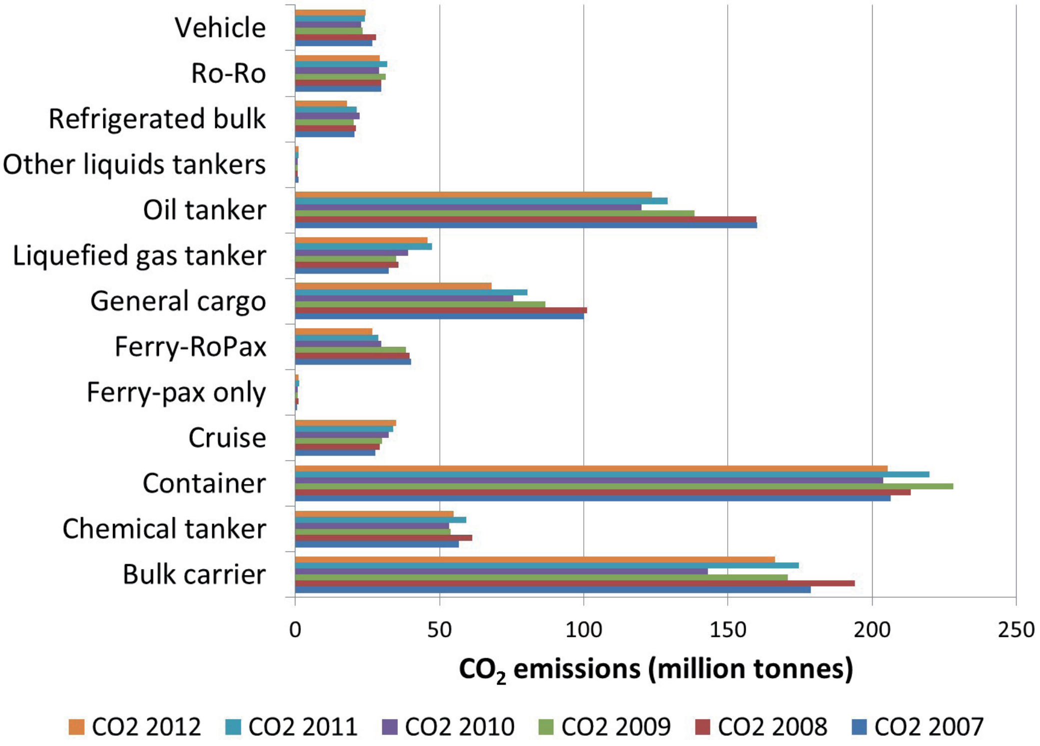


Figure 29: *CO_2 emissions by ship type (international shipping only), calculated using the bottom-up method for all years 2007–2012*

Table 15 – *International, domestic and fishing CO_2 emissions 2007–2011 (million tonnes), using the top-down method*

Marine sector	Fuel type	2007	2008	2009	2010	2011
International shipping	HFO	542.1	551.2	516.6	557.1	554.0
	MDO	83.4	72.8	79.8	90.4	94.9
	LNG	0.0	0.0	0.0	0.0	0.0
Top-down international total	**All**	**625.5**	**624.0**	**596.4**	**647.5**	**648.9**
Domestic navigation	HFO	62.0	44.2	47.6	44.5	39.5
	MDO	72.8	76.6	75.7	82.4	87.8
	LNG	0.1	0.1	0.1	0.1	0.2
Top-down domestic total	**All**	**134.9**	**121.0**	**123.4**	**127.1**	**127.6**
Fishing	HFO	3.4	3.4	3.1	2.5	2.5
	MDO	17.3	15.7	16.0	16.7	16.4
	LNG	0.1	0.1	0.1	0.1	0.1
Top-down fishing total	**All**	**20.8**	**19.2**	**19.3**	**19.2**	**19.0**
Total CO_2 emissions		**781.2**	**764.1**	**739.1**	**793.8**	**795.4**

Table 16 – *International, domestic and fishing CO_2 emissions 2007–2012 (million tonnes), using the bottom-up method*

Marine sector	**Fuel type**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
International shipping	HFO	773.8	802.7	736.6	650.6	716.9	667.9
	MDO	97.2	102.9	104.2	102.2	109.8	105.2
	LNG	13.9	15.4	14.2	18.6	22.8	22.6
Bottom-up international total	**All**	**884.9**	**920.9**	**855.1**	**771.4**	**849.5**	**795.7**
Domestic navigation	HFO	53.8	57.4	32.5	45.1	61.7	39.9
	MDO	142.7	138.8	80.1	88.2	98.1	91.6
	LNG	0	0	0	0	0	0
Bottom-up domestic total	**All**	**196.5**	**196.2**	**112.6**	**133.3**	**159.7**	**131.4**
Fishing	HFO	1.6	1.5	0.9	0.8	1.4	1.1
	MDO	17.0	16.4	9.3	9.2	10.9	9.9
	LNG	0	0	0	0	0	0
Bottom-up fishing total	**All**	**18.6**	**18.0**	**10.2**	**10.0**	**12.3**	**11.0**
Total CO_2 emissions		**1,100.1**	**1,135.1**	**977.9**	**914.7**	**1,021.6**	**938.1**

Total fuel consumption estimates for 2007–2012 using the bottom-up method are presented in Figure 30 for all ships and in Figure 31 for international shipping. These results are presented alongside the multi-year top-down fuel consumption results presented in Section 1.1.3. Section 1.4.4 discusses the differences between fuel consumption and emissions estimates from these methods.

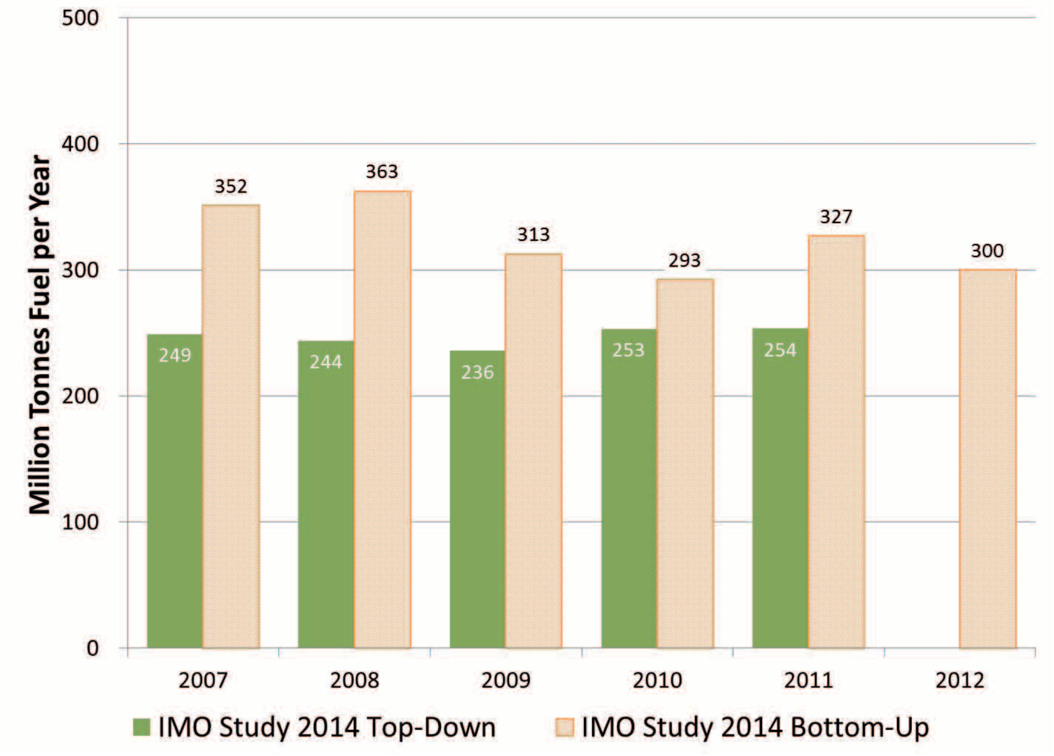


Figure 30: *Summary graph of annual fuel use by all ships, estimated using the top-down and bottom-up methods*

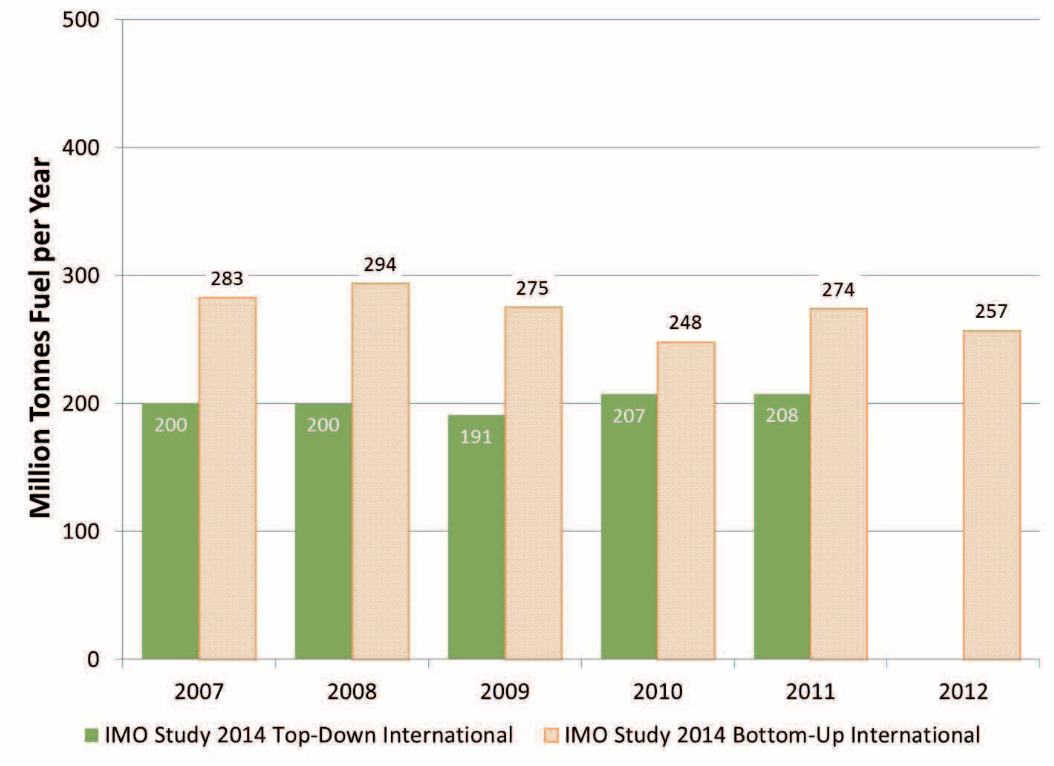


Figure 31: *Summary graph of annual fuel use by international shipping, estimated using the top-down and bottom-up methods*

Particular care must be taken when interpreting the domestic fuel consumption and emissions estimates from both the top-down and the bottom-up methods. Depending on where domestic shipping and fishing buys its fuel, it may or may not be adequately captured in the IEA marine bunkers. For example, inland or leisure and fishing vessels may purchase fuel at locations that also sell fuel to other sectors of the economy and therefore be misallocated. In the bottom-up method, fuel consumption is included only for ships that appear in the IHSF database (and have an IMO number). While this should cover all international shipping, many domestic vessels (inland, fishing or cabotage) may not be included in this database. An indication of the number of vessels excluded from the bottom-up method was obtained from the count of MMSI numbers observed on AIS but for which no match to the IHSF database was obtained. The implications of this count for both the bottom-up and top-down analysis are discussed in Section 1.4.

1.3.3 Trends in emissions and drivers of emissions 2007–2012

Figures 32–37 present indexed time series of the total CO_2 emissions for three ship types – oil tankers, container ships and bulk carriers – during the period studied. The figures also present a number of key drivers of CO_2 emissions estimated in the bottom-up method that can be used to decompose CO_2 emissions trends:

- the total CO_2 emissions are a function of the total number of ships and average annual fuel consumption;
- the average annual fuel consumption is primarily a function of days at sea and the extent of adoption of slow steaming;
- all trends are indexed to their values in 2007.

These drivers of average annual fuel consumption can also be influenced by changes in the average specification of the fleet (average capacity, average installed power, etc.). These are of less significance than the key trends of speed and days at sea.

The contrast between the three plots shows that these three sectors of the shipping industry have changed in different ways over the period 2007–2012. The oil tanker sector reduced its emissions by a total of 20%. During the same period the dry bulk and container ship sectors also saw absolute emissions reductions but by smaller amounts. All ship types experienced similar reductions in average annual fuel consumption, but the difference in fleet total CO_2 emissions is explained by the combination of these reductions with differences in the number of ships in service. The reduction in average days at sea during the period studied is greatest in the dry bulk fleet, whereas the container ship fleet has seen a slight increase. Consistent with the results presented in Table 17, more container ships adopted slow steaming operations. In other words, similar reductions in average fuel consumption per ship over the study period were achieved through different combinations of speed and days at sea.

The analysis of trends in speed and days at sea are consistent with the findings from Section 3 that the global fleet is currently at or near the historic low in terms of productivity (transport work per unit of capacity). (See Section 3.2.4 and related text and Annex 7, Figures 38–40, for further details.) The consequence is that these (and many other) sectors of the shipping industry represent latent emissions increases, because the fundamentals (number of ships in service, fleet total installed power and demand tonne-miles) have seen upward trends. These upward trends have been controlled because economic pressures (excess supply of fleet as demonstrated by the relative supply and demand growth in each plot), together with high fuel prices, have acted to reduce productivity (reducing both average operating speeds and days spent at sea in both the oil tanker and bulk carrier fleets, and only operating speeds in the container fleets). These two components of productivity are both liable to change if the supply and demand differential returns to historical long-run trends. Therefore, whether and when the latent emissions may appear is uncertain, as this depends on the future market dynamics of the industry. However, the risk is high that fleet "potential to emit" (e.g. fleet-average installed power and design speeds) could encounter conditions favouring the conversion of latent emissions to actual emissions; this could mean that shipping reverts to the trajectory estimated in the Second IMO GHG Study 2009. The potential for latent emissions to be realized is quantified in the sensitivity analysis in Section 3.3.4 (see Figure 88 and related text).

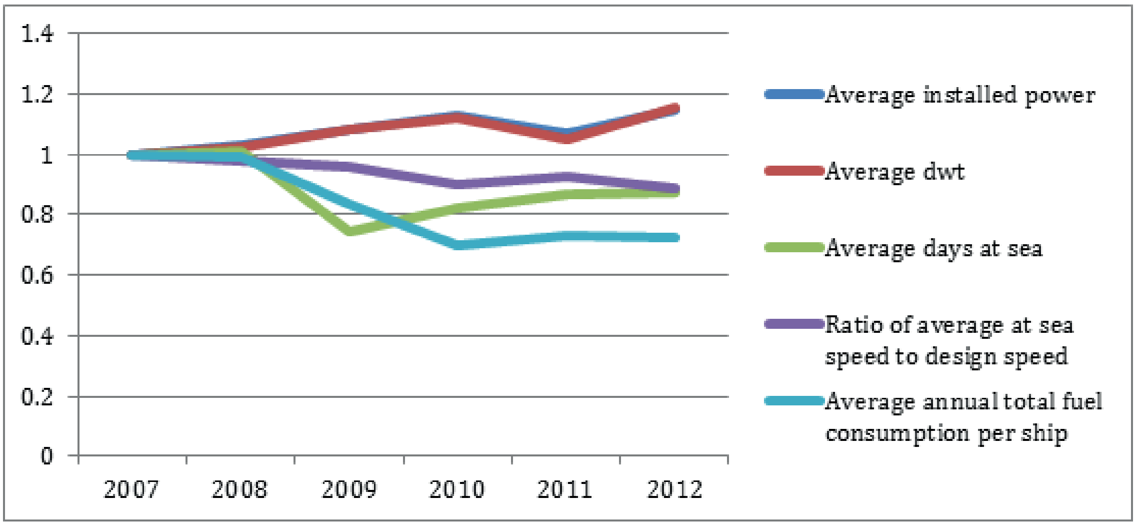


Figure 32: *Average trends in the tanker sector 2007–2012, indexed to 2007*

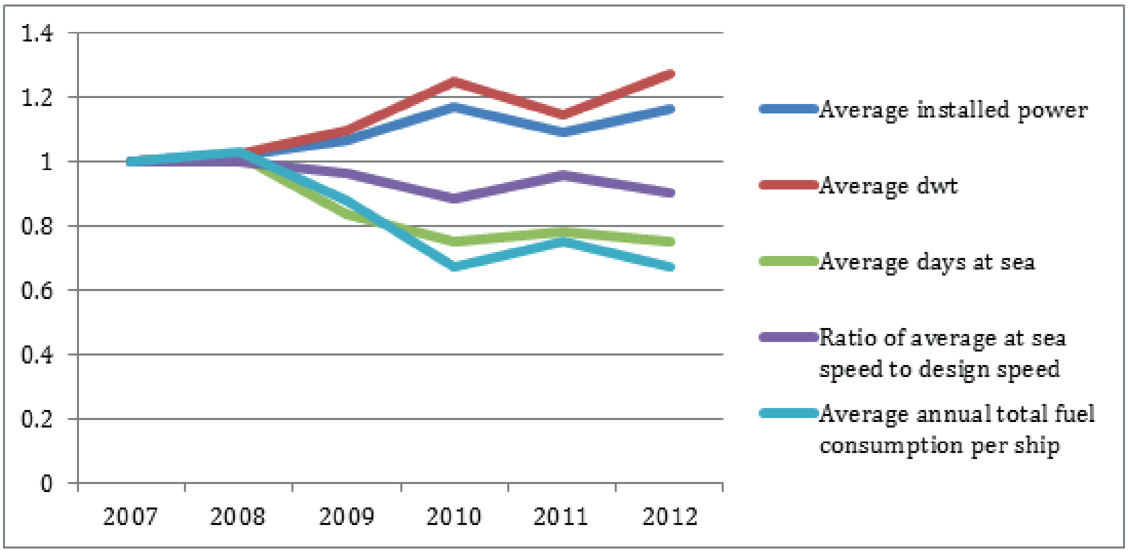


Figure 33: *Average trends in the bulk carrier sector 2007–2012, indexed to 2007*

Figure 34: *Average trends in the container ship sector 2007–2012, indexed to 2007*

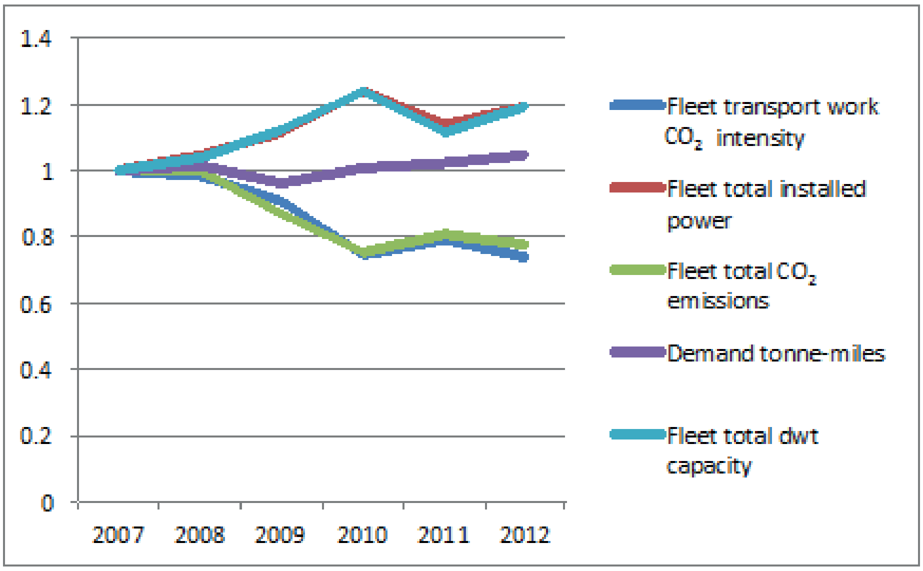


Figure 35: *Fleet total trends in the oil tanker sector (2007–2012), indexed to 2007*

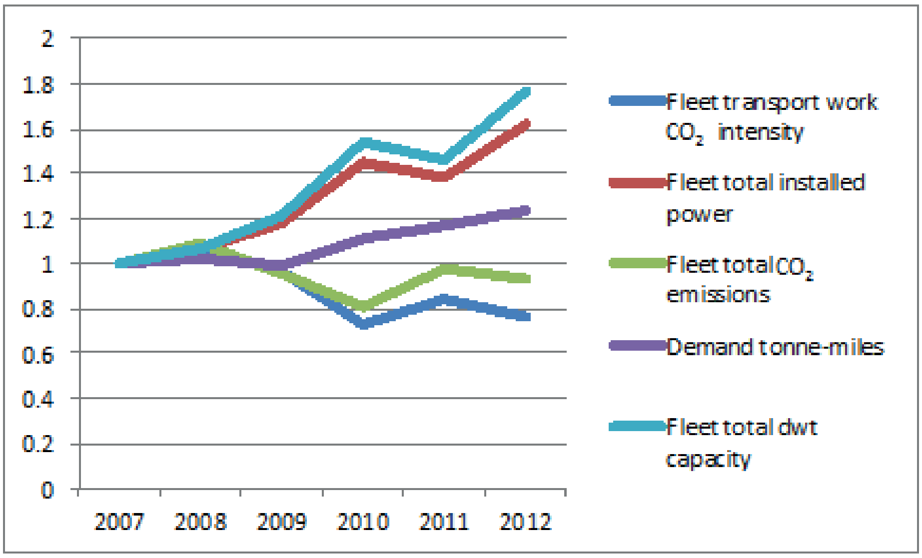


Figure 36: *Fleet total trends in the bulk carrier sector (2007¬–2012), indexed to 2007*

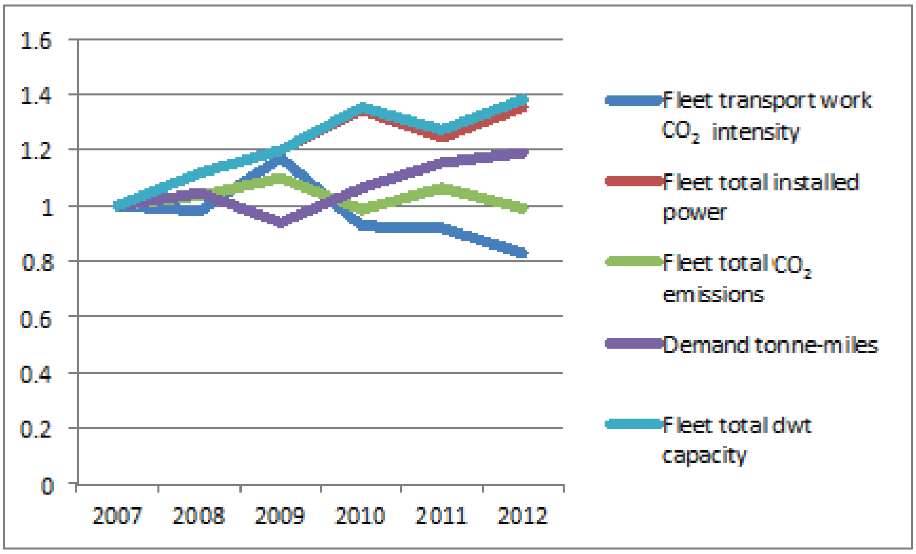


Figure 37: *Fleet total trends in the container ship sector (2007–2012), indexed to 2007*

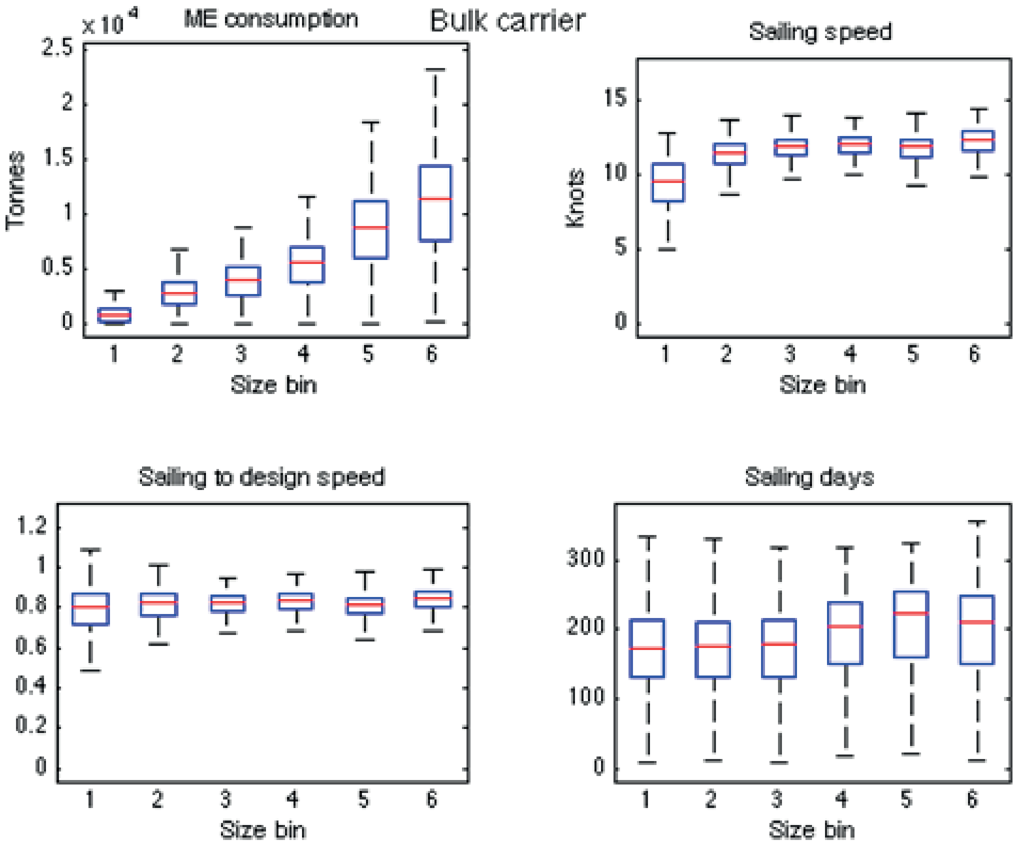


Figure 38: *Variability within ship size categories in the bulk ship fleet (2012). Size category 1 is the smallest bulk carrier (0–9,999 dwt) and size category 6 is the largest (200,000+ dwt)*

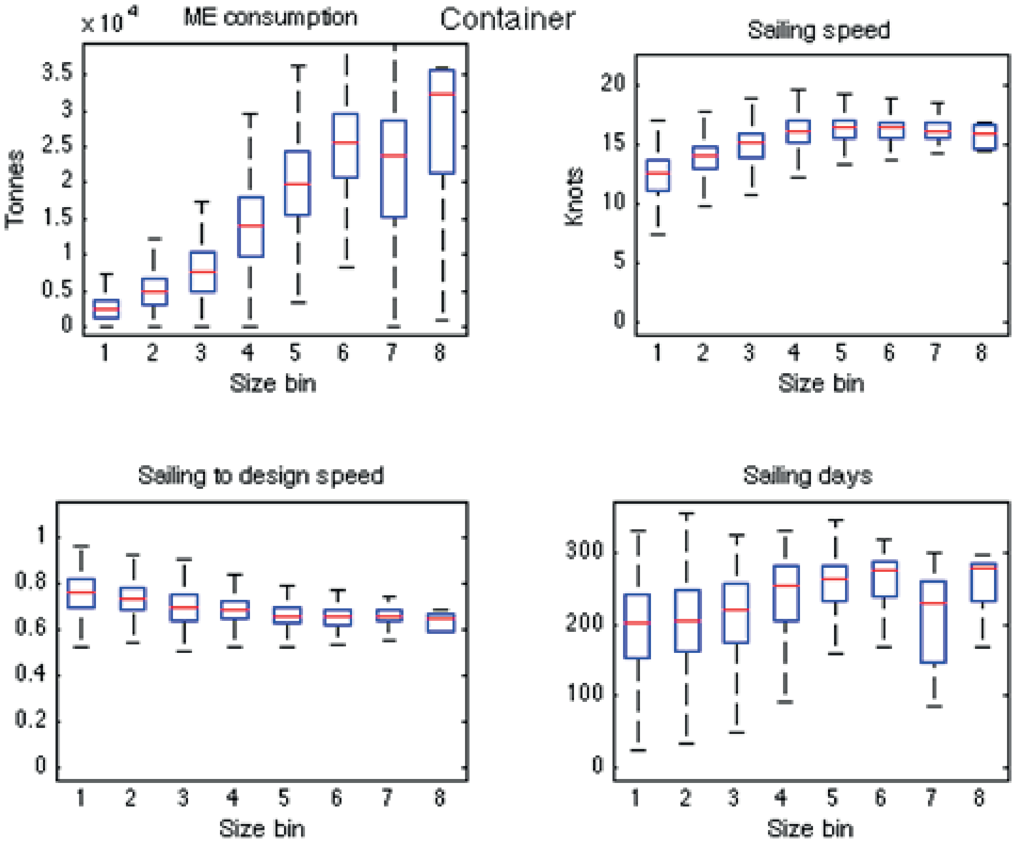


Figure 39: *Variability within ship size categories in the container ship fleet (2012). Size category 1 is the smallest container ship (0–999 TEU) and size category 8 is the largest (14,500+ TEU)*

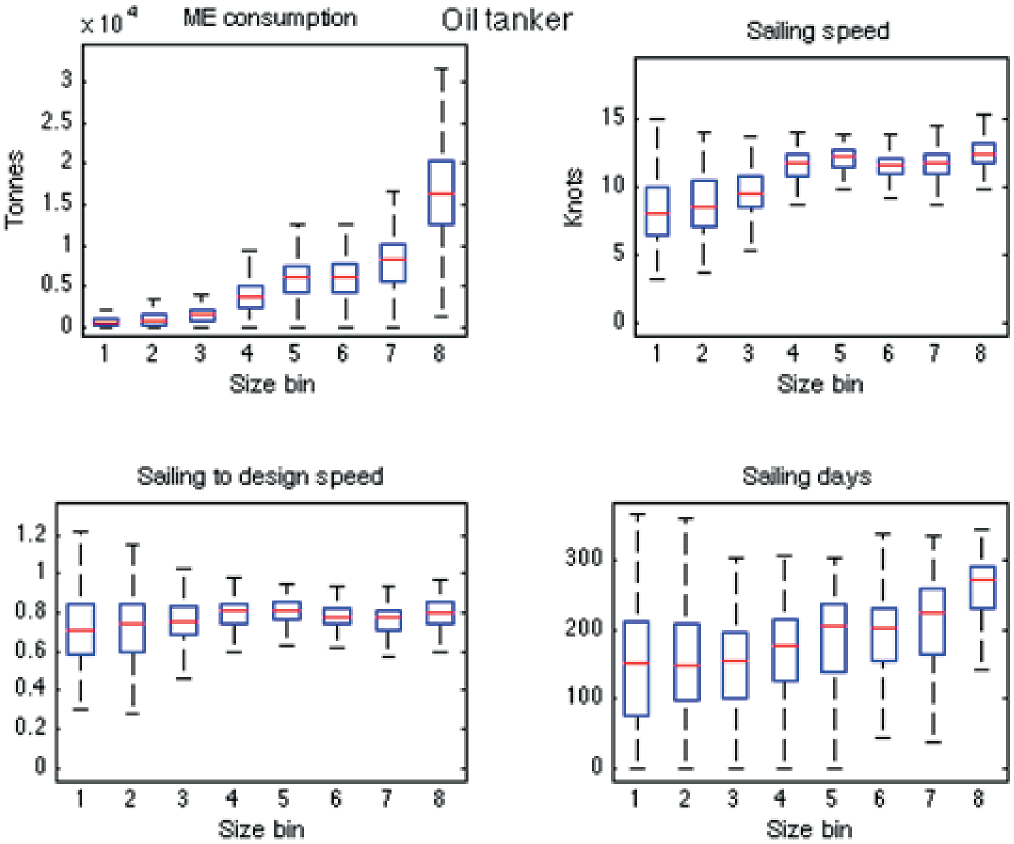


Figure 40: *Variability within ship size categories in the tanker fleet (2012). Size category 1 is the smallest oil tanker (0–9,999 dwt) and size category 8 is the largest (200,000+ dwt)*

1.3.4 Variability between ships of a similar type and size and the impact of slow steaming

The bottom-up method calculates ship type totals by summing the calculations for each individual ship identified as in service in the IHSF database. This study therefore supersedes the Second IMO GHG Study 2009 in providing insight into individual ships within fleets of similar ships. To illustrate this, Figures 38–40 display the statistics for the bulk carrier, container ship and tanker fleets. The plots represent each ship type's population by ship size category (on the x-axis). The box plots convey the average ship (red line in the middle of the box), the interquartile range (between the 25th and 75th percentile of the population) and the 2nd to 98th percentile range (the extremes of the "whiskers"). Tabular data characterizing each ship type and size category studied are included in Annex 2.The average sailing speed in 2012 of container ships in size categories 4–7 (3,000 TEU to 14,500 TEU capacity) is between 16 knots and 16.3 knots (Figure 39). The interquartile range of sailing speed is approximately 1 knot to 2 knots, depending on the size. This shows little variability in operating speed across the sector (nearly 2,000 ships). The average speed of ships in those four size categories varies between 24 knots and 29 knots. Therefore the sailing speed plot also shows the extent to which ships are slow steaming in 2012. The ratio of operating speed to design speed (here approximated as the IHSF reference speed) can be seen in the bottom left-hand plot (Figure 39), showing that larger ships (bin 8 in Figure 39) are on average operating at between 55% and 65% of their design speed. Although they have lower design speeds than the larger ships, in ratio terms the smaller container ships (sizes 1 and 2) are slow steaming less than the larger ships.

The top left of the plots portrays the estimated total annual main engine fuel consumption. In this instance there is a comparatively higher variability within the population than observed for sailing speed. Some of this is due to the variability in ship technical specifications (hull form, installed power and design speed). There is also variability in the total fuel consumption because of variability in the number of sailing days in a year (bottom right-hand plot). Holding all else equal, an increase in days at sea will increase total annual main-engine fuel consumption by the same percentage.

The results for oil tankers show a similar level of variability within a given ship size group, a significant (although not as significant as container ships) uptake of slow steaming and similarities between the larger ship types in terms of sailing speeds and days spent at sea.

The bottom-up method also allows the influence of slow steaming to be quantified. Across all ship types and sizes, the average ratio of operating speed to design speed was 0.85 in 2007 and 0.75 in 2012. This shows that, in relative terms, ships have slowed down: the widely reported phenomenon of slow steaming that has occurred since the financial crisis. The consequence of this observed slow steaming is a reduction in daily fuel of approximately 27% expressed as an average across all ship types and sizes. However, that average value belies the significant operational changes that have occurred in certain ship type and size categories. Table 17 describes, for three of the ship types studied, the ratio between slow steaming percentage (average at-sea operating speed expressed as a percentage of design speed), the average at-sea main engine load factor (a percentage of the total installed power produced by the main engine) and average at-sea main engine daily fuel consumption. Many of the larger ship sizes in all three ship type categories are estimated to have experienced reductions in daily fuel consumption well in excess of the average value of 25%.

The ships with the highest design speeds have adopted the greatest levels of slow steaming (e.g. container ships are operating at average speeds much lower than their design speeds); there is also widespread adoption of significant levels of slow steaming in many of the oil tanker size categories. Concurrent with the observed trend, technical specifications changed for ships. The largest bulk carriers (200,000+ dwt capacity) saw increases in average size (dwt capacity), as well as increased installed power (from an average of 18.9 MW to 22.2 MW), as a result of a large number of new ships entering the fleet over the time period (the fleet grew from 102 ships in 2007 to 294 ships in 2012).

A reduction in speed and the associated reduction in fuel consumption do not relate to an equivalent percentage increase in efficiency, because a greater number of ships (or more days at sea) are required to do the same amount of transport work. This relationship is discussed in greater detail in Section 3.

Table 17 – *Relationship between slow steaming, engine load factor (power output) and fuel consumption for 2007 and 2012*

Ship type	Size category	Unit	2007			2012			% change in average at-sea tonnes per day (tpd) 2007–2012
			Ratio of average at-sea speed to design speed	Average at-sea main engine load factor (% MCR)	At-sea consumption in tonnes per day (tpd)	Ratio of average at-sea speed to design speed	Average at-sea main engine load factor (% MCR)	At-sea consumption in tonnes per day (tpd)	
Bulk carrier	0–9,999	dwt	0.92	92%	7.0	0.84	70%	5.5	–24%
	10,000–34,999		0.86	68%	22.2	0.82	59%	17.6	–23%
	35,000–59,999		0.88	73%	29.0	0.82	58%	23.4	–21%
	60,000–99,999		0.90	78%	37.7	0.83	60%	28.8	–27%
	100,000–199,999		0.89	77%	55.5	0.81	57%	42.3	–27%
	200,000–+		0.82	66%	51.2	0.84	62%	56.3	10%
Container	0–999	TEU	0.82	62%	17.5	0.77	52%	14.4	–19%
	1,000–1,999		0.80	58%	33.8	0.73	45%	26.0	–26%
	2,000–2,999		0.80	58%	55.9	0.70	39%	38.5	–37%
	3,000–4,999		0.80	59%	90.4	0.68	36%	58.7	–42%
	5,000–7,999		0.82	63%	151.7	0.65	32%	79.3	–63%
	8,000–11,999		0.85	69%	200.0	0.65	32%	95.6	–71%
	12,000–14,500		0.84	67%	231.7	0.66	34%	107.8	–73%
	14,500–+		–	–	–	0.60	28%	100.0	–
Oil tanker	0–4,999	dwt	0.89	85%	5.1	0.80	67%	4.3	–18%
	5,000–9,999		0.83	64%	9.2	0.75	49%	7.1	–26%
	10,000–19,999		0.81	61%	15.3	0.76	49%	10.8	–34%
	20,000–59,999		0.87	72%	28.8	0.80	55%	22.2	–26%
	60,000–79,999		0.91	83%	45.0	0.81	57%	31.4	–35%
	80,000–119,999		0.91	81%	49.2	0.78	51%	31.5	–44%
	120,000–199,999		0.92	83%	65.4	0.77	49%	39.4	–50%
	200,000–+		0.95	90%	103.2	0.80	54%	65.2	–45%

1.3.5 Shipping's CO_2e emissions

Carbon dioxide equivalency (CO_2e) is a quantity that describes, for a given amount of GHG, the amount of CO_2 that would have the same global warming potential (GWP) as another long-lived emitted substance, when measured over a specified timescale (generally, 100 years). A total CO_2e estimate is produced by combining CO_2 emissions totals estimated in Section 1 with other GHG substances estimated in Section 2 and their associated GWP.

The Fifth IPCC Assessment Report (AR5) has changed the 100-year global warming potentials (GWP100) from previous assessments because of new estimates of lifetimes, impulse response functions and radiative efficiencies. IPCC (2013) acknowledges that the inclusion of indirect effects and feedbacks in metric values has been inconsistent in IPCC reports, and therefore the GWPs presented in previous assessments may underestimate the relative impacts of non-CO_2 gases.

The GWPs reported in IPCC (2013) include climate-carbon feedbacks for the reference gas CO_2, and for the non-CO_2 gases, GWPs are presented both with and without climate-carbon feedbacks. In accord with IPCC (2013), such feedbacks may have significant impacts on metrics and should be treated consistently.

Using GWP100 with climate-carbon feedbacks, primary GHGs (CO_2, N_2O and CH_4) from shipping account for approximately 961 million tonnes of CO_2e in 2012. International shipping is estimated to account for 816 million tonnes of CO_2e for primary GHGs in 2012.

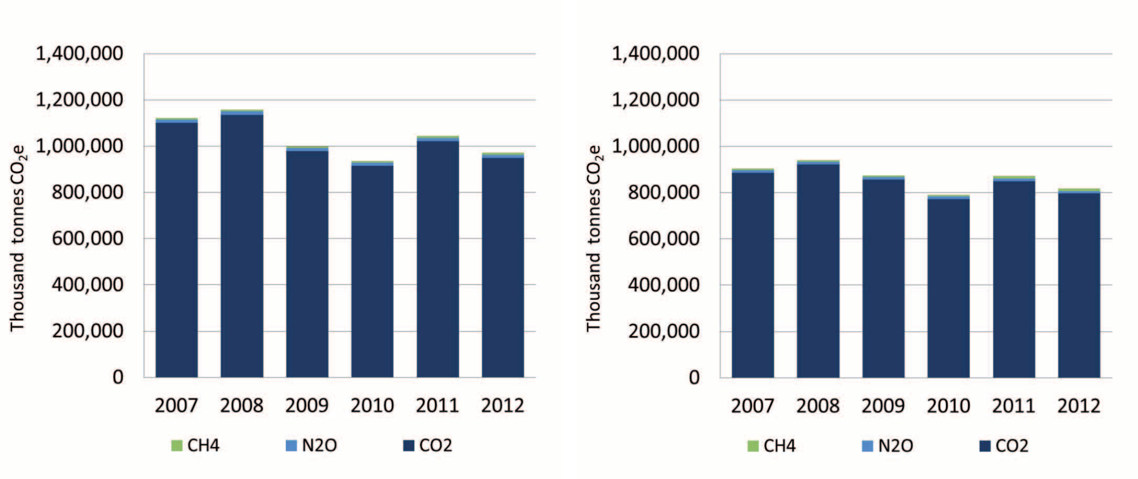
Time series of bottom-up CO_2e emissions estimates with climate-carbon feedbacks can be found in Table 18 and Table 19 and are presented in Figure 41.

Table 18 – *Bottom-up CO_2e emissions estimates with climate-carbon feedbacks from total shipping (thousand tonnes)*

	2007	2008	2009	2010	2011	2012
CH_4	6,018	6,657	6,369	8,030	9,807	9,802
N_2O	14,879	15,404	13,318	12,453	13,428	12,707
CO_2	1,100,100	1,135,100	977,900	914,700	1,021,600	938,100
Total	**1,120,997**	**1,157,160**	**997,587**	**935,183**	**1,044,835**	**960,608**

Table 19 – *Bottom-up CO_2e emissions estimates with climate-carbon feedbacks from international shipping (thousand tonnes)*

	2007	2008	2009	2010	2011	2012
CH_4	5,929	6,568	6,323	7,969	9,740	9,742
N_2O	12,152	12,689	11,860	10,615	11,437	10,931
CO_2	884,900	920,900	855,100	771,400	849,500	795,700
Total	**902,981**	**940,157**	**873,284**	**789,983**	**870,678**	**816,372**



a) Total shipping

b) International shipping

Figure 41: *Time series of bottom-up CO_2e emissions estimates for a) total shipping and b) international shipping*

1.3.6 Shipping as a share of global emissions

Inventories of ship emissions can be compared with global anthropogenic totals to quantify the contribution of shipping to GHG totals from all human activity. The consortium evaluated AR5, a comprehensive technical document that has assembled global emissions estimates (IPCC 2013). AR5 provides global emissions totals for the year 2010 for a number of GHG substances, including CO_2, CH_4 and N_2O. It also refers to two sources that provide annual CO_2 emissions for the years 2007–2012 (Boden et al., 2013; Peters et al., 2013). Totals were converted from elemental C to CO_2 for comparison with the current study.

Comparisons of major GHGs from shipping are presented in Tables 20–23, using global totals identified in the recent AR5 (IPCC 2013). For the period 2007-2012, on average, shipping accounted for approximately 3.1% of annual global CO_2 and approximately 2.8% of annual GHGs on a CO_2e basis. International shipping accounts, on average, for approximately 2.6% and 2.4% of CO_2 and GHGs on a CO_2e basis, respectively. These CO_2 and CO_2e comparisons are similar to, but slightly smaller than, the 3.3% and 2.7% of global CO_2 emissions reported by Second IMO GHG Study 2009 for total shipping and international shipping respectively.

Table 20 – *Shipping CO_2 emissions compared with global CO_2 (values in million tonnes CO_2)*

		Third IMO GHG Study 2014			
Year	**Global CO_2[1]**	**Total shipping CO_2**	**Percentage of global**	**International shipping CO_2**	**Percentage of global**
2007	31,409	1,100	3.5%	885	2.8%
2008	32,204	1,135	3.5%	921	2.9%
2009	32,047	978	3.1%	855	2.7%
2010	33,612	915	2.7%	771	2.3%
2011	34,723	1,022	2.9%	850	2.4%
2012	35,640	938	2.6%	796	2.2%
Average	33,273	1,015	3.1%	846	2.6%

[1] Global comparator represents CO_2 from fossil fuel consumption and cement production, converted from Tg C y^{-1} to million tonnes CO_2. Sources: Boden et al., 2013, for years 2007–2010; Peters et al., 2013, for years 2011–2012, as referenced in IPCC (2013).

Table 21 – *Shipping CH_4 emissions compared with global CH_4 (values in thousand tonnes CH_4)*

		Third IMO GHG Study 2014			
Year	**Global CH_4[1]**	**Total shipping CH_4**	**Percentage of global**	**International shipping CH_4**	**Percentage of global**
Average annual CH_4 for decade 2000–09	96,000	177	0.18%	174	0.18%
		196	0.20%	193	0.20%
		187	0.20%	186	0.19%
		236	0.25%	234	0.24%
		288	0.30%	286	0.30%
		288	0.30%	287	0.30%
Average		229	0.24%	227	0.24%

[1] Global comparator represents CH_4 from fossil fuel consumption and cement production. Source: IPCC (2013, Table 6.8).

Table 22 – *Shipping N_2O emissions compared with global N_2O (values in thousand tonnes N_2O)*

		Third IMO GHG Study 2014			
Year	**Global N_2O[1]**	**Total shipping N_2O**	**Percentage of global**	**International shipping N_2O**	**Percentage of global**
Average annual N_2O for decade 2000–09	700	50	7.1%	41	5.8%
		52	7.4%	43	6.1%
		45	6.4%	40	5.7%
		42	6.0%	36	5.1%
		45	6.4%	38	5.5%
		43	6.1%	37	5.2%
Average		46	6.6%	39	5.6%

[1] Global comparator represents N_2O from fossil fuel consumption and cement production. Source: IPCC (2013, Table 6.9).

Table 23 – *Shipping GHGs (in CO_2e) compared with global GHGs (values in million tonnes CO_2e)*

		Third IMO GHG Study 2014			
Year	**Global CO_2e[1]**	**Total shipping CO_2e**	**Percentage of global**	**International shipping CO_2e**	**Percentage of global**
2007	34,881	1,121	3.2%	903	2.6%
2008	35,677	1,157	3.2%	940	2.6%
2009	35,519	998	2.8%	873	2.5%
2010	37,085	935	2.5%	790	2.1%
2011	38,196	1,045	2.7%	871	2.3%
2012	39,113	961	2.5%	816	2.1%
Average	36,745	1,036	2.8%	866	2.4%

[1] Global comparator represents N_2O from fossil fuel consumption and cement production. Source: IPCC (2013, Table 6.9).

For the year 2012, total shipping emissions were approximately 938 million tonnes CO_2 and 961 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping emissions for 2012 are estimated to be 796 million tonnes CO_2 and 816 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O. International shipping accounts for approximately 2.2% and 2.1% of CO_2 and GHGs on a CO_2e basis, respectively.

Table 20 and Table 23 are also illustrated graphically in Figure 42 a) and b) respectively. The bar graphs may show more intuitively that global CO_2 and CO_2e are increasing at different rates than recently observed in the bottom-up results for shipping presented here. In other words, ship fuel use, CO_2 emissions and GHG emissions (on a CO_2e basis) have trended nearly flat while estimated global totals of these emissions have increased; this results in a recent-year decline in the percentage of shipping emissions as a fraction of global totals.

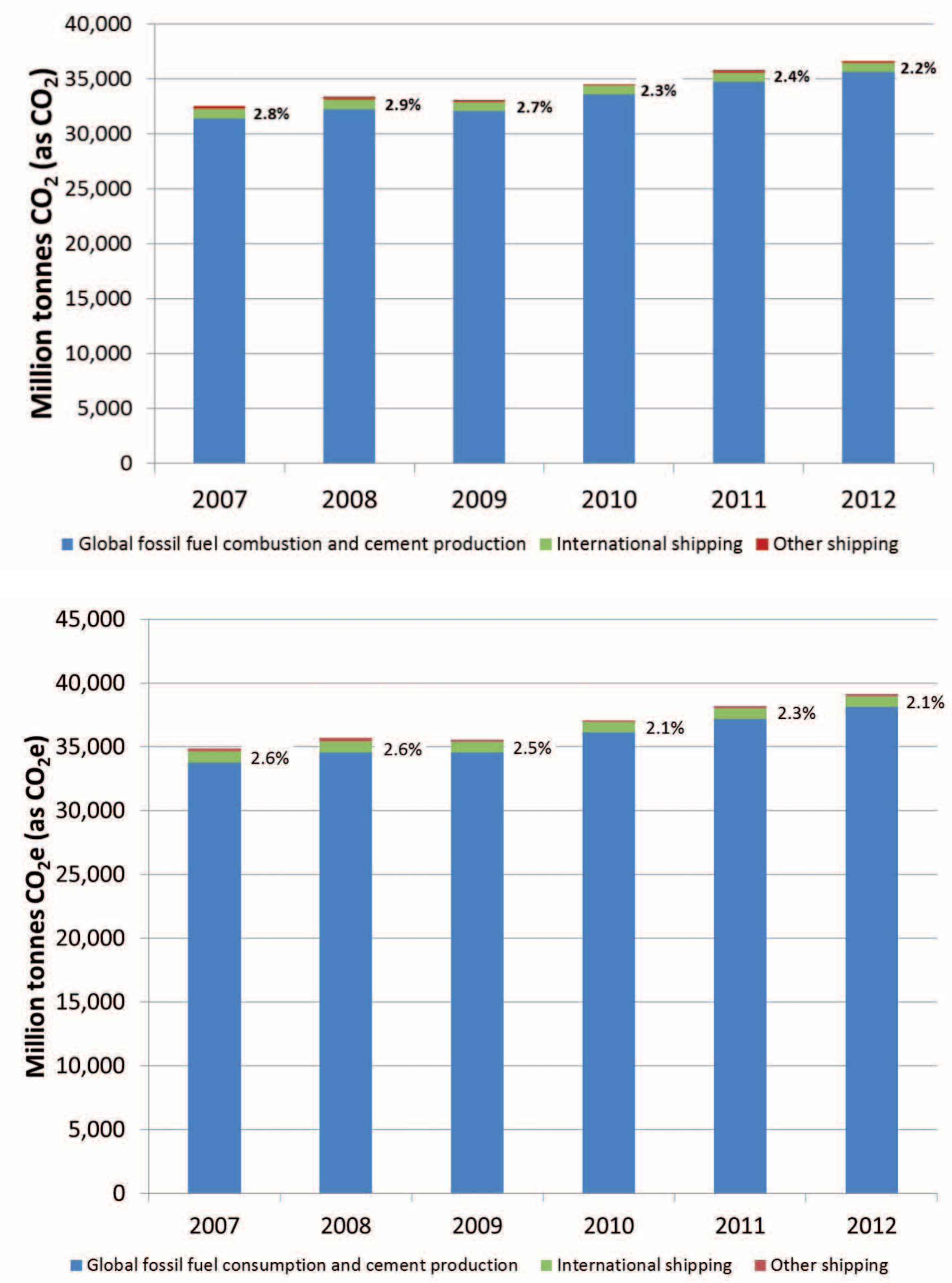


Figure 42: *Comparison of shipping with global totals: a) CO_2 emissions compared, where the percentage indicates international shipping emissions of CO_2 as a percentage of global CO_2 from fossil fuels; b) CO_2e emissions compared, where the percentage indicates international shipping emissions of CO_2e as a percentage of global CO_2e from fossil fuels*

1.4 Quality assurance and control of top-down and bottom-up inventories

The quality analysis is presented in three sections. The first section discusses QA/QC for the top-down emissions inventory. The second section summarizes the QA/QC elements of the bottom-up fuel and emissions inventory. The third section contains a comparison of the top-down and bottom-up emissions inventories. Sections 1.1 and 1.2 contain many detailed processes that constitute QA/QC effort; these sections therefore discuss QA/QC mainly in summary and provide context for the quantitative bottom-up uncertainty analysis in Section 1.5.

1.4.1 Top-down QA/QC

Top-down statistics were evaluated for transparency and any significant discrepancies that might reflect confidence in inventories based on fuel statistics.

This section begins with a review of the Second IMO GHG Study 2009 and a brief discussion of data quality, confidence and uncertainty. It reviews relevant data quality information provided by IEA, including information about likely causes of potential under- or overestimation of marine fuel use (both domestic and international). Top-down method QA/QC efforts undertaken specifically for this study are described. Lastly, this section gives a QA/QC summary of the study.

Second IMO GHG Study 2009: review of top-down data quality

The Second IMO GHG Study 2009 performed qualitative analyses of errors and inconsistencies of IEA statistics to help explore how the top-down and bottom-up discrepancy may be explained by uncertainty in reported fuel statistics. That study identified the following potential issues with top-down data:

- different data quality between OECD and non-OECD countries (fishing);
- identical numbers from year to year for some countries;
- big swings from year to year for other countries;
- differences in EIA bunkers statistics.

Although a number of challenges were recognized, mainly arising from the use of different data sources, the sources of uncertainty remained unexplored and potential corrections were not attempted.

The Second IMO GHG Study 2009 explicitly quoted provisions in the IEA Agreement on an International Energy Program (IEP) that determined which fuels would be considered in national oil stocks and which were considered to be counted as international data. In particular, international marine bunkers were “treated as exports under a 1976 Governing Board decision incorporated into the Emergency Management Manual” (Scott, 1994). This information and subsequent discussion in the Second IMO GHG Study 2009 suggested that some degree of allocation error among international bunkers, exports and/or imports could be a factor in the accuracy of top-down fuel statistics for shipping.

IEA statistics: review of top-down data quality

IEA collects data from OECD countries that have agreed to report mandatory data through monthly and joint annual IEA/Eurostat/UNECE questionnaires. For non-OECD countries, IEA collects data through voluntary submissions (using no standard format) or through estimates made by IEA or its contractors. Figure 43 presents a map of OECD and non-OECD countries that provide energy data to IEA; not all of these countries have marine fuel sales to report (Morel, 2013).

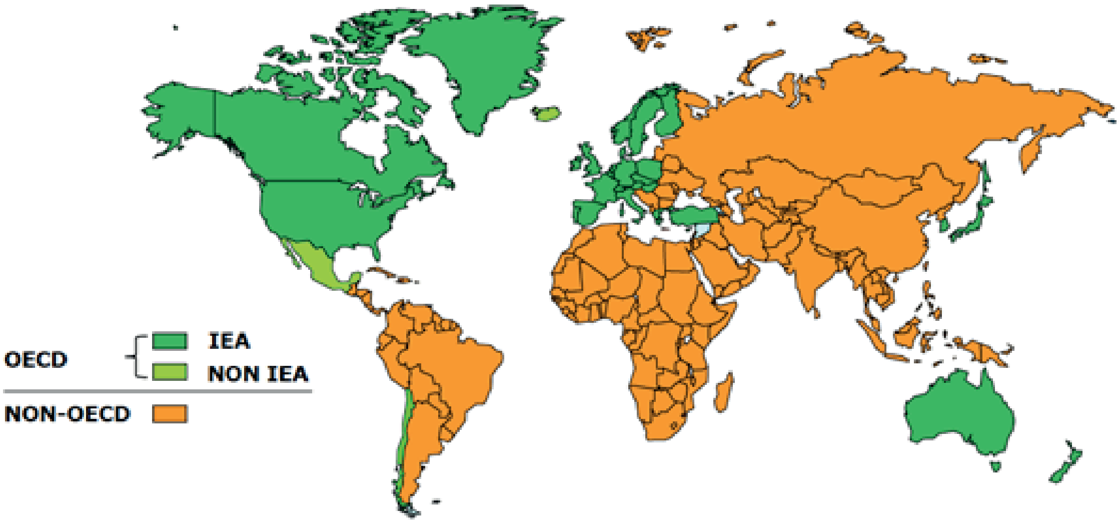


Figure 43: *OECD versus non-OECD data collection system*

IEA acknowledges that challenges remain in collecting international marine bunkers data worldwide; however, compared to other sources, the IEA database seems consistent across the years and is regulary updated. According to Morel (2013), the revisions in the IEA international marine bunkers database have improved its quality. The database published in 2012 covers 139 individual countries compared to the 137 of the 2007 database. Of these 139 countries, the 54 countries that represent 80% of the total sale have used official energy statistics. Another six countries, representing 14% of the total sale, have used other sources, such as port authorities, oil companies and data provided by FACTS Global Energy (http://www.fgenergy.com). Lastly, in 2012 edition, data have been estimated for 33 countries that represent only 6% of the total sale, considering, for example, residual GDP growth and marine traffic growth (Morel, 2013).

In addition to directly reported IEA marine fuel statistics, the consortium reviewed the energy balances of each fuel to inform the uncertainty analysis for top-down marine fuel consumption in Section 1.5. This provides QA/QC and enables an estimate of potential uncertainty around reported fuel sales for the marine sector (domestic and international).

For example, corroborating information about the potential for under- or overreporting international marine bunkers includes:

1 From *Energy Statistics for Non-OECD Countries*, IEA, 2009 edition: “For a given product, imports and exports may not sum up to zero at the world level for a number of reasons. Fuels may be classified differently (i.e. residual fuel oil exports may be reported as refinery feedstocks by the importing country; NGL exports may be reported as LPG by the importing country, etc.). Other possible reasons include discrepancies in conversion factors, inclusion of international marine bunkers in exports, timing differences, data reported on a fiscal year basis instead of calendar year for certain countries, and underreporting of imports and exports for fiscal reasons.”

2 From the OECD Factbook 2013: *Economic, Environmental and Social Statistics* (“Energy supply”, page 108) and the Factbook website: “Data quality is not homogeneous for all countries and regions. In some countries, data are based on secondary sources, and where incomplete or unavailable, the IEA has made estimates. In general, data are likely to be more accurate for production and trade than for international bunkers or stock changes. Moreover, statistics for biofuels and waste are less accurate than those for traditional commercial energy data.”

In summary, IEA and OECD identify specific types of error in energy data that involve marine bunkers. The first is allocation or classification error involving imports, exports and marine bunker statistics. The second is country-to-country differences in data quality, specifically related to poor accuracy for international bunkers or stock changes. These insights helped inform the consortium’s direct QA/QC and uncertainty efforts.

1.4.2 Top-down QA/QC efforts specific to this study

This study independently confirmed the statistical balances of IEA energy statistics on both global and large regional scales. Specifically, the calculation of statistical difference at the national and regional levels was verified and discrepancy between imports and exports reported by IEA was confirmed.

Second, as in the Second IMO GHG Study 2009, the consortium researched other international energy data providers to understand whether international marine bunker records were considered to be similar to or different from IEA statistics. This included research into data quality studies for non-IEA energy statistics.

Comparisons with EIA top-down statistics and other resources

The following resources were evaluated for a) their similarity to IEA statistics and b) complementary data quality investigations.

The consortium evaluated EIA international marine bunker fuel oil data for 2007–2010 (IEA did not provide more recent data than 2010 during the period in which this study was conducted). Moreover, the EIA statistics available on the United States Department of Energy website did not provide data for gas diesel international marine bunkers, nor break down domestic marine fuel consumption, nor identify fishing vessel consumption. These data may be available from the EIA; however, given that additional EIA data provide limited opportunities to improve QA/QC in top-down estimates, these data were not pursued.

Table 24 and Figure 44 illustrate continued discrepancies in statistical reporting between IEA and EIA, similar to those documented in the Second IMO GHG Study 2009. Namely, the IEA data report consistently greater fuel oil consumption than the EIA data for international marine bunkers. This is indicated in Figure 45 by the scatter plot for the period 2000–2010, the regression line and the confidence interval of the best-fit line.

Table 24 – *Comparison of fuel sales data between IEA and EIA in international shipping (million tonnes)*

Fuel oil statistics	**Source**	**2007**	**2008**	**2009**	**2010**	**2011**
International marine bunkers	IEA	174.1	177.0	165.9	178.9	177.9
	EIA	155.3	158.8	160.9	171.2	
Percentage difference		11%	10%	3%	4%	

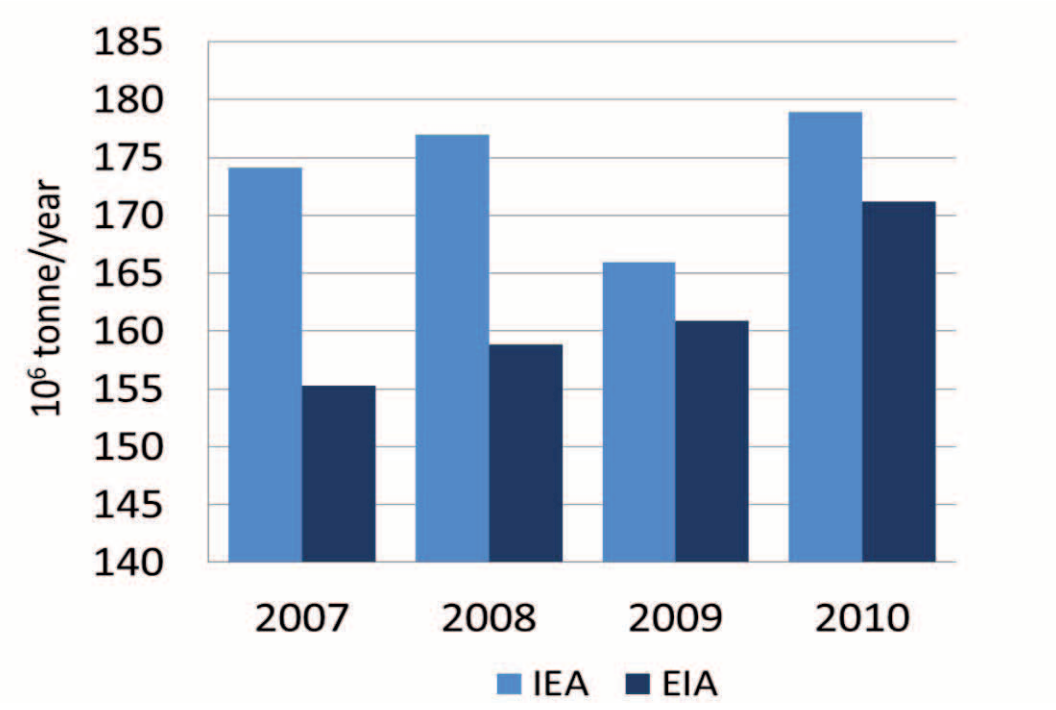


Figure 44: *Comparison of IEA and EIA international marine bunker fuel oil statistics*

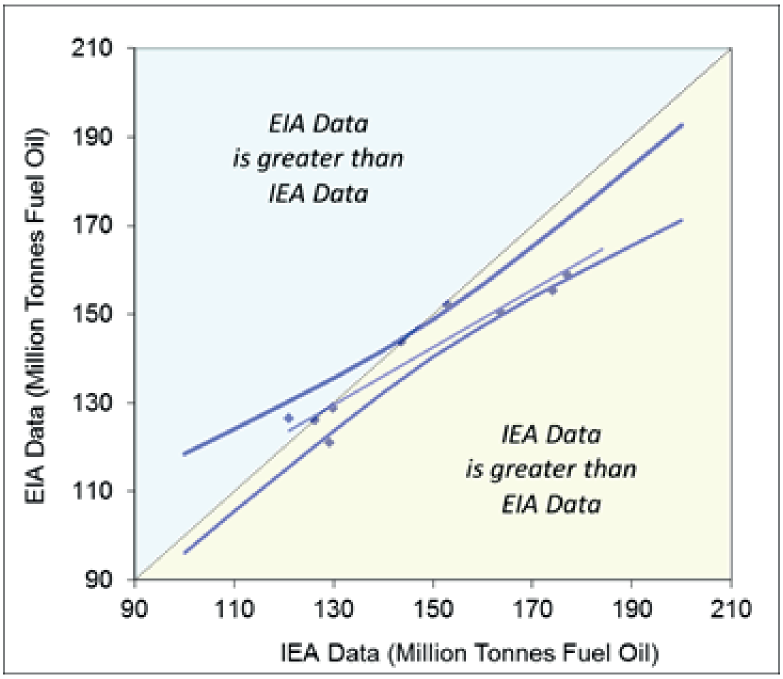


Figure 45: *Confidence bands showing statistical difference between IEA and EIA data, 2000–2010*

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. This review shows that IEA revisions to statistics can change the total fuel sales estimate by as much as 10% owing to documented quality controls in place at IEA. A rigorous review of IEA QA/QC practices indicates that the energy balances continue to represent high-quality representation of OECD and non-OECD energy statistics.

Our IEA data comparison with EIA fuel oil statistics for international marine bunkers indicate that year-on-year fuel sales data can differ by more than 10% and that IEA tends to report more international marine bunkers over the period 2000–2010.

Lastly, the IEA presentation to the IMO Expert Workshop in 2013 indicated that significant uncertainties are not fully documented and require further analysis (see Section 1.5). For example, under- or overestimates of international marine bunkers could result from allocation or classification errors – imports, exports, marine bunker statistics, fuel transfers between sectors (as is typical for blending marine bunkers with other fuels to meet ship/engine fuel quality specifications) – and poor data quality among reporting countries could restrict the accuracy of international bunkers estimates.

1.4.3 Bottom-up QA/QC

The key findings of the bottom-up quality assurance and quality control analysis include:

- Quality in fuel consumption totals is extensively analysed by a number of independent sources (both independent of the data used in the model and independent of each other).
- This assurance effort represents significant progress relative to all prior global ship inventories (including the Second IMO GHG Study 2009). These QA/QC efforts demonstrate that a reliable inventory of fuel consumption broken down by fleets of ships and their associated activity statistics has been achieved in this study.
- There is a step change improvement in quality in the bottom-up inventory between the earlier years (2007–2009 inclusive) and the later years (2010–2012 inclusive), which can be attributed to the increased coverage (both temporal and spatial) of AIS data and therefore the accuracy of the activity estimate. This also underpins better confidence in bottom-up emissions totals, based on the same methods, using consensus emissions factors derived from reviewing published emissions factors.
- The key data sources that have enabled the high quality of this study, particularly S-AIS data, continue to increase in quality. This is owing to continuous improvement of the algorithms on the receivers,

increased numbers of satellites providing greater spatial and temporal coverage, and increased experience in filtering and processing the raw data for use in modelling.

- A quality advantage in this work is that our approach for the bottom-up activity-based inventory uses calculations for individual vessels. By maximizing vessel-specific activity characterization using AIS data sources, this work quantifies the variability among vessels within a type and size category. This eliminates the dominant uncertainties reported by the Second IMO GHG Study 2009 and most published inventories.
- The AIS-informed bottom-up methodologies cannot directly distinguish between fuel type and voyage type, which requires additional analyses and some expert judgement. Our QA/QC on allocation of residual/distillate fuels (HFO/MDO) and international/domestic shipping provides transparent and reproducible methodologies, with the opportunity to adjust these if and when better information becomes available in the future.

At the time that this report was written, there were too few data sets of on-board measurements of CO_2 emissions for any statistically representative quality assurance investigation of the modelled CO_2 emission to be carried out. The closest that the quality assurance can therefore get to the end product of this study is the fuel consumption comparison (modelled estimate compared with operator data), carried out using noon report data. This is done for a sample of approximately 500 ships (approximately 1% of all vessels) representing over 60,000 days of at-sea operation. This sample is described in detail in Annex 3. It should be noted that noon report data are not infallible; their reliability and the implications for the comparative analysis undertaken here are discussed in greater detail in Annex 3.

To provide further assurance of the inputs and assumptions of the bottom-up method, specifically the activity estimate, the consortium also performed analysis with LRIT data (approximately 8,000 ships and 10% of the global fleet) and third-party literature study.

Noon reports, LRIT data and the literature were used for the following components of quality assurance work:

- The activity estimation quality was assured using:
  – spatial coverage analysis with information on the number of messages received in different geographical locations and contrasting the AIS coverage with coverage maps obtained from alternative sources (e.g. LRIT);
  – temporal coverage analysis to test whether the derived profiles of time spent in different modes of operation (e.g. in port, at sea) and at different speeds are representative;
  – comparison of the AIS-derived activity parameters speed and draught against noon report data;
  – description of coverage statistics for each year and each fleet (to evaluate AIS completeness and facilitate imputed algorithms to estimate CO_2 emissions from periods when observations are missing).
- Fleet specifications and model assumption quality were assured using:
  – investigations into the robustness of the IHSF database;
  – comparative evaluation of prior work, independently produced and published by consortium members, including peer-reviewed reports and scientific articles;
  – consultation of third-party inventory and shipping literature (including the work of consortium partners) providing substantial fleet data.
- Fuel consumption estimate quality was assured using:
  – comparison of calculated fuel consumption to operators' data recorded in noon reports pooled from data independently collected by several consortium partners.

It should be noted that noon report data are not infallible; their reliability and the implications for the comparative analysis undertaken here are discussed in greater detail in Annex 3, along with detailed QA/QC for the source data and other analyses.

Spatial coverage of activity estimates QA/QC

The AIS data coverage, in terms of both space and time, is not consistent year-on-year during the period studied (2007–2012). For the first three years (2007–2009), no satellite AIS data were available, only data from shore-based stations. This difference can be seen by contrasting the first (2007) and last (2012) years' AIS data sets, depicted by geographical coverage in Figure 46.

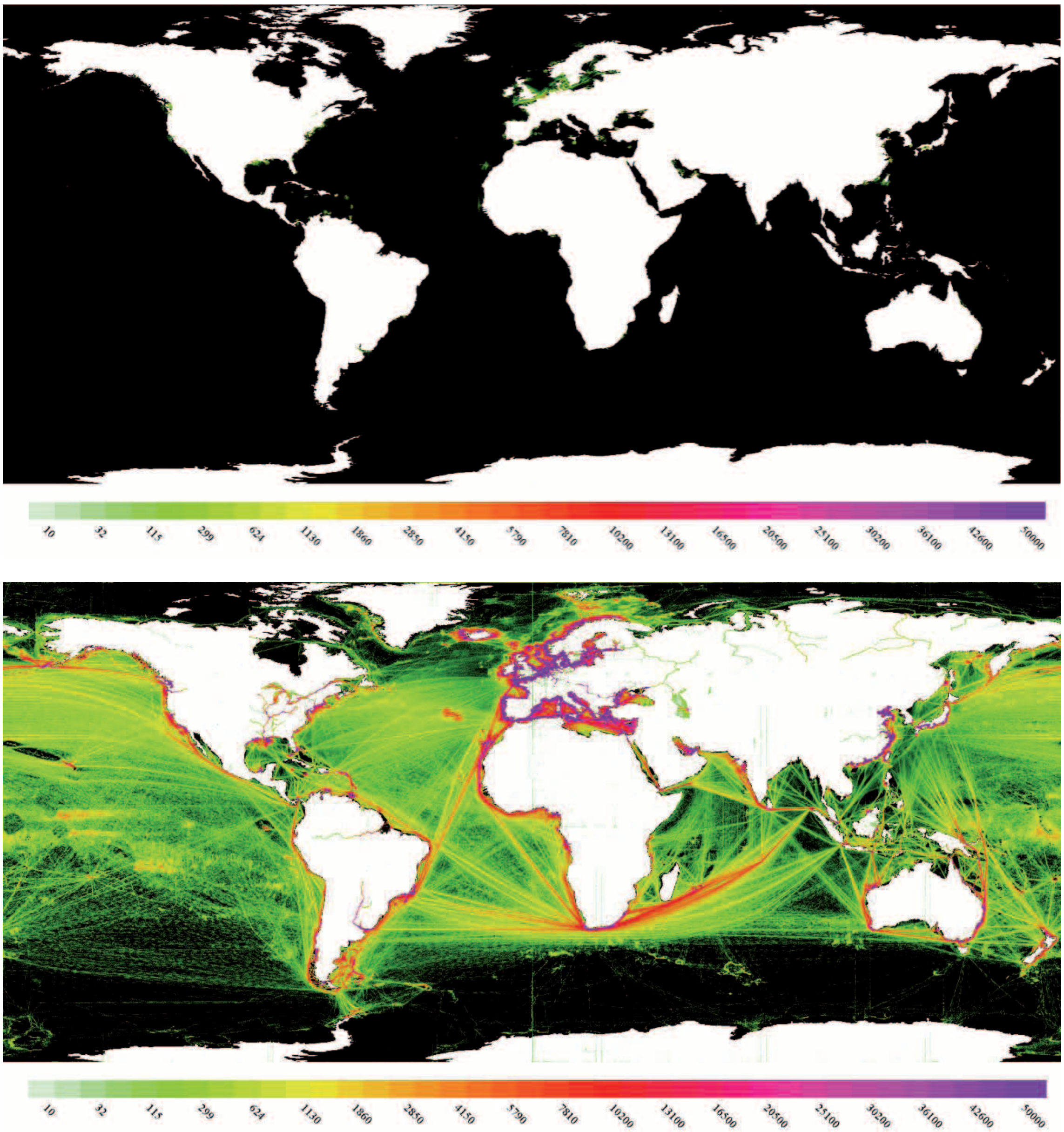


Figure 46: *Geographical coverage in 2007 (top) and 2012 (bottom), coloured according to the intensity of messages received per unit area. This is a composite of both vessel activity and geographical coverage; intensity is not solely indicative of vessel activity*

The consequence of the change in coverage over time and the quality of the regional coverage can be inferred from an analysis of the number of messages received in different sea regions. Two investigations were carried out, on large oil tankers and large bulk carriers, both ship types that were anticipated to be engaged in activity on routes that encompassed most of the world's sea areas. Figure 47 displays the trend over time in the number of messages received in different sea regions for a random sample of 300 large oil tankers. The number of messages received is a composite of the number of ships in an area, the duration of time they spend in an area and the geographical coverage of an area. This analysis cannot isolate the change in geographical coverage alone. However, the marked contrast in open ocean regions (e.g. Indian Ocean, South Atlantic Ocean and North Atlantic Ocean) over time shows increased quality of coverage on a regional level. Importantly, by 2012, there are no sea areas for which no activity is observed, which implies that by the latter years coverage quality has minimal regional bias. Greater detail and maps of both AIS and LRIT data for further years is provided in Annex 3 (details for Section 1.4).

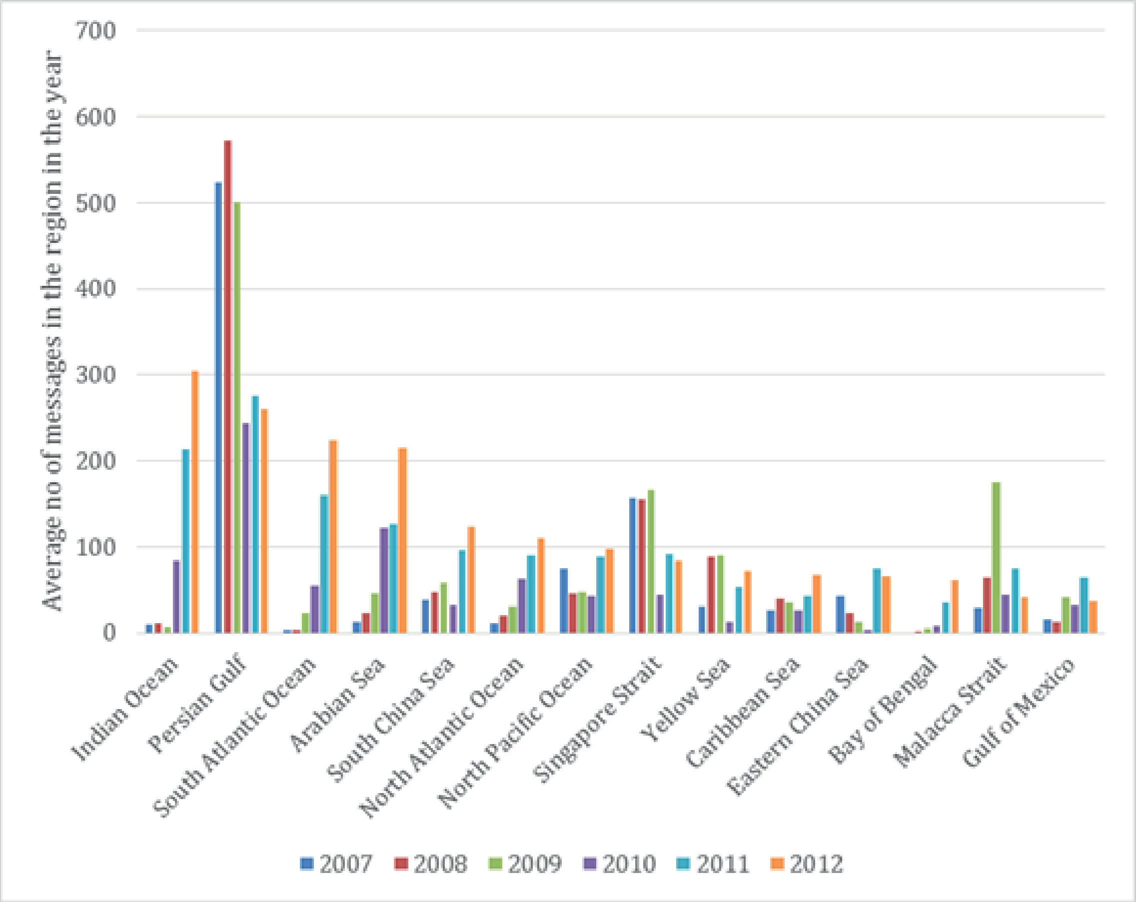


Figure 47: *The average volume of AIS activity reports for a region reported by a vessel for up to 300 randomly selected VLCCs (2007–2012)*

Temporal coverage of activity estimates QA/QC

LRIT data were used for the quality assurance of the AIS-derived activity estimates. The total time spent at sea and in port for individual ships over the course of a year was analysed using both the LRIT data (which have consistently high reliability) and the AIS data (for varying levels of coverage and reliability). This analysis was carried out for each of the ships observed in both the LRIT and the AIS data sets (approximately 8,000, for 2009–2012). Figure 48 shows the evaluation of the difference between the LRIT- and AIS-derived estimates of days at sea. In this comparison, the LRIT-derived estimate is assumed to be the benchmark; deviations from a mean difference of zero therefore imply deterioration in quality of the AIS-derived estimate.

Figure 48 shows that in 2012, for reliable observation of a ship above 50% of the time during the year, the mean difference between the AIS and LRIT converges to approximately zero. However, as the percentage of time for which reliable observations reduces, a significant bias occurs with the AIS-derived activity estimate, which appears to underestimate time spent at sea. Figures in Annex 3 demonstrate that a similar trend (good quality of reliable observations for 50% of the year or more) can be observed in 2010 and 2011.

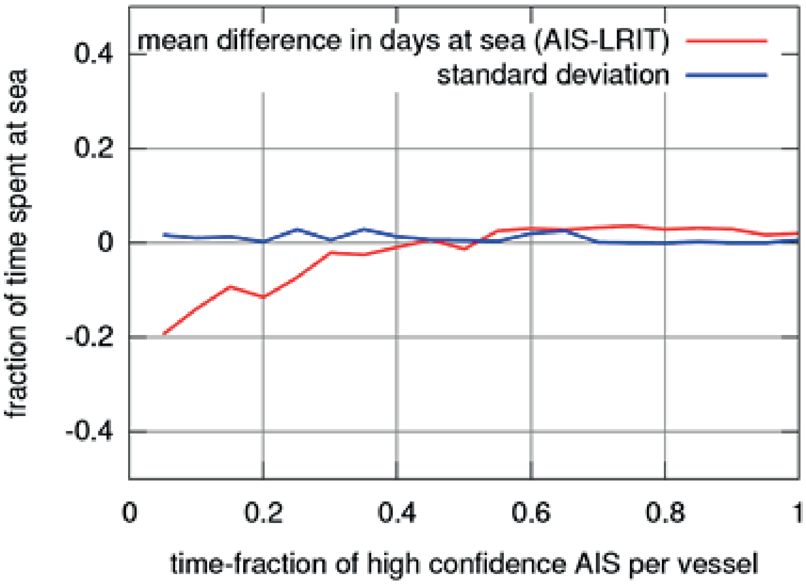


Figure 48: *Activity estimate quality assurance (2012)*

Greater detail of the derivation of parameters from the LRIT data sets and their application in this comparative analysis is given in Annex 3, along with analysis for 2010 and 2011.

Activity estimates and derived parameters (speed and draught)

In addition to the analysis carried out using LRIT data, a further quality analysis of the bottom-up method's estimate of activity (time in mode, speed estimation, draught estimation and distance covered) can be obtained using noon report data. Noon report data record information daily, including average speed during the period of the report and distance travelled. Noon reports also record the date and time a voyage begins and ends. This information was aggregated over quarters, compared with the same data calculated using the bottom-up model, and aggregated to the same quarter of each year.

The results for 2012 are presented in Figure 49 and Figure 50. The red line represents an ideal match (equal values) between the bottom-up and noon report outputs, the solid black line the best fit through the data and the dotted black lines the 95% confidence bounds on the best fit. The "x" symbols represent individual ships, coloured according to the ship type category listed in the legend. The plots include all results, with no outliers removed.

The activity estimation of days at sea and at port can be seen to have some scatter. This scatter is related to the fact that for some of the time the ship is not observed and an extrapolation algorithm is used to estimate activity. For any one ship, the reliability of that extrapolation is low. However, overall, the distribution is approximately even and does not represent a significant degree of bias, as the best-fit line shows. The reliability of the estimate of at-port and at-sea days appears consistent regardless of ship type.

The quality of the estimation of ship speed when at sea is higher than the quality of the port- and sea-time estimation. The best-fit line shows close alignment with the red equilibrium line, albeit with a trend towards underestimating the speeds of the larger container ships. The confidence bounds are closely aligned to the best-fit line.

The draught observation shows the lowest quality of fit. The observed scatter implies a bias for the bottom-up method to slightly overestimate draught. The agreement for ship types with low draught variability (e.g. container ships) is good. This implies that the overall poor reliability is likely to be due to infrequent updating of the draught data reported to the AIS receiver.

In earlier years (see Annex 3 for the data), similar relative quality assurance between the variables plotted can be obtained; however, the absolute quality reduces for the earlier years, particularly 2007, 2008 and 2009. This can be seen by comparing the 2012 results with Figure 51, even accounting for the fact that in 2009 there are fewer ships in the noon reports data set. Days at sea and at-sea speed have significantly more scatter and therefore wider confidence bounds than the equivalent plots in 2012. With the exception of some outlier data in 2009, the speed agreement is moderate. However, the days-at-sea agreement implies that there is some bias, with the bottom-up method consistently overestimating the time that the ship is at sea. This supports the findings of the activity estimate quality assurance work undertaken using LRIT data.

A more detailed description of the noon report data sources, the method for assembling the data for comparison purposes and further years' analysis results can be found in Annex 3.

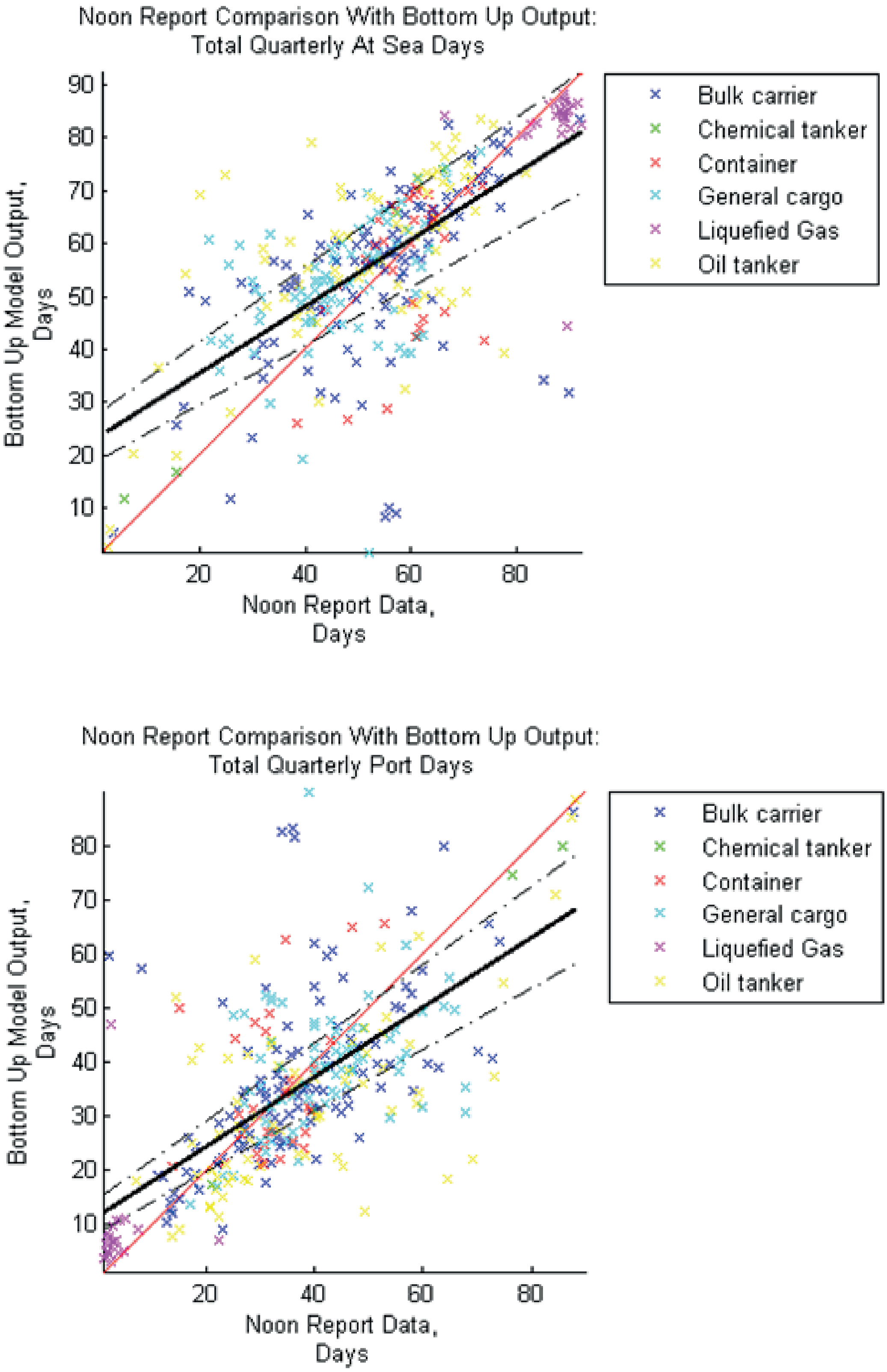


Figure 49: *Comparison of at-sea and at-port days, calculated using both the bottom-up model output (y-axis) and noon report data (x-axis) (2012)*

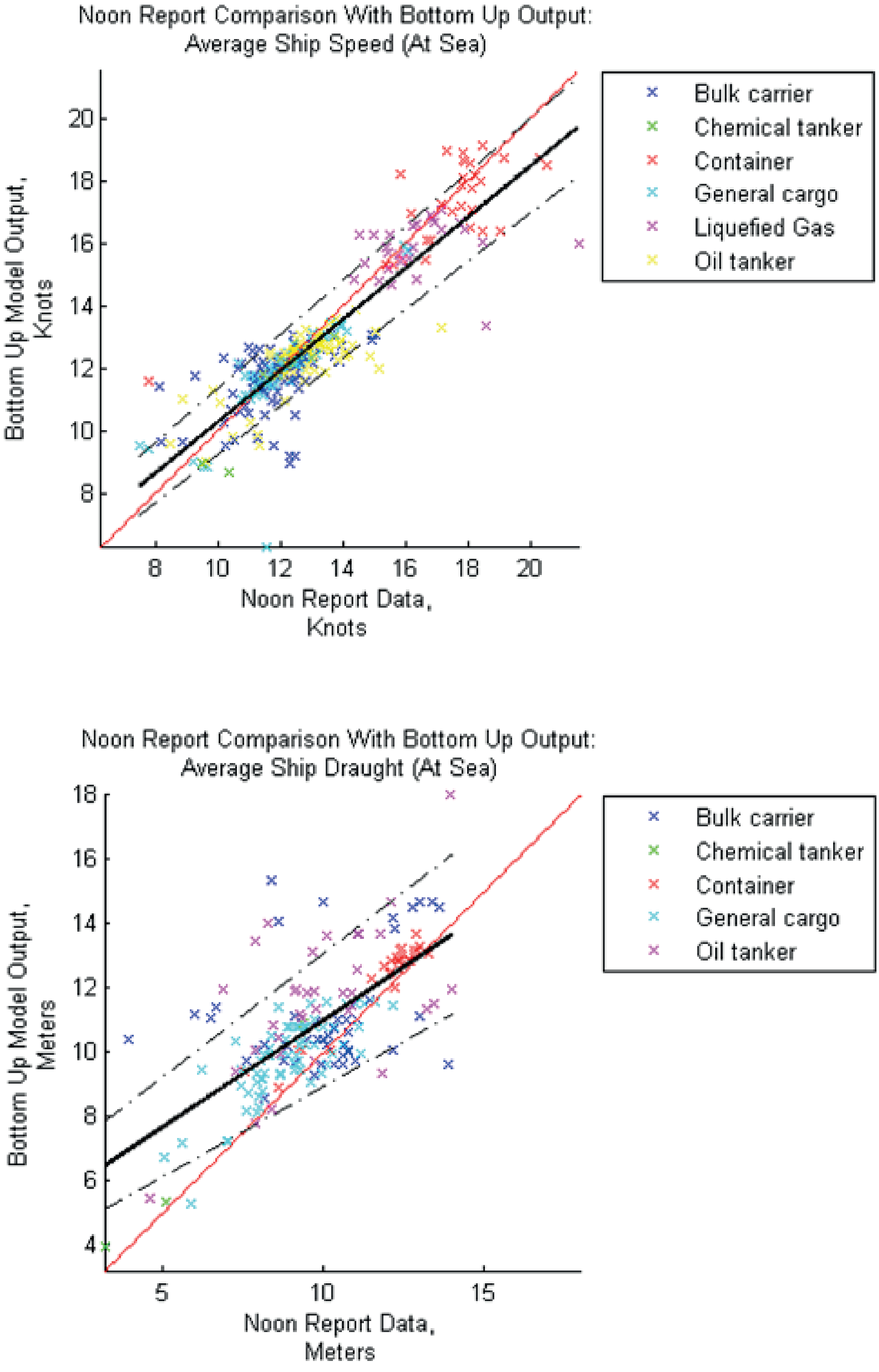


Figure 50: *Comparison of average ship speed and average ship draught calculated using both the bottom-up model output (y-axis) and noon report data (x-axis) (2012)*

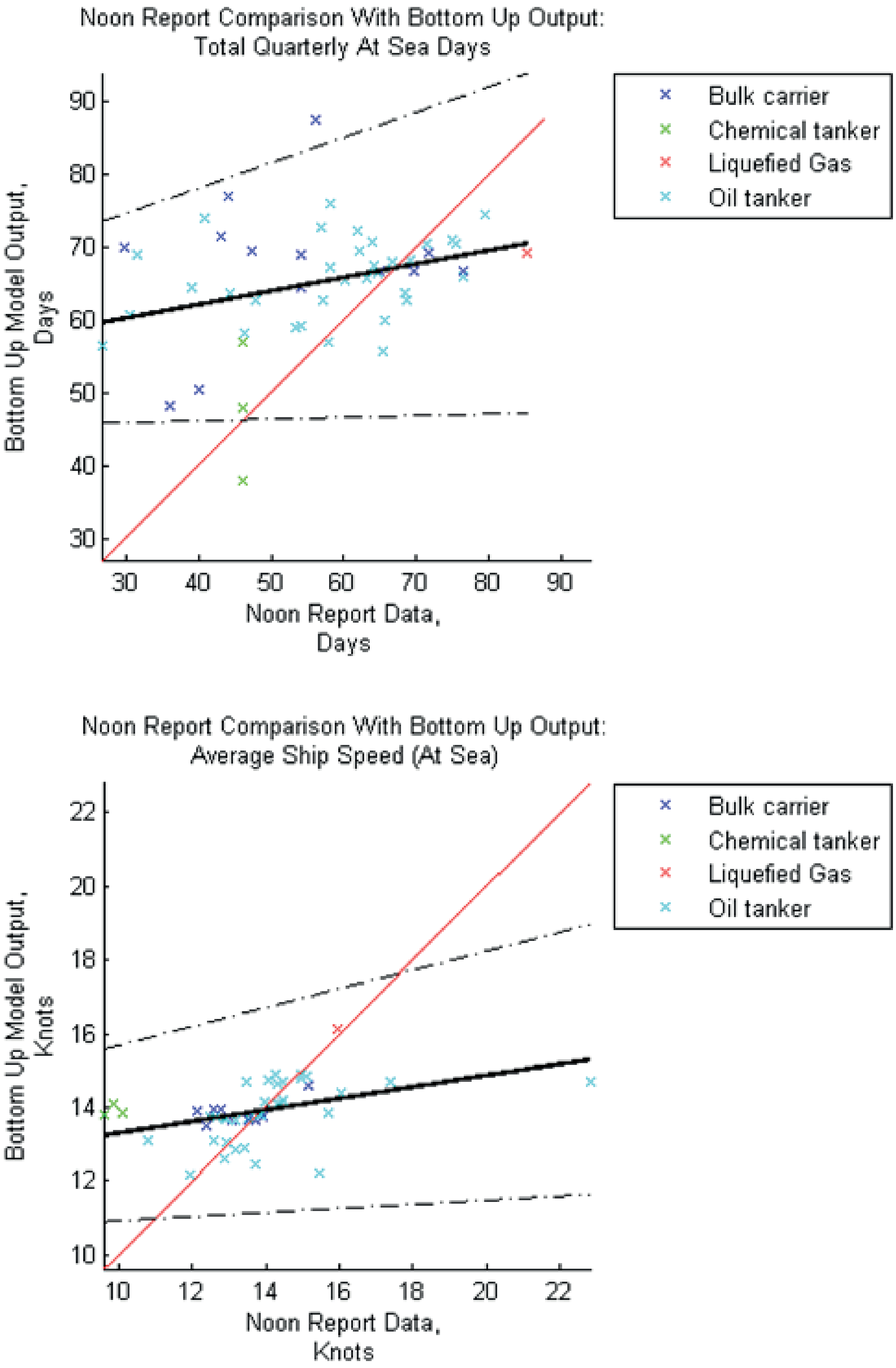


Figure 51: *Comparison of at-sea days and average ship speed, calculated using both the bottom-up model output (y-axis) and noon report data (x-axis) (2009)*

Fleet specifications and model assumptions quality assurance

Fleet specifications were based on the IHS vessel characteristics database, which was used in the following ways:

- identifying the various vessel types using Statcode3 and Statcode5;
- counts of vessels within the various vessel types making up the world fleet;

- subdividing common vessel types into bin sizes based on deadweight tonnage or various capacity parameters;
- providing vessel technical details, such as installed main engine power, maximum sea trial speed and other parameters used in estimating vessel emissions;
- determining each vessel's operational status by quarter for each year inventoried.

The IHS data were treated as accurate; however, this accuracy assumption introduces uncertainties if the data fields used are inaccurate or unrepresentative. Potential uncertainties with the vessel characteristics data include:

- data quality – does the field consistently represent the actual ship's parameter?
- data source accuracy – is the field measured/recorded/verified on board the ship directly and is the field accurate?
- update frequency – is the field updated at least quarterly (when a change has occurred)?

Data fields that have been independently spot-checked by consortium members indicate that the vessel class fields (Statcode3 and Statcode5), main engine installed power, maximum sea trial speed and deadweight tonnage appear to be generally representative of actual vessel conditions. The ship status field, which is used to identify whether the ship is in service, is shown consistently to include more ships than are observed in AIS (see Section 1.4 for details), for all ship size and type categories. There are two explanations for this observation: either that the AIS coverage is not capturing all in-service ships, or that the IHSF database is incomplete in its coverage of the number of active ships.

Another uncertainty associated with the vessel characteristics database concerns blanks and zeros in fields that should not be blank or contain zero (i.e. length, deadweight, speed, etc.). To fill blanks or zeros, valid entries were averaged on a field-by-field basis for each vessel type and bin size. These averages were used to fill blanks and zeros (as appropriate) within the same vessel type and bin size to allow emission estimates to be completed. The fields in which gap filling was used included main engine installed power, deadweight tonnage, length, draught maximum, maximum sea trial speed, RPM and gross tonnage. This assumes that the average of each vessel type and bin size is representative of vessels with a blank or zero and that the blanks and zeros are evenly distributed across the bin.

In addition to the uncertainties listed here, there is uncertainty about the auxiliary engine and boiler loads by vessel class and mode. As stated previously in Section 1.2.5 and Annex 1, there are no definitive data sets that include loads by vessel class and operational mode for auxiliary engines and boilers. This study incorporates observed vessel data collected by Starcrest as part of VBP programmes in North America (Starcrest, 2013) and vessel auxiliary engine data collected by the Finnish Meteorological Institute for use in its modelling to build upon the Second IMO GHG Study 2009 findings in this topic area. This improvement injects real observed data and additional technical details but still relies on significant assumptions. Owing to the nature of the sources profiled, the wide array of vessel configurations and operational characteristics, this area of the global vessel emissions inventory will remain an area of significant assumption for the foreseeable future.

Relating to auxiliary engine and boiler loads, by mode, the following uncertainties that are inherent in AIS and satellite data have a direct impact on the emissions estimated. For example:

- Vessels moving at less than 1 knot, for a certain period of time, are assumed to be at berth. This assumption has implications for the oil tanker vessel class in which tankers at berth and not moving faster than 1 knot will have auxiliary loads associated with discharging cargoes, which are significantly higher than a vessel at anchorage.
- Vessels moving at less than 3 knots are assumed to be at anchorage. This assumption will cover vessels that are manoeuvring and that will typically have a higher auxiliary load than those at anchorage. However, tankers at offshore discharge buoys would not be assigned at-berth discharging loads for the auxiliary boilers.

Finally, EF and SFOC remain areas of uncertainty. Emissions testing is typically limited for vessels and when the various engine types, vessel propulsion and auxiliary engine system configurations and diverse operational conditions are considered, emissions tests do not cover all the combinations. Testing that has been conducted to date relies on previously agreed duty cycles, like the E3 duty cycle for direct-drive propulsion engines. With the advent of slow steaming, is the E3 duty cycle still relevant? There are very few tests that evaluate engine loads below 25%, which is the lowest load in the E3 cycle. Further, when looking at emissions beyond NO_x, which is required to be tested during engine certification, the number of valid tests available for review significantly drops off. Similar to EF testing, published SFOC data are limited, particularly over wide engine load factor ranges (% MCR). There is uncertainty around the effects that engine deterioration has on an engine's emissions profile and SFOC.

Boiler usage

Hot steam on board ships is used to provide cargo and fuel oil heating as well as to run cargo operations with steam-driven pumps. The energy required to run these operations is usually taken from auxiliary boilers running on fossil fuels, mainly HFO. During voyages, waste heat from the main engine is used to provide the energy needed for steam generation. However, at low engine loads, the heat provided by the exhaust boiler is not enough to meet all the heating demand on board. At low engine loads, both the auxiliary boiler and waste heat recovery provide the heat needed by the vessels. The shift from exhaust to auxiliary boilers happens at 20%–50% engine load range (Myśków & Borkowski, 2012), as illustrated in Figure 52.

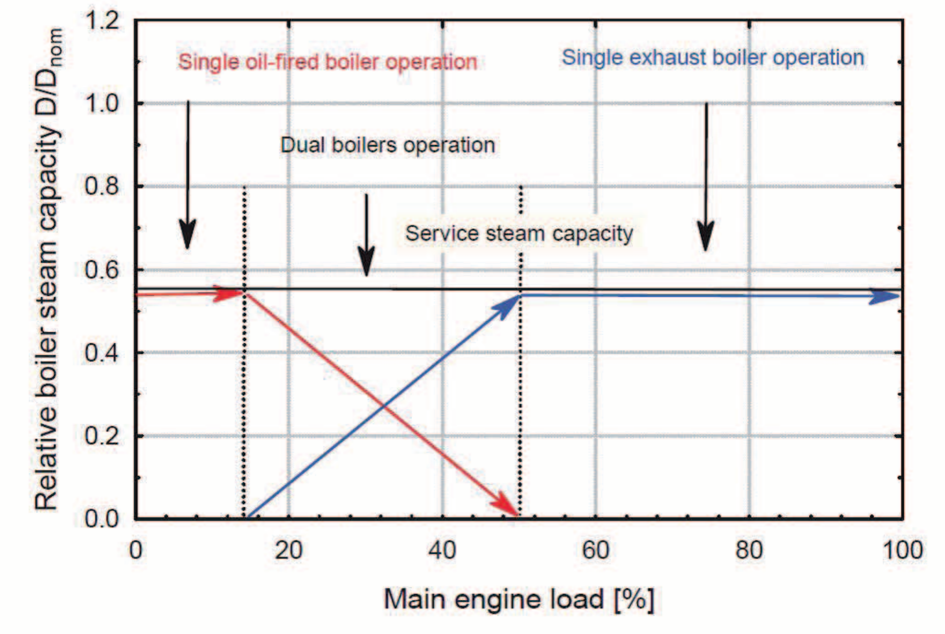


Figure 52: *General boiler operation profile (Myśków & Borkowski, 2012)*

With lower engine loads, the auxiliary boiler is the main source of heat on board a vessel. With sufficiently high engine loads, waste heat recovery can produce enough steam for the vessel and the auxiliary boiler may be switched off. The operational profile of the auxiliary boiler of a container carrier is presented in Figure 53.

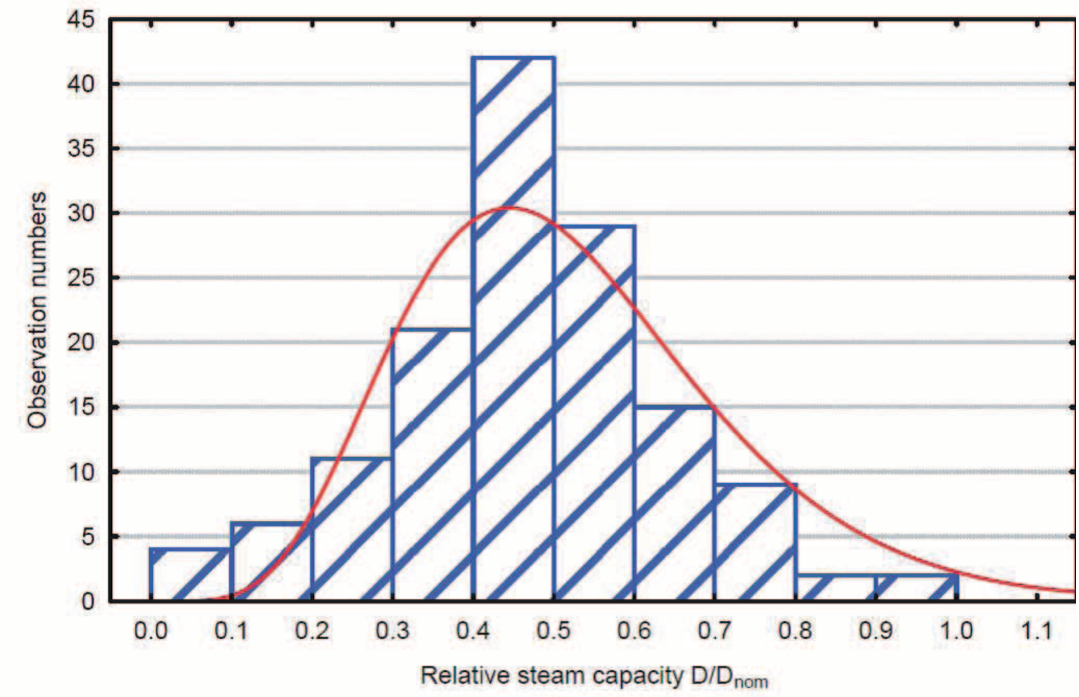


Figure 53: *Operational profile of an auxiliary boiler of a container vessel during six months of operations (Myśków & Borkowski, 2012)*

For a container vessel, less than half of the auxiliary boiler capacity was reported in use most of the time. Over six months of operation, 40%–60% of the boiler steam capacity was used for nearly 100 days. Of the total 182 days, 125 were spent at port or in low load conditions, where auxiliary boilers were needed (Myśków & Borkowski, 2012).

Sources of boiler data

Determination of installed boiler capacity on board vessels cannot be done based on IHSF data, because this information is excluded. Class societies report boiler installations and capacity for their vessels only rarely and scant details about boilers are available from publications like *Significant Ships*. Because of this lack of data, boiler usage profiles have been estimated from vessel boarding programmes and crew interviews. This method is similar to the data collection procedure used to obtain information about auxiliary engine power profiles.

Waste heat recovery (exhaust economizers) is assumed to be in use during cruising. Vessel operational profiles for low load manoeuvring, berthing and anchoring have auxiliary boiler use. For further details, see Annex 3.

Fuel consumption estimate quality assurance

Following the same method used to produce the activity estimate comparison between the bottom-up model and noon report data, Figure 54 and Figure 55 show the results for average daily fuel consumption at sea (main engine and auxiliary engine), and the total main and auxiliary fuel consumption at sea (excluding port fuel consumption) in 2012. (Comparative analysis results for all other years of the study can be found in Annex 3.) No data were available in the noon report data set for the fuel consumption in boilers and so the quality of boiler information from noon reports could not be independently verified for quality.

The average daily fuel consumption plot for the main engine demonstrates the reliability of the marine engineering and naval architecture relationships and assumptions used in the model to convert activity into power and fuel consumption. An exception to this is the largest container ships, whose daily fuel consumption appears to be consistently underestimated in the bottom-up method.

The total quarterly fuel consumption for the main engine plot demonstrates that the activity data (including days at sea) and the engineering assumptions combine to produce generally reliable estimates of total fuel consumption, at least in recent years when AIS observations are more complete. The underestimation of the daily fuel consumption of the container ships can also be seen in this total quarterly fuel consumption.

Both auxiliary engine comparisons (daily and total quarterly) imply that the bottom-up estimates of auxiliary fuel consumption are of lower quality than those of the main engine. There are two possible explanations for this: the low quality of noon report data for auxiliary fuel consumption, or the low quality of bottom-up method estimates. Both are likely. Auxiliary fuel consumption in the noon report data set is commonly reported as zero. This could be because:

1 a shaft generator is used;

2 the main and auxiliary power is derived from the same engine (in the case of LNG carriers);

3 the auxiliary fuel consumption is not monitored or reported.

Discussion with the operators from whom the data originated suggested that the second and third explanations are the most likely.

As described in Section 1.2, the method for auxiliary engine fuel consumption estimation is derived from samples taken from vessel boardings and averaged for ship type- and size-specific modes (at berth, at anchor and at sea). This method is used because of the scarcity of data about the installed auxiliary engine in the IHSF database and the shortage of other information in the public domain describing operational profiles of auxiliary engines.

Figure 56 presents the comparison between the noon report and the bottom-up method in 2012, but with a filter applied to include only data for which the AIS-derived activity was deemed reliable for more than 75% of the time in the quarter. Otherwise, the data source is the same. The marked improvement of the agreement is demonstration of the reliability of the bottom-up method in converting activity into fuel consumption and shows that the largest source of uncertainty in the total fuel consumption is the estimate of activity, particularly the estimate of days at sea.

Figure 57 and Figure 58 present the comparison between the noon report and the bottom-up method for 2007 and 2009 respectively. These quality assurance plots show that, consistent with the comparison of the activity estimate data to noon report data, quality deteriorates between the earlier years (2007, 2008 and 2009) and later years (2010, 2011 and 2012). The availability of noon report data in the earlier years is also limited, which makes rigorous quality assurance difficult. However, even with the sample sizes available, the confidence bounds clearly indicate that the quality deteriorates.

Table 25 summarizes the findings from the quality assurance analysis of the fuel consumption. Further data from earlier years can be found in Annex 3.

Table 25 – *Summary of the findings on the QA of the bottom-up method estimated fuel consumption using noon report data*

Consumer	**Quality, as assessed using noon report data**	**Importance to the inventory of fuel consumption and emissions**
Main engine	Good: consistent agreement and close confidence bounds to the best fit	High (71% of total fuel in 2012)
Auxiliary engine	Poor: moderate, with some ships showing good agreement but many anomalies (very low values in noon reports)	Low (25% of total fuel in 2012)
Boilers	Unassessed	Very low (3.7% of total fuel in 2012)

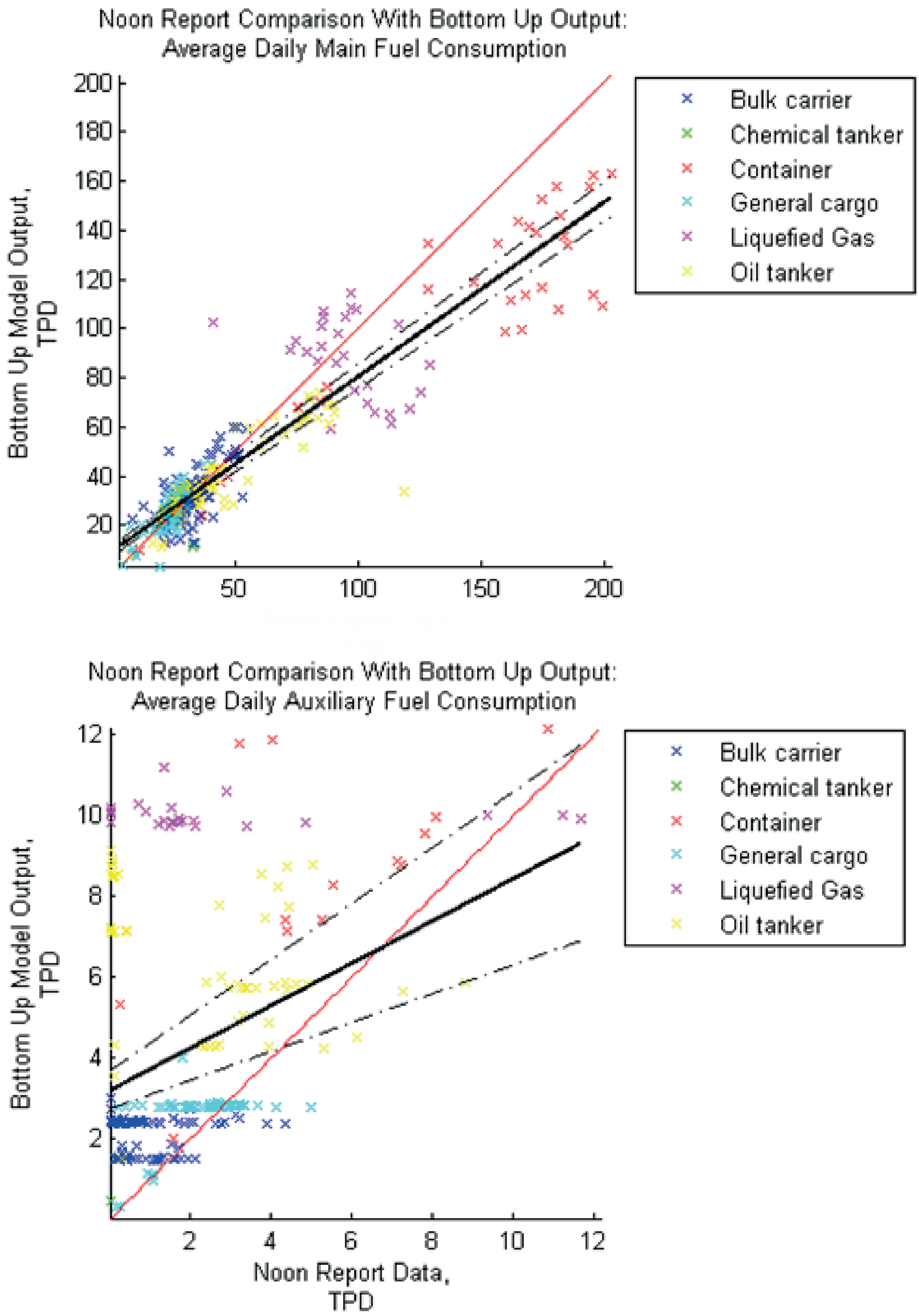


Figure 54: *Average noon-reported daily fuel consumption of the main and auxiliary engines compared with the bottom-up estimate over each quarter of 2012*

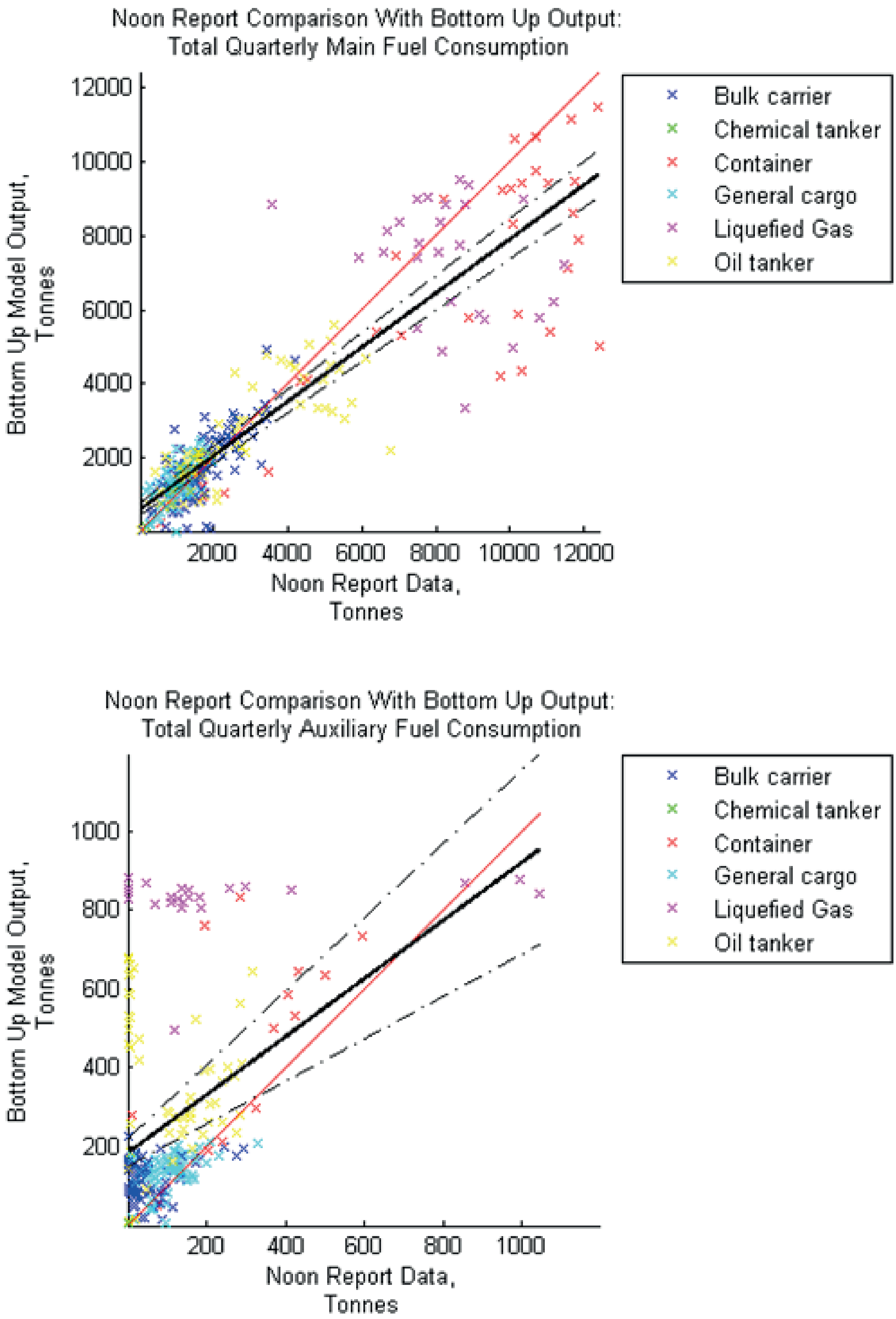


Figure 55: *Total noon-reported quarterly fuel consumption of the main and auxiliary engines compared with the bottom-up estimate over each quarter of 2012*

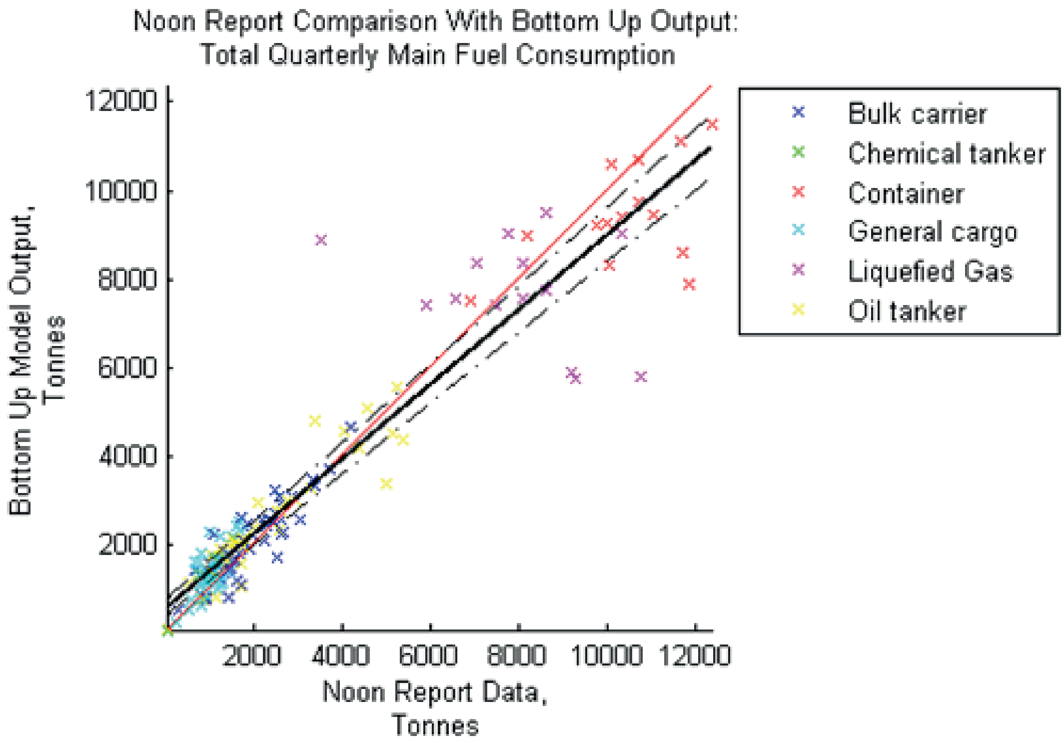


Figure 56: *Total noon-reported quarterly fuel consumption of the main engine compared with the bottom-up estimate over each quarter of 2012, with a filter to select only days with high reliability observations of the ship for 75% of the time or more*

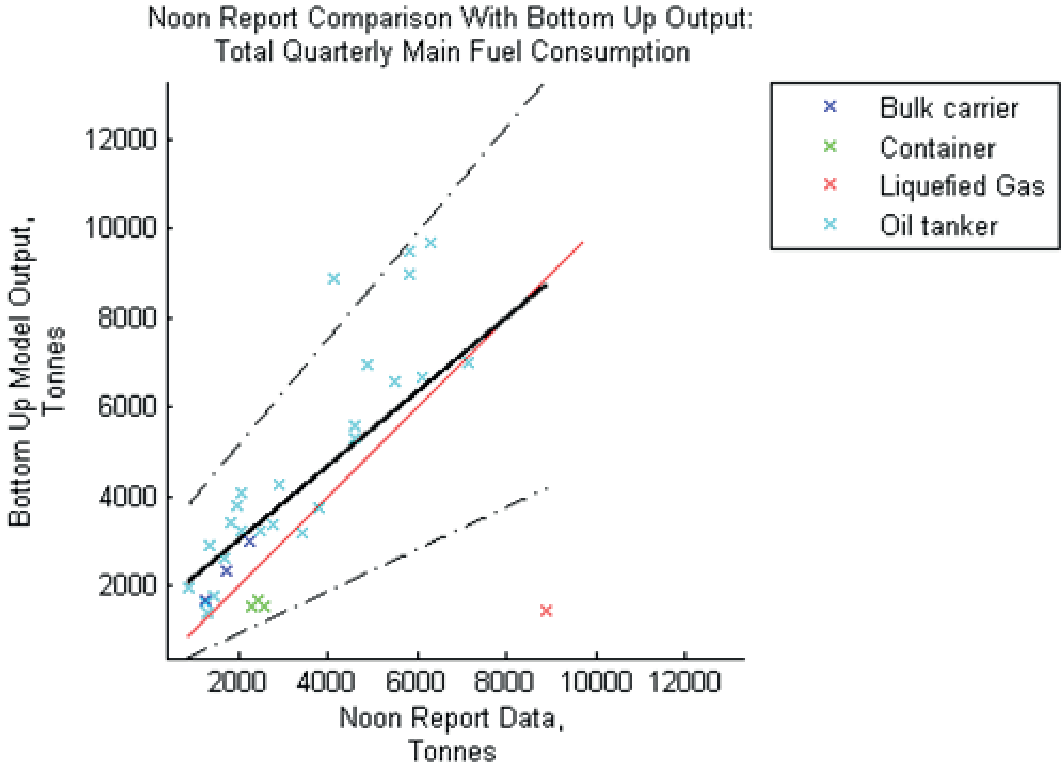


Figure 57: *Total noon-reported quarterly fuel consumption of the main engine compared with the bottom-up estimate over each quarter of 2007*

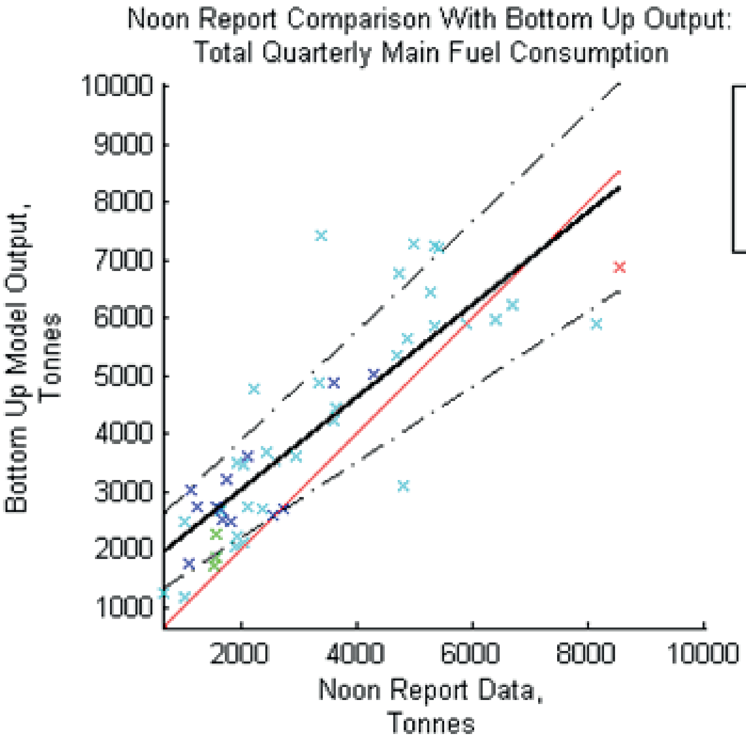


Figure 58: *Total noon-reported quarterly fuel consumption of the main engine compared with the bottom-up estimate over each quarter of 2009*

Coverage statistics and fleet size quality assurance

The total emissions for each fleet (and the sum of emissions of all fleets) are found from:

- the emissions of any ships observed on AIS, during the period of observation;
- extrapolation to cover periods of time when the observed ships are not currently under observation by AIS;
- estimation for ships that are deemed "active" in the IHSF database but are not observed on AIS at all.

The maximum reliability of the inventory is achieved if all the ships are observed all the time, as demonstrated by the main engine comparison in Figure 56. However, the reality is that AIS coverage is not perfect. The statistics of coverage by AIS therefore provide important insight into the quality of the estimate and the quantity of emissions calculated directly versus the quantity of data calculated from imputed and extrapolated estimates of activity. This section examines the quality of the AIS data coverage of the fleets of international, domestic and fishing ships by answering two questions:

- How many of the in-service ships are observed in the AIS data set?
- Of the ships that are observed, what is the duration of the observation period?

The number of in-service ships observed in the AIS data set

Table 26 describes the size of the fleet in the IHSF database in each year along with the percentage of the total fleet classified as in service and, of those ships, the percentage that also appears in the AIS database.

Transport ships are ships that carry goods and people (all merchant shipping, ferries and cruise passenger ships); non-transport ships include service vessels, workboats, yachts and fishing vessels.

Table 26: *Observed, unobserved and active ship counts (2007–2012)*

Year	Transport ships			Non-transport ships		
	Total	% in service	% of in-service ships observed on AIS	Total	% in service	% of in-service ships observed on AIS
2007	58,074	89%	62%	49,396	99%	19%
2008	59,541	89%	66%	50,704	98%	24%
2009	61,065	90%	69%	50,872	100%	29%
2010	69,431	83%	68%	52,941	98%	31%
2011	72,462	75%	69%	51,961	96%	32%
2012	60,670	93%	76%	54,077	96%	42%

There is a large discrepancy between the number of AIS-observed and in-service ships, with fewer in-service ships appearing on AIS than would be expected. This discrepancy is far greater for non-transport ships but still significant for transport ships. Explanations for this discrepancy include:

- a large number of ships classified as in service were not actually so;
- the AIS transponders of in-service ships were not turned on during the year or were faulty/sending spurious signals;
- ships were out of range of any AIS receiving equipment (shore-based or satellite).

The maps of AIS coverage shown in Annex 3 demonstrate that the third explanation (out of range) is plausible for the shortfall in the earlier years (2007, 2008 and 2009). However, the consistency in the shortfall between the number of observed ships and in-service ships across the years (particularly from 2010 onwards, when satellite AIS data are available) does not support this as the only explanation.

Table 27 lists the statistics for four ship types: bulk carriers, container ships, general cargo ships and oil tankers. For these fleets, which account for the majority of shipping emissions, the percentage of in-service ships that also appear in AIS is generally excellent (90%–100%), although there are some notable exceptions. Only 50% or less of the smallest size category of oil tankers, bulk carriers and general cargo ships are observed on AIS, regardless of the year and the quality of AIS coverage.

This implies that the quality of AIS coverage for the ships most important to the inventory is good, but that there are shortcomings in the quality of either the AIS coverage or the IHSF database for the smallest ship size categories. Even as the geographical coverage of the AIS database increases over time, there are many ship types and sizes for which the percentage of in-service ships observed in AIS reduces over time (this is particularly true of the larger container ships and bulk carriers). This trend is indicative of deterioration in the quality of the IHSF status indicator since 2007, 2008 and 2009.

The average duration period for ships that are observed

Table 27 also describes the percentage of the year for which there is a reliable estimate of activity for ships observed on AIS. (The method and judgement of reliability are described in detail in Annex 3.) Consistent with the switch from solely shore-based AIS in 2007, 2008 and 2009 to shore-based and satellite AIS in the later years, there is a substantial increase over the period of this study in the percentage of the year for which a ship can be reliably observed from its AIS transmissions. Many of the smaller ship categories are well observed even in the early years of this study, which is indicative of the ships being operated in coastal areas of land masses where there was good shore-based AIS reception (e.g. particularly Europe and North America).

A composite of the number of ships observed and the duration for which they are observed can be found by taking the product of the two statistics in Table 27:

% total in-service coverage = % in-service ships on AIS × % of the year for which they are observed

Figure 59 displays the trend over time of the percentage of total in-service coverage for four of the fleets sampled in Table 27. As expected from the increased geographical coverage of AIS data with time, the total in-service coverage increases. In 2012, the average in-service large container or bulk carrier can be reliabily observed in the AIS data set assembled by this consortium for nearly 70% of the time. Coverage of the largest bulk carriers nearly tripled between 2010 and 2012, showing that rapid improvements have been observed during the period of this study. The trend for the smaller ship types is for increased coverage but the average total in-service coverage remains 40% and lower for the smallest general cargo carriers and bulk carriers.

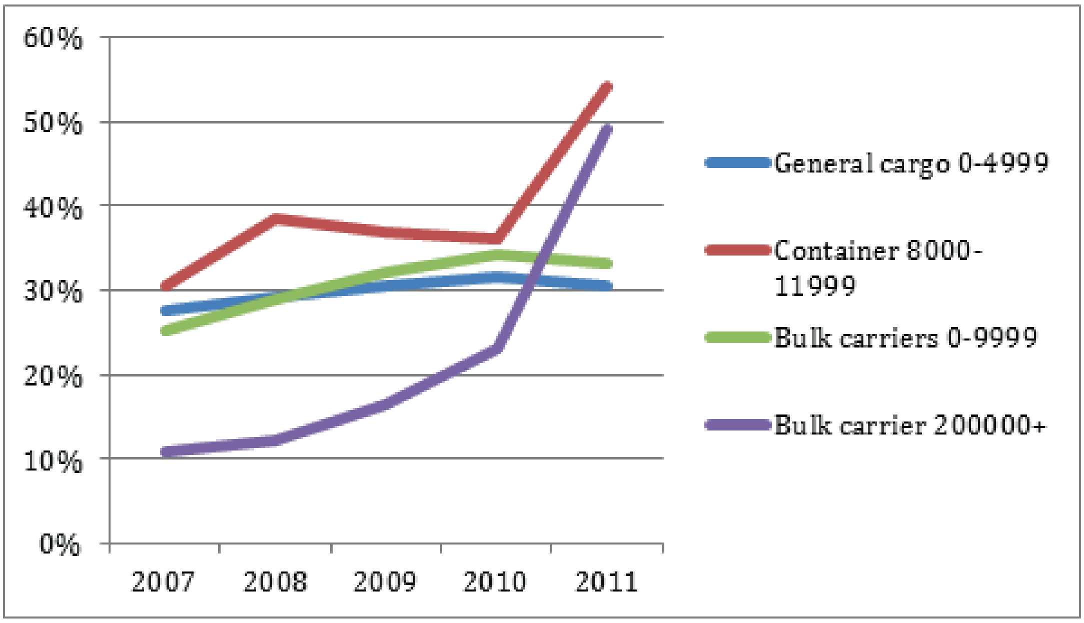


Figure 59: *Total percentage of in-service time for which high-reliability activity estimates are available from AIS*

However, for the purposes of a high-quality inventory, it is more important for the quality of the AIS coverage for the ship types and sizes with the greatest share of emissions to be high. Since the coverage statistics of the highest contributing CO_2 emitters (i.e. the largest ship types and sizes) are also the highest, this is generally the case. Figure 60 displays the CO_2 emissions weighted average of the percentage of total in-service coverage. This is decomposed into two categories: i) ships classified as international shipping (see Section 1.2) and ii) ships classified as domestic and fishing. The subject of the inventories in Section 1.3, international shipping, has significantly higher coverage quality than the domestic and fishing fleet.

In Section 1.4, where the days-at-sea estimate from LRIT is compared with the estimate obtained from AIS, there is a significant improvement in quality for the AIS-derived activity estimates when reliable coverage exceeds 50% of the year. When this finding is placed in the context of the coverage statistics described in this section, it can be seen that in 2011 and 2012 the coverage statistics lead to high-quality activity and therefore inventory estimates. However, in the earlier years of this study, the comparatively lower coverage statistics, relative to the later years, increase the uncertainty of the estimated inventories.

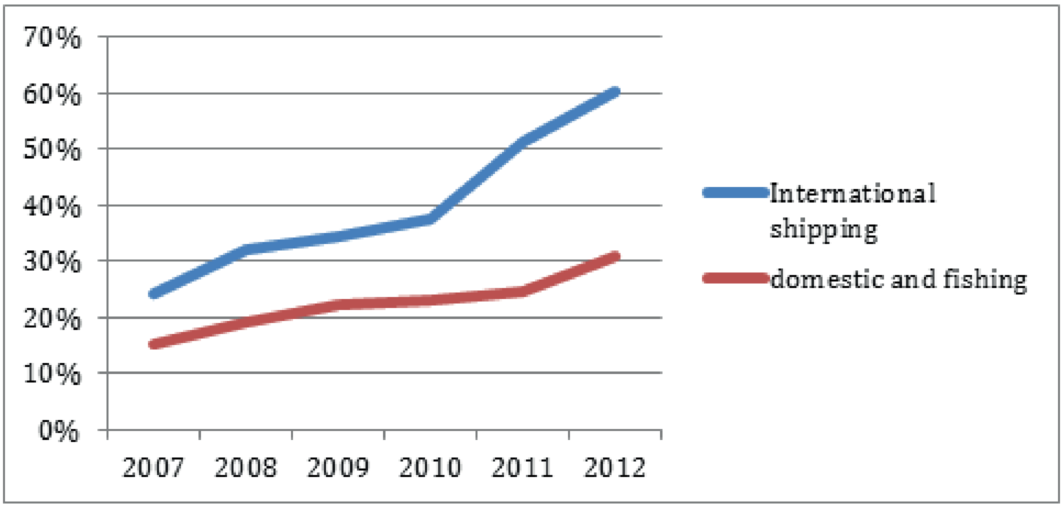


Figure 60: *Emissions weighted average of the total percentage of in-service time for which high-reliability activity estimates are available from AIS*

Table 27 – *Statistics of the number of in-service ships observed on AIS and of the average amount of time during the year for which a ship is observed*

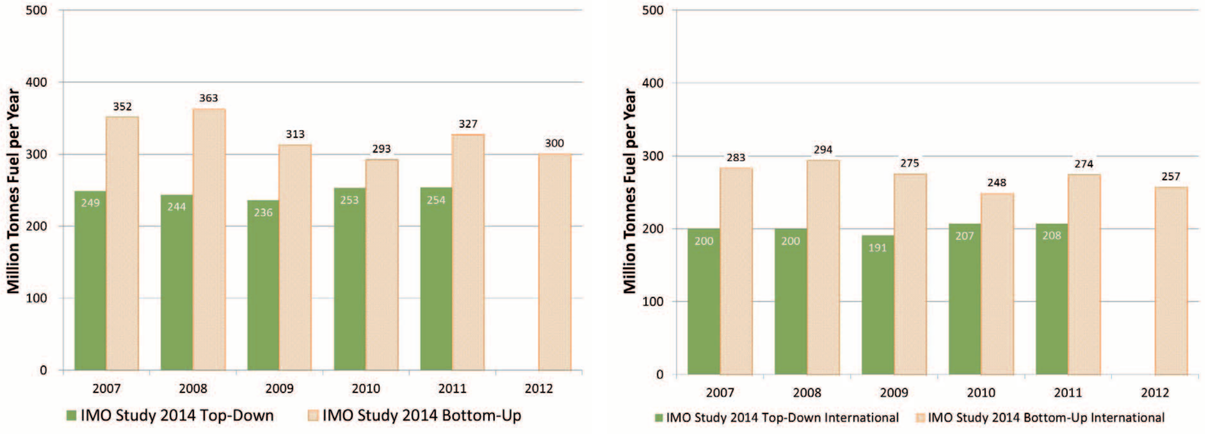
		% of in-service ships observed on AIS						% of year for which high-reliability activity estimates are available					
Ship type	**Size category**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Bulk carrier	0–9,999	34%	41%	45%	50%	47%	55%	75%	71%	72%	68%	71%	74%
	10,000–34,999	91%	92%	91%	89%	86%	92%	23%	26%	31%	38%	56%	65%
	35,000–59,999	97%	96%	97%	96%	91%	95%	17%	20%	22%	28%	52%	65%
	60,000–99,999	99%	99%	98%	98%	93%	95%	14%	16%	19%	24%	51%	65%
	100,000–199,999	99%	99%	99%	99%	93%	94%	10%	14%	18%	28%	51%	63%
	200,000–+	98%	99%	99%	100%	95%	93%	11%	12%	17%	23%	52%	68%
Container	0–999	89%	90%	90%	84%	82%	88%	42%	45%	49%	49%	62%	70%
	1,000–1,999	99%	98%	99%	96%	92%	98%	21%	30%	36%	36%	56%	65%
	2,000–2,999	99%	98%	99%	96%	92%	96%	20%	26%	29%	36%	63%	66%
	3,000–4,999	99%	98%	99%	97%	92%	95%	23%	28%	28%	35%	63%	70%
	5,000–7,999	99%	98%	99%	100%	95%	96%	27%	33%	30%	32%	59%	70%
	8,000–11,999	100%	100%	99%	100%	91%	98%	31%	39%	37%	36%	60%	68%
	12,000–14,500	100%	100%	100%	97%	94%	95%	56%	34%	38%	68%	65%	81%
	14,500–+	0%	0%	0%	0%	0%	88%	0%	0%	0%	0%	0%	71%
General cargo	0–4,999	38%	41%	42%	40%	39%	44%	72%	72%	73%	79%	78%	83%
	5,000–9,999	81%	83%	83%	79%	77%	86%	34%	37%	41%	49%	56%	64%
	10,000–+	87%	89%	89%	84%	84%	90%	28%	29%	34%	43%	55%	66%
Oil tanker	0–4,999	72%	30%	34%	37%	38%	43%	46%	43%	48%	48%	58%	66%
	5,000–9,999	98%	70%	73%	78%	78%	87%	15%	17%	22%	26%	49%	59%
	10,000–19,999	100%	78%	81%	77%	80%	90%	69%	67%	50%	23%	53%	59%
	20,000–59,999	24%	93%	93%	91%	91%	95%	84%	81%	80%	77%	78%	81%
	60,000–79,999	62%	95%	95%	96%	90%	97%	56%	53%	55%	46%	55%	59%
	80,000–119,999	74%	98%	98%	97%	91%	97%	44%	45%	47%	43%	52%	58%
	120,000–199,999	91%	98%	98%	97%	91%	95%	29%	30%	33%	38%	52%	61%
	200,000–+	95%	99%	99%	95%	95%	96%	27%	29%	33%	34%	55%	64%

1.4.4 Comparison of top-down and bottom-up inventories

Four main comparators are essential to understanding the similarities, differences and joint insights that derive from the top-down and bottom-up inventories:

1. estimates of fuel totals (in million tonnes);
2. allocation of fuel totals by fuel type (residual, distillate and natural gas, or HFO, MDO and LNG as termed in this study);
3. estimates of CO_2 totals (in million tonnes), which depend in part upon the allocation of different fuel types with somewhat different carbon contents;
4. allocation of fuel totals as international and not international (e.g. domestic and fishing).

Given the results presented in Sections 1.1.3 and 1.3.2, there is a clear difference between the best estimates of the top-down and bottom-up methods. This difference has been documented in the scientific peer-reviewed literature and in previous IMO reports. This study finds that the best estimates of fuel consumption differ by varying quantities across the years studied. Smaller differences between top-down and bottom-up total fuel consumption are observed after the availability of better AIS coverage in 2010. However, in all cases, the activity-based bottom-up results for all fuels are generally greater than the top-down statistics.



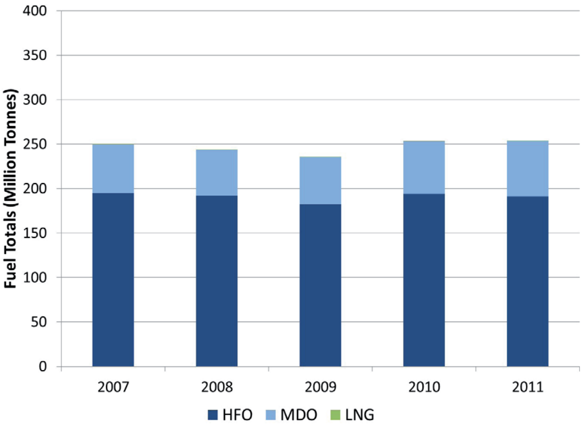
a) All marine fuels

b) International shipping

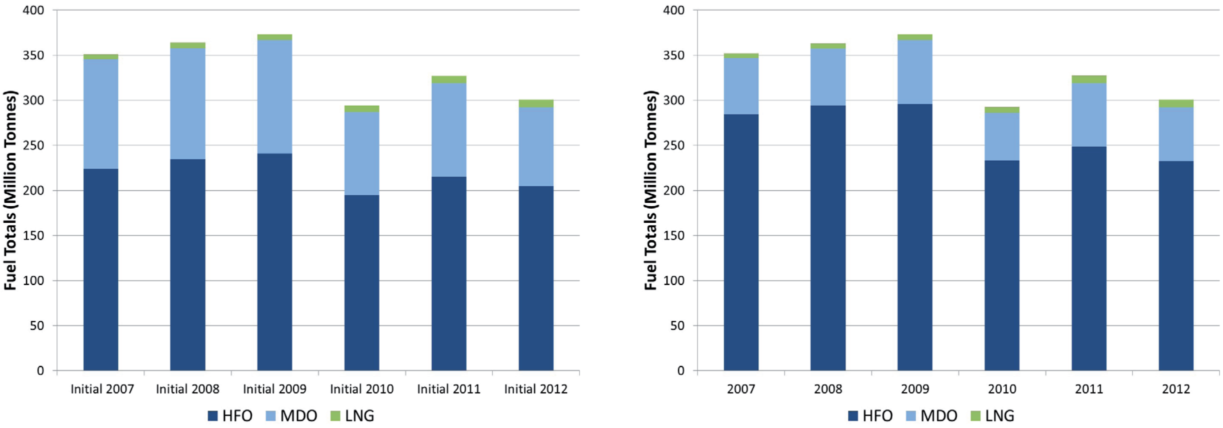
Figure 61: *Top-down and bottom-up comparison for a) all marine fuels and b) international shipping*

Allocation of fuel inventories by fuel type is important and comparison of top-down allocations with initial bottom-up fuel type results provided important QA/QC that helped reconcile bottom-up fuel type allocation.

The fuel split between residual (HFO) and distillate (MDO) for the top-down approach is explicit in the fuel sales statistics from IEA. However, the HFO/MDO allocation for the bottom-up inventory could not be finalized without consideration of top-down sales insights. This is because the engine-specific data available through IHSF are too sparse, incomplete or ambiguous with respect to fuel type for large numbers of main engines and nearly all auxiliary engines on vessels. QA/QC analysis with regard to fuel type assignment in the bottom-up model was performed using top-down statistics as a guide together with fuel allocation information from the Second IMO GHG Study 2009. This iteration was important in order to finalize QA/QC on fuel-determined pollutant emissions (primarily SO_x and PM), and results in slight QA/QC adjustments for other emissions. Figure 62 presents a side-by-side comparison of top-down, initial and updated bottom-up approaches to fuel type allocations.



a) Top-down fuel type allocation



b) Initial bottom-up allocation

c) Updated bottom-up allocation

Figure 62: *Comparison of top-down fuel allocation with initial and updated bottom-up fuel allocation (2007–2012)*

Figure 62 a) and c) show that relative volumes of residual to distillate marine fuel (HFO to MDO) are similar. This is because the updated allocation in the bottom-up inventory is constrained to replicate the reported IEA fuel sales ratios. The year-on-year allocations are also constrained by bottom-up analysis that identifies vessel categories with engines likely to use distillate fuel. A further constraint is that an MDO assignment applied to a vessel category in any year requires that MDO be assigned to that category in every year.

The CO_2 comparison corresponds closely to the total fuel values, with the exception of the LNG consumption identified in the bottom-up inventory. The IEA statistics report zero international marine bunkers of natural gas (LNG), as shown in Table 9 in Section 1.1.3. Trends in CO_2 emissions are nearly identical to total fuel estimates, with negligible modification by the fuel type allocation. Trends in the top-down inventory suggest a low-growth trend in energy use by ships during the period 2007–2012. This is consistent with known adaptations and innovations in the international shipping fleet to conserve fuel during a period of increasing energy prices and global recession.

Table 28 – *International, domestic and fishing CO_2 emissions 2007–2011 (million tonnes), using top-down method*

Marine sector	Fuel type	2007	2008	2009	2010	2011
International shipping	HFO	542.1	551.2	516.6	557.1	554.0
	MDO	83.4	72.8	79.8	90.4	94.9
	LNG	0.0	0.0	0.0	0.0	0.0
Top-down international total	**All**	**625.5**	**624.0**	**596.4**	**647.5**	**648.9**
Domestic navigation	HFO	62.0	44.2	47.6	44.5	39.5
	MDO	72.8	76.6	75.7	82.4	87.8
	LNG	0.1	0.1	0.1	0.1	0.2
Top-down domestic total	**All**	**134.9**	**121.0**	**123.4**	**127.1**	**127.6**
Fishing	HFO	3.4	3.4	3.1	2.5	2.5
	MDO	17.3	15.7	16.0	16.7	16.4
	LNG	0.1	0.1	0.1	0.1	0.1
Top-down fishing total	**All**	**20.8**	**19.2**	**19.3**	**19.2**	**19.0**
All fuels top-down		**781.2**	**764.1**	**739.1**	**793.8**	**795.4**

Table 29 – *International, domestic and fishing CO_2 emissions 2007–2012 (million tonnes), using bottom-up method*

Marine sector	Fuel type	2007	2008	2009	2010	2011	2012
International shipping	HFO	773.8	802.7	736.6	650.6	716.9	667.9
	MDO	97.2	102.9	104.2	102.2	109.8	105.2
	LNG	13.9	15.4	14.2	18.6	22.8	22.6
Bottom-up international total	**All**	**884.9**	**920.9**	**855.1**	**771.4**	**849.5**	**795.7**
Domestic navigation	HFO	53.8	57.4	32.5	45.1	61.7	39.9
	MDO	142.7	138.8	80.1	88.2	98.1	91.6
	LNG	0	0	0	0	0	0
Bottom-up domestic total	**All**	**196.5**	**196.2**	**112.6**	**133.3**	**159.7**	**131.4**
Fishing	HFO	1.6	1.5	0.9	0.8	1.4	1.1
	MDO	17.0	16.4	9.3	9.2	10.9	9.9
	LNG	0	0	0	0	0	0
Bottom-up fishing total	**All**	**18.6**	**18.0**	**10.2**	**10.0**	**12.3**	**11.0**
All fuels bottom-up		**1,100.1**	**1,135.1**	**977.9**	**914.7**	**1,021.6**	**938.1**

Across the set of years 2007–2012, CO_2 emissions from international shipping range between approximately 739 million and 795 million tonnes, according to top-down methods, and between approximately 915 million and 1,135 million tonnes, according to bottom-up methods. The trend in top-down totals has been generally flat or slightly increasing since the low point of the recession in 2009; the trend in bottom-up totals can be interpreted as generally flat (since 2010 at least, when AIS data coverage became consistently global).

Domestic navigation and fishing

The top-down results are explicit in distinguishing between fuel delivered to international shipping, domestic navigation or fishing. (Potential uncertainty in this explicit classification is discussed in Section 1.6.) Bottom-up methods do not immediately identify international shipping, so the consortium considered ways to deduct domestic navigation or fishing fuel from the total fuel estimates. For example, bottom-up results allow for categorical identification of fishing fuel by virtue of ship type.

For domestic navigation and fishing, some categories of vessel presumably would be devoted mainly to domestic navigation service, according to allocation method 2 in Section 1.2.8. To evaluate the quality of this method, the consortium visually inspected AIS plots of service vessels, passenger ferries, ro-pax ferries and other vessel types without respect to vessel size. The intensity of AIS reporting revealed generally local operations for service vessels, as expected. Service vessels were observed operating in international waters, but their patterns strongly conformed to EEZ boundaries as a rule. These were interpreted as non-transport services that would result in a domestic-port-to-domestic-port voyage with offshore service to domestic platforms for energy exploration, extraction, scientific missions, etc. Similar behaviour was observed for offshore vessels and miscellaneous vessel categories (other than fishing). Cruise passenger ships exhibited much more international voyage behaviour than passenger ferries (with some exceptions attributed to larger ferries); similar observations were made after visualizing ro-pax vessel patterns. Moreover, no dominant patterns of local operations for bulk cargo ships, container ships or tankers were identified.

The consortium mapped the set of AIS-observed but unidentified vessels and observed that these vessels generally (but not exclusively) operated in local areas. This led to an investigation of the available message data in these AIS observations. It was possible to evaluate the MMSI numbers that were unmatched with IHSF vessel information, at least according to the MMSI code convention. A count of unique MMSI numbers was made for each year and associated with its region code; only vessel identifiers were included.

Europe, Asia and North America were the top regions with unknown vessels, accounting for more than 85% of the umatched MMSI numbers on average across 2007–2012 (approximately 36%, 30% and 21% respectively). Oceania, Africa and South America each accounted for approximately 6%, 5% and 3% respectively. To evaluate whether these vessel operations might qualify as domestic navigation, the top-down domestic fuel sales statistics from IEA were classified according to these regions and the pattern of MMSI counts was confirmed as mostly correlated with domestic marine bunker sales. This is illustrated in Table 30, which shows that correlations in all but one year were greater than 50%. This evidence allows for a designation of these vessels as mostly in domestic service, although it is not conclusive.

Table 30 – *Summary of average domestic tonnes of fuel consumption per year (2007–2012), MMSI counts and correlations between domestic fuel use statistics*

	Correlations:	**0.87**	**0.56**	**0.66**	**0.13**	**0.66**	**0.87**
	Domestic fuel consumption (tonnes per year)	**2007 MMSI**	**2008 MMSI**	**2009 MMSI**	**2010 MMSI**	**2011 MMSI**	**2012 MMSI**
Africa	430	4,457	7,399	2,501	3,336	10,801	13,419
Asia	9,900	18,226	23,588	15,950	12,530	82,198	112,858
Europe	3,000	13,856	23,368	20,972	75,331	94,379	88,286
North and Central America and Caribbean	4,800	14,100	48,261	16,104	22,590	26,878	55835
Oceania	430	3,903	7,188	4,135	5,200	13,889	21,320
South America	1,300	1,023	2,583	1,939	1,842	6,808	9,532
Grand total	**19,900**	**55,565**	**112,387**	**8,301**	**120,829**	**234,953**	**301,250**

1.5 Analysis of the uncertainty of the top-down and bottom-up CO_2 inventories

Section 1.5 requires an analysis of the uncertainties in the emissions estimates to provide IMO with reliable and up-to-date information on which to base its decisions. Uncertainties are associated with the accuracy of top-down fuel statistics and with the emissions calculations derived from marine fuel sales statistics. Uncertainties also exist in the bottom-up calculations of energy use and emissions from the world fleet of ships. These uncertainties can affect the totals, distributions among vessel categories and allocation of emissions between international and domestic shipping.

1.5.1 Top-down inventory uncertainty analysis

An overview of the twofold approach applied to top-down statistics and emissions estimates is provided. A full description of this approach is given in Annex 4. First, this work builds upon the QA/QC findings that suggest that sources of uncertainty in fuel statistics relate to data quality and work to quantify the bounding impacts of these. Second, this analysis quantifies uncertainties associated with emissions factors used to estimate GHGs using top-down statistics.

Table 31 – *Upper range of top-down fuel consumption by vessel type (million tonnes)*

Fuel type	**2007**	**2008**	**2009**	**2010**	**2011**
MDO	71	73	77	64	73
HFO	258	258	245	256	244
All fuels	329	331	321	319	318
Fuel type	**2007**	**2008**	**2009**	**2010**	**2011**
MDO	22%	22%	24%	20%	23%
HFO	78%	78%	76%	80%	77%
All fuels	100%	100%	100%	100%	100%

The Third IMO GHG Study 2014 acknowledges that additional uncertainty about marine fuel sales to consumers is not identified in the IEA data and cannot be quantified. For example, some ships that purchase fuel (probably domestic and almost certainly MDO) are identified by IEA as "transport sector". This includes fuel purchased in places that might not be counted as "marine bunkers" (e.g. leisure ports and marinas). The quantities of fuel sold to boats in a global context appear to be small compared to the volumes reported as bunker sales but this cannot be evaluated quantitatively. Given that these sales are all domestic, the additional uncertainty does not affect estimates of international shipping fuel use. However, uncertainty in the HFO/MDO allocation may be slightly affected but remains unquantified; again, this analysis suggests such fuel allocation uncertainty appears to be small.

Export-import discrepancy represents the primary source of uncertainty, as measured by the quantity of adjustment that is supported by our analysis. This discrepancy exists because the total fuel volumes reported as exports exceeds the total fuel volumes reported as imports. Evidence associating the export-import discrepancy with marine fuels includes the known but unquantified potential to misallocate bunker fuel sales as exports, as documented above. The magnitude of this error increased during the period of globalization, particularly since the 1980s. In fact, the percentage adjustment due to export-import allocation uncertainty has never been lower than 22% since 1982, as discussed in Annex 4. Table 32 and Figure 63 illustrate the top-down adjustment for the years 2007–2011. During these years, the average adjustment due to export-import allocation uncertainty averaged 28%.

Table 32 – *Results of quantitative uncertainty analysis on top-down statistics (million tonnes)*

Marine sector	**2007**	**2008**	**2009**	**2010**	**2011**
Total marine fuel consumption (reported)	249.2	243.7	235.9	253.0	253.5
Adjustment for export-import discrepancy	71.5	79.4	78.0	59.0	56.0
Adjustment for fuel transfers balance	8.1	8.1	7.5	7.5	8.2
Adjusted top-down marine fuel estimate	**329.8**	**331.2**	**321.4**	**319.5**	**317.7**

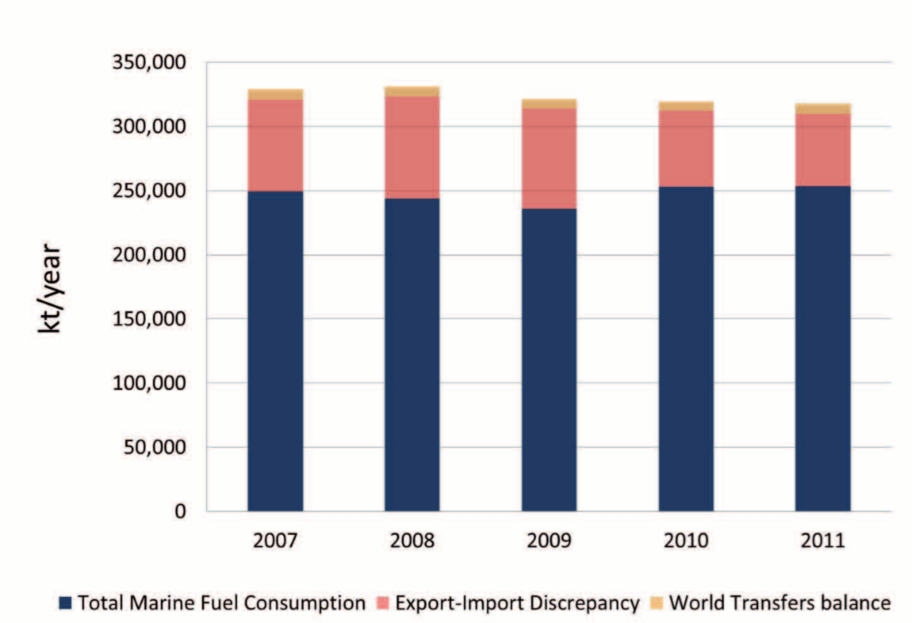


Figure 63: *Adjusted marine fuel sales based on quantitative uncertainty results (2007–2011)*

1.5.2 Bottom-up inventory uncertainty analysis

Bottom-up uncertainty in this study is conditioned on the quality control of information for specific vessels, application of known variability in vessel activity to observed vessels within similar ship type and size fleets and the way in which activity assumptions are applied to unobserved vessels within similar ship type and size fleets. In other words, the quantification of uncertainty is linked to the quality control section of this report. One of the most important contributions of this study in reducing uncertainty is the explicit quality control to calculate fuel use and emissions using specific vessel technical details; this directly accounts for variability within a fleet bin, and replaces the uncertainty with the average technical parameters in the Second IMO GHG Study 2009 calculations with the average technical parameters. Another important contribution to reducing uncertainty is the direct observation of activity data for individual vessels, i.e. speed and draught aggregated hourly, then annually.

Figure 64 presents the uncertainty ranges around the top-down and bottom-up fuel totals for the years studied. The vertical bars attached to the total fuel consumption estimate for each year and each method represent uncertainty. This study estimates higher uncertainty in the bottom-up method in the earlier years (2007, 2008 and 2009), with the difference between these uncertainty estimates being predominantly attributable to the change in AIS coverage over the period of the study. The uncertainty in the earlier years is dominated by uncertainty in the activity data, due to the lack of satellite AIS data. In later years (2010, 2011 and 2012), this uncertainty reduces, but the discrepancy between the number of ships identified as in service in IHSF and the ships observed on AIS increases (relative to the earlier years). The result is that the total bottom-up uncertainty only reduces slightly in the later years when improved AIS data is available.

The top-down estimates are also uncertain, and include observed discrepancies between global imports and exports of fuel oil and distillate oil, observed transfer discrepancies among fuel products that can be blended into marine fuels and the potential for misallocation of fuels between sectors of shipping (international, domestic and fishing).

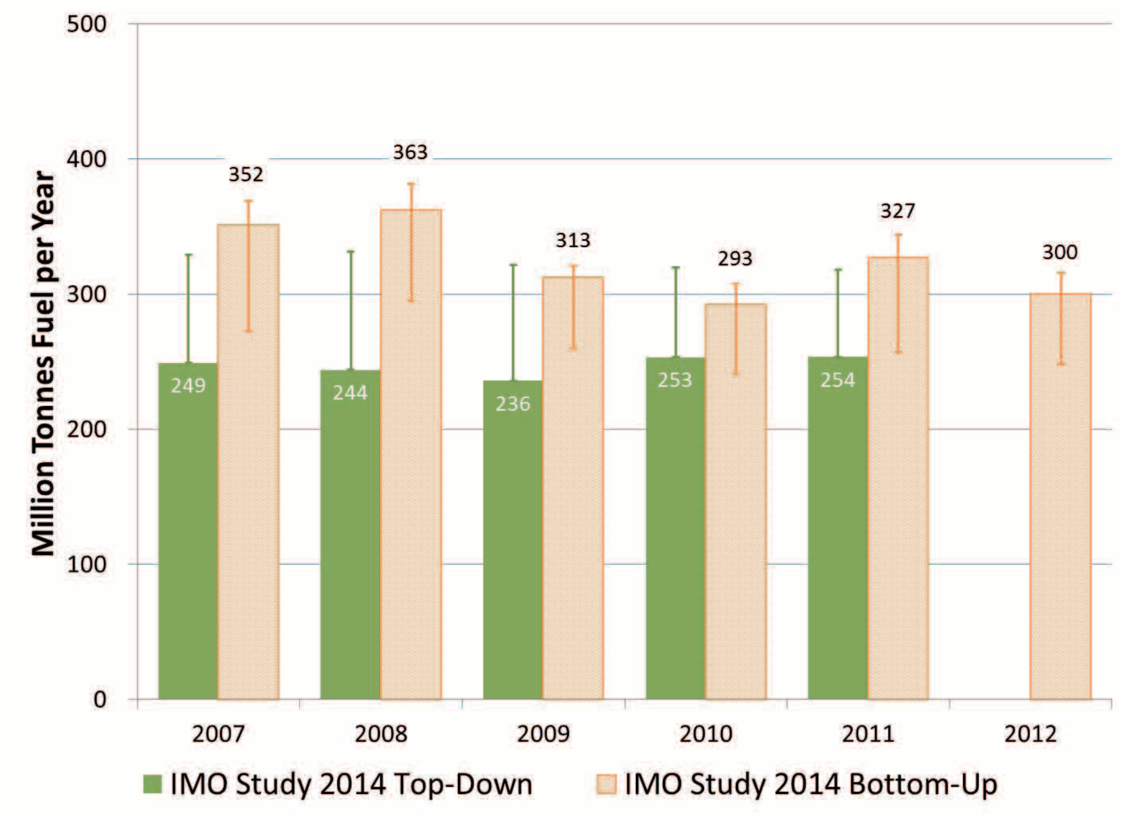


Figure 64: *Summary of uncertainty on top-down and bottom-up fuel inventories for a) all ships and b) international shipping*

1.6 Comparison of the CO_2 inventories in this study to the Second IMO GHG Study 2009 inventories

The Third IMO GHG Study 2014 produces multi-year inventories including 2007, which is the year that the Second IMO GHG Study 2009 selected for its most detailed inventory. The two top-down inventories compare very closely, at 249 million versus 234 million metric tonnes of fuel for the 2014 and 2009 studies respectively. Top-down comparisons differ by less than 10% and can be explained by the extrapolation of 2005 IEA data used by the Second IMO GHG Study 2009 to estimate 2007 top-down totals. Similarly, the best estimates for bottom-up global fuel inventories for 2007 in both studies differ by just over 5%, at 352 million versus 333 million metric tonnes fuel respectively. Bottom-up fuel inventories for international shipping differ by less than 3%.

Figure 65 and Figure 66 present results from this study (all years) and also from the Second IMO GHG Study 2009 (2007 only), including the uncertainty ranges for this work as presented in Section 1.5. The comparison of the estimates in 2007 shows that for both the top-down and bottom-up analysis methods, for both the total fuel inventory and international shipping, the results of the Third IMO GHG Study 2014 are in close agreement with findings from the Second IMO GHG Study 2009. Similarly, the CO_2 estimate of 1,054 million metric tonnes reported by the Second IMO GHG Study 2009 falls within the multi-year range of CO_2 estimates reported in the bottom-up method for this study.

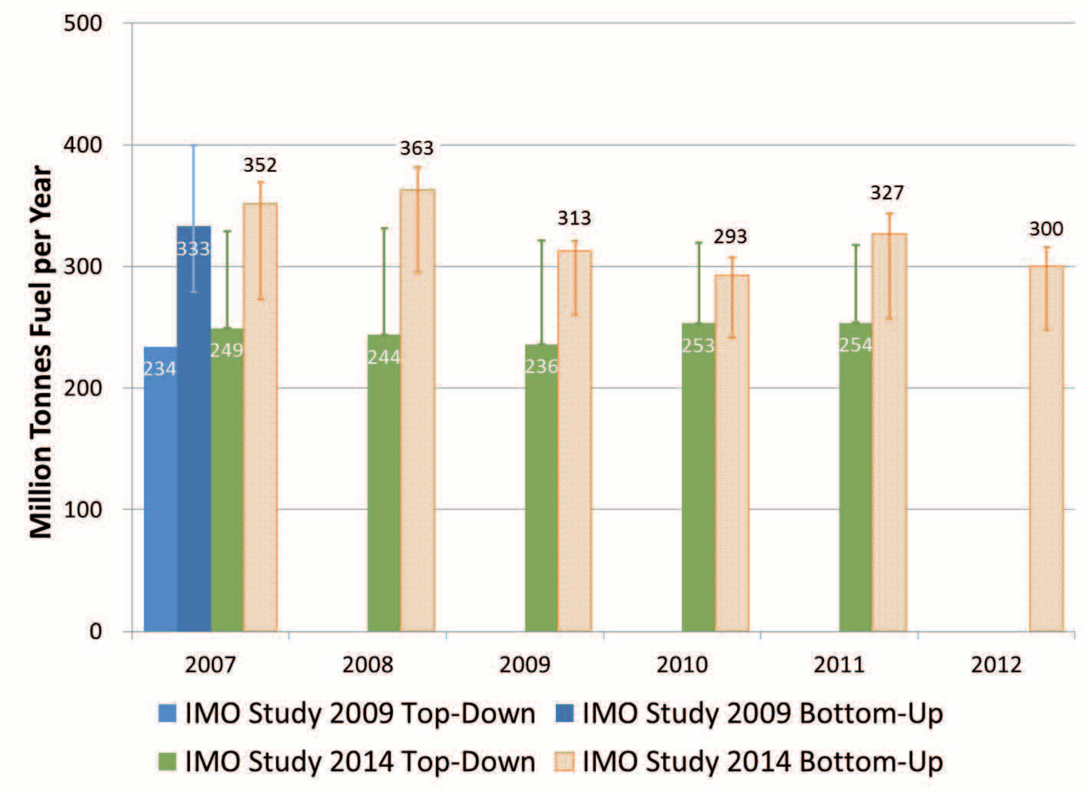


Figure 65: *Top-down and bottom-up inventories for all ship fuels, from the Third IMO GHG Study 2014 and the Second IMO GHG Study 2009*

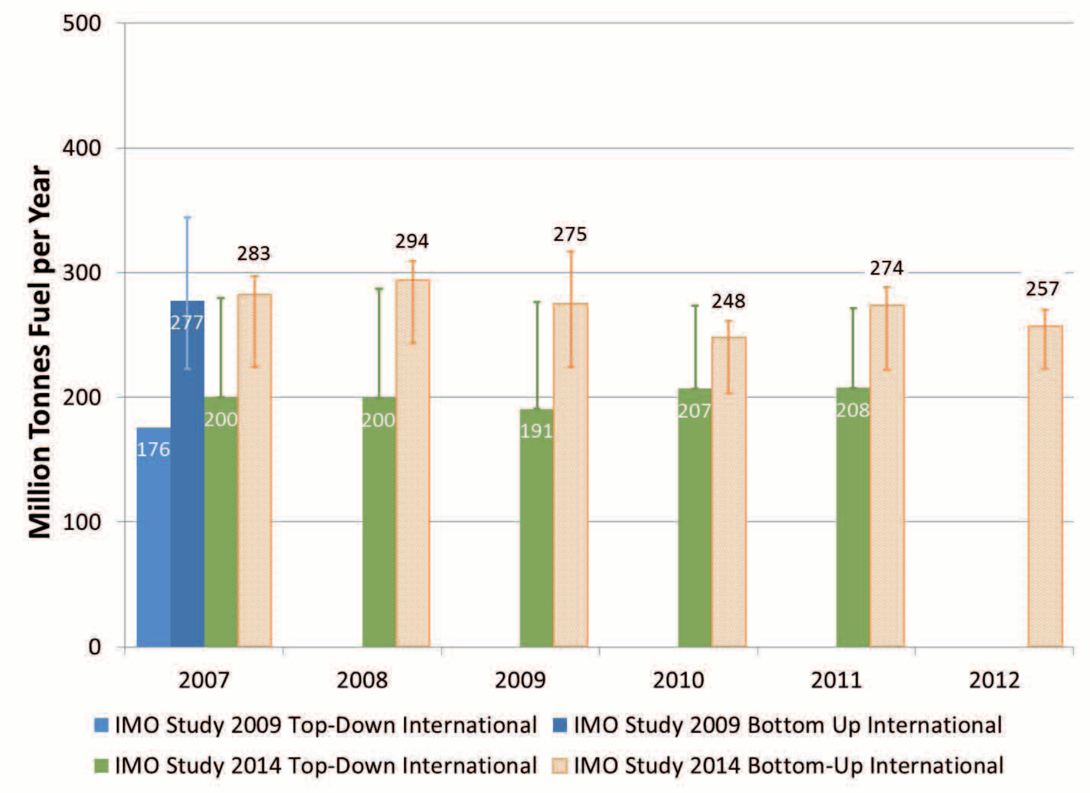
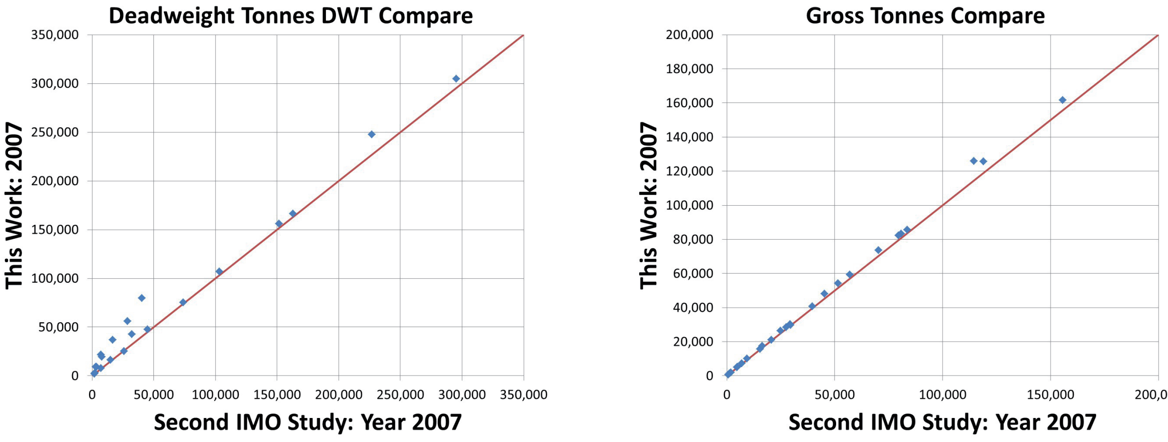


Figure 66: *Top-down and bottom-up inventories for international shipping fuels, from the Third IMO GHG Study 2014 and the Second IMO GHG Study 2009*

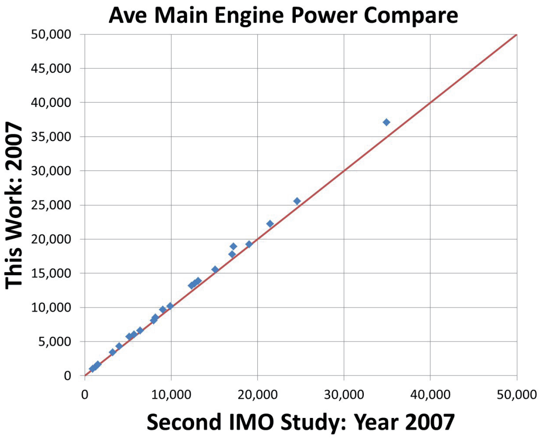
Differences between the bottom-up and top-down estimated values are consistent with the Second IMO GHG Study 2009. This convergence is important because, in conjunction with the quality (Section 1.4) and uncertainty (Section 1.5) analyses, it provides evidence that increasing confidence can be placed in both analytic approaches.

There are some important explanatory reasons for the detailed activity method reported here to have fundamental similarity with other activity-based methods, even if they are less detailed. Crossplot comparisons in Figure 67 indicate that the fundamental input data to the bottom-up inventory in the Second IMO GHG Study 2009 appear valid, compared to the best available data used in the Third IMO GHG Study 2014.



a) Deadweight tonnes

b) Gross registered tonnes

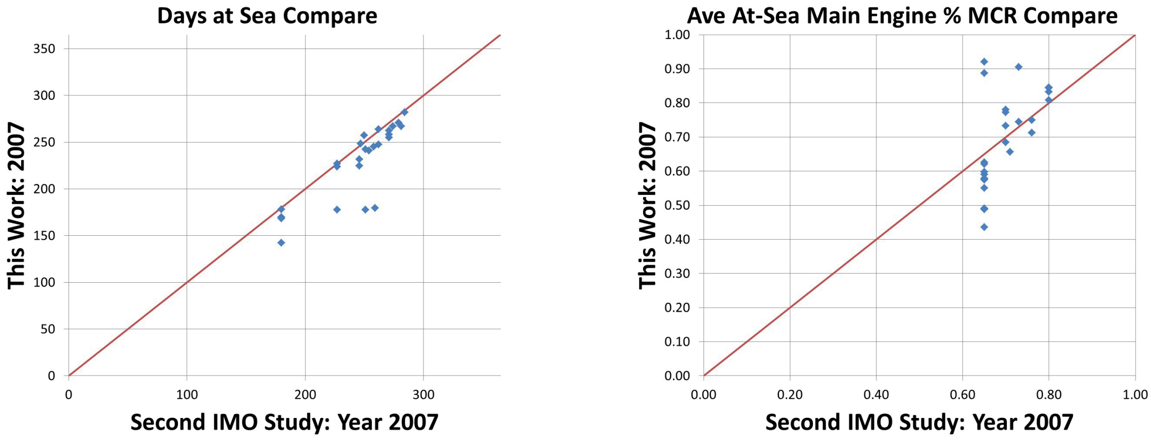


c) Main engine power installed

Figure 67: *Crossplots of deadweight tonnes, gross tonnes and average installed main engine power for the year 2007, as reported by the Second IMO GHG Study 2009 (x-axis) and the Third IMO GHG Study 2014 (y-axis)*

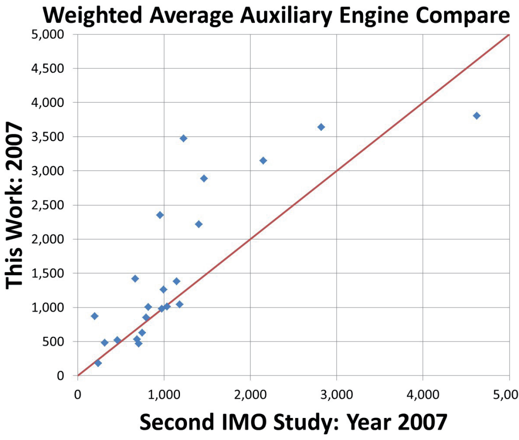
There are differences in parameters between the studies. The most important uncertainty identified by the Second IMO GHG Study 2009 was engine operating days, especially for main engines. The 2009 study considered confidence to be "moderate, but dominat[ing] uncertainty", and explained that the coverage accuracy of the AIS data would affect uncertainty in several ways. Uncertainty in main engine load was reported as the second most important parameter affecting confidence in the 2009 bottom-up calculations.

Generally, uncertainty in auxiliary engine inputs was assessed as moderate to low in the Second IMO GHG Study 2009 (i.e. the study reported confidence in these to be moderate to high). The 2009 study identified several ways in which auxiliary engine information was uncertain, including engine size, auxiliary engine operating days, auxiliary engine load and auxiliary engine specific fuel oil consumption. The IHSF data on auxiliary engines used in the Third IMO GHG Study 2014 remained sparse, although the consortium was able to access auxiliary data for more than 1,000 ships from noon reports, previous vessel boardings, etc. These are shown in Figure 68.



a) Days at sea

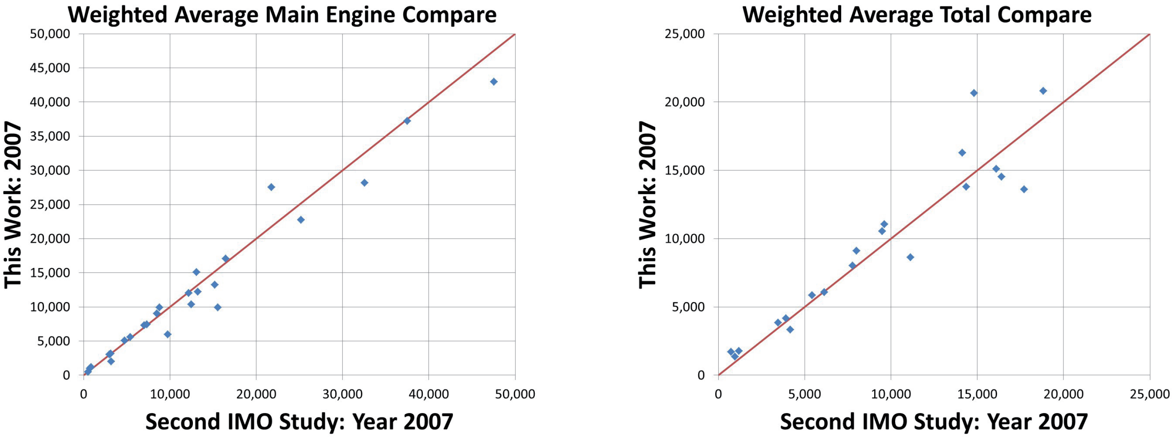
b) Engine load (average % MCR)



c) Auxiliary engine fuel consumption

Figure 68: *Crossplots for days at sea, average engine load (% MCR) and auxiliary engine fuel use for the year 2007, as reported by the Second IMO GHG Study 2009 (x-axis) and the Third IMO GHG Study 2014 (y-axis)*

As a result, activity-based calculations of fuel consumption are generally similar. Figure 69 presents crossplots showing that average main engine fuel consumption and average total vessel fuel consumption patterns are consistent between the Second IMO GHG Study 2009 and the Third IMO GHG Study 2014.

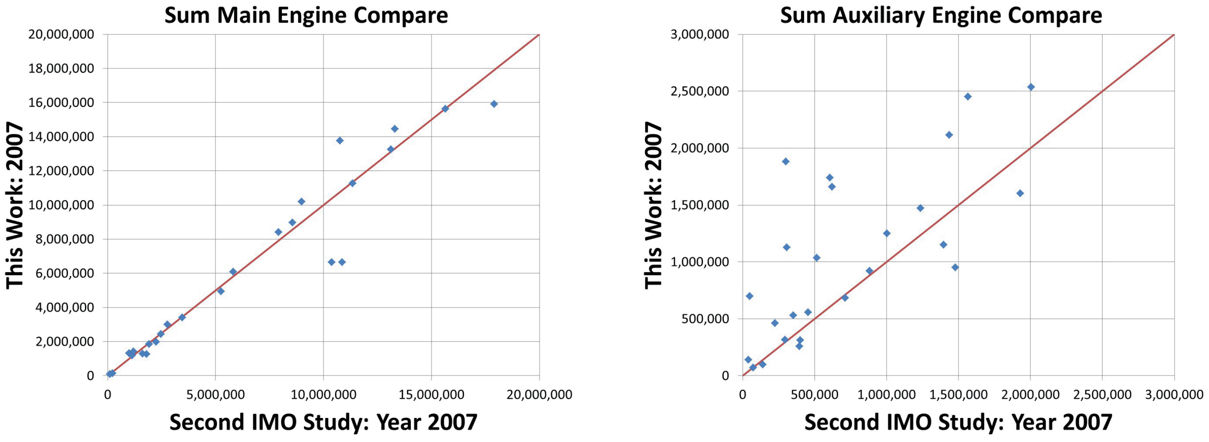


a) Main engine fuel consumption

b) Total vessel fuel consumption

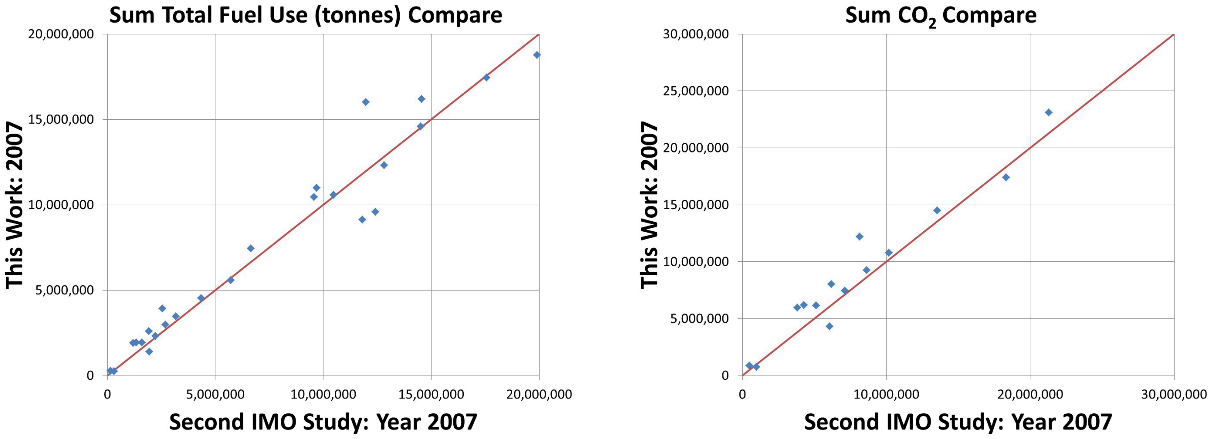
Figure 69: *Crossplots for average main engine daily fuel consumption and total vessel daily fuel consumption for 2007, as reported by the Second IMO GHG Study 2009 (x-axis) and the Third IMO GHG Study 2014 (y-axis)*

Figure 70 demonstrates good agreement between the various components of the calculation of fuel consumption. This provides evidence that observed good agreement in total fuel consumption is underpinned by good agreement in model design. These crossplots are most directly related to the international shipping totals reported in Figure 66. This is because the crossplots are limited to vessel categories that are known to be engaged in international shipping and where the Third IMO GHG Study 2014 categories can be directly matched to categories reported in 2009 study.



a) Main engine fuel consumption

b) Total vessel fuel consumption



c) Vessel type annual fuel

c) Vessel type annual CO$_2$

Figure 70: *Crossplots for main engine annual fuel consumption, total vessel annual fuel consumption, aggregated vessel type annual fuel consumption and CO$_2$ for the year 2007, as reported by the Second IMO GHG Study 2009 (x-axis) and the Third IMO GHG Study 2014 (y-axis)*

Table 33 summarizes this discussion by making explicit the key differences between the 2009 study and the current study. Given these observations, the general conclusion is that better AIS data on activity are determinants of the precision of individual vessel calculations for activity-based emissions inventories. The variation between vessel voyage days, vessels in a vessel category and other important variations can only be evaluated with access to very detailed activity data. However, if a more general approach uses representative input parameters that reflect the best composite activity data, the results will generally be similar.

Table 33 – *Summary of major differences between the Second IMO GHG Study 2009 and Third IMO GHG Study 2014*

Key variable	**Differences**	**2009 study**	**2014 study**	**Overall effect**
Days at sea	Data and method	Annual IHSF status indicator only	Uses quarterly IHSF status indicator to indicate if laid up for part of the year	Minor decrease in emissions
At-sea main engine MCR	Data and method	AIS-informed expert judgement	Uses AIS data extrapolation, quality-checked using LRIT and noon reports	Minor increase in emissions
Auxiliary engine	Data and method	Expert judgement annual aggregates	Auxiliary power outputs derived from vessel boarding data and applied according to mode of operation	Minor increase in emissions

2

Inventories of emissions of GHGs and other relevant substances from international shipping 2007–2012

2.1 Top-down other relevant substances inventory calculation method

2.1.1 Method for combustion emissions

The top-down calculation of non-CO_2 GHGs and other relevant substances is divided into two components:

- emissions resulting from the combustion of fuels;
- other emissions (HFCs, PFCs and SF_6) from ships.

The emissions from the combustion of fuels are found in the fuel sales statistics (see Section 1.1) and emissions factors (EFs) data. The method for other emissions replicates the methods used in the Second IMO GHG Study 2009.

The data for the fuel sales statistics were obtained and compiled for all available years (2007–2011) and are described in greater detail in Section 1.1. These fuel statistics, and their uncertainty, form the basis for top-down emissions estimates.

Estimation of emissions factors

EFs are obtained from Section 2.2, as weighted averages for a given fuel type, taking into account the variation in engine type and operation. These values are more general in some cases than EFs used in bottom-up methods, because the limited detail for top-down methods does not allow the application of specific EFs to auxiliaries, varying engine load or other activity-based conditions. Generally, EFs corresponding to Tier 0 (pre-2000) engines and load factors of 70% are listed in Table 34.

Where it is known that varying fuel sulphur levels can affect the SO_x and PM emissions factors, that information can be used to produce yearly EFs for these top-down calculations, as shown in Table 34 and Table 35. The fuel statistics used are aggregated for fuel use in all engine types (main engine, boiler and auxiliary). These emissions factors are therefore not machinery-type-specific but an aggregate for fuel use in all engine types with the preliminary working assumption that representative EFs can be derived from main engines only.

Table 34 – *Emissions factors for top-down emissions from combustion of fuels*

Emissions substance	Marine HFO emissions factor (g/g fuel)	Marine MDO emissions factor (g/g fuel)	Marine LNG emissions factor (g/g fuel)
CO_2	3.11400	3.20600	2.75000
CH_4	0.00006	0.00006	0.05120
N_2O	0.00016	0.00015	0.00011
NO_x	0.09300	0.08725	0.00783
CO	0.00277	0.00277	0.00783
NMVOC	0.00308	0.00308	0.00301

Table 35 – *Year-specific emissions factors for sulphur-dependent emissions (SO_x and PM)*

% Sulphur content averages – wt IMO[1]						
Fuel type	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Average non-ECA HFO S%	2.42	2.37	2.6	2.61	2.65	2.51
SO_x EF (g/g fuel)						
Marine fuel oil (HFO)	0.04749	0.04644	0.05066	0.05119	0.05171	0.04908
Marine gas oil (MDO)	0.00264	0.00264	0.00264	0.00264	0.00264	0.00264
Natural gas (LNG)	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002
PM EF (g/g fuel)						
Marine fuel oil (HFO)	0.00684	0.00677	0.00713	0.00713	0.00721	0.00699
Marine gas oil (MDO)	0.00102	0.00102	0.00102	0.00102	0.00102	0.00102
Natural gas (LNG)	0.00018	0.00018	0.00018	0.00018	0.00018	0.00018

[1] Source: MEPC annual reports on Sulphur Monitoring Programme.

All emissions factors are in mass of emissions per unit mass of fuel and the data compiled in Section 1.1 are in units of mass of fuel, so for oil-based fuels the production of the total emissions is a straightforward multiplication. Further work is needed to compile the gas fuel emissions factors and the method for emissions calculation (the units for gas fuel use are mass of oil equivalent).

2.1.2 Methane slip

Some of the fuel used in gas engines is emitted unburned to the atmosphere. This feature is specific to LNG marine engines running on LNG with low engine loads. A new generation of gas engines, based on the Otto cycle (spark-ignited, lean-burn engines), is reported to reduce methane slip significantly with improvements made to cylinder, cylinder head and valve systems. In this study, methane slip is included in the combustion EF for CH_4 in LNG-fuelled engines. However, for the top-down analysis it was not feasible to estimate the energy usage (kWh) for the global LNG fleet.

2.1.3 Method for estimation for non-combustion emissions

Refrigerants, halogenated hydrocarbons

Refrigerants are used on board vessels for air conditioning and provisional and cargo cooling purposes. The ozone-depleting substances (HCFCs and CFCs) have been replaced with other refrigerants, like HFCs 1,1,1,2-tetrafluoroethane (R134a) and a mixture of pentafluoroethane, trifluoroethane and tetrafluoroethane (R404a). All these refrigerants, including the replacements for ozone-depleting substances, have significant GWP. The GWP is reported as CO_2 equivalent (CO_2e): this describes the equivalent amount of CO_2 that would be needed to achieve the same warming effect. The numerical values of GWP for different substances used in this study were taken from the IPCC Fourth Assessment Report and are based on the latest IPCC estimate of CO_2 concentration in the atmosphere.

This part of the report builds on the findings of two others: the United Nations Environmental Programme (UNEP) *2010 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee* and the European Commission (DG Environment) 2007 report *The analysis of the emissions of fluorinated greenhouse gases from refrigeration and air conditioning equipment used in the transport sector other than road transport and options for reducing these emissions – Maritime, Rail, and Aircraft Sector.*

Other refrigerants, SF_6

Sulphur hexafluoride (SF_6) is a colourless, odourless, non-toxic, non-flammable gas that has a high dielectric strength. It has been used as a dielectric in microwave frequencies, as an insulating medium for the power supplies of high-voltage machines and in some military applications, for example as a torpedo propellant. Sulphur hexafluoride is also gaining use in non-electrical applications, including blanketing of molten magnesium (molten magnesium will oxidize violently in air), leak detection and plasma etching in the semi-conductor industry. Sulphur hexafluoride also has some limited medical applications. SF_6 is extensively used as a gaseous dielectric in various kinds of electrical power equipment, such as switchgear, transformers, condensers and medium- to high-voltage (>1 kV) circuit breakers (Compressed Gas Association, 1990). In circuit breakers, SF_6 is typically used in a sealed pressurized chamber to prevent electrical arcing between conductors.

According to World Bank data (2010), global SF_6 emissions were 22,800 thousand tonnes CO_2e, which corresponds to 463 tons (i.e. short tons, as per key definition of "ton") of SF_6 emitted from all sectors. (According to UNFCCC, SF_6 has a GWP of 23,900.) The use of SF_6 in electrical switchgear in general (all land, air and sea installations) is primarily (90%) concentrated on the high-voltage segment (>36 kV) and the remaining 10% for the medium (1 kV–36 kV) voltage segment (Schneider 2003). Ships rarely use electrical systems over 11 kV and typical nominal voltages are in the 1 kV–11 kV range (Ackermann and Planitz, 2009). The leaks from sealed systems are small: EPA (2006) estimates a range of 0.2%–2.5% per year. However, the mass of SF_6 on board the global fleet is unknown, which prohibits detailed analysis of SF_6 emissions from shipping.

If this 90%/10% division is assumed, which represents SF_6 use in high/medium voltage systems, and also applies to emissions, medium-voltage systems would be responsible for 46.3 tons of SF_6 emitted annually. If all medium-voltage systems were installed in ships (i.e. no medium-voltage installations on land), the maximum contribution to total GHG emissions from shipping would be 1.1 million tons (46.3 tons × 22,800 CO_2e/ton) of CO_2e (IPCC, 2007), which is less than 0.1% of the total CO_2 emissions from shipping in 2010. The actual emissions of SF_6 are likely to be less than this, because alternative solutions (vacuum, CO_2) are also available in arc quenching. Because SF_6 emissions from ships are negligible, they are not considered further in this report.

Other refrigerants, PFCs

Several binary and ternary blends of various HFC, HCFC, PFC and hydrocarbon refrigerants have been developed to address continuing service demand for CFC-12. These blends are tailored to have physical and thermodynamic properties comparable to the requirements of the original CFC-12 refrigerant charge.

HFCs were used to replace halon-based systems in the mid 1990s. A small quantity of PFC (mainly C_4F_{10}) was imported by a US company into the EU to be used as an alternative fluid in firefighting fixed systems. The main application of these PFC-based fixed systems is for fire protection by flooding closed rooms (e.g. control rooms) with halon to replace oxygen. Imports for new systems stopped in 1999, as this application of PFCs was not regarded as an essential use (AEA, 2010). The electronics and metal industry is a large consumer of PFC compounds, which are used as etching agents during manufacturing (IPCC/TEAP, 2005). The main PFC used as a refrigerant is octafluoropropane (C_3F_8), which is a component of the R-413a refrigerant (Danish EPA, 2003). The composition of R-413a is 88% R134a, 9% C_3F_8 and 3% isobutane and it is used in automotive air conditioning (Danish EPA, 2003). Another refrigerant with C_3F_8 is Isceon 89, a mixture of 86% HFC-125, 9% C_3F_8 and 5% propane. Isceon 89 is used for deep-freezing purposes (−40°C to −70°C), like freeze-dryers, medical freezers and environmental chambers (DuPont, 2005).

The annual leakage of all refrigerants from cooling equipment of reefer and fishing vessels is estimated at 2,200 tons. The extreme worst-case estimate assumes that all this is Isceon 89, which contains 9% of C_3F_8. This would total 201 tons of C_3F_8 and correspond to (8,830 CO_2e/ton × 201 tons) 1.8 million tons of CO_2e, which is about 0.2% of the total CO_2 emitted from ships in 2010. The emissions of C_3F_8 from ships are likely to be smaller than this value because the need for extreme cooling is limited; only some reefer cargo ships and fishing vessels may need this temperature range. Because PFC emissions from ships are likely to be negligible, they are not considered further in this report.

Method used in this study

In this study the use of ozone-depleting R-22 has been restricted to vessels built before 2000. The amounts of refrigerant used in various types of ship for air conditioning of passenger areas and provision of refrigeration (galley, cargo) are described in Table 36.

Table 36 – *Amounts of refrigerants carried by various types of ships (from DG ENV report)*

Ship type	kg/AC	kg/refr	% vessels built after 1999
Bulk carrier	150	10	59%
Chemical tanker	150	10	63%
Container	150	10	59%
Cruise	6,000	400	37%
Ferry – pax only	500	20	23%
Ferry – ro-pax	500	20	27%
General cargo	150	10	27%
Liquefied gas tanker	150	10	53%
Miscellaneous –fishing	150	210**	15%
Miscellaneous – other	150	10	32%
Offshore	150	10	56%
Oil tanker	150	10	45%
Other liquids tankers	150	10	45%
Refrigerated bulk	150	2,500*	7%
Ro-ro	500	20	26%
Service – tug	150	10	45%
Service – other	150	10	32%
Vehicle	150	10	57%
Yacht	150	10	66%
Total, tons in global fleet	21,917 tons	8,569 tons	

* Vessels using cargo cooling are assigned 2,500 kg refrigerant charge, which is an average of the range (1,000 kg–5,000 kg) indicated in the DG ENV report.

** Refrigerant carried by fishing vessels has been calculated as a weighted average of 7,970 fishing vessels described in DG ENV report.

In addition to the vessels, there are 1.7 million refrigerated containers, each of which carries approximately 6 kg of refrigerant (80% R134a, 20% R-22) (DG ENV, 2007).

Refrigerants used in the calculation are assumed as R-22 for both air conditioning and cooling for vessels built before 2000. For newer vessels, R134a is assumed for air conditioning and R404a for provisional cooling purposes. Refrigerant loss of 40% is assumed for all ships, except for passenger vessels for which 20% annual loss of refrigerants is assumed.

Fishing vessels and reefer ships

In Table 36, two distinctions between the existing reports (UNEP, DG ENV) are made. First, the refrigerant charge carried by the world fishing fleet ("Miscellaneous – fishing") was based on the DG ENV report, which describes the use of refrigerants on board the European fishing fleet. In this study, the weighted average (number of vessels, refrigerant charge carried) of the European fishing fleet (approximately 8,000 vessels) was used to estimate the air conditioning and cooling needs of the global fishing fleet. The composition of the EU fishing fleet is likely to be different from the global fleet, and this will be reflected in the estimates of the refrigerant emissions of the global fishing fleet. The second difference concerns reefer ships. According to both existing reports (UNEP, DG ENV), the reefer fleet carries 1 ton–5 tons of refrigerants per ship for cargo cooling. This study takes the average (2.5 tons of refrigerants) and assumes R-22 to be used in vessels built before 2000 (DG ENV, 2007).

Reefer containers

Refrigerants can also be found in the cooling systems of reefer containers, which are used to provide a controlled environment for perishable goods, like fruit, during cargo transport. The fleet of dedicated refrigerated cargo-carrying vessels has decreased over the years and is slowly being replaced by container ships carrying reefer containers. According to the DG ENV report (2007), each reefer container carries 6 kg refrigerant charge, of which 15% is lost annually. The number of refrigerated containers has been estimated in the DG ENV report (2006 figure) as 1.6 million TEU. In this study the number of refrigerated containers for 2012 was based on the projected number of reefer plugs of the world container fleet (1.7 million TEU). The reefer container count was based on the IHS Fairplay data for 5,400 container ships (1.7 million TEU). The projection has some inherent uncertainty, because reefer plug installations (rather than reefer TEU counts) have been used. Also, the completeness of the container ship fleet in the data set used to determine the reefer plug count is likely to have some impact on the reefer TEU numbers, because this data set consists of some 85,000 vessels and so does not cover the complete global fleet.

Estimated emissions of refrigerants from ships

Both the UNEP and DG ENV reports use the 100 gt limit to indicate a vessel that has refrigerants on board. This assumption was based on expert judgements on vessels that operate in a variety of climate conditions and need air conditioning.

In this study, the fleet-wide assessment is made according to the vessel construction year (before 2000, constructed that year or later) and refrigerant type is assigned on the basis of the vessels' age. For old vessels, HCFCs (R-22) were assumed, while new vessels use HFCs (R134a/R404a).

The estimated annual total of refrigerant loss in the global fleet in 2012 is described in Table 37.

Table 37 – *Annual loss of refrigerants from the global fleet during 2012. Annual release of 40% total refrigerant carried is assumed except for passenger-class vessels, where 20% refrigerant loss is assumed. Ro-ro, pax, ro-pax and cruise vessels are calculated as passenger ships*

Ship type	Annual loss, air conditioning, tons	Annual loss, cooling, tons	R-22, tons	R134a, tons	R404, tons
Bulk carrier	466.9	31.1	195.7	275.4	14.6
Chemical tanker	221.7	14.8	83.6	140.0	6.7
Container	230.5	15.4	96.4	136.2	7.2
Cruise	622.8	41.5	407.9	228.1	20.8
Ferry – pax only	313.9	12.6	245.9	72.8	6.3
Ferry – ro-pax	285.6	11.4	211.8	78.0	5.7
General cargo	740.0	49.3	555.2	196.9	28.5
Liquefied gas tanker	72.4	4.8	35.1	38.1	2.4
Miscellaneous – fishing	1,000.3	1,421.1	1,259.8	145.4	878.6
Miscellaneous – other	261.0	17.4	180.9	84.0	9.7
Offshore	309.2	20.6	138.2	174.0	9.9
Oil tanker	332.1	22.1	186.0	150.1	11.4
Other liquids tankers	6.7	0.4	3.8	3.0	0.2
Refrigerated bulk	48.7	812.3	297.5	3.4	522.9
Ro-ro	173.9	7.0	130.7	45.7	3.5
Service – tug	657.5	43.8	372.9	292.7	22.7
Service – other	26.1	1.7	18.1	8.4	1.0
Vehicle	37.5	2.5	16.6	21.3	1.2
Yacht	70.2	4.7	24.2	46.6	2.1
Total, tons	5,877.1	2,534.6	4,460.1	2,140.2	1,555.4

The estimated reefer TEU count globally is 1.7 million TEU, which would result in 10,070 tons of refrigerant charge and 1,510 tons of refrigerant release in 2012. This means an additional 1,208 tons of R134a and 302 tons of R404 on top of the values in Table 37, if the 80:20 ratio of the DG ENV (2007) report is used.

There is large uncertainty about the leakage rate of refrigerants from ships. A range of 20%–40% is reported by both UNEP and DG ENV, attributed to the permanent exposure of refrigerated systems to continuous motion (waves), which can cause damage and leakage to piping (DG ENV). The average estimate, using a 30% leakage rate, is described in Table 37 and amounts to 8,412 tons. The corresponding values for low- and high-bound estimates are 5,967 tons and 10,726 tons respectively. In the 2010 UNEP report, the annual loss of refrigerants is reported as 7,850 tons, which is close to the estimate of this study. If the refrigerant emissions from reefer containers are included, then an additional 1,510 tons (80% R134a, 20% R404a) should be added to these numbers.

Global warming potential of refrigerant emission from ships

According to the results of this study, the share of R-22 is 70%, R134a 26% and R404a 4%. The balance of refrigerant shares will shift towards R134a when old vessels using R-22 as a cooling agent are replaced with new ships using HFCs (R134a). The use of R-22 in industrial refrigeration in developed countries is on the decline because it is banned in new refrigerating units. However, the Montreal Protocol has determined that it can be used until 2040 in developing countries.

Table 38 – *Global warming potential of refrigerants commonly used in ships. The GWP100 is described relative to CO_2 warming potential (IPCC Fourth Assessment Report: Climate Change 2007)*

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

The release of refrigerants from global shipping is estimated at 8,412 tons, which corresponds to 15 million tons (range 10.8 million tons–19.1 million tons) in CO_2e emissions. Inclusion of reefer container refrigerant emissions yields 13.5 million tons (low) and 21.8 million tons (high) of CO_2e emissions. If these numbers are compared to CO_2 emissions of shipping during 2011 (top-down estimate of 794 million tons of CO_2), refrigerant emissions constitute about 1.9% of the GHG emissions of shipping. Inclusion of the reefer TEU increases this to 2.2% of the total GHG emissions from shipping.

Refrigerant emissions from ships 2007–2012

The emissions of refrigerants from ships are mainly affected by changes in the size and composition of the global fleet. The methodology used to assess refrigerant emissions is driven by the age structure of each ship type rather than the activity patterns of vessels. This assumption makes the annual emission changes small (Figure 71) but nevertheless consistent with the UNEP report (2010). Also, the dominant substance is R-22 (70% share), which is in line with previous studies (UNEP 2010; DG ENV 2007).

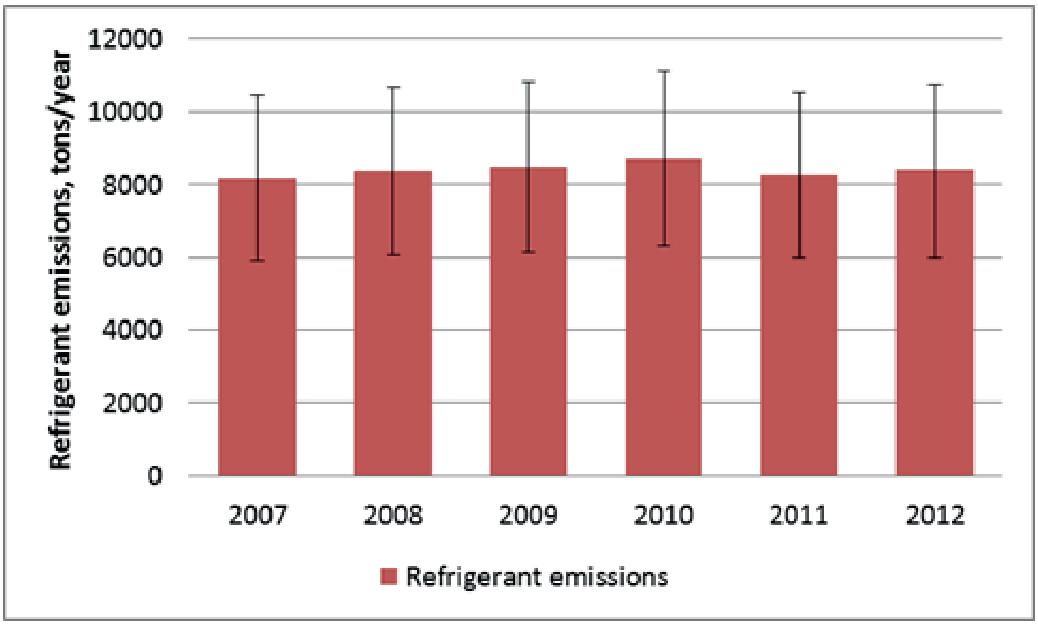


Figure 71: *Estimated refrigerant emissions of the global fleet 2007–2012*

The slow decrease of R-22 share in ship systems (Table 39) means that R-22 will be present for a long time, possibily decades, before it is replaced by other substances.

Table 39 – *Annual emissions of refrigerants from the global fleet and estimated shares of different refrigerants*

Year	Refrigerant emissions, tons, reefer TEU excluded	Low bound, tons	High bound, tons	%, R-22	%, R134a	%, R404
2007	8,185	5,926	10,444	80%	17%	4%
2008	8,349	6,045	10,654	77%	19%	4%
2009	8,484	6,144	10,825	75%	21%	4%
2010	8,709	6,307	11,110	73%	23%	4%
2011	8,235	5,967	10,503	71%	24%	4%
2012	8,412	5,967	10,726	70%	26%	4%
UNEP 2010	7,850					

Non-exhaust emissions of NMVOCs from ships

The reported global crude oil transport in 2012 was 1,929 million tons (UNCTAD *Review of Maritime Transport 2013*). This study applies the same methodology as the Second IMO GHG Study 2009 and uses the net standard volume (= NSV at bill of lading – NSV at out-turn) loss of 0.177%. This corresponds to 0.124% mass loss and results in VOC emissions of 2.4 million tons, which is very close to the value of the 2009 study figures for 2006 (crude oil transport 1,941 million tons, VOC emissions 2.4 million tons).

2.2 Bottom-up other relevant substances emissions calculation method

2.2.1 Method

Three primary emission sources are found on ships: main engine(s), auxiliary engines and boilers. The consortium studied emissions from main and auxiliary engines as well as boilers in this report. Emissions from other energy-consuming sources were omitted because of their small overall contribution. Emissions from non-combustion sources, such as HFCs, are estimated consistent with the Second IMO GHG Study 2009 methods.

2.2.2 Main engine(s)

Emissions from the main engine(s) or propulsion engine(s) (both in terms of magnitude and emissions factor) vary as a function of main engine rated power output, load factor and the engine build year. The main engine power output and load factor vary over time as a result of a ship's operation and activity specifics: operational mode (e.g. at berth, anchoring, manoeuvring), speed, loading condition, weather, etc. Emissions are also specific to a ship, as individual ships have varying machinery and activity specifications. The bottom-up model described in Section 1.2 calculates these specifics (main engine power output and load factor) for each individual ship in the global fleet and for activity over the year disaggregated to an hourly basis. This same model is therefore used for the calculations of the other main engine emissions substances.

2.2.3 Auxiliary engines

Emissions from auxiliary engines (both in terms of magnitude and emissions factor) vary as a function of auxiliary power demand (typically changing by vessel operation mode), auxiliary engine rated power output, load factor and the engine build year. Technical and operational data about auxiliary engines are often missing from commercial databases, especially for older ships (constructed before 2000). Technical data (power rating, stroke, model number, etc.) for auxiliary engines of new vessels can be found much more frequently than for those of old vessels; however, these form a very small percentage of the entire fleet. There are typically two or more auxiliary engines on a ship and the number and power rating (not necessarily the same for all engines on a ship) of each engine is determined by the ship owner's design criteria. This means that the actual operation of the specific auxiliary engines, by vessel type and operational mode, can vary significantly from ship to ship. There are no commercial databases that provide these operational profiles on the basis of operational mode or vessel class. This lack of data will hinder the determination of auxiliary engine power estimation using predetermined auxiliary engine load levels. For this reason, the approach taken in this study is based on the vessel surveys conducted by Starcrest for various ports in North America. These surveys allow the determination of auxiliary engine power requirements or total auxiliary loads in various operating modes of vessels. Further information relating to the approaches used to estimate auxiliary engine loads are provided in Section 1.2.5 and Annex 1. A detailed explanation of auxiliary engine power prediction can be found in Starcrest (2013).

2.2.4 Boilers

Emissions from auxiliary boilers vary based on vessel class and operational mode. For example, tankers typically have large steam plants powered by large boilers that supply steam to the cargo pumps and in some cases heat cargoes. For most non-tanker class vessels, boilers are used to supply hot water to keep the main engine(s) warm (during at-berth or anchorage calls) and for crew and other ancillary needs. These boilers are typically smaller and are not used during open-ocean operations because of the waste heat recovery systems (i.e. economizers) that take the waste head from the main engine(s). Unlike main and auxiliary engines, the emissions factors do not change, as there are no regulatory frameworks associated with boilers. Of the three emission source types, boilers typically have significantly fewer emissions than main and auxiliary engines. Further details about auxiliary boilers are provided in Section 1.2.5 and Annex 1.

2.2.5 Operating modes

The auxiliary engine use profiles have been specifically defined for each ship type and size class. Furthermore, auxiliary engine use varies according to vessel operating modes, which are defined by vessel speed ranges. The modes used in this study are defined in Table 40. Auxiliary engine use during harbour visits is divided into two modes: "at berth" describes the auxiliary engine use during cargo loading or unloading operations and "anchoring" involves extended waiting periods when cargo operations do not take place.

Table 40 – *Vessel operating modes used in this study*

Speed	**Mode**
Less than 1 knot	At berth
1 knot–3 knots	Anchored
Greater than 3 knots and less than 20% MCR	Manoeuvring
Between 20% MCR and 65% MCR	Slow-steaming
Above 65% MCR	Normal cruising

Further details on auxiliary engine and boiler loads, by vessel class and mode, are given in Section 1.2.5 and Annex 1.

2.2.6 Non-combustion emissions

Emissions from non-combustion sources (refrigerants and NMVOCs from oil transport) on board vessels were evaluated with the top-down approach using the fleet-wide methodology described in Section 2.1.3 to maintain consistency with the Second IMO GHG Study 2009. The emissions factors of non-combustion sources have wide variations and the significance to overall GHG emissions is small (less than 3%). It is very unlikely that the bottom-up approach to the modelling of non-combustion sources would change this conclusion.

Methane emissions

Emissions of CH_4 to the atmosphere are associated with LNG-powered vessels and include venting, leakage and methane slip. Venting and leakage related to maritime LNG operations are not included in this report. Methane slip during the combustion process is accounted for in the combustion emissions factors detailed in Section 2.2.7.

NMVOC emissions from non-combustion sources

The NMVOC emissions from crude oil cargo operations and transport have not been included in the bottom-up analysis. An estimate of global NMVOC emissions has been presented in the top-down analysis (see Section 2.1.3).

2.2.7 Combustion emissions factors

Emissions factors are used in conjunction with energy or fuel consumption to estimate emissions and can vary by pollutant, engine type, duty cycle and fuel. Emissions tests are used to develop emissions factors in g/kWh and are converted to fuel-based emissions factors (grams of pollutant per grams of fuel consumed) by dividing by the brake-specific fuel consumption (BSFC) or specific fuel oil consumption (SFOC) corresponding to the test associated with the emissions factors. Pollutant-specific information relating to emissions factors is provided later in this section. Emissions factors vary by: engine type (main, auxiliary, auxiliary boilers); engine rating (SSD, MSD, HSD); whether engines are pre-IMO Tier I or meet IMO Tier I or II requirements; and type of service (duty cycle) in which they operate (propulsion or auxiliary). Emissions factors are adjusted further for fuel type (HFO, MDO, MGO and LNG) and the sulphur content of the fuel being burned. Finally, engine load variability is incorporated into the factors used for estimating emissions. All these variables were taken into account when estimating the bottom-up emissions inventories (2007–2012) using the following methodology:

1. Identify baseline emissions factors with the following hierarchy: IMO emissions factors; if none published, then consortium-recommended emissions factors from other studies that members are using in their published work. Emissions factors come in two groups: energy-based in g pollutant/kWh and fuel-based in g pollutant/g fuel consumed. The baseline fuel for the bottom-up emissions factors is defined as HFO fuel with 2.7% sulphur content.

2. Convert energy-based baseline emissions factors in g pollutant/kWh to fuel-based emissions factors in g pollutant/g fuel consumed, as applicable, using:

$$EF_{\text{baseline}}\ (\text{g pollutant})/(\text{g fuel}) = \frac{EF_{\text{baseline}}\ (\text{g pollutant/kWh})}{SFOC_{\text{baseline}}\ (\text{g fuel/kWh})} \qquad \text{Eq. (1)}$$

   where

   EF_{baseline} = cited emissions factor

   $SFOC_{\text{baseline}}$ = SFOC associated with the cited emissions factor

3. Use FCFs, as applicable, to adjust emissions factors for the specific fuel used by the engine:

$$EF_{\text{actual}}\ (\text{g pollutant})/(\text{g fuel}) = EF_{\text{baseline}}\ (\text{g pollutant})/(\text{g fuel}) \times FCF \qquad \text{Eq. (2)}$$

   Convert to kg pollutant/tonne fuel consumed (for presentation/comparison purposes consistent with Second IMO GHG Study 2009).

4. Adjust EF_{actual} based on variable engine loads using SFOC engine curves and low load adjustment factors to adjust the SFOC.

Emissions factors were developed for the following GHGs and pollutants:

- carbon dioxide (CO_2)
- nitrogen oxides (NO_x)
- sulphur oxides (SO_x)
- particulate matter (PM)
- carbon monoxide (CO)
- methane (CH_4)
- nitrous oxide (N_2O)
- non-methane volatile organic compounds (NMVOC)

An overview of baseline emissions factors, fuel correction factors and adjustments based on variable engine loads and SFOC is provided in the following sections on GHGs and pollutants. For comparison purposes with the Second IMO GHG Study 2009, emissions factors are provided in kg of pollutant per tonne of fuel. Emissions factors in grams of pollutant per gram of fuel and grams of pollutant per kWh or g/kWh along with associated references are provided in Table 22 in Annex 6.

CO_2 baseline

The carbon content of each fuel type is constant and is not affected by engine type, duty cycle or other parameters when looking on the basis of kg CO_2 per tonne fuel. The fuel-based CO_2 emissions factors for main and auxiliary engines at slow, medium and high speeds are based on MEPC 63/23, annex 8, and include:

HFO $EF_{baseline}\ CO_2 = 3{,}114$ kg CO_2/tonne fuel
MDO/MGO $EF_{baseline}\ CO_2 = 3{,}206$ kg CO_2/tonne fuel
LNG $EF_{baseline}\ CO_2 = 2{,}750$ kg CO_2/tonne fuel

It should be noted that CO_2 emissions are also unaffected by the sulphur content of the fuel burned. For further information on specific emissions factors and references, see Annex 6.

NO_x baseline

The NO_x emissions factors for main and auxiliary engines rated at slow, medium and high speeds were assigned according to the IMO NO_x emission Tiers I and II standards as defined in MARPOL Annex VI, regulation 13. Emissions for Tier 0 engines (constructed before 2000) were modelled in accordance with Starcrest (2013). The SFOC corresponding to the energy-based emissions factors was used to convert to fuel-based emissions factors. NO_x $EF_{baseline}$ for boilers (denoted by STM in Table 41) remains the same, as there are no IMO emissions standards that apply to boiler emissions. The emissions factors used in the study are presented in Table 41.

Table 41 – *NO_x baseline emissions factors*

IMO Tier	Eng speed/type	Fuel type	SFOC ME/Aux	ME $EF_{baseline}$ (kg/tonne fuel)	Aux eng $EF_{baseline}$ (kg/tonne fuel)	Reference
0	SSD	HFO	195/na	92.82	na	ENTEC, 2002
	MSD	HFO	215/227	65.12	64.76	ENTEC, 2002
	HSD	HFO	na/227	na	51.10	ENTEC, 2002
1	SSD	HFO	195/na	87.18	na	IMO Tier I
	MSD	HFO	215/227	60.47	57.27	IMO Tier I
	HSD	HFO	na/227	na	45.81	IMO Tier I
2	SSD	HFO	195/na	78.46	na	IMO Tier II
	MSD	HFO	215/227	52.09	49.34	IMO Tier II
	HSD	MDO	na/227	na	36.12	IMO Tier II
all	Otto	LNG	166	7.83	7.83	Kristensen, 2012
na	GT	HFO	305	20.00	na	IVL, 2004
na	STM	HFO	305	6.89	na	IVL, 2004

Notes: GT – gas turbine; STM – steam boiler

Fuel consumption efficency improvements associated with Tier I and II engines is taken into account and further explained in the SFOC variability with load section below.

It should be noted that NO_x emissions are not affected by fuel sulphur content but do change slightly between HFO and distillate fuels. For further information on specific emissions factors, FCFs and references, see Annex 6.

SO_x baseline

For all three ship emissions sources, SO_x emissions are directly linked to the sulphur content of the fuel consumed. For emission estimating purposes, the typical fuel types (based on ISO 8217 definitions) include:

- heavy fuel oil (HFO)/intermediate fuel oil (IFO);
- marine diesel oil (MDO)/marine gas oil (MGO);
- liquefied natural gas (LNG).

The SO_x $EF_{baseline}$ factors are based on the percentage sulphur content of the fuel, with 97.54% of the fuel sulphur fraction converted to SO_x (IVL 2004), while the remaining fraction is emitted as a PM sulphate component. Therefore, SO_x and PM emissions are directly tied to the sulphur content of the fuel consumed.

This study used the following SO_x $EF_{baseline}$ factors, based on HFO with 2.7% sulphur content. The $EF_{baseline}$ factors for SO_x are presented in Table 42. It should be noted that SO_x and SO_2 are basically interchangeable for marine-related engine emissions.

Table 42 – *SO_x baseline emissions factors*

Eng speed/type	Fuel[1] type	ME $EF_{baseline}$ (kg/tonne fuel)	Aux eng $EF_{baseline}$ (kg/tonne fuel)	Reference
SSD	HFO	52.77	na	Mass balance[2]
MSD	HFO	52.79	52.78	Mass balance[2]
HSD	HFO	na	52.78	Mass balance[2]
Otto	LNG	0.02	0.02	Kunz & Gorse, 2013
GT	HFO	52.79	na	Mass balance[2]
STM	HFO	52.79	na	Mass balance[2]

Notes: [1] assumes HFO fuel with 2.7% sulphur content
[2] assumes 97.54% of sulphur fraction is converted to SO_x; remainder is converted to PM SO_4

These baseline emissions factors are adjusted using FCF to account for the changing annual fuel sulphur content world averages (2007–2012) or as required regionally within an ECA. The global sulphur content of marine fuel oils was modelled according to IMO global sulphur fuel oil monitoring reports, as presented in Table 43. For regional variations driven by regulation (ECAs), the fuel sulphur content is assumed to be equivalent to the minimum regulatory requirement (see the description in Section 1.2 on how the shipping activity is attributed to different global regions). Further regional variations of fuel sulphur content were not taken into account owing to the complexity associated with points of purchase of fuel and where and when it is actually burned. It is assumed that the world average is representative across the world fleet for each year.

Table 43 – *Annual fuel oil sulphur worldwide averages*

Fuel type	2007	2008	2009	2010	2011	2012
HFO/IFO	2.42	2.37	2.6	2.61	2.65	2.51
MDO/MGO	0.15	0.15	0.15	0.15	0.14	0.14

For further information on specific emissions factors, FCFs and references, see Annex 6.

PM baseline

The current literature contains a rather large variation of PM emissions factors, which vary significantly between studies because of differences in methodology, sampling and analysis techniques. The United States Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) evaluated the available PM test data and determined that along with direct PM there is secondary PM associated with the sulphur in fuel (2.46% fuel sulphur fraction is converted to secondary PM while the remainder is emitted as SO_x, as discussed previously). This study used the following PM $EF_{baseline}$ factors based on 2.7% sulphur content HFO. The $EF_{baseline}$ factors for PM are presented in Table 44. It should be noted there is virtually no difference between total PM and PM less than 10 microns or PM_{10} for diesel-based fuels.

Table 44 – *PM baseline emissions factors*

Eng speed/type	Fuel[1] type	ME $EF_{baseline}$ (kg/tonne fuel)	Aux eng $EF_{baseline}$ (kg/tonne fuel)	Reference
SSD	HFO	7.28	na	EPA, 2007
MSD	HFO	6.65	6.34	EPA, 2007
HSD	HFO	na	6.34	EPA, 2007
Otto	LNG	0.18	0.18	Kristensen, 2012
GT	HFO	0.20	na	IVL, 2004
STM	HFO	3.05	na	IVL, 2004

Notes: [1] assumes HFO fuel with 2.7% sulphur content

The approach taken in this study is compatible with the Second IMO GHG Study 2009, which defined PM as substances including sulphate, water associated with sulphate ash and organic carbons, measured by dilution method. Therefore, the model can accommodate changes in fuel sulphur content. This reflects the changes in PM emissions factors arising from ECAs as defined in MARPOL Annex VI.

For further information on specific emissions factors, FCFs and references, see Annex 6.

CO baseline

Emissions of carbon monoxide (CO) were determined by methods originally described in Sarvi et al. (2008), Kristensen (2012) and IVL (2004). From these sources, the CO $EF_{baseline}$ factors presented in Table 45 were used.

Table 45 – *CO baseline emissions factors*

Eng speed/type	**Fuel type**	**ME $EF_{baseline}$ (kg/tonne fuel)**	**Aux eng $EF_{baseline}$ (kg/tonne fuel)**	**Reference**
SSD	HFO	2.77	na	EPA, 2007
MSD	HFO	2.51	2.38	EPA, 2007
HSD	HFO	na	2.38	EPA, 2007
Otto	LNG	7.83	7.83	Kristensen, 2012
GT	HFO	0.33	na	IVL, 2004
STM	HFO	0.66	na	IVL, 2004

It should be noted that CO emissions are also unaffected by the sulphur content of the fuel burned and are the same for HFO and distillates. For further information on specific emissions factors and references, see Annex 6.

CH_4 baseline

Emissions of methane (CH_4) were determined by analysis of test results reported in IVL (2004) and MARINTEK (2010). Methane emissions factors for diesel-fuelled engines, steam boilers and gas turbines are taken from IVL (2004), which states that CH_4 emissions are approximately 2% magnitude of VOC. Therefore, the $EF_{baseline}$ is derived by multiplying the NMVOC $EF_{baseline}$ by 2%. The emissions factor for LNG Otto-cycle engines is 8.5g/kWh, which is on a par with the data for LNG engines (MARINTEK, 2010 and 2014). However, this value may be slightly low for older gas-fuelled engines, especially if run on low engine loads, and slightly high for the latest generation of LNG engines (Wärtsilä, 2011). This emissions factor was used in the bottom-up approach to determine the amount of methane released to the atmosphere from each of the vessels powered by LNG. The majority of LNG-powered engines operating during the 2007–2012 time frame are assumed to be Otto-cycle; all LNG engines have been modelled as low-pressure, spark injection Otto-cycle engines, which have low NO_x emissions. From these sources, the CH_4 $EF_{baseline}$ factors presented in Table 46 were used.

Table 46 – *CH_4 baseline emissions factors*

Eng speed/type	**Fuel type**	**ME $EF_{baseline}$ (kg/tonne fuel)**	**Aux eng $EF_{baseline}$ (kg/tonne fuel)**	**Reference**
SSD	HFO	0.06	na	IVL, 2004
MSD	HFO	0.05	0.04	IVL, 2004
HSD	HFO	na	0.04	IVL, 2004
Otto	LNG	51.2	51.2	MARINTEK, 2010
GT	HFO	0.01	na	IVL, 2004
STM	HFO	0.01	na	IVL, 2004

It should be noted that CH_4 emissions are also unaffected by the sulphur content of the fuel burned and are the same for HFO and distillates. For further information on specific emissions factors and references, see Annex 6.

N_2O baseline

Emissions factors for N_2O and LNG were taken from the EPA 2014 report on GHGs and Kunz & Gorse (2013), respectively. The LNG N_2O $EF_{baseline}$ was converted from g/mmBTU to g/kWh assuming 38% engine efficiency, and then converted to grams of N_2O per gram of fuel using an SFOC of 166g fuel/kWh. From these sources, the N_2O $EF_{baseline}$ factors presented in Table 47 were used.

Table 47 – *N_2O baseline emissions factors*

Eng speed/type	Fuel type	ME $EF_{baseline}$ (kg/tonne fuel)	Aux eng $EF_{baseline}$ (kg/tonne fuel)	Reference
SSD	HFO	0.16	na	EPA, 2014
MSD	HFO	0.16	0.16	EPA, 2014
HSD	HFO	na	0.16	EPA, 2014
Otto	LNG	0.11	0.11	Kunz & Gorse, 2013
GT	HFO	0.16	na	EPA, 2014
STM	HFO	0.16	na	EPA, 2014

It should be noted that, similar to NO_x, N_2O emissions are unaffected by fuel sulphur content but do change slightly between HFO and distillate fuels. For further information on specific emissions factors, FCFs and references, see Annex 6.

NMVOC baseline

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 emissions factor was conservatively assumed to be the same as the hydrocarbon emissions factor. From these sources, the NMVOC $EF_{baseline}$ factors presented in Table 48 were used for this study. It should be noted that NMVOCs and non-methane hydrocarbons have the same emissions factors.

Table 48 – *NMVOC baseline emissions factors*

Eng speed/type	Fuel type	ME $EF_{baseline}$ (kg/tonne fuel)	Aux eng $EF_{baseline}$ (kg/tonne fuel)	Reference
SSD	HFO	3.08	na	ENTEC, 2002
MSD	HFO	2.33	1.76	ENTEC, 2002
HSD	HFO	na	1.76	ENTEC, 2002
Otto	LNG	3.01	3.01	Kristensen, 2012
GT	HFO	0.33	na	ENTEC, 2002
STM	HFO	0.33	na	ENTEC, 2002

NMVOC emissions are also unaffected by the sulphur content of the fuel burned and are the same for HFO and distillates. For further information on specific emissions factors and references, see Annex 6.

SFOC variability with load

Marine diesel engines have been optimized to work within a designated load range, in which fuel economy and engine emissions are balanced. Optimizing for fuel economy will lead to higher NO_x emissions and vice versa; MARPOL Annex VI NO_x emission Tiers thus indirectly regulate the specific fuel oil consumption (SFOC) range of the engine. Using an MDO outside the optimum load range (usually 85%–100% MCR) will lead to higher specific fuel oil consumption per power unit (g/kWh) unless the electronic engine control unit can adjust the engine accordingly (valve timing, fuel injection). This is possible to achieve with modern smart engine control units by changing the engine control programming, but for older mechanical set-ups greater effort may be required from the engine manufacturer. For slow steaming purposes, the optimum working load range of a diesel engine can be adjusted to be lower than the default load range.

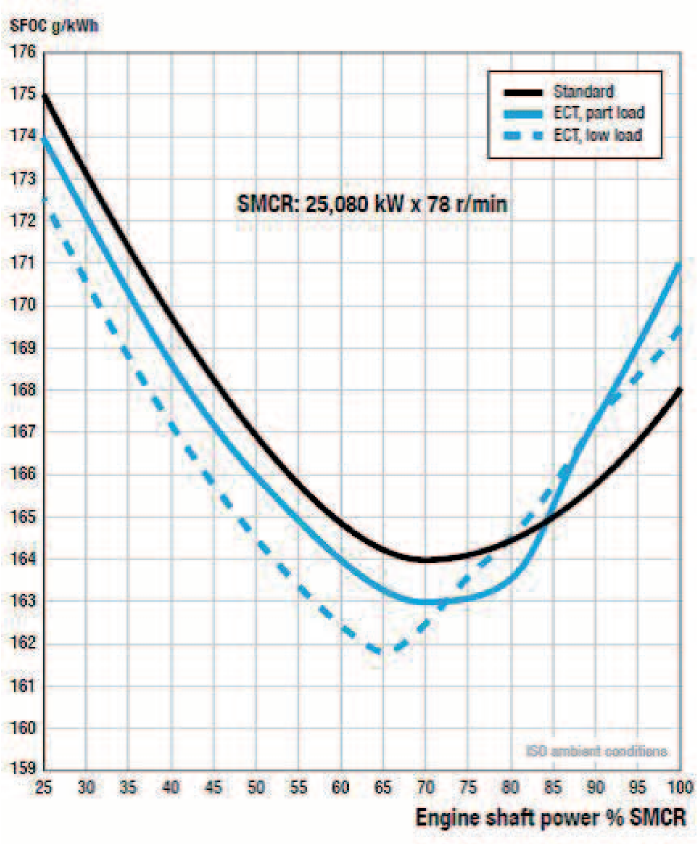


Figure 72: *Impact of engine control tuning (ECT) to specific fuel oil consumption during low load operation of MAN 6S80ME-C8.2. Standard tuning is shown by the solid black line, part load optimization by the solid blue line and low load tuning by the broken line (from MAN, 2012)*

The changes in specific fuel oil consumption (SFOC) for a specified maximum continuous rating (SMCR) of a large two-stroke engine are illustrated in Figure 72. It is possible to achieve a lower optimum load range for the purpose of slow steaming, but this will make the engine less efficient in the high load range.

SFOC assumptions used in this study for marine diesel engines

Engines are classified as SSD, MSD and HSD and assigned SFOC or BSFC in accordance with the Second IMO GHG Study 2009.

Table 49 – *Specific fuel oil consumption of marine diesel engines (ll values in g/kWh)*

Engine age	**SSD**	**MSD**	**HSD**
before 1983	205	215	225
1984–2000	185	195	205
post 2001	175	185	195

Table 49 gives the values used in this study. Main engines are typically SSD and MSD while auxiliary engines are typically MSD and HSD. The SFOC data for turbine machinery, boilers and auxiliary engines are listed in Table 50.

Table 50 – *Specific fuel oil consumption ($SFOC_{baseline}$) of gas turbines, boiler and auxiliary engines used in this study as the basis to estimate dependency of SFOC as a function of load. Unit is grams of fuel used per power unit (g/kWh) (IVL, 2004)*

Engine type	HFO	MDO/MGO	HSD
Gas turbine	305	300	225
Steam boiler	305	300	205
Auxiliary engine	225	225	195

The values in Table 49 and Table 50 represent the lowest point in the SFOC/load curve illustrated in Figure 72. In this study each MDO engine is assumed to maintain a parabolic dependency on engine load, which has been applied to SSD/MSD/HSD engines. This approach is described further in Jalkanen et al. (2012). The changes of SFOC as a function of engine load are computed using the base values in Table 49 and a parabolic representation of changes over the whole engine load range.

$$\mathrm{SFOC(load)} = \mathrm{SFOC}_{base} \times (0.455 \times \mathrm{load}^2 - 0.71 \times \mathrm{load} + 1.28) \qquad \text{Eq. (3)}$$

In equation (3), engine load range (0–1) adjusts the base value of SFOC and describes the SFOC as a function of the engine load. This provides a mechanism that will increase SFOC on low engine loads (see Table 49) and allow the energy-based (grams of emissions per grams of fuel) and power-based (grams of emissions per kWh used) emissions factors to be linked. Different curves are used for SSD, MSD and HSD, depending on the values in Table 49, but all diesel engines use identical load dependency across the whole load range (0–100%) in this study. The default engine tuning is assumed (SFOC lowest at 80% engine load) for all diesel engines because it was not possible to determine the low load optimizations from the IHS Fairplay data.

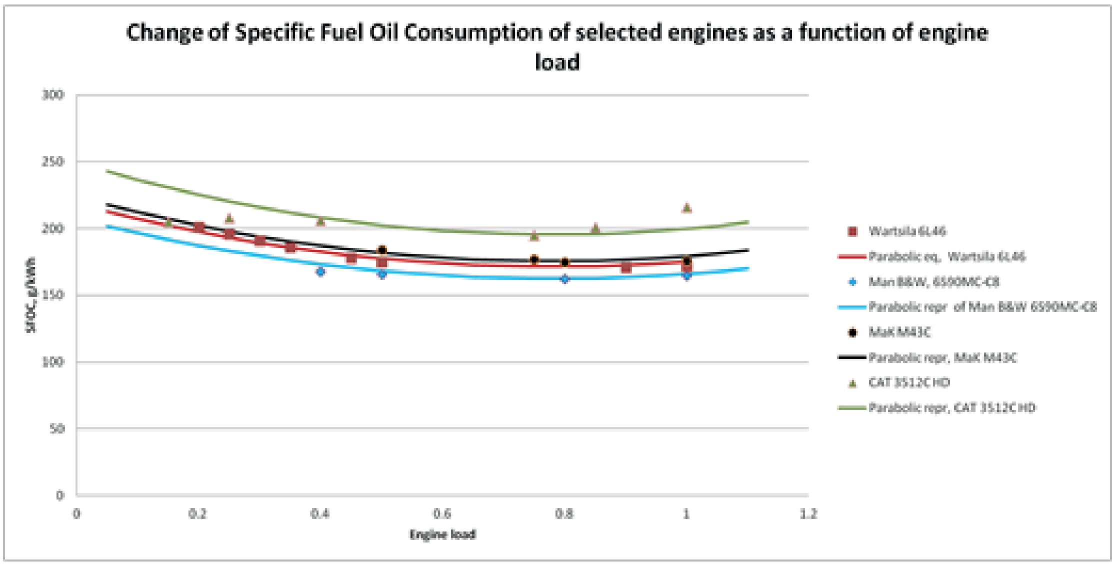


Figure 73: *Impact of engine load on brake-specific fuel consumption of various selected SSD, MSD and HSD engines (emissions factors by engine type)*

Figure 73 illustrates the change of SFOC as a function of engine load for a large two-stroke engine (31,620 kW, MAN 6S90MC-C8), two medium-size four-stroke engines (6,000 kW, Wärtsilä 6L46; 6,000 kW, MaK M43C) and a small four-stroke engine (1,700 kW, CAT 3512C HD). The methodology used in this study allows SFOC changes of approximately 28% above the optimum engine load range.

Load dependency of SFOC in the case of a gas turbine

There is only a limited amount of information available about the load dependency and fuel economy of gas turbines. In this study, gas turbine SFOC load dependency was not modelled.

SFOC of auxiliary boilers

In this study, a constant value of 305 g/kWh SFOC was used for auxiliary boilers.

SFOC of auxiliary engines

A constant value for auxiliary engine SFOC was used (indicated in Table 50). The load/SFOC dependency was not used for auxiliary engines, because the engine load of operational auxiliary engines is usually adjusted by switching multiple engines on or off. The optimum working range of auxiliary engines is thus maintained by the crew and it is not expected to have large variability, in contrast to the main engine load.

CO_2

The power-based CO_2 emissions factors for main, auxiliary and boiler engines at slow, medium and high speeds were taken from either ENTEC (2002) or IVL (2004) and were converted to mass-based factors using the corresponding SFOC.

NO_x

The NO_x emissions factors for main and auxiliary engines at slow, medium and high speeds were assigned according to the three IMO NO_x emission Tiers defined in MARPOL Annex VI. Emissions for Tier 0 engines (constructed before 2000) were modelled in accordance with Starcrest (2013). This approach will give an energy-based emissions factor as a function of engine RPM. The SFOC corresponding to the energy-based emissions factor provided a link between the energy- and fuel-based emissions factors. NO_x EF for boilers remains the same, as there are no emissions standards that apply to boiler emissions.

SO_x

For all three emissions sources, SO_x emissions are directly linked to the sulphur content of the fuel consumed. For emissions estimating purposes, the typical fuel types (based on ISO 8217 definitions) include HFO, IFO, MDO and MGO.

The emissions factor for SO_x was determined directly from fuel sulphur content by assuming conversion of fuel sulphur to gaseous SO_2 according to

$$EF(SO_x) = SFOC \times 2 \times 0.97753 \times fuel\_sulphur\_content \qquad \text{Eq. (4)}$$

Equation (4) includes a constant indicating that approximately 98% of the fuel sulphur will be converted to gaseous SO_2 and that about 2% of the sulphur can be found in particulate matter (SO_4) (IVL, 2004). In order to obtain the mass-based emissions factors from the power-based factors given by equation (4), division with SFOC was made. The SFOC was obtained from the $SFOC_{baseline}$ after adjusting with the load dependency (Eq. (3)).

The global sulphur content of marine fuel oils was modelled according to IMO global sulphur fuel oil monitoring reports, as shown in Table 51. For regional variations driven by regulation (ECAs), the fuel sulphur content is assumed to be equivalent to the minimum regulatory requirement (see the description in Section 1.2 of how shipping activity is attributed to different global regions).

Table 51 – *Annual fuel oil sulphur worldwide averages*

Fuel type	2007	2008	2009	2010	2011	2012
HFO/IFO	2.42	2.37	2.60	2.61	2.65	2.51
MDO/MGO	0.15	0.15	0.15	0.15	0.14	0.14

PM

The current literature contains a large range of PM emissions factors, which vary significantly between studies because of differences in methodology, sampling and analysis techniques. Again, the approach taken in the current study is compatible with the Second IMO GHG Study 2009, which defined PM as substances including sulphate, water associated with sulphate ash and organic carbons, measured by dilution method. Therefore, the model can accommodate changes in fuel sulphur content. This reflects the changes in PM emissions factors arising from ECAs as defined in MARPOL Annex VI. For main engines, PM was adjusted for low engine loads (<20%), as described in Starcrest (2013).

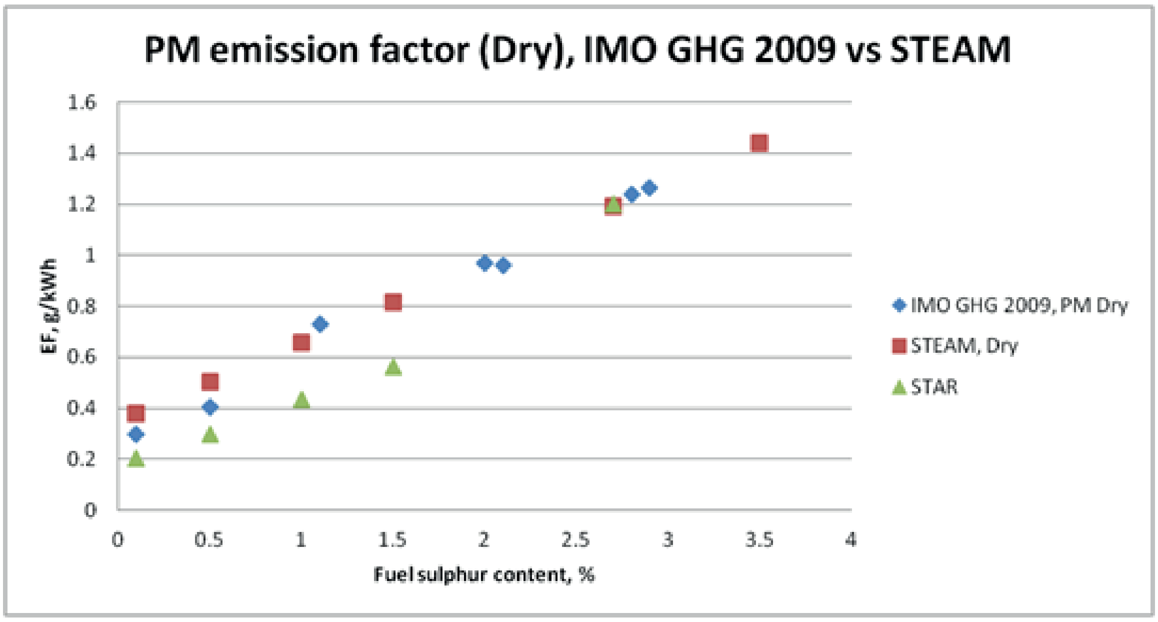


Figure 74: *Comparison of PM emissions factors reported in Second IMO GHG Study 2009 [blue diamond] (Figure 7.7, based on data from Germanischer Lloyd) with values from Jalkanen et al. (2012) [red square] and Starcrest (2013) [green triangle]*

CO

Emissions of CO were determined by the method originally described in Sarvi et al. (2008) and included in Jalkanen et al. (2012). The methodology describing transient engine loads and their changes were not used and all CO emissions factors represent steady-state operation and emissions. For main engines, PM was adjusted for low engine loads (<20%), as described in Starcrest (2013).

CH_4

The power-based CH_4 emissions factors for main, auxiliary and boiler engines at slow, medium and high speeds were taken from ENTEC (2002) and were converted to mass-based factors using the corresponding SFOC. The main engine CH_4 emissions factors are further adjusted at low load (<20%) using engine load adjustment, as reported in the *Port of Los Angeles Inventory of Air Emissions – 2012* (Starcrest, 2013). The mass-based factors are further adjusted for various loads dependent on SFOC, as described in Jalkanen et al. (2012).

N_2O

Emissions factors for N_2O for main, auxiliary and boiler engines were taken from the ENTEC study (2002). For main engines the factors were adjusted for low engine loads (<20%) as described in Starcrest (2013). As for CH_4, conversion from power-based to fuel-based emissions factors was carried out. In addition, the mass-based factors are adjusted for various loads dependent on SFOC as described in Jalkanen et al. (2012) (see Table 23 and Figure 35).

NMVOC

Emissions factors for NMVOC for main, auxiliary and boiler engines were taken from the ENTEC study (2002), and for main engines were adjusted for low engine loads (<20%) as described in Starcrest (2013). As for CH_4, convesion from power-based to fuel-based emissions factors was carried out. In addition, the mass-based factors are adjusted for various loads dependent on SFOC as described in Jalkanen et al. (2012) (see Figure 72).

2.3 Other relevant substances emissions inventories for 2007–2012

This section presents summary tables of top-down and bottom-up results for other substances besides CO_2 that are emitted from ships. Section 2.4.3 presents top-down and bottom-up inventory results graphically.

This section groups these tables (52–67) as follows:

- top-down fuel consumption (repeated from earlier sections);
- top-down GHG totals, including CH_4 and N_2O;
- top-down air pollutant inventories, including SO_x, NO_x, PM, CO and NMVOC;
- bottom-up fuel consumption (repeated from earlier sections);
- bottom-up GHG totals, including CH_4 and N_2O;
- bottom-up air pollutant inventories, including SO_x, NO_x, PM, CO and NMVOC.

2.3.1 Top-down fuel inventories

Table 52 – *Top-down fuel consumption inventory (million tonnes)*

Marine sector	Fuel type	2007	2008	2009	2010	2011
International marine bunkers	HFO	174.1	177	165.9	178.9	177.9
	MDO	26	22.7	24.9	28.2	29.6
	LNG	0	0	0	0	0
International total		**200.1**	**199.7**	**190.8**	**207.1**	**207.5**
Domestic navigation	HFO	19.9	14.2	15.3	14.3	12.7
	MDO	22.7	23.9	23.6	25.7	27.4
	LNG	0.04	0.05	0.05	0.05	0.07
Domestic total		**42.64**	**38.15**	**38.95**	**40.05**	**40.17**
Fishing	HFO	1.1	1.1	1	0.8	0.8
	MDO	5.4	4.9	5	5.2	5.1
	LNG	0.04	0.02	0.04	0.02	0.05
Fishing total		**6.54**	**6.02**	**6.04**	**6.02**	**5.95**
Total		**249.28**	**243.87**	**235.79**	**253.17**	**253.62**

2.3.2 Top-down GHG inventories

Table 53 – *Top-down CH_4 emissions estimates (tonnes)*

Marine sector	Fuel type	2007	2008	2009	2010	2011
International marine bunkers	HFO	10,446	10,620	9,954	10,734	10,674
	MDO	1,560	1,362	1,494	1,692	1,776
	LNG	0	0	0	0	0
International total		**12,006**	**11,982**	**11,448**	**12,426**	**12,450**
Domestic navigation	HFO	1,194	852	918	858	762
	MDO	1,362	1,434	1,416	1,542	1,644
	LNG	2,048	2,560	2,560	2,560	3,584
Domestic total		**4,604**	**4,846**	**4,894**	**4,960**	**5,990**
Fishing	HFO	66	66	60	48	48
	MDO	324	294	300	312	306
	LNG	2,048	1,024	2,048	1,024	2,560
Fishing total		**2,438**	**1,384**	**2,408**	**1,384**	**2,914**
Total		**19,048**	**18,212**	**18,750**	**18,770**	**21,354**

Table 54 – *Top-down N_2O emissions estimates (tonnes)*

Marine sector	**Fuel type**	**2007**	**2008**	**2009**	**2010**	**2011**
International marine bunkers	HFO	27,856	28,320	26,544	28,624	28,464
	MDO	3,900	3,405	3,735	4,230	4,440
	LNG	0	0	0	0	0
International total		**31,756**	**31,725**	**30,279**	**32,854**	**32,904**
Domestic navigation	HFO	3,184	2,272	2,448	2,288	2,032
	MDO	3,405	3,585	3,540	3,855	4,110
	LNG	4	6	6	6	8
Domestic total		**6,593**	**5,863**	**5,994**	**6,149**	**6,150**
Fishing	HFO	176	176	160	128	128
	MDO	810	735	750	780	765
	LNG	4	2	4	2	6
Fishing total		**990**	**913**	**914**	**910**	**899**
Total		**39,340**	**38,501**	**37,187**	**39,913**	**39,952**

2.3.3 Top-down air pollutant inventories

Table 55 – *Top-down SO_x emissions estimates (thousand tonnes as SO_2)*

Marine sector	**Fuel type**	**2007**	**2008**	**2009**	**2010**	**2011**
International marine bunkers	HFO	8,268	8,220	8,404	9,158	9,199
	MDO	69	60	66	74	78
	LNG	0	0	0	0	0
International total		**8,337**	**8,280**	**8,470**	**9,232**	**9,277**
Domestic navigation	HFO	945	659	775	732	657
	MDO	60	63	62	68	72
	LNG	0	0	0	0	0
Domestic total		**1,005**	**723**	**837**	**800**	**729**
Fishing	HFO	52	51	51	41	41
	MDO	14	13	13	14	13
	LNG	0	0	0	0	0
Fishing total		**66**	**64**	**64**	**55**	**55**
Total		**9,408**	**9,066**	**9,371**	**10,087**	**10,061**

Table 56 – *Top-down NO_x emissions estimates (thousand tonnes as NO_2)*

Marine sector	**Fuel type**	**2007**	**2008**	**2009**	**2010**	**2011**
International marine bunkers	HFO	16,191	16,461	15,429	16,638	16,545
	MDO	2,269	1,981	2,173	2,460	2,583
	LNG	0	0	0	0	0
International total		**18,460**	**18,442**	**17,601**	**19,098**	**19,127**
Domestic navigation	HFO	1,851	1,321	1,423	1,330	1,181
	MDO	1,981	2,085	2,059	2,242	2,391
	LNG	0	0	0	0	1
Domestic total		**3,832**	**3,406**	**3,482**	**3,573**	**3,572**
Fishing	HFO	102	102	93	74	74
	MDO	471	428	436	454	445
	LNG	0	0	0	0	0
Fishing total		**574**	**530**	**530**	**528**	**520**
Total		**22,865**	**22,378**	**21,613**	**23,199**	**23,219**

Table 57 – *Top-down PM emissions estimates (thousand tonnes)*

Marine sector	**Fuel type**	**2007**	**2008**	**2009**	**2010**	**2011**
International marine bunkers	HFO	1,191	1,198	1,183	1,276	1,283
	MDO	27	23	25	29	30
	LNG	0	0	0	0	0
International total		**1,217**	**1,221**	**1,208**	**1,304**	**1,313**
Domestic navigation	HFO	136	96	109	102	92
	MDO	23	24	24	26	28
	LNG	0	0	0	0	0
Domestic total		**159**	**121**	**133**	**128**	**120**
Fishing	HFO	8	7	7	6	6
	MDO	6	5	5	5	5
	LNG	0	0	0	0	0
Fishing total		**13**	**12**	**12**	**11**	**11**
Total		**1,390**	**1,354**	**1,354**	**1,444**	**1,443**

Table 58 – *Top-down CO emissions estimates (thousand tonnes)*

Marine sector	**Fuel type**	**2007**	**2008**	**2009**	**2010**	**2011**
International marine bunkers	HFO	482.3	490.3	459.5	495.6	492.8
	MDO	72.0	62.9	69.0	78.1	82.0
	LNG	0.0	0.0	0.0	0.0	0.0
International total		**554.3**	**553.2**	**528.5**	**573.7**	**574.8**
Domestic navigation	HFO	55.1	39.3	42.4	39.6	35.2
	MDO	62.9	66.2	65.4	71.2	75.9
	LNG	0.3	0.4	0.4	0.4	0.5
Domestic total		**118.3**	**105.9**	**108.1**	**111.2**	**111.6**
Fishing	HFO	3.0	3.0	2.8	2.2	2.2
	MDO	15.0	13.6	13.9	14.4	14.1
	LNG	0.3	0.2	0.3	0.2	0.4
Fishing total		**18.3**	**16.8**	**16.9**	**16.8**	**16.7**
Total		**690.9**	**675.9**	**653.6**	**701.6**	**703.1**

Table 59 – *Top-down NMVOC emissions estimates (thousand tonnes)*

Marine sector	Fuel type	2007	2008	2009	2010	2011
International marine bunkers	HFO	536.2	545.2	511.0	551.0	547.9
	MDO	80.1	69.9	76.7	86.9	91.2
	LNG	0.0	0.0	0.0	0.0	0.0
International total		**616.3**	**615.1**	**587.7**	**637.9**	**639.1**
Domestic navigation	HFO	61.3	43.7	47.1	44.0	39.1
	MDO	69.9	73.6	72.7	79.2	84.4
	LNG	0.1	0.2	0.2	0.2	0.2
Domestic total		**131.3**	**117.5**	**120.0**	**123.4**	**123.7**
Fishing	HFO	3.4	3.4	3.1	2.5	2.5
	MDO	16.6	15.1	15.4	16.0	15.7
	LNG	0.1	0.1	0.1	0.1	0.2
Fishing total		**20.1**	**18.5**	**18.6**	**18.5**	**18.3**
Total		**767.8**	**751.1**	**726.2**	**779.8**	**781.1**

2.3.4 Bottom-up fuel inventories

Table 60 – *Bottom-up fuel consumption estimates (million tonnes)*

Fleet sector	2007	2008	2009	2010	2011	2012
International shipping	283	294	275	248	274	257
Domestic navigation	42	43	24	26	35	27
Fishing	27	25	14	18	18	16
Total bottom-up estimate	**352**	**363**	**313**	**293**	**327**	**300**

2.3.5 Bottom-up GHG inventories

Table 61 – *Bottom-up CH_4 emissions estimates (tonnes)*

Fleet sector	2007	2008	2009	2010	2011	2012
International shipping	174,370	193,180	185,980	234,370	286,480	286,520
Domestic navigation	1,510	1,570	770	1,020	1,180	1,060
Fishing	1,110	1,040	570	780	780	700
Total bottom-up estimate	**176,990**	**195,790**	**187,320**	**236,170**	**288,440**	**288,280**

Table 62 – *Bottom-up N_2O emissions estimates (tonnes)*

Fleet sector	2007	2008	2009	2010	2011	2012
International shipping	40,780	42,580	39,800	35,620	38,380	36,680
Domestic navigation	5,220	5,380	2,790	3,440	3,950	3,560
Fishing	3,930	3,730	2,100	2,730	2,730	2,400
Total bottom-up estimate	**49,930**	**51,690**	**44,690**	**41,790**	**45,060**	**42,640**

2.3.6 Bottom-up air pollutant inventories

Table 63 – *Bottom-up SO_x emissions estimates (thousand tonnes as SO_2)*

Fleet sector	2007	2008	2009	2010	2011	2012
International shipping	10,771	11,041	11,164	9,895	10,851	9,712
Domestic navigation	278	331	202	251	358	268
Fishing	533	521	280	405	423	261
Total bottom-up estimate	**11,581**	**11,892**	**11,646**	**10,550**	**11,632**	**10,240**

Table 64 – *Bottom-up NO_x emissions estimates (thousand tonnes as NO_2)*

Fleet sector	2007	2008	2009	2010	2011	2012
International shipping	19,943	20,759	19,104	16,708	18,047	16,997
Domestic navigation	1,564	1,639	930	1,114	1,323	1,171
Fishing	1,294	1,242	722	935	940	834
Total bottom-up estimate	**22,801**	**23,639**	**20,756**	**18,756**	**20,310**	**19,002**

Table 65 – *Bottom-up PM emissions estimates (thousand tonnes)*

Fleet sector	2007	2008	2009	2010	2011	2012
International shipping	1,493	1,545	1,500	1,332	1,446	1,317
Domestic navigation	51	58	33	41	56	44
Fishing	78	76	41	59	61	41
Total bottom-up estimate	**1,622**	**1,679**	**1,574**	**1,432**	**1,563**	**1,402**

Table 66 – *Bottom-up CO emissions estimates (thousand tonnes)*

Fleet sector	2007	2008	2009	2010	2011	2012
International shipping	823	864	816	763	834	806
Domestic navigation	99	103	60	72	82	76
Fishing	76	72	46	59	58	53
Total bottom-up estimate	**998**	**1,039**	**921**	**893**	**975**	**936**

Table 67 – *Bottom-up NMVOC emissions estimates (thousand tonnes)*

Fleet sector	2007	2008	2009	2010	2011	2012
International shipping	696	727	672	593	643	609
Domestic navigation	76	78	38	51	59	53
Fishing	55	52	28	39	39	35
Total bottom-up estimate	**827**	**858**	**739**	**683**	**741**	**696**

While these global totals differ from primary GHGs in terms of regional distribution, typical substance lifetimes and air quality impacts, NO_x and SO_x play indirect roles in tropospheric ozone formation and indirect aerosol warming at regional scales; moreover, ship emissions of NO_x and SO_x have been compared with global anthropogenic emissions.

These totals are slightly greater than reported in the Second IMO GHG Study 2009. The Third IMO GHG Study 2014 estimates multi-year (2007–2012) average annual totals of 11.3 million tonnes and 20.9 million tonnes for SO_x (as SO_2) and NO_x (as NO_2) from all shipping respectively (corresponding to 5.6 million tonnes and 6.3 million tonnes converted to elemental weights for nitrogen and sulphur respectively). A multi-year average of international shipping results in an annual average estimate of some 10.6 million tonnes and 18.6 million tonnes of SO_x (as SO_2) and NO_x (as NO_2) respectively; this converts to totals of 5.3 million tonnes and 5.6 million tonnes of SO_x and NO_x respectively (as elemental sulphur and nitrogen respectively). These totals can be compared with totals reported in AR5 (IPCC, 2013). Global NO_x and SO_x emissions from all shipping represent about 15% and 13% of global NO_x and SO_x from anthropogenic sources respectively; international shipping NO_x and SO_x represent approximately 13% and 12% of global NO_x and SO_x totals respectively. Comparisons with AR5 are also consistent with comparisons in peer-reviewed journal publications reporting global SO_x (Smith et al., 2011) and NO_x (Miyazaki et al., 2012).

Multi-year averages for PM, CO and NMVOC are calculable but are rarely compared with global totals. Moreover, AR5 only reports global values for CO and NMVOC, and IPCC reports substances of particulate matter such as black carbon and organic carbon. Interested readers are referred to annex II of AR5 (IPCC, 2013) for tables with global totals for CO (AR5, Table AII.2.16), NMVOC (AR5, Table AII.2.17), organic carbon (AR5, Table AII.2.21) and black carbon (AR5, Table AII.2.22).

2.4 Quality assurance and quality control of other relevant substances emissions inventories

Because the input data and method for Section 2.1 and Section 2.2 have substantial similarity to the input data and method for Sections 1.1 and Section 1.2, Section 2.4 is closely connected to Section 1.4. The two areas where there is specific additional content are in the QA/QC of the emissions factors used and in the comparison of emissions inventories obtained using the two approaches (bottom-up and top-down).

2.4.1 QA/QC of bottom-up emissions factors

As stated in Section 2.2.7, the emissions factors used in the Third IMO GHG Study 2014 were selected by the consortium with first preference going to published IMO factors (e.g. NO_x by fuel type). Other factors were selected with the unanimous agreement of the emissions factor working group based on what various members are currently using in their work. It should also be noted that emissions factors are typically derived from emissions testing results and reported as energy-based (g pollutant/kWh) factors. Both the Second IMO GHG Study 2009 and this study used fuel-based (g pollutant/g fuel) factors. The following observations can be made about the comparison of the two sets of emissions factors:

- The Second IMO GHG Study 2009 emissions factors (presented in its Table 3.6) do not differentiate for various engine types (SSD, MSD, HSD, auxiliary boilers, LNG Otto, steam, gas turbine), engine tier (0, I, II) or duty cycle (propulsion, auxiliary). Exceptions to these are fuel type differentiation (CO_2, SO_2, NO_x, PM_{10}) and auxiliary boilers (NO_x). The Third IMO GHG Study 2014 includes each of these differentiations and further adjusts the emissions factors based on engine load.

Since the emissions factors are significantly more detailed in the Third IMO GHG Study 2014, comparisons are somewhat difficult; however, they are compared in Table 68.

Table 68 – *Comparison of emissions factors, Second IMO GHG Study 2009 and Third IMO GHG Study 2014*

Pollutant	IMO Study	Engine type	Tier	Fuel type	EF[1]	Correlation 2014/2009 EFs	Correlation
CO_2	2009	unk	unk	HFO	3,130	0.99	good
	2014	all	all	HFO	3,114		
	2009	unk	unk	MDO	3,190	1.01	good
	2014	all	all	MDO	3,206		
NO_x	2009	SSD	0	?	90	1.03	good
	2014	SSD	0	HFO	92.82		
	2009	SSD	1	?	78	1.12	good
	2014	SSD	1	HFO	87.18		
	2009	MSD	0	?	60	1.09	good
	2014	MSD	0	HFO	65.12		
	2009	MSD	1	?	51	1.19	moderate difference
	2014	MSD	1	HFO	60.47		
	2009	Boiler	na	?	7	0.98	good
	2014	Boiler	na	HFO	6.89		
SO_x	2009	unk	unk	HFO 2.7%	54	0.98	good
	2014	SSD	0	HFO 2.7%	52.77		
	2014	SSD	0	HFO 2.42%	47.49	0.88	as modelled for 2007
	2009	unk	unk	MDO 0.5%	10	0.98	good
	2014	SSD	0	MDO 0.5%	9.76		
	2014	SSD	0	MDO 0.15%	2.64	0.26	as modelled for 2007
PM	2009	unk	unk	HFO 2.7%	6.7	1.09	good
	2014	SSD	0	HFO 2.7%	7.28		
	2014	SSD	0	HFO 2.42%	6.84	1.02	as modelled for 2007
	2009	unk	unk	MDO 0.5%	1.1	1.65	significant difference
	2014	SSD	0	MDO 0.5%	1.82		
	2014	SSD	0	MDO 0.1%	1.24	1.13	as modelled for 2007
CO	2009	unk	unk	unk	7.4	0.37	significant difference
	2014	SSD	0	HFO	2.77		
CH_4	2009	unk	unk	unk	0.3	0.20	significant difference
	2014	SSD	0	HFO	0.06		
N_2O	2009	unk	unk	unk	0.08	2.00	significant difference
	2014	SSD	0	HFO	0.16		
NMVOC	2009	unk	unk	unk	2.4	1.28	significant difference
	2014	SSD	0	HFO	3.08		

Notes: [1] kg pollutant/tonne of fuel; unk = unknown; moderate difference 10%–25%; significant difference >25%

In Table 68, some pollutant emissions factors do not correlate well (values in red) between the two studies and are discussed further below:

- NO_x – The Third IMO GHG Study 2014 MSD Tier I emissions factor is 19% higher than the Second IMO GHG Study 2009, which could be because of the assumed SFOC rates.
- SO_x – The modelled Third IMO GHG Study 2014 SSD Tier 0 HFO emissions factors are 12% lower owing to use of the annual average IMO published fuel sulphur contents (2.42% for 2007) in the Third IMO GHG Study 2014, compared to the 2.7% used in the Second IMO GHG Study 2009.

- SO_x – The modelled Third IMO GHG Study 2014 SSD Tier 0 MDO emissions factors are 74% lower owing to use of the annual average IMO published fuel sulphur contents (0.15% for 2007) in the Third IMO GHG Study 2014 compared to the 0.5% used in the Second IMO GHG Study 2009.
- PM – the modelled Third IMO GHG Study 2014 SSD Tier 0 MDO emissions factors are 13% higher owing to use of fuel correction factors as described in Section 2.2.7 and Annex 6 compared to the value developed in the Second IMO GHG Study 2009.
- CO – The Third IMO GHG Study 2014 SSD Tier 0 HFO emissions factors are 63% lower than the Second IMO GHG Study 2009. The 2009 study used CORINAIR emissions factors for CO, which can be traced back to the Lloyd's Register report *Marine Exhaust Emissions Research Programme* (1995). The Third IMO GHG Study 2014 used an updated CO emissions factor that was recently supported in the Kristensen (2012) report.
- CH_4 – The Third IMO GHG Study 2014 SSD Tier 0 HFO emissions factor is 80% lower than the Second IMO GHG Study 2009. The 2009 study used the IPCC 2013 emissions factor for CH_4, which can be traced back to the Lloyd's Register report *Marine Exhaust Emissions Research Programme* (1995). The 2014 study used an updated CH_4 emissions factor. In addition to the CH_4 combustion product, methane is also released into the atmosphere as an unburnt fuel from engines operating on LNG Otto-cycle engines. In this report, the methane slip has been included in the methane emission inventory and an additional non-combustion emissions factor has been assigned for CH_4 to account for this feature. For further details, see Section 2.2.6.
- N_2O – The Third IMO GHG Study 2014 SSD Tier 0 HFO emissions factor is two times higher than the Second IMO GHG Study 2009. The 2009 study used CORINAIR emissions factors for N_2O, which can be traced back to the Lloyd's Register report *Marine Exhaust Emissions Research Programme* (1995). The IPCC guidelines state that the uncertainty of the emissions factor is as high as 140%. The Third IMO GHG Study 2014 used an updated N_2O emissions factor.
- NMVOC – The Third IMO GHG Study 2014 SSD Tier 0 HFO emissions factor is 28% higher than the Second IMO GHG Study 2009. The 2009 study used CORINAIR emissions factors for NMVOC, which can be traced back to Lloyd's Register report *Marine Exhaust Emissions Research Programme* (1995). The Third IMO GHG Study 2014 used an updated NMVOC emissions factor.

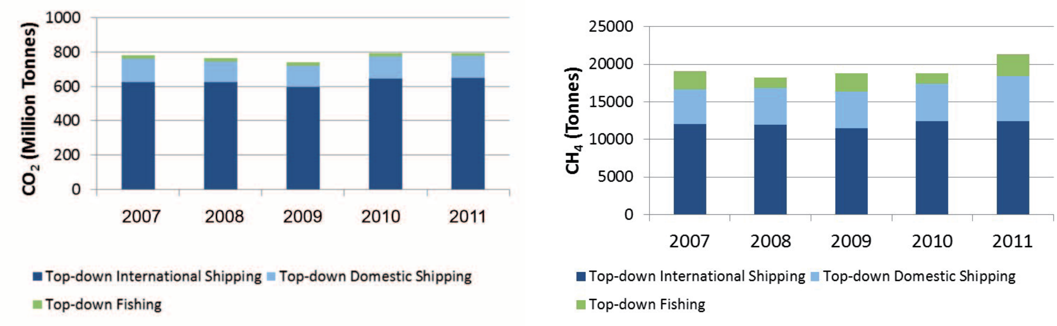
2.4.2 QA/QC of top-down emissions factors

The top-down emissions factors (Table 34, Section 2.1.1) are a subset of the bottom-up emissions factors and were selected as described in Section 2.2.7. They have the same correlations to the Second IMO GHG Study 2009 as presented in Section 2.4.1.

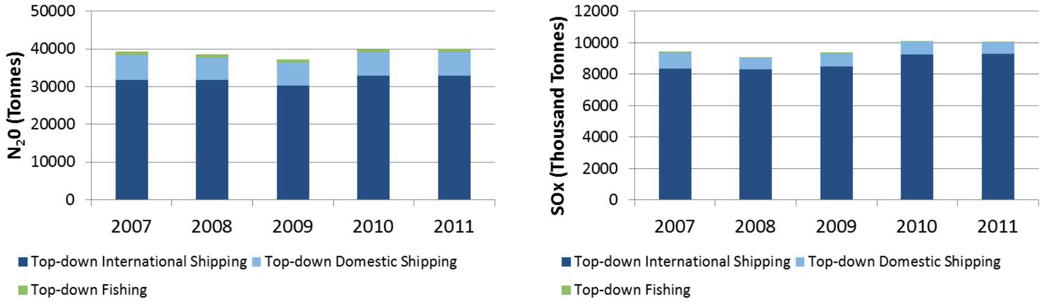
2.4.3 Comparison of top-down and bottom-up inventories

Top-down and bottom-up time series for each pollutant inventory are presented in Figure 75 and Figure 76 respectively. These results are provided with the same units and similar (but not identical) scales for visual comparison.

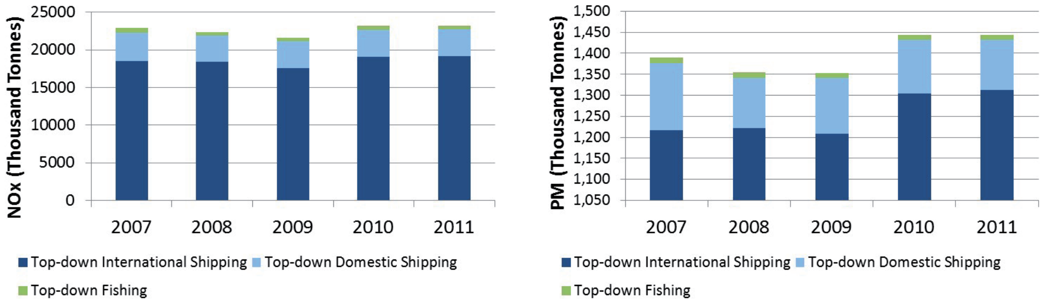
One clear difference is the trend pattern across years for some pollutants. For example, the top-down data among all pollutants remains similar. Most top-down inventories reveal a decline after 2007, to 2009 or so, and an increase in subsequent years. This can be explained because the top-down data do not include technology detail and the inventories are therefore computed using a best-judgement fleet-average emissions factor. Conversely, the bottom-up inventories can exhibit diverging patterns from one another and very different patterns from the top-down inventory trends. Whereas CO_2 in the bottom-up results exhibits a trend similar to SO_x, NO_x and PM, the pattern for CH_4 is increasing over the years. This is because the number of larger vessels using LNG has increased, despite the fact that top-down statistics have not begun reporting any LNG in international sales statistics.



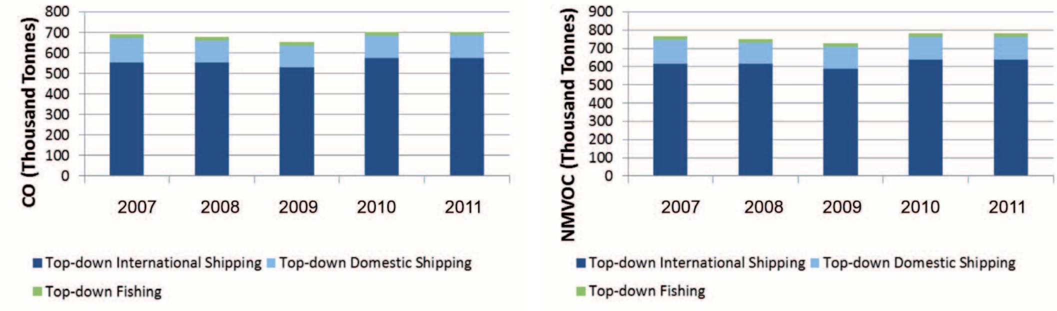
a) CO_2 b) CH_4



c) N_2O d) SO_X

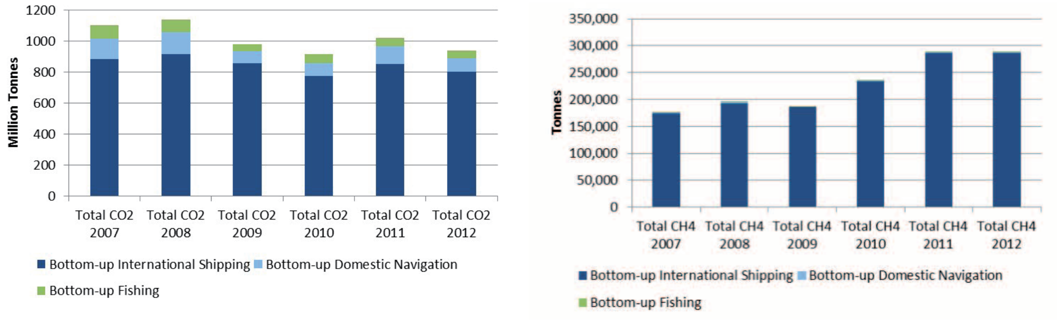


e) NO_X f) PM

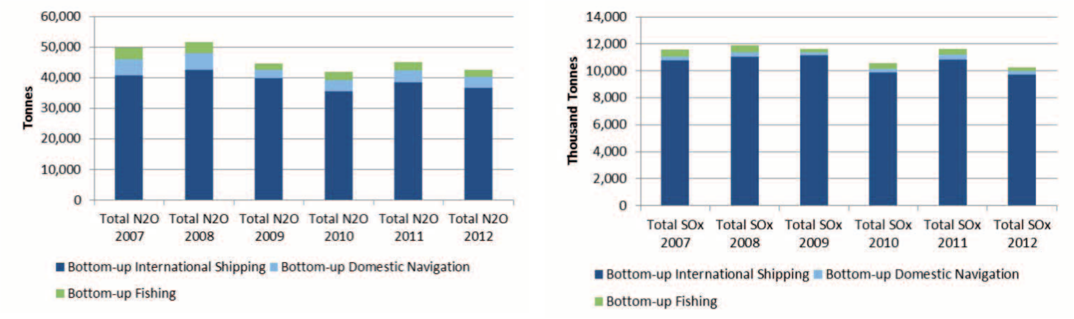


g) CO h) NMVOC

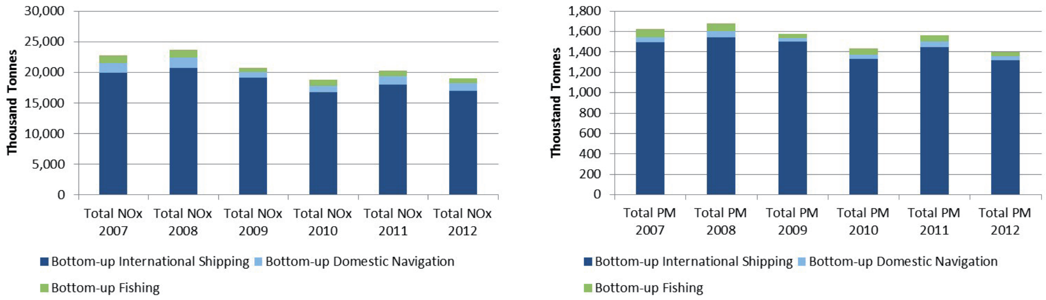
Figure 75: *Time series of top-down results for a) CO_2, b) CH_4, c) N_2O, d) SO_x, e) NO_x, f) PM, g) CO, and h) NMVOC, delineated by international shipping, domestic navigation and fishing*



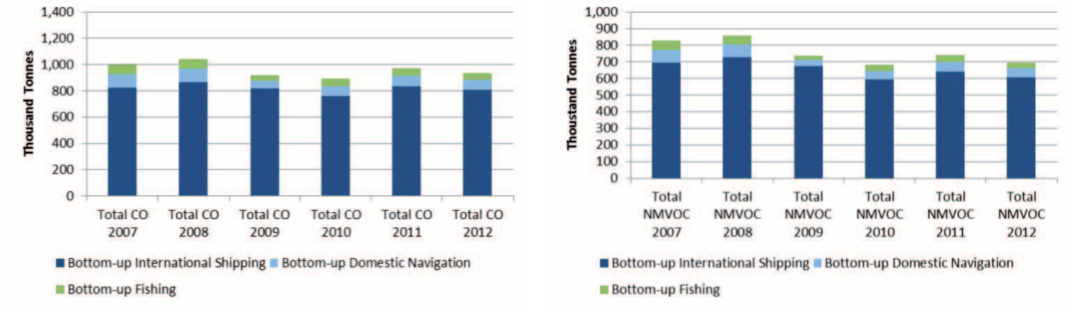
a) CO_2 b) CH_4



c) N_2O d) SO_X



e) NO_X f) PM



g) CO h) NMVOC

Figure 76: *Time series of bottom-up results for a) CO_2, b) CH_4, c) N_2O, d) SO_x, e) NO_x, f) PM, g) CO, and h) NMVOC, delineated by international shipping, domestic navigation and fishing*

2.5 Other relevant substances emissions inventory uncertainty analysis

The uncertainties involved with missing technical data for ships, incomplete geographical/temporal coverage of activity data and resistance/powering prediction are described in Section 1. Other sources of uncertainty include estimates of fuel consumption, allocation of fuel types consumed versus actual fuels consumed, auxiliary engine and boiler loads by mode, assignment of modes based on AIS data, IMO sulphur survey annual averages, and the factors used to estimate emissions. Uncertainty associated with these, with the exception of the emissions factors, is discussed in Section 1.5. The uncertainties associated with emissions factors include the vessels tested compared to the fleet modelled and robustness of the number of ships tested in each subclass. While some emissions factors have remained within the same ranges since the Second IMO GHG Study 2009, there were several pollutants that had moderate to significant changes, as detailed in Section 2.4.1.

2.6 Other relevant substances emissions inventory comparison against Second IMO GHG Study 2009

Figure 75 presents the time series results for non-CO_2 relevant substances estimated in this study using bottom-up methods, with explicit comparison with the Second IMO GHG Study 2009 results. Section 1.6 shows that for ship types that could be directly compared, fuel consumption and CO_2 emissions totals estimated by the methods used in this study compare very well with methods used in the earlier study. As reported in Section 1.6, the additional precision in observing vessel activity patterns in the Third IMO GHG Study 2014 largely match general vessel activity assumptions in the 2009 study, at least for the inventory year 2007. (The updated methodology provides greatest value in the ability to observe year-on-year changes in shipping patterns, which the Second IMO GHG Study 2009 methods were less able to do.)

Given that the Second IMO GHG Study 2009 "concluded that activity-based estimates provide a more correct representation of the total emissions from shipping", only bottom-up emissions for other relevant substances can be compared. The Third IMO GHG Study 2014 estimates of non-CO_2 GHGs and some air pollutant substances differ substantially from the Second IMO GHG Study 2009 results for the common year 2007. The Third IMO GHG Study 2014 produces higher estimates of CH_4 and N_2O than the Second IMO GHG Study 2009, higher by 43% and 40% respectively (approximate values). The Third IMO GHG Study 2014 estimates lower emissions of SO_x (approximately 30% lower) and approximately 40% of the CO emissions estimated in the Second IMO GHG Study 2009. Estimates for NO_x, PM and NMVOC in both studies are similar for 2007, within 10%, 11% and 3% respectively (approximate values).

These underlying activity similarities essentially reduce the comparisons of other relevant substances estimated in the Second IMO GHG Study 2009 to a description of differences in EFs, as illustrated in Table 68. Differences in EFs essentially relate to static values in the 2009 study, which assumed an average MCR and EFs representative of the average engine's actual duty cycle. The consortium made more detailed calculations in the Third IMO GHG Study 2014, which computes hourly fuel consumption and engine load factors and applies a load-factor specific EF. In theory, if the average EFs across a duty cycle in the earlier study were computed for the same or similar activity, then the average EFs would mathematically represent the weighted average of the hourly load-dependent calculations. The crossplots presented in Section 1.6 provide evidence that the duty cycle assumptions in the Second IMO GHG Study 2009 were generally consistent with the more detailed analyses presented in this study.

Another source of differences may be related to fuel quality or engine parameter data representing a different understanding of the fleet technology. For example, the 2009 study assumed fuel sulphur content was 2.7%, while the current study documents that the typical fuel sulphur content in 2007 was closer to 2.4%. Moreover, the Third IMO GHG Study 2014 updates these sulphur contents for later years.

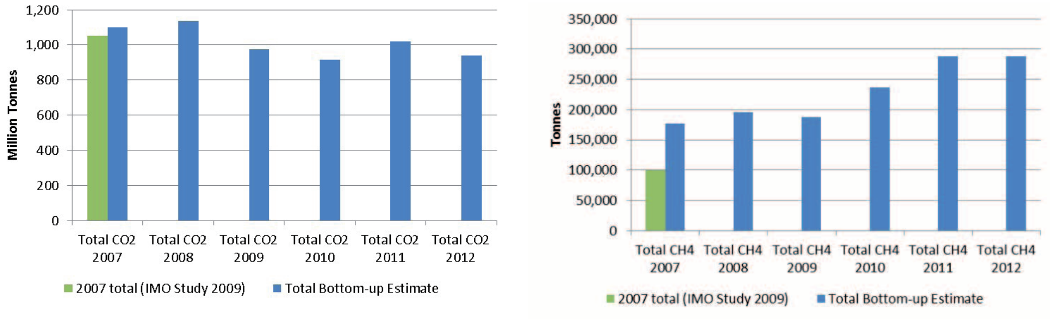
Another example is natural-gas-fuelled engines, which are observed in the Third IMO GHG Study 2014 fleet but were not addressed in the 2009 study. This enables better characterization of methane emissions (sometimes called methane slip), which has been significantly reduced through engine innovations. The Second IMO GHG Study 2009 characterized methane losses due to evaporation during transport of fuels as cargo (Second IMO GHG Study 2009, non-exhaust emissions, paragraph 3.47), and used a top-down methodology to evaluate methane emissions from engine exhaust (Second IMO GHG Study 2009, Tables 3.6 and 3.7). The 2009 study reported total methane emissions (combining exhaust and cargo transport estimates in Table 3.11), but did not determine any value for international shipping (Second IMO GHG Study 2009,

Table 1-1). The 2009 study allocated significant discussion in sections describing potential reductions in GHGs to characterizing natural gas methane emissions, and identified efforts to achieve reductions in methane emissions from marine engines. The Third IMO GHG Study 2014 explicitly applied current knowledge of methane slip in marine engines to those vessels fuelled by natural gas in our bottom-up inventories, thereby better characterizing CH_4 emissions.

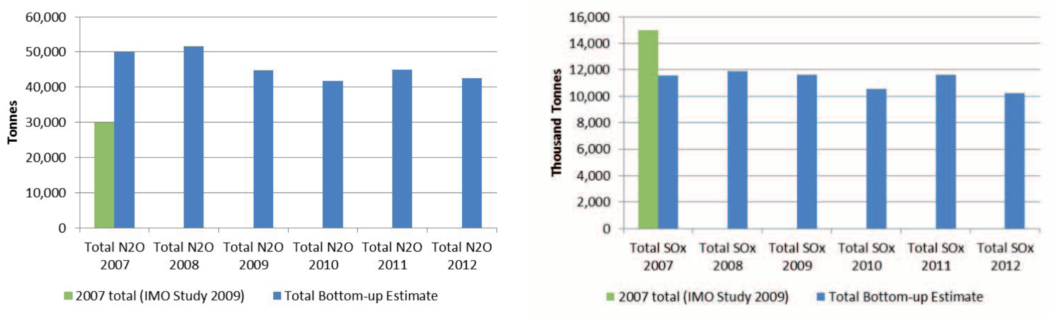
However, more detailed characterization of fleet technology can result in different technology mixes. For example, the Second IMO GHG Study 2009 documented auxiliary boilers for crude oil tankers only, whereas the Third IMO GHG Study 2014 identified boiler technology on some bulk carriers, chemical tankers, container ships, general cargo ships, cruise passenger ships, refrigerated bulk, ro-ro and vehicle carriers. The Third IMO GHG Study 2014 assigned engine-specific EFs at the individual ship level where possible, including differentiating between MSD and SSD engines, and residual versus distillate fuel types. These differences can help explain inventory differences between the two studies.

For CO_2, NO_x and PM, the Third IMO GHG Study 2014 values for 2007 closely match the results reported in the Second IMO GHG Study 2009. The differences in these EFs are 1% for CO_2, 3%–9% for NO_x and 2%–13% for PM respectively (approximate values). (The two values for NO_x represent SSD and MSD respectively; similarly, the two values for PM represent HFO and MDO typical values respectively.) The match is best where vessel activity comparisons are similar, where observed fleet technology matches and where the emissions factors have changed little. This again confirms that the general impact of the updated methodology is greater precision and ability to update year-on-year variation in technology or activity among individual vessels in the fleet. Major differences in emissions results for other relevant substances, therefore, can be explained by the different EFs used in the Second IMO GHG Study 2009 compared with the more detailed assignment of EFs in the Third IMO GHG Study 2014. This mainly relates to the emissions of CH_4, N_2O, CO and NMVOC. These EF differences are 80%, 100% and 63% lower in the current study for CH_4, N_2O and CO respectively, and 30% higher for NMVOC (approximate values). These emissions represent combustion emissions of fuels and do not include evaporative losses from the transport of cargos; the Second IMO GHG Study 2009 estimated the CH_4 losses from the transport of crude oil to be 140,000 tonnes. Table 1-1 of that study added direct emissions from engine combustion with the estimated losses of CH_4 from the transport of crude oil; no equivalent calculation is performed here.

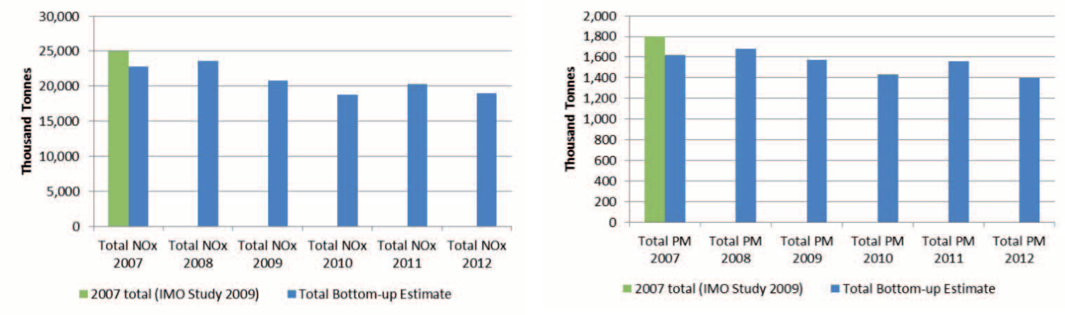
Differences in sulphur (SO_x) emissions are similarly attributed to different fuel sulphur contents, using updated IMO sulphur reports. In this study, the bottom-up model allocation of fuel types for auxiliaries and some main engine technologies enables more detailed delineation of heavy residual and distillate fuel use; this accounts for most of the difference in sulphur emissions inventories between the studies. Moreover, the use of updated fuel sulphur contents can account for about 12% difference in the heavy residual fuel sulphur contents in 2007.



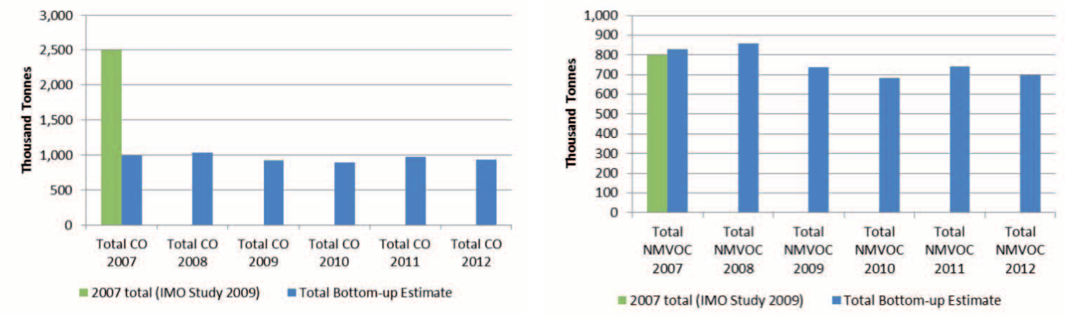
a) CO_2 b) CH_4



c) N_2O d) SO_X



e) NO_X f) PM



g) CO h) NMVOC

Figure 77: *Time series of bottom-up results for a) CO_2, b) CH_4, c) N_2O, d) SO_X, e) NO_X, f) PM, g) CO, and h) NMVOC. The green bar represents the Second IMO GHG Study 2009 estimate for comparison*

3

Scenarios for shipping emissions 2012–2050

3.1 Introduction

This chapter presents emissions scenarios for all six GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) and for other relevant substances as defined in this study (NO_x, NMVOC, CO, PM, SO_x).

Emissions scenarios present possible ways in which emissions could develop, building on plausible socioeconomic, energy and policy scenarios. The emissions scenarios can inform policymakers, scientists and other stakeholders about the development of the environmental impacts of shipping, its drivers and the relevance of possible policy instruments to address emissions.

3.1.1 Similarities with and differences from Second IMO GHG Study 2009

The emissions scenarios have been developed using a similar approach to that of the Second IMO GHG Study 2009, i.e. by modelling the most important drivers of maritime transport and efficiency trends in order to project energy demand in the sector. For most emissions, the energy demand is then multiplied by an emissions factor to arrive at an emissions projection. More detail about the methods and modelling can be found in Section 3.2.

Even though the approach is similar, the methods have been improved in important ways, taking into account advances in the literature and newly developed scenarios. Some of the most important improvements are highlighted below.

Socioeconomic and energy scenarios

In the Second IMO GHG Study 2009, a range of transport and corresponding emissions projections to 2050 were presented. The underlying overall basis for these projections were the IPCC Special Report on Emissions Scenarios (SRES) (based upon the IPCC 2000 SRES, which were widely in use at the time). There has been increased recognition across the climate-scenario-modelling community that there is a need for an updated set of scenarios, but also recognition of the need to circumvent the time and expense associated with another IPCC-focused exercise. Thus, the relevant community itself developed the concept of RCPs. Since these are now in use across the climate community, they have been adopted for this study (see Section 3.2.2). Outside the climate research community, other long-term scenarios exist (e.g. IEA, 2013; OECD, 2012; IMF, 2014; RTI, 2013).

Previously, shipping emissions scenarios were based more loosely on a consortium consensus approach, the so-called Delphi method. This study adopts a more disaggregated numerical approach with explicit improvements to the projection methodology by splitting the projections by ship type, using a non-linear regression model of a type widely adopted in the econometric literature (as opposed to simple linear models), and decoupling the transport of fossil fuels from GDP. In the previous report, there was no such discrimination by type, or consideration of future worlds where fossil fuel energy demand is decoupled from GDP. More details are provided in Section 3.2.2 and Annex 7.

Business as usual and policy scenarios

The Second IMO GHG Study 2009 presented a multitude of scenarios but did not consider any of them to be BAU. All scenarios presented in this study are combinations of trade scenarios, ship efficiency scenarios and emissions scenarios. The trade scenarios are based on combinations of RCPs and SSPs and, as discussed in detail in Section 3.2.2, all four are equally likely to occur. Their differences reflect either inherent uncertainties about the future (e.g. economic development, demographics and technological development), or uncertainties related to policy choices outside the remit of IMO (e.g. climate, energy efficiency or trade policies). In many cases, these uncertainties are interrelated and cannot be disentangled.

The ship efficiency and emissions scenarios can be classified in two groups. Each of the scenarios has an option in which no policies are assumed beyond the policies that are currently in place, and one in which IMO continues to adopt policies to address air emissions or the energy efficiency of ships. The first type is labelled BAU, as it does not require policy interventions. In this way, each of the four trade scenarios has one BAU variant and three policy intervention variants. As both policy interventions result in lower GHG emissions, all policy intervention scenarios have emissions below the BAU scenario. These lower emission scenarios require additional policies beyond those that are currently adopted.

Marginal abatement cost curves

This study employs MACCs containing 22 measures in 15 groups (measures within the same group are mutually exclusive), taking into account the fact that measures may be applicable to certain ship types only. The benefit of using MACCs over holistic efficiency improvement assumptions is that they allow for feedback between fuel prices and improvements in efficiency.

MARPOL Annex VI revisions (EEDI, SEEMP)

After the publication of the Second IMO GHG Study 2009, State Parties adopted a new chapter for MARPOL Annex VI on energy efficiency for ships, mandating EEDI for new ships and SEEMP for all ships. The impact of these regulations on the energy efficiency of ships is analysed and included in the model.

Ship types

Since the Second IMO GHG Study 2009, there has been a remarkable increase in ship size, especially for container ships. The earlier study assumes that all container ships over 8,000 TEU would have an average size of 100,000 dwt, but in 2011 the size of the average new-build ship had increased to 125,000 dwt, while ships of 165,000 dwt have entered the fleet and larger ones are being studied. Larger ships are more efficient, i.e. they require less energy to move an amount of cargo over an amount of distance. In response, this study analyses the development of ship types in the last year and includes new categories for the largest ships.

3.1.2 Outline

The remainder of this chapter is organized as follows. Section 3.2 provides a brief description of the methods and data used to project emissions. It begins by presenting the emissions model, the factors taken into account in our projections and the long-term scenarios used as a basis for our projections. All the relevant factors of the projections are then discussed individually, showing which assumptions are made in each case and the basis on which they are made. Section 3.3 presents the projections of international maritime transport demand and associated emissions of CO_2 and of other relevant substances up to 2050.

3.2 Methods and data

3.2.1 The emissions projection model

The model used to project emissions starts with a projection of transport demand, building on long-term socioeconomic scenarios developed for IPCC (see Section 3.2.2). Taking into account developments in fleet productivity (see Section 3.2.4) and ship size (see Section 3.2.5), it projects the fleet composition in each year. Subsequently, it projects energy demand, taking into account regulatory and autonomous improvements in efficiency (see Section 3.2.6). Fuel consumption is calculated together with the fuel mix (see Section 3.2.7);

this, combined with emissions factors (see Section 3.2.8), yields the emissions. Emissions are presented both in aggregate and per ship type and size category.

A schematic presentation of the emissions projection model is shown in Figure 78.

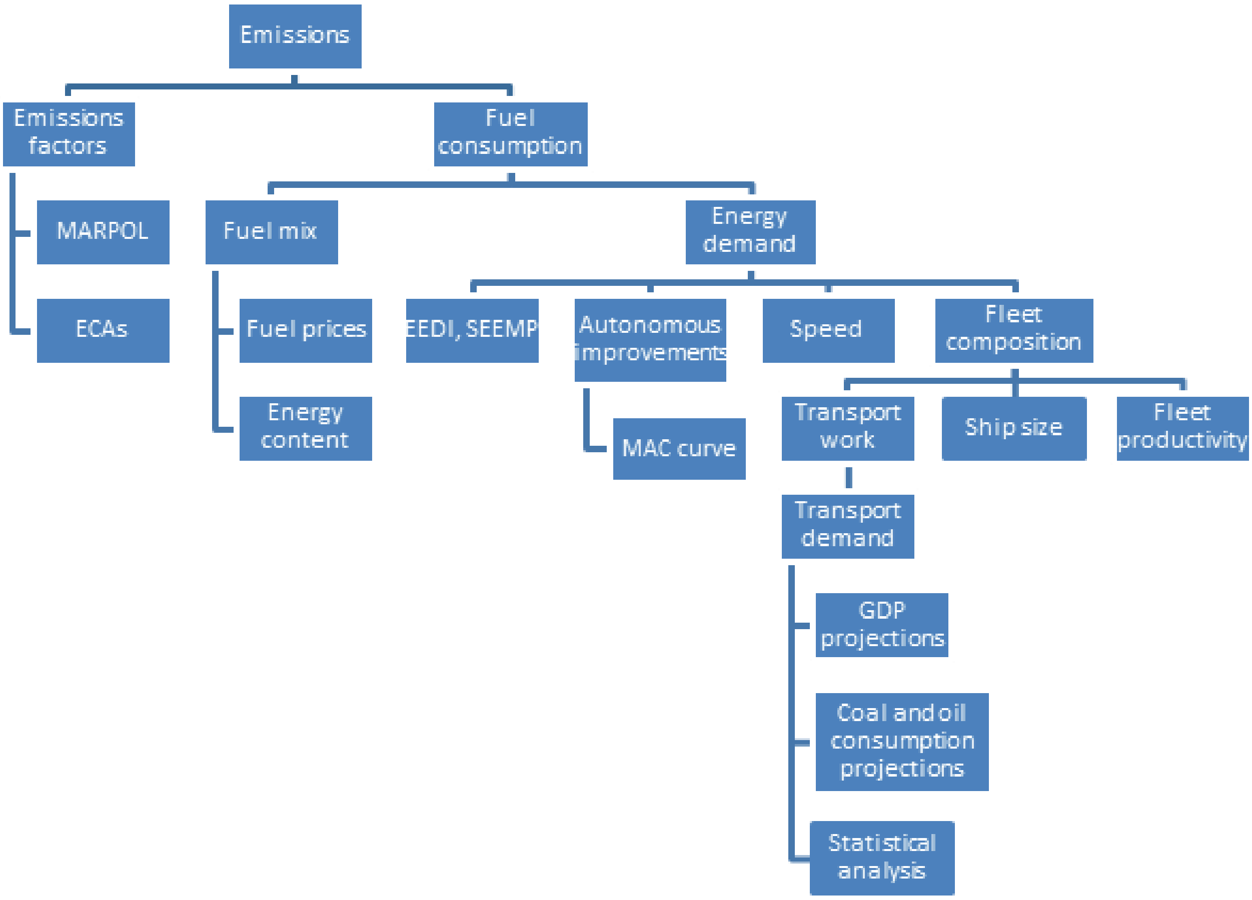


Figure 78: *Schematic presentation of the emissions projection model*

3.2.2 Base scenarios

Scenario construction is necessary to gain a view of what may happen in the future. In the Second IMO GHG Study 2009, background scenarios (SRES – see Section 3.1.1) were chosen from IPCC activities, since the 2009 study was primarily about emissions and it made sense to make the emissions scenarios consistent with other associated climate projections. Here, this study basically follows the same logic; while other visions of the future are available, and arguably equally plausible, since the overall subject of the present study is emissions, this study follows the earlier precedent and uses approaches and assumptions that will ultimately allow the projections to be used in climate studies. Moreover, data from climate projections studies include the essential socioeconomic and energy drivers that are essential for the emissions projections made here.

After its Fourth Assessment Report, published in 2007, IPCC decided to update the projections to be used in its next assessment report (AR5). The scenarios are called representative concentration pathways (RCPs). Their naming and use are best explained in the quote below:

> "The name 'representative concentration pathways' was chosen to emphasize the rationale behind their use. RCPs are referred to as *pathways* in order to emphasize that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. In addition, the term pathway is meant to emphasize that it is not only a specific long-term concentration or radiative forcing outcome, such as a stabilization level, that is of interest, but also the trajectory that is taken over time to reach that outcome. They are *representative* in that they are one of several different scenarios that have similar radiative forcing and emissions characteristics." (*Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies – IPCC Expert Meeting Report*, 2007).

A useful summary and guide to the origin and formulation of the RCP scenarios is provided by Wayne (2013). The "concentration" refers to that of CO_2 and the "pathways" are "representative" of possible outcomes of energy, population, policy and other drivers that will ultimately determine the concentration of CO_2 in the atmosphere. There are four main RCPs in use, detailed in Table 69.

Table 69 – *Descriptions and sources of representative concentration pathways*

RCP	Description	Source references	Model
RCP2.6 (or 3PD)	Peak in radiative forcing at ~3 W/m^2 before 2100 and decline	Van Vuuren et al., 2006, 2007	IMAGE
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100	Clarke et al., 2007; Wise et al., 2009	GCAM
RCP6.0	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100	Hijoka et al., 2008	AIM
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	Riahi et al., 2007	MESSAGE

The numbers associated with the RCPs (2.6–8.5) simply refer to resultant radiative forcing in W/m^2 by 2100. Further technical details of the RCPs are given in Moss et al. (2010). The RCPs cover a range of ultimate temperature projections by 2100 (i.e. global mean surface temperature increases over the pre-industrial period from GHGs), from around 4.9 °C (RCP8.5) to 1.5 °C in the most optimistic scenario (RCP2.6 or RCP3PD, where PD refers to peak and decline).

These RCPs are used to project shipping coal and liquid fossil fuel transport work, on the basis of a historical correlation with global coal and oil consumption (see Section 3.2.3), using the IAM energy demand projections of different fuel/energy types (EJ/yr). A set of GDP projections from the associated five SSP scenarios (see Kriegler et al., 2012) was used for non-fossil-fuel transport projections (see Section 3.2.3).

The five SSPs each have different narratives (Ebi et al., 2013) and are summarized in Table 70.

Table 70 – *Short narratives of shared socioeconomic pathways*

SSP number and name	Short narrative
SSP1: Sustainability	A world making relatively good progress towards sustainability, with ongoing efforts to achieve development goals while reducing resource intensity and fossil fuel dependency. It is an environmentally aware world with rapid technology development and strong economic growth, even in low-income countries.
SSP2: Middle of the road	A world that sees the trends typical of recent decades continuing, with some progress towards achieving development goals. Dependency on fossil fuels is slowly decreasing. Development of low-income countries proceeds unevenly.
SSP3: Fragmentation	A world that is separated into regions characterized by extreme poverty, pockets of moderate wealth and a large number of countries struggling to maintain living standards for a rapidly growing population.
SSP4: Inequality	A highly unequal world in which a relatively small, rich global elite is responsible for most GHG emissions, while a larger, poor group that is vulnerable to the impact of climate changes contributes little to the harmful emissions. Mitigation efforts are low and adaptation is difficult due to ineffective institutions and the low income of the large poor population.
SSP5: Conventional development	A world in which development is oriented towards economic growth as the solution to social and economic problems. Rapid conventional development leads to an energy system dominated by fossil fuels, resulting in high GHG emissions and challenges to mitigation.

This presented the problem of how to combine the RCPs with the SSPs and guidance was taken from Kriegler et al. (2012), as follows.

In principle, several SSPs can result in the same RCP, so in theory many BAU scenarios can be developed. However, in order to limit the number of scenarios, while still showing the variety in possible outcomes, it was decided to combine each SSP with one RCP, under the constraint that this combination is feasible. The SSPs are thus aligned with the RCPs on the basis of their baseline warming. Increased mitigation effort would potentially result in less fossil fuel transport, probably somewhat lower economic growth until 2050 and therefore probably lower transport demand and maritime emissions.

This procedure has resulted in the following scenarios:

- RCP8.5 combined with SSP5;
- RCP6 combined with SSP1;
- RCP4.5 combined with SSP3;
- RCP2.6 combined with SSP4/2.

In all the work by IPCC on future scenarios of climate and its impacts, it has never assumed a BAU underlying growth scenario. IPCC has always argued that it does not produce any one emissions scenario that is more likely than another, ergo no overall BAU scenario exists. This is therefore reflected in this study and no one basic RCP/SSP scenario that underlies the shipping emissions scenarios can be considered more likely than another: they are all BAU scenarios.

3.2.3 Transport demand projections

Transport work data (in billion tonne-miles per year) were kindly provided for the years 1970–2012 by UNCTAD (see Annex 7). The categories considered were crude oil and oil products (combined), coal bulk dry cargo, non-coal bulk dry cargo (iron ore, coal, grain, bauxite and aluminia and phosphate, all combined) and other dry cargo (essentially considered as container and other similar purpose shipping). The data were for international shipping only. Transport work (i.e. tonne-miles), as opposed to the absolute amount transported (tonnes), is considered to be a better variable to predict transport demand and emissions. However, this assumes that average hauls remain constant: this is in fact borne out by the data and the two variables correlate significantly with an R^2 value of >0.95.

Cargo types were treated separately, as it is evident from the data that they are growing at different rates and subject to different market demands.

Thus, as a refinement to the approach taken in the Second IMO GHG Study 2009, the current study has developed the methodology of CE Delft (2012), which considered different ship types and has gone a step further by decoupling the transport of fossil fuel (oil and coal products) from GDP, as in the RCP/SSP scenarios in which fossil fuel use is decoupled from economic development.

In order to predict ship transport work (by type, or total), the general principle is to look for a predictor variable that has a meaningful physical relationship with it. In previous scenario studies, global GDP has been used as a predictor for total ship transport work, in that it has a significant positive statistical correlation, and is also meaningful in the sense that an increase in global GDP is likely to result in an increase in global trade and therefore ship transport of goods.

If an independent assessment of the predictor variable (e.g. GDP) is available for future years, this allows prediction of ship transport work. It assumes that such a physical relationship is as robust for the future as it has been for the past. Previously, a linear assumption has been made, i.e. a linear regression model has been used between the ratio of historical transport work to historical GDP against time. In this study, this assumption has been improved by the use of a non-linear model, commonly used in economics, that assumes classic emergence, growth and maturation phases.

However, the assumption of a historical relationship between coal and oil transport by shipping and GDP inherently means that GDP growth and fossil fuel use will remain tightly coupled in the future, i.e. that with increased economic growth, it is not possible to limit fossil fuel use. This clearly does not reflect certain desired policy and environmental outcomes, where a decrease in fossil fuel dependence and an increase in GDP can be achieved.

In order to overcome this, this study has investigated the relationship between historical ship-transported coal and oil and historical global coal and oil consumption. This relationship has been found to be as robust as that between historical coal and oil transport work and historical GDP ($r2 > 0.9$) and is arguably a better physical relationship than between fossil fuel transported by shipping and GDP. The RCP scenarios have provided projections of fossil fuel consumption, split between coal and oil. This conveniently allows us to use these predictor variables to determine potential future ship transport of coal and oil but decoupled from GDP. Other ship transported goods and products remain predicted by independent future GDP assessments provided by the RCPs.

In all cases of ship-transported products, the non-linear Verhulst regression model (with S-shaped curve) is used to reflect more realistic market behaviour rather than continued linear relationships. The historical data on transport work (by type) and demand and GDP are shown in Figure 79.

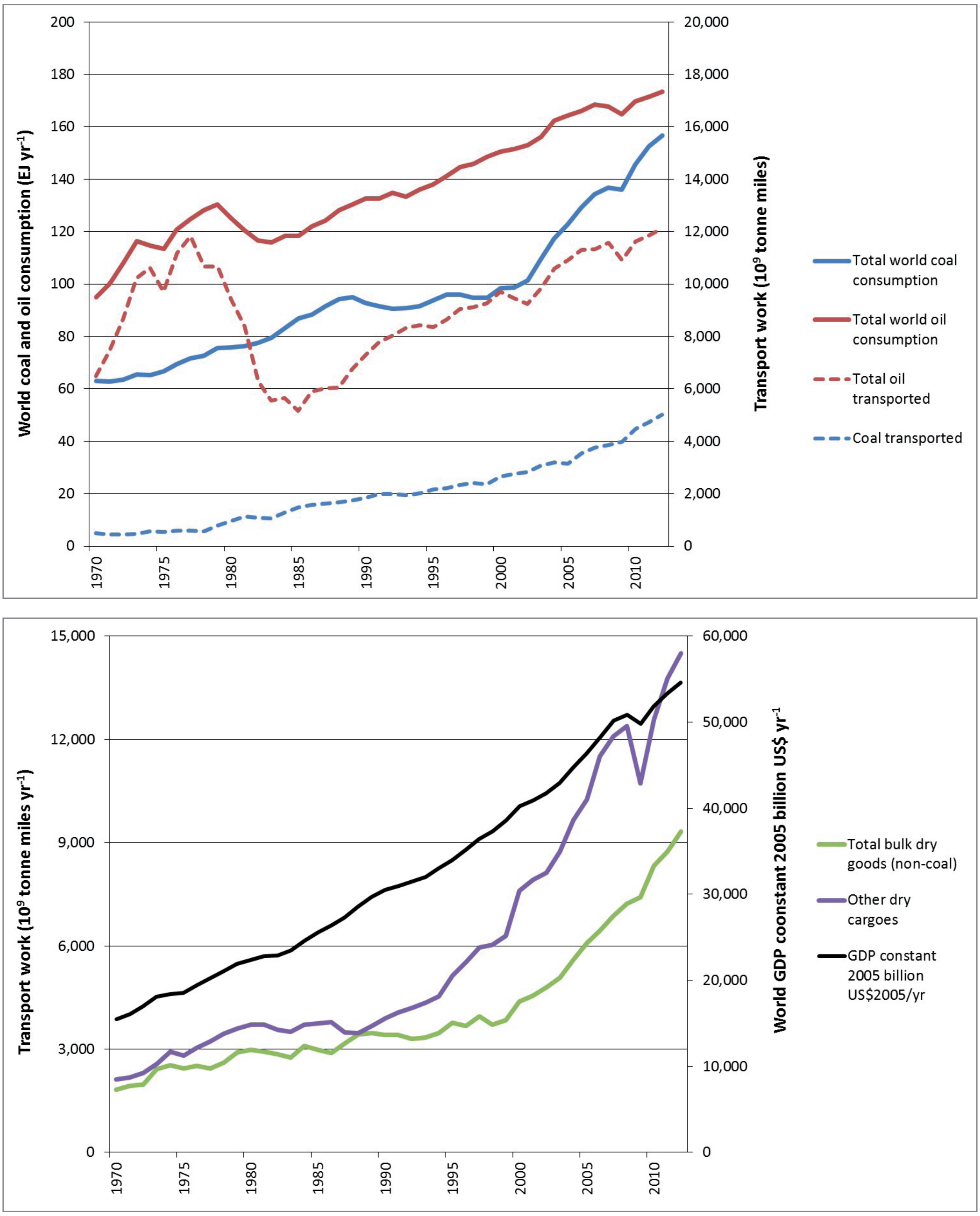


Figure 79: *Historical data on world coal and oil consumption, coal and oil transported (upper panel), total (non-coal) bulk dry goods, other dry cargoes and global GDP (lower panel)*

Predicted proxy data of (separate) coal and oil demand and GDP were provided by the RCP/SSP scenarios and the associated underlying IAMs. In one case (RCP6.0), fossil energy demand data could not be obtained and data from the IAM GCAM were used.

3.2.4 Fleet productivity

For the emissions projection, the development of the tonnage of the different ship types is determined by a projection of the ships' productivity, defined as transport work per deadweight tonne. More precisely, the fleet is assumed to grow if, given the projected productivity, the expected transport demand cannot be met by the fleet. On the other hand, if, given the projected productivity, the expected transport demand could be met by a smaller fleet, the active fleet is not assumed to decrease. This means that ships are assumed to reduce their cargo load factor – i.e. become less productive – rather than being scrapped or laid up or reducing their speed.

The projection of ship productivity is based on the historical productivity of the ship types. For all ship types, the 2012 productivity of the ship types is lower than the long-term historical average (see Annex 7 for more details). This is assumed to be caused by the business cycle, rather than by structural changes in the shipping market; this study therefore applies a future productivity development that converges towards the ship type's average productivity, reverting back to the 25-year[1] mean value within 10 years, i.e. until 2022.

The ship productivity indices used in the emissions projection model, which can be specified per five-year period, are given in Table 71.

Table 71 – *Ship type productivity indices used in emissions projection model*

	2012	2017	2022–2050
Liquid bulk vessels	100	113	125
Dry bulk vessels	100	102	104
Container ships	100	109	118
General cargo vessels	100	109	118
Liquefied gas carriers	100	106	113
All other vessels	100	100	100

3.2.5 Ship size development

In the emissions projection model, ship types are divided into the same ship size categories as in the emissions inventory model. For the emissions projection, the future number of ships per size category has to be determined.

The distribution of ships over their size categories can be expected to change over time according to the number of ships that are scrapped and enter the fleet, as well as their respective sizes.

In the emissions projection model, it is assumed that total capacity per ship type meets projected transport demand, that all ships have a uniform lifetime of 25 years and that the average size of the ships per size category will not change compared to the base year 2012, while the number of ships per bin size will.

The development of the distribution of vessels over the size categories until 2050 is determined based on a literature review, taking into account historical developments in distribution, expected structural changes in the markets and infrastructural constraints. In Table 72 and Table 73, 2012 distributions and expected distributions for 2050 are presented.

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[1] Due to a lack of historical data, for container vessels and liquefied gas vessels we take the average of the 1999–2012 period, i.e. a 13-year period.

Table 72 – *2012 distribution and expected distribution 2050 of container and LG carriers over bin sizes*

Ship type	Bin sizes (dwt)	Distribution in terms of numbers	
		2012	2050
Container vessels	0–999	22%	22%
	1,000–1,999 TEU	25%	20%
	2,000–2,999 TEU	14%	18%
	3,000–4,999 TEU	19%	5%
	5,000–7,999 TEU	11%	11%
	8,000–11,999 TEU	7%	10%
	12,000–14,500 TEU	2%	9%
	14,500–+ TEU	0.2%	5%
Liquefied gas carriers	0–49,000 m^3	68%	32%
	50,000–199,999 m^3	29%	66%
	>200,000 m^3	3%	2%

Table 73 – *2012 distribution and expected distribution 2050 of oil/chemical tankers and dry bulk carriers over bin sizes*

Ship type	Bin sizes (dwt)	Distribution in terms of numbers	
		2012	2050
Oil/chemical tankers	0–4,999	1%	1%
	5,000–9,999	1%	1%
	10,000–19,999	1%	1%
	20,000–59,999	7%	7%
	60,000–79,999	7%	7%
	80,000–119,999	23%	23%
	120,000–199,999	17%	17%
	200,000–+	43%	43%
Dry bulk carriers	0–9,999	1%	1%
	10,000–34,999	9%	6%
	35,000–59,999	22%	20%
	60,000–99,999	26%	23%
	100,000–199,999	31%	40%
	200,000–+	11%	10%

For the other ship types, the 2012 size distribution is presumed not to change until 2050.

3.2.6 EEDI, SEEMP and autonomous improvements in efficiency

The projection of the future emissions of maritime shipping requires the projection of future developments in the fleet's fuel efficiency. In the period up to 2030, this study distinguishes between market-driven efficiency changes and changes required by regulation, i.e. EEDI and SEEMP. Market-driven efficiency changes are modelled using a MACC, assuming that a certain share of the cost-effective abatement options is implemented. In addition, regulatory requirements may result in the implementation of abatement options irrespective of their cost-effectiveness. Between 2030 and 2050, there is little merit in using MACCs, as the uncertainty about the costs of technology and its abatement potential increases rapidly for untested technologies. In addition, regulatory improvements in efficiency for the post 2030 period have been discussed but not defined. This study therefore takes a holistic approach towards ship efficiency after 2030.

Our MACC is based on data collected for IMarEST and submitted to the IMO in MEPC 62/INF.7. The cost curve uses data on the investment and operational costs and fuel savings of 22 measures to improve the energy efficiency of ships, grouped into 15 groups (measures within one group are mutually exclusive and cannot be implemented simultaneously on a ship). The MACC takes into account that some measures can be implemented on specific ship types only. It is also assumed that not all cost-effective measures are implemented immediately but that there is a gradual increase in the uptake of cost-effective measures over time.

EEDI will result in more efficient ship designs and consequently in ships that have better operational efficiency. In estimating the impact of 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 (see Annex 7 for a more detailed explanation).

It is likely that improvements in efficiency will continue after 2030, although it is impossible to predict what share of the improvements will be market-driven and what regulation-driven. Because of the high uncertainty of technological development over such a timescale, two scenarios are adopted. One coincides with the highest estimates in the literature (excluding speed and alternative fuels, which are accounted for elsewhere): a 60% improvement over current efficiency levels. The second has more conservative estimates: a 40% improvement over current levels.

3.2.7 Fuel mix: market- and regulation-driven changes

Two main factors will determine the future bunker fuel mix of international shipping:

1. the relative costs of using the alternative fuels;
2. the relative costs of the sector's alternative options for compliance with environmental regulation.

The environmental regulations that can be expected to have the greatest impact on the future bunker fuel mix are the SO_x and NO_x limits set by the IMO (regulations 13 and 14 of MARPOL Annex VI), which will become more stringent in the future. This will also apply in any additional ECAs that may be established in the future.

In the emissions projection model, two fuel mix scenarios are considered, a low LNG/constant ECAs case and a high LNG/extra ECAs case.

In the low LNG/constant ECAs case, the share of fuel used in ECAs will remain constant. In this case, it is assumed that half of the fuel currently used in ECAs is used in ECAs that control SO_x only, and the other half in ECAs where both SO_x and NO_x emissions are controlled. In this scenario, NO_x controls are introduced in half of the ECAs from 2016 and in the other half from 2025. In this case, demand for LNG is limited.

The high LNG/extra ECAs case assumes that new ECAs will be established in 2030, doubling the share of fuel used in ECAs. In this case, there is a strong incentive to use LNG to comply with ECAs. In Table 74, the fuel mix is given per scenario.

Table 74 – *Fuel mix scenarios used for emissions projection (mass %)*

High LNG/extra ECAs case	LNG share	Distillates and LSHFO*	HFO
2012	0%	15%	85%
2020	10%	30%	60%
2030	15%	35%	50%
2050	25%	35%	40%

Low LNG/constant ECAs case	LNG share	Distillates and LSHFO*	HFO
2012	0%	15%	85%
2020	10%	30%	60%
2030	15%	35%	50%
2050	25%	35%	40%

* Sulphur content of 1% in 2012 and 0.5% from 2020.

Both scenarios assume that the global 0.5% sulphur requirement will become effective in 2020. A later enforcement (2025) is accounted for in a sensitivity analysis.

3.2.8 Emissions factors

The emissions factors for NO_x and SO_2 will change as a result of MARPOL Annex VI regulations, and the HFC emissions factors will change owing to the R-22 phase-out. The impact of these regulations on the emissions factors is described below.

NO_x emissions factors decline over time as Tier I engines replace pre-2000 engines and later Tier II engines replace pre-2000 and Tier I engines. Scenarios in which LNG, which has low NO_x emissions, is given preference in ECAs are modelled. When the share of fuel used in ECAs exceeds the share of LNG in the fuel mix, exhaust gas treatment or engine modifications are used to meet Tier III NO_x regulation in ECAs, thus lowering the average emissions factor per unit of fuel. The resulting emissions factors are shown in Table 75. If LNG is used to a higher degree outside ECAs, emissions factors and total NO_x emissions will be lower, as more ships using HFO or MGO will use other means to meet Tier III emissions levels.

Table 75 – *NO_x emissions factors in 2012, 2030 and 2050 (g/g fuel)*

Scenario	Fuel type	Year		
		2012	2030	2050
Global average, low ECA, low LNG scenario	HFO	0.090	0.083*	0.076
	MGO	0.096	0.088	0.081
	LNG	0.014	0.014	0.014
Global average, high ECA, high LNG scenario	HFO	0.090	0.083	0.069
	MGO	0.096	0.089	0.073
	LNG	0.014	0.014	0.014

* The lower emissions factor for NO_x in the low LNG scenario in 2030 is the result of the fact that this scenario requires more ships to use selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) to meet Tier III instead of switching to LNG.

For the SO_x emissions factors, it is assumed that LNG and MGO will be used to meet the ECA fuel requirements and scrubbers will be used to reduce the effective emissions factors of fuels used outside ECAs to 0.5% from 2020 onwards.

Emissions from HFCs result from leaks from cooling systems and air conditioners. They do not emerge from fuel combustion but are assumed to be driven by the number of ships. There are several HFCs with different GWPs. The most relevant are presented in Table 76.

Table 76 – *HFCs used on board ships*

Substance	GWP	Notes
R-22	1,810	R-22 (chlorodifluoromethane) has been the dominant refrigerant in air conditioners used on board ships. The production of R-22 has been phased out under the Montreal Protocol in many countries. It is assumed that it is used only in vessels built before 2000.
R134a	1,300	R134a (1,1,1,2-Tetrafluoroethane) is used as a replacement for R-22 in vessels built from 2000 onwards.
R404a	3,700	R404a is a mixture of R125, R143a and R134a. It is used predominantly in fishing vessels but also in freezing and cooling equipment in other vessels.

Assuming that ships built before 2000 have a 25-year lifetime, R-22 will have become obsolete in shipping by 2025. The study does not model that other HFCs will be phased out, that air conditioner leakage rates will change or that other coolants will replace HFCs.

The emissions factors of other relevant substances are assumed to remain constant over time.

3.3 Results

3.3.1 Transport demand

The projections of GDP are shown in Figure 80, where SSP5 (associated in this study with RCP8.5) results in a world GDP that is approximately seven times greater than present-day values by 2050 (at constant 2005 US$); SSP3 (the lowest) projects GDP to triple in the same period.

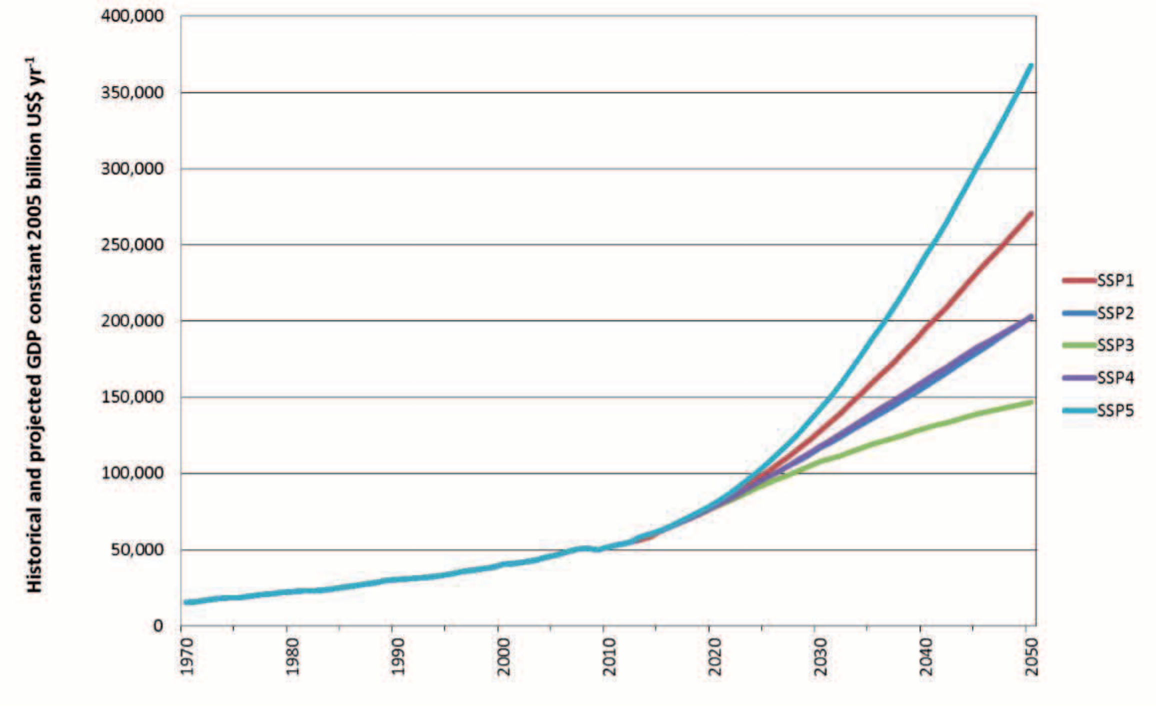

Figure 80: *Historical data to 2012 on global GDP (constant 2005 US$ billion/yr) coupled with projections of GDP from SSP1 through to SSP5 by 2050*

Historical and projected data on consumption of coal and oil were taken from the *Statistical Review of World Energy 2014* (BP, 2014) and RCPs (see Figure 81).

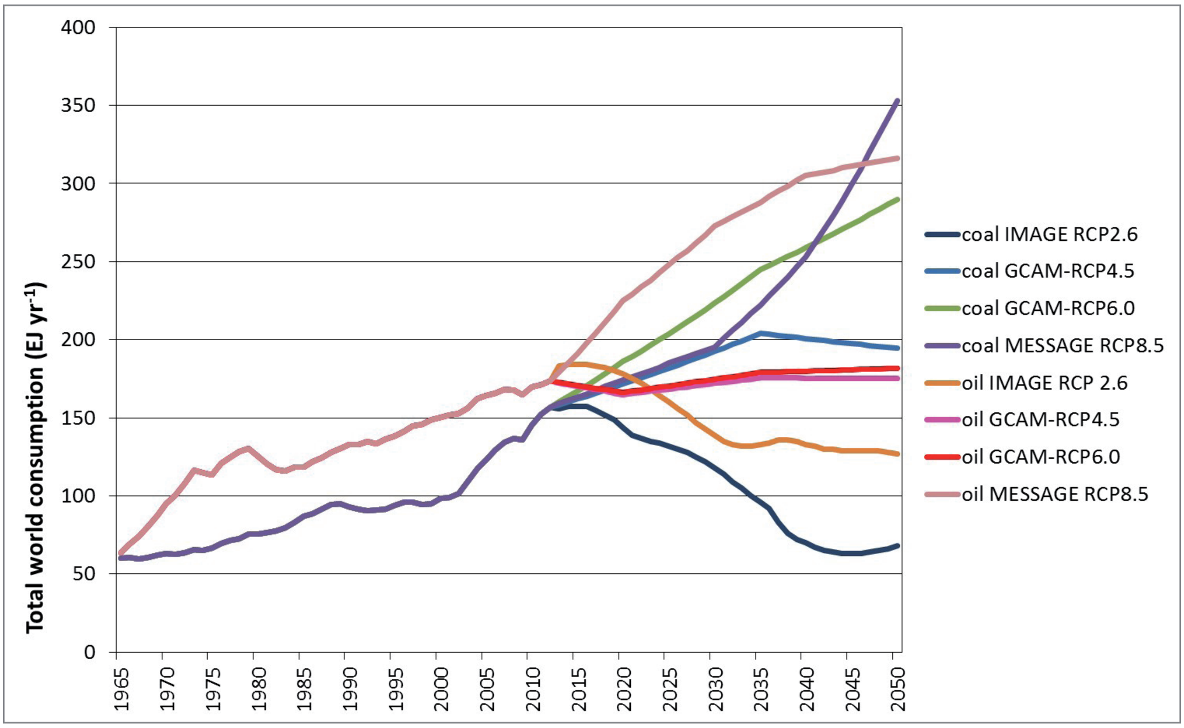

Figure 81: *Historical data to 2012 on global consumption of coals and oil (EJ/yr) coupled with projections from RCP2.6 through to RCP8.5 by 2050*

The GDP projections were used to project shipping transport work for non-coal combined bulk ship traffic and other dry cargo ship traffic demand, resulting in the ranges of transport shown in Figure 82.

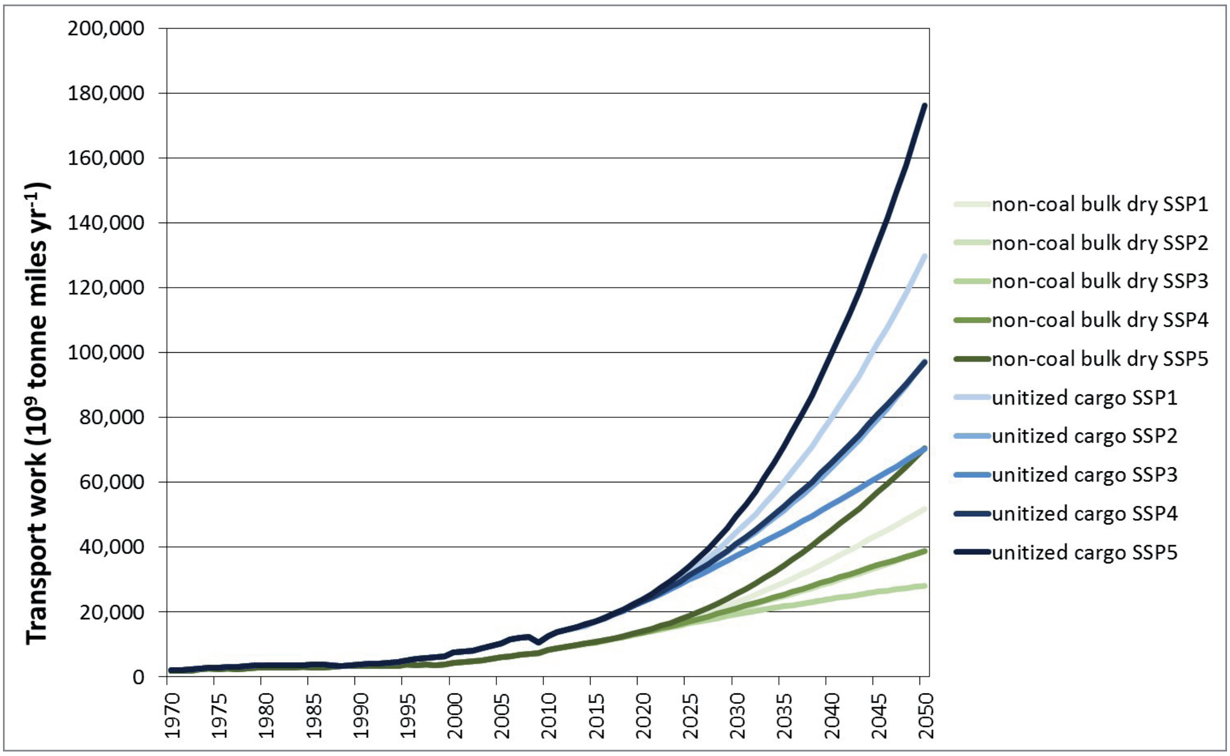

Figure 82: *Historical data to 2012 on global transport work for non-coal combined bulk dry cargoes and other dry cargoes (billion tonne-miles) coupled with projections driven by GDPs from SSP1 through to SSP5 by 2050*

Lastly, the decoupling of future use of fossil fuel from GDP is illustrated by the decline in the use of coal and oil in some scenarios, shown in Figure 83. This is in line with the storylines of the lower RCP scenarios (e.g. RCP2.6/3PD and RCP4.5).

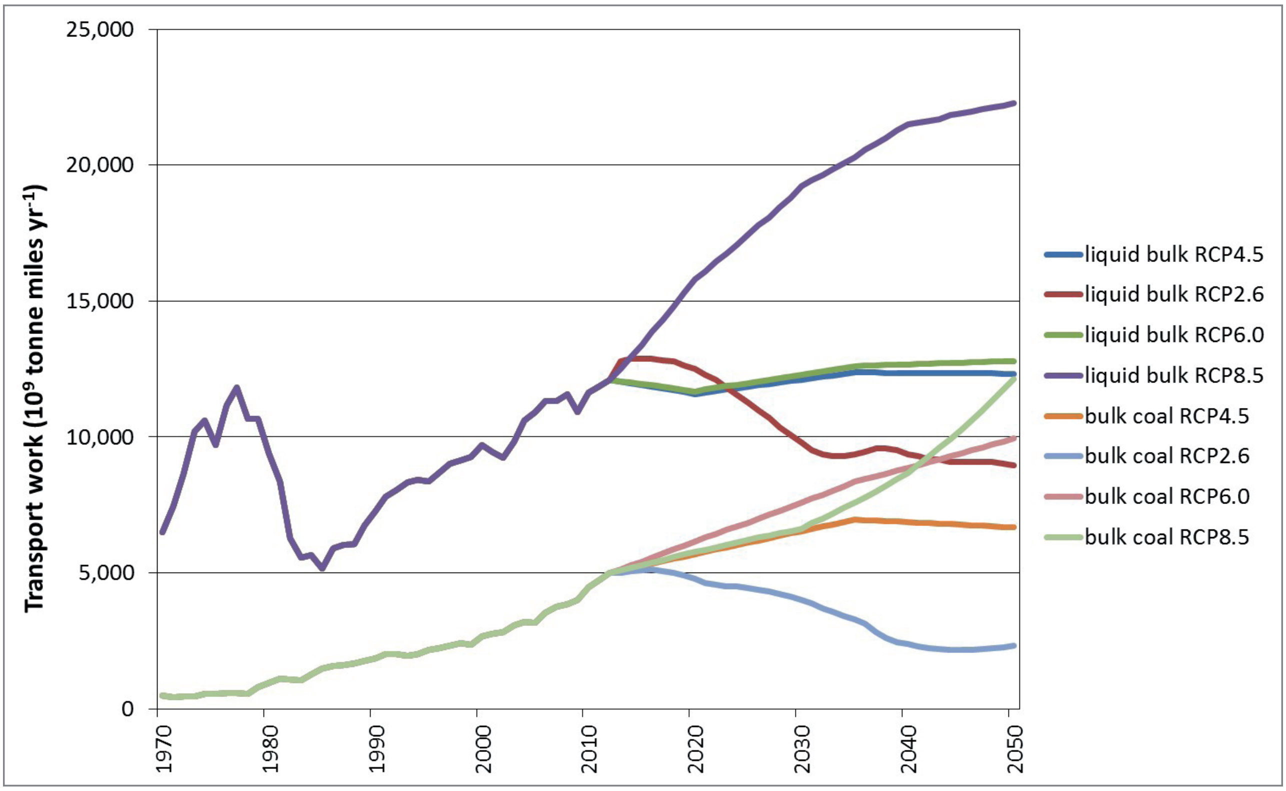

Figure 83: *Historical data to 2012 on global transport work for ship-transported coal and liquid fossil fuels (billion tonne-miles) coupled with projections of coal and energy demand driven by RCPs 2.6, 4.5, 6.0 and 8.5 by 2050*

3.3.2 Projected CO_2 emissions

Using the model and input described above, this study has projected CO_2 emissions for 16 scenarios:

- four RCP/SSP-based scenarios of transport demand, disaggregated into cargo groups;
- for each of these four scenarios, one ECA/fuel mix scenario that keeps the share of fuel used in ECAs constant over time and has a slow penetration of LNG in the fuel mix, and one that projects a doubling of the amount of fuel used in ECAs and has a higher share of LNG in the fuel mix;
- for each of the eight combinations of demand and ECA scenarios, two efficiency trajectories, one assuming an ongoing effort to increase the fuel-efficiency of new and existing ships after 2030, resulting in a 60% improvement over the 2012 fleet average by 2050, and the other assuming a 40% improvement by 2050.

The scenarios and their designations are summarized in Table 77.

Table 77 – *Overview of assumptions per scenario*

Scenario	**RCP scenario**	**SSP scenario**	**Fuel mix (LNG, ECA)**	**Efficiency improvement 2050**
1	RCP8.5	SSP5	high LNG/extra ECA	High
2	RCP6.0	SSP1	high LNG/extra ECA	High
3	RCP4.5	SSP3	high LNG/extra ECA	High
4	RCP2.6	SSP4	high LNG/extra ECA	High
5	RCP8.5	SSP5	high LNG/extra ECA	Low
6	RCP6.0	SSP1	high LNG/extra ECA	Low
7	RCP4.5	SSP3	high LNG/extra ECA	Low
8	RCP2.6	SSP4	high LNG/extra ECA	Low
9	RCP8.5	SSP5	low LNG/no ECA	High
10	RCP6.0	SSP1	low LNG/no ECA	High
11	RCP4.5	SSP3	low LNG/no ECA	High
12	RCP2.6	SSP4	low LNG/no ECA	High
13 (BAU)	RCP8.5	SSP5	low LNG/no ECA	Low
14 (BAU)	RCP6.0	SSP1	low LNG/no ECA	Low
15 (BAU)	RCP4.5	SSP3	low LNG/no ECA	Low
16 (BAU)	RCP2.6	SSP4	low LNG/no ECA	Low

The resulting projections of CO_2 emissions are presented graphically in Figure 84 and in tabular form in Table 78. The average emissions growth across all scenarios in 2020 amounts to 7% of 2012 emissions. For 2030, the average emissions increase is 29% and for 2050 95%. Some scenarios have higher growth, such as those with high economic growth (SSP5) and high fossil fuel consumption (RCP8.5), while the scenarios with low economic growth (SSP3) and moderate fossil fuel use (RCP4.5) have the lowest emissions growth. All BAU scenarios show an increase in emissions, ranging from 50% to 250% in 2050.

Scenarios with high improvements in efficiency after 2030 (1–4 and 9–12) exhibit either decelerating emissions growth after 2035 or 2040 or a downward trend after those years, when combined with moderate economic growth and decreasing fossil fuel use. Figure 84 shows that in many cases the lines representing high-efficiency scenarios cross the lines of low-efficiency but higher growth scenarios. This suggests that, to some extent, more ambitious improvements in efficiency can offset higher transport demand.

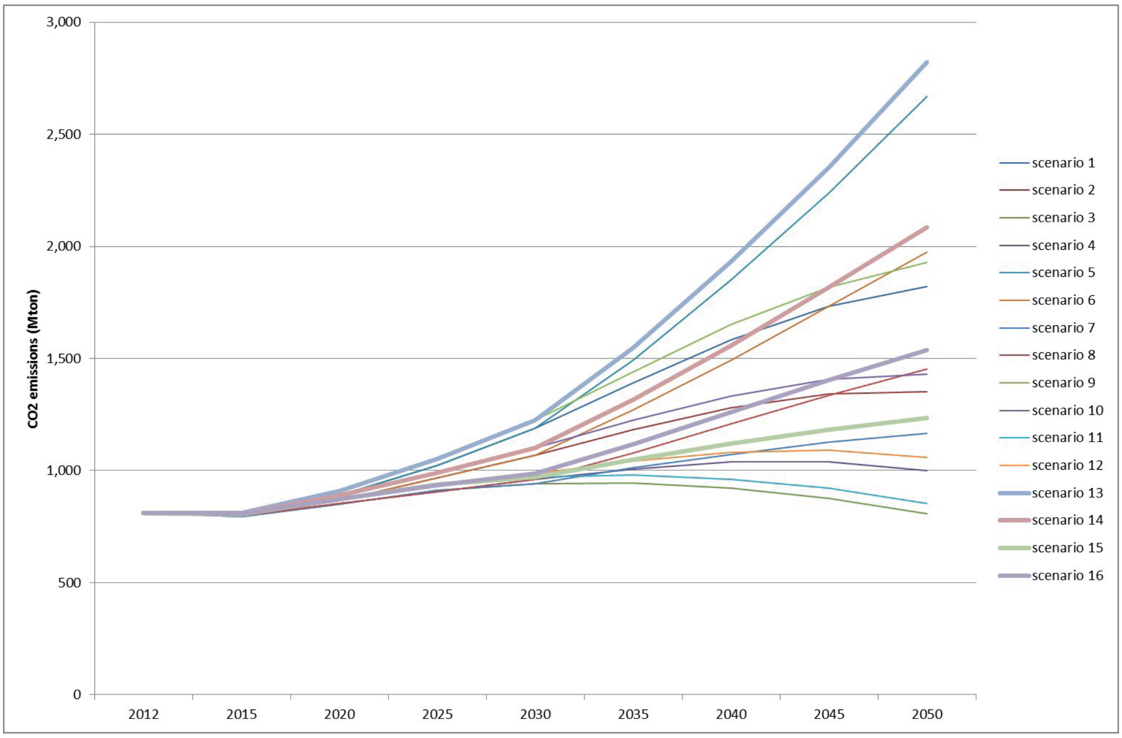

Figure 84: *CO_2 emissions projections*

Table 78 – *CO_2 emissions projections (million tonnes)*

Scenario	**Base year**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Scenario 1	810	800	890	1,000	1,200	1,400	1,600	1,700	1,800
Scenario 2	810	800	870	970	1,100	1,200	1,300	1,300	1,400
Scenario 3	810	800	850	910	940	940	920	880	810
Scenario 4	810	800	850	910	960	1,000	1,000	1,000	1,000
Scenario 5	810	800	890	1,000	1,200	1,500	1,800	2,200	2,700
Scenario 6	810	800	870	970	1,100	1,300	1,500	1,700	2,000
Scenario 7	810	800	850	910	940	1,000	1,100	1,100	1,200
Scenario 8	810	800	850	910	960	1,100	1,200	1,300	1,500
Scenario 9	810	810	910	1,100	1,200	1,400	1,700	1,800	1,900
Scenario 10	810	810	890	990	1,100	1,200	1,300	1,400	1,400
Scenario 11	810	800	870	940	970	980	960	920	850
Scenario 12	810	810	870	930	990	1,000	1,100	1,100	1,100
Scenario 13 (BAU)	810	810	910	1,100	1,200	1,500	1,900	2,400	2,800
Scenario 14 (BAU)	810	810	890	990	1,100	1,300	1,600	1,800	2,100
Scenario 15 (BAU)	810	800	870	940	970	1,000	1,100	1,200	1,200
Scenario 16 (BAU)	810	810	870	930	990	1,100	1,300	1,400	1,500

Figure 85 shows how emissions projections depend on different transport demand scenarios. The graph shows the emissions trajectories for the four BAU scenarios, all assuming modest increase in efficiency after 2030, a constant share of fuel used in ECAs and a modest increase in the share of LNG in the fuel mix. It demonstrates that the highest transport demand scenario results in emissions that are over twice as large as the lowest transport demand scenario. This ratio is also apparent in the other scenario families.

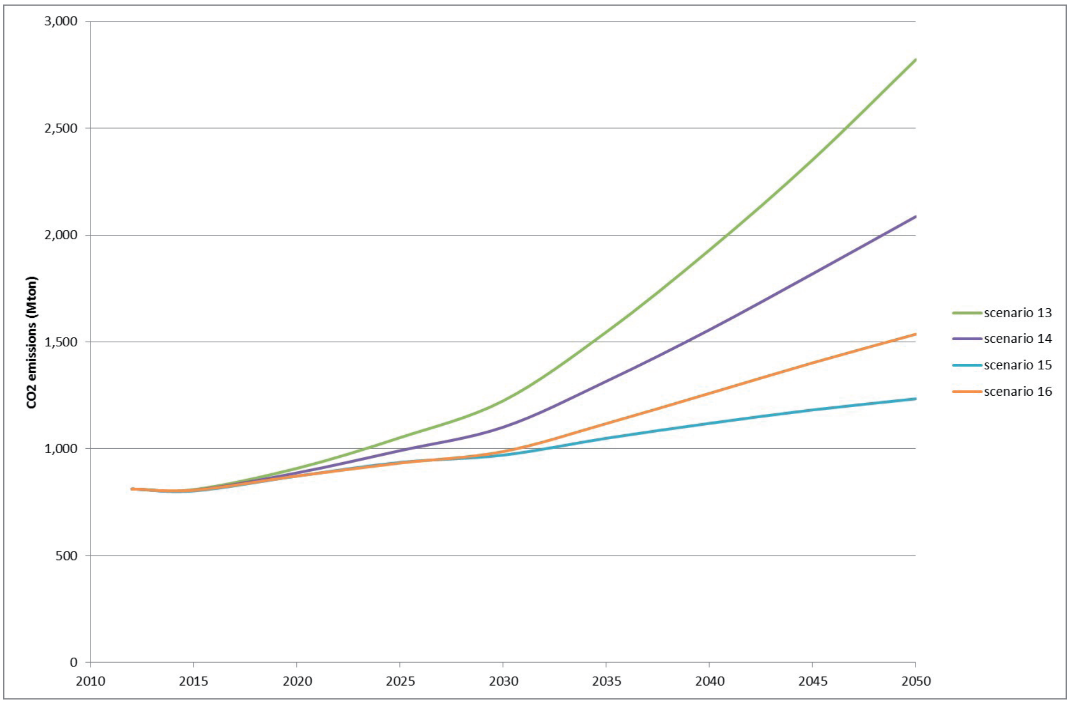

Figure 85: *Emissions projections for the BAU transport demand scenarios*

Figure 86 analyses the impact of the fuel/ECA and efficiency scenarios. It shows for one transport demand scenario (RCP8.5 SSP5, i.e. high economic growth and high fossil fuel use) the impact of different assumptions on the other scenario parameters. The two lower projections assume an efficiency improvement of 60% instead of 40% over 2012 fleet average levels in 2050. The first and third projections have a 25% share of LNG in the fuel mix in 2050 instead of a share of 8%. Under these assumptions, improvements in efficiency have a larger impact on emissions trajectories than changes in the fuel mix.

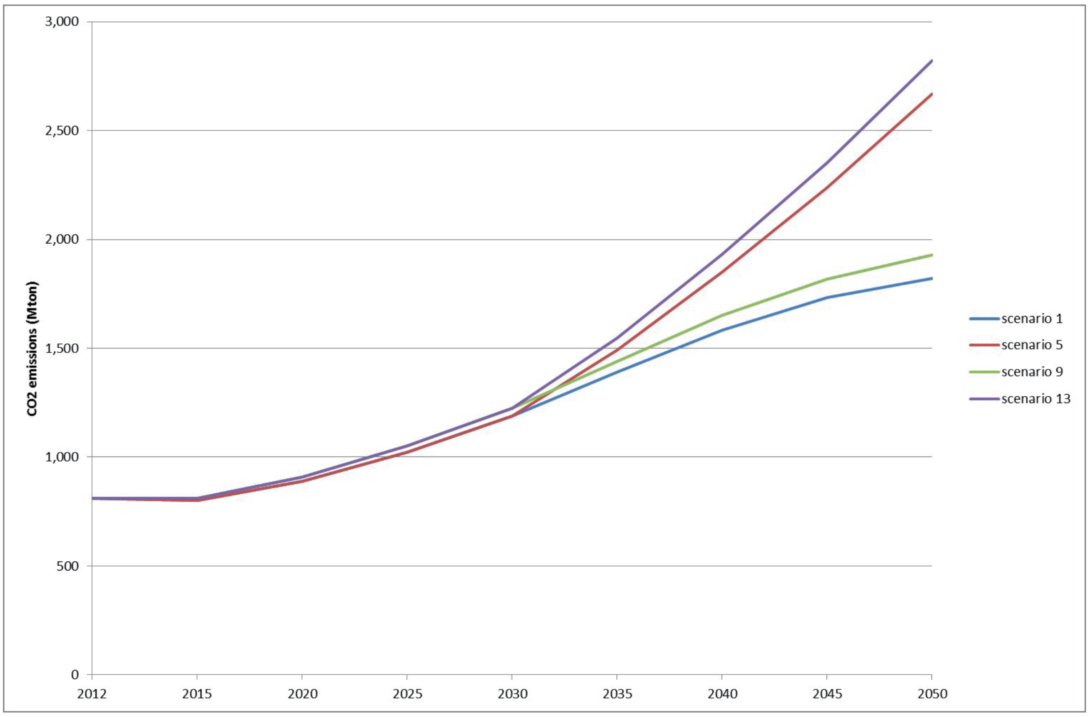

Figure 86: *Output for demand scenarios under conditions of high LNG/extra ECA and high efficiency*

Figure 87 shows the contribution of various ship types to the total emissions in one scenario. Unitized cargo vessels (container and general cargo ships) are projected to show a rapid increase in number and in emissions. In comparision, emissions from other ship types, such as dry bulk and liquid bulk carriers, grow at a lower rate or decline as a result of improvements in efficiency and (in this case) limited growth of transport demand. While in other scenarios the relative contributions of ship types will be different, all scenarios show a larger increase in emissions from unitized cargo ships than from other ship types. While unitized cargo ships accounted for a little over 40% of maritime transport CO_2 emissions in 2012, they are projected to account for 50% or more by 2025 in all scenarios. In scenarios with a high economic growth, they are projected to account for two thirds by 2045 or 2050.

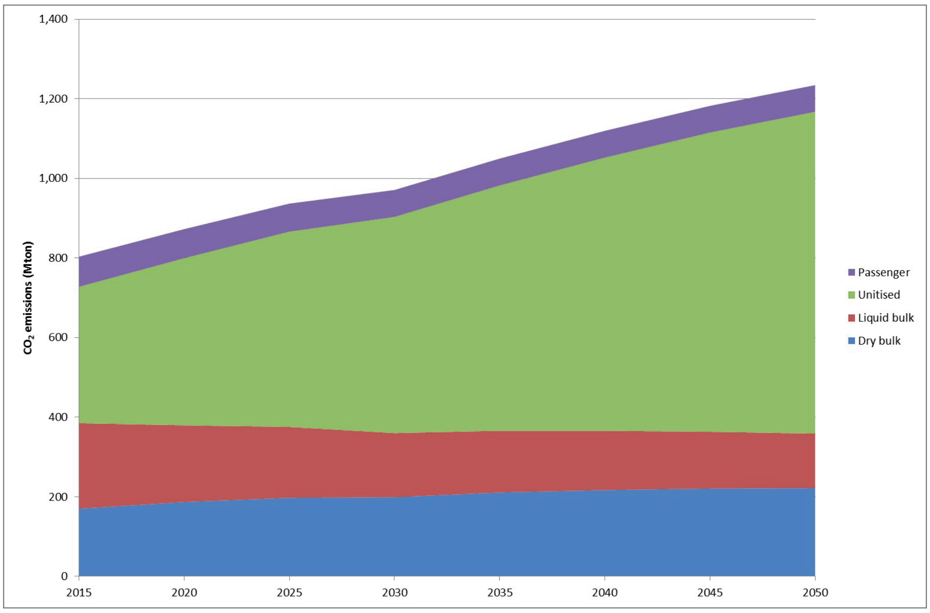

Figure 87: *Specific output for scenario 15 (RCP4.5, SSP3, low LNG/no additional ECA, low efficiency)*

3.3.3 Results for other substances

Table 79 shows the projection of the emissions of other substances. For each year, the median, minimum and maximum emissions are expressed as a share of their 2012 emissions. Most emissions increase in parallel with CO_2 and fuel, with minor changes due to changes in the fuel mix. However, there are some notable exceptions:

- Methane emissions are projected to increase rapidly (albeit from a very low base) as the share of LNG in the fuel mix increases. In high ECA/high LNG scenarios, the increase is naturally higher than in the constant ECA/low LNG scenarios.
- HFC emissions result from leakage of refrigerants and coolants and are a function of the number of ships rather than of the amount of fuel used.
- Emissions of nitrogen oxides increase at a lower rate than CO_2 emissions as a result of the replacement of old engines by Tier I and Tier II engines and the increasing share of LNG in the fuel mix. In addition, the engines of new ships in ECAs will meet Tier III requirements, so scenarios that assume an increase in the share of fuel used in ECAs show a slower increase in NO_x emissions or in some scenarios a decrease.
- Emissions of sulphurous oxides and PM emissions also increase at a lower rate than CO_2 emissions. This is driven by MARPOL Annex VI requirements on the sulphur content of fuels (which also impact PM emissions). In scenarios that assume an increase in the share of fuel used in ECAs, the impact of these regulations is stronger.

Table 79 – *Emissions of CO_2 and other substances in 2012, 2020 and 2050 (million tonnes)*

		Scenario	**2012**	**2020**	**2050**
			index (2012 = 100)	**index (2012 = 100)**	**index (2012 = 100)**
Greenhouse gases	CO_2	Low LNG	100	108 (107–112)	183 (105–347)
		High LNG	100	106 (105–109)	173 (99–328)
	CH_4	Low LNG	100	1,600 (1,600–1,700)	10,500 (6,000–20,000)
		High LNG	100	7,550 (7,500–7,900)	32,000 (19,000–61,000)
	N_2O	Low LNG	100	108 (107–112)	181 (104–345)
		High LNG	100	105 (104–109)	168 (97–319)
	HFC		100	106 (105–108)	173 (109–302)
	PFC		–	–	–
	SF_6		–	–	–
Other relevant substances	NO_x	Constant ECA	100	107 (106–110)	161 (93–306)
		More ECAs	100	99 (98–103)	130 (75–247)
	SO_x	Constant ECA	100	64 (63–66)	30 (17–56)
		More ECAs	100	55 (54–57)	19 (11–37)
	PM	Constant ECA	100	77 (76–79)	84 (48–159)
		More ECAs	100	65 (64–67)	56 (32–107)
	NMVOC	Constant ECA	100	108 (107–112)	183 (105–348)
		More ECAs	100	106 (105–110)	175 (101–333)
	CO	Constant ECA	100	112 (111–115)	206 (119–392)
		More ECAs	100	123 (122–127)	246 (142–468)

3.3.4 Sensitivity to productivity and speed assumptions

The scenario approach to these results allows an evaluation of the sensitivity of maritime transport emissions to economic growth, fossil fuel energy use, marine fuel mix, market-driven or regulatory efficiency changes and maritime emissions regulation.

This section discusses the most important remaining sensitivity: the impact of productivity and speed assumptions on emissions projections.

All the projections presented here assume that the productivity of the fleet returns to long-term average values without increasing the emissions of individual ships. This is possible if the cause of the current low productivity is a low cargo load factor of ships. If, however, fleet productivity has decreased because ships have been laid up or have slowed down, a return to long-term average productivity levels would result in higher emissions.

There are no data that enable the evaluation of whether cargo load factors are below their long-term average levels and if so by how much. The data on speed and days at sea do show that ships have slowed down and reduced their number of days at sea since 2007. Productivity of container ships and bulk carriers in 2007 was at or near a 15-year maximum, while for tankers it was declining but still above the long-term average. Hence, these factors have contributed to a reduction in productivity.

Figure 88 shows the impact of our assumption that the productivity of different ship types will return to its long-term average values on the emissions projections. For reasons of clarity, the figure shows the impact on one scenario; however, the impact on other scenarios is similar. If it is assumed that the productivity of the fleet will remain at its 2012 level, CO_2 emissions will be 12% higher. This means that if the response to a transport demand increase is to add proportionately more ships to the fleet, rather than to increase the cargo load of ships, emissions will be 12% higher.

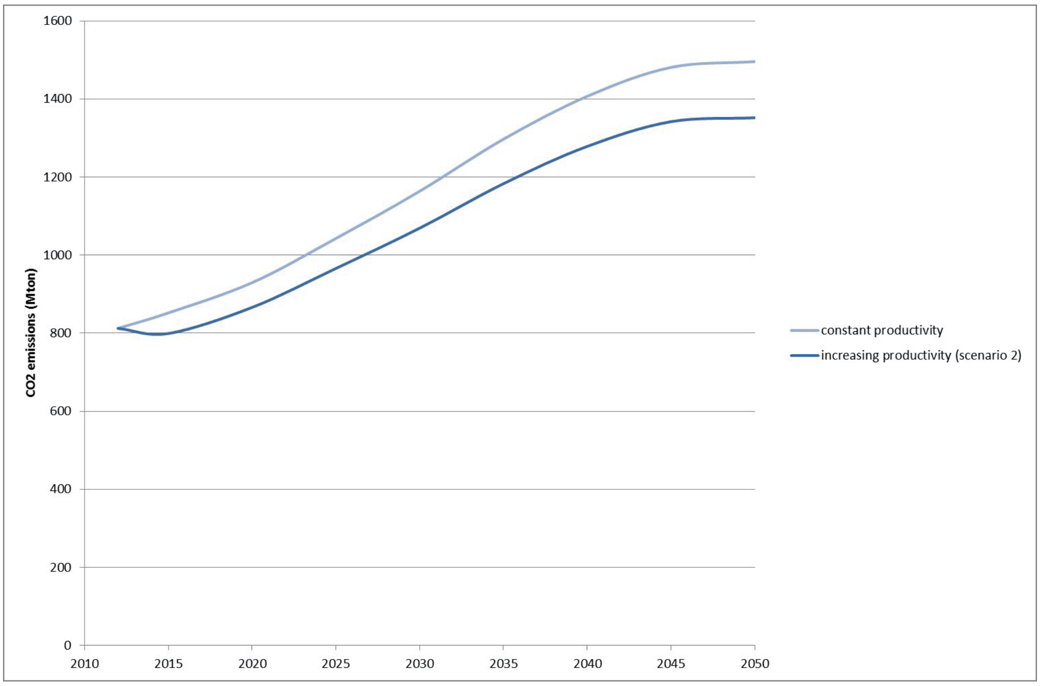

Figure 88: *Impact of productivity assumptions on emissions projections*

There are other ways of increasing productivity than increasing the average cargo load. When demand increases and the size of the fleet cannot keep up with the rising demand, a natural response is for ships to increase their speed. This also increases productivity. However, since fuel use and emissions per tonne-mile are roughly proportional to the square of the speed, a speed increase would result in emissions that are higher than emissions at constant productivity.

In sum, our emissions projections are sensitive to our assumption that productivity will revert to its long-term average value without increasing emissions per ship. If productivity remains constant (because ships will continue to operate at their current load factors, with their current number of days at sea and at their current speed), emissions are likely to be 10% higher than projected. If productivity increases because ships increase their speed at sea, emissions are likely to increase by a higher amount.

3.3.5 Uncertainty

There are two sources of uncertainty in the scenarios. The first is that the estimates of emissions in the base year have an uncertainty range, which has been discussed in Section 1.5. As our emissions projection model calculated future emissions on the basis of base-year emissions and relative changes in parameters (discussed in Section 3.2), uncertainty in the base year carries forward into future years. The second source of uncertainty is that the future is, in itself, uncertain. This type of uncertainty is addressed by showing different scenarios. While the scenarios are stylized representations of the future, and have no uncertainty of their own, uncertainty is introduced by the fact that each of the BAU scenarios is equally likely to occur. Hence, on top of the uncertainty in the base-year emissions, there is uncertainty in future developments that increases over time.

3.4 Main results

Maritime emissions projections show an increase in fuel use and GHG emissions in the period up to 2050, despite significant regulatory and market-driven improvements in efficiency. Depending on future economic and energy developments, our BAU scenarios project an increase of 50%–250% in the period up to 2050. Further action on efficiency and emissions can mitigate emissions growth, although all scenarios but one project emissions in 2050 to be higher than in 2012. The main driver of the emissions increase is the projected rise in demand for maritime transport. This rise is most pronounced in scenarios that combine the sustained use of fossil fuels with high economic growth and is lower in scenarios that involve a transition to renewable energy sources or a more moderate growth pattern.

Among the different cargo categories, demand for transport of unitized cargoes is projected to increase most rapidly in all scenarios.

The emissions projections show that improvements in efficiency are important in mitigating emissions growth, but even the most significant improvements modelled do not result in a downward trend. Compared to regulatory or market-driven improvements in efficiency, changes in the fuel mix have a limited impact on GHG emissions, assuming that fossil fuels remain dominant.

The projections are sensitive to the assumption that the productivity of the fleet, which is currently low, will revert to its long-term average by taking more cargo on board. If productivity does remain at its current level, or if it increases by increasing the number of days at sea or ship speed, emissions are likely to increase to a higher level.

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Annex 1
Details for Section 1.2: bottom-up method

IHSF technical data and method for populating missing data

Ship specific technical data was sourced from the IHSF vessel characteristics database through which the consortium had access to quarterly data sets from 2007–2012. The coverage (percentage of fields with valid data) and quality of each of the fields utilized is different between fields.

In order to develop a complete ship technical data set for the project, gap filling was performed for selected fields. The only fields listed above that were not gap-filled were: Statcode3, Statcode5, propulsion type, number of screws, and date of build. Gap filling was performed using the average value for each ship class, subclass and capacity bin for the technical fields and the ship's date of build for substitution for missing keel laid date. The Second IMO GHG Study 2009 employed a lower resolution of classes so resulted in more ships in each bin compared to this study, which utilizes a higher resolution of classes and subclasses resulting in fewer and more similar ships per bin. The Second IMO GHG Study 2009 used a regression fit based on tonnage or power depending on the field being backfilled, while the update uses an average over the subclass/capacity bins. This change has negligible effects on the gap-filling results and, due to the higher resolution of ship classes/subclasses/capacity bins, the overall result has a higher level of certainty than the Second IMO GHG Study 2009. A summary of the fields and methods is shown in Table 1. The quality assurance and quality control implications of this gap filling are discussed in greater detail in Section 1.4.

Table 1 – *Data gap-filling methods by IHSF ship technical field*

Field	**Gap filling?**	**Gap-filling method**
Statcode3	No	na
Statcode5	No	na
gt	Yes	Average of class, subclass and capacity bin
dwt	Yes	Average of class, subclass and capacity bin
length	Yes	Average of class, subclass and capacity bin
beam	Yes	Average of class, subclass and capacity bin
max draught	Yes	Average of class, subclass and capacity bin
ship speed	Yes	Average of class, subclass and capacity bin
installed main engine power	Yes	Average of class, subclass and capacity bin
RPM	Yes	Average of class, subclass and capacity bin
main engine consumption	Yes	Average of class, subclass and capacity bin
total consumption	Yes	Average of class, subclass and capacity bin
propulsion type	No	na
number of screws	No	na
date of build	No	na
keel laid date	Yes	Default to date of build

IHSF operational data

As stated above, IHSF provides a ship status field, which has the following field designations:

- In service/commission
- Laid-up
- Launched
- Keel laid
- On order/not completed
- Under construction
- Converting/rebuilding
- U.S. reserve fleet
- In casualty or repairing
- To be broken up
- Projected

The ship status field has 100% coverage for the entire 2007–2012 IHSF data sets. The data quality for this and other IHSF fields is discussed later. The intended use of the field for the project is to assist with the extrapolation of activity data captured through AIS. Because we have the field on a quarterly basis, tracking the field by quarter can help inform the extrapolation process. For example, if a ship is observed for half a year, the quarterly ship status data could inform that the ship was either laid up, in service or under repair. If laid up or under repair, the extrapolation process would not assume activity for periods in which the ship was not observed.

The operational IHSF fields are used in a similar manner to the Second IMO GHG Study 2009 in that they are used to inform whether a ship was active or in another state; however, for this study we have access to quarterly IHSF data sets for 2007–2012 whereas the Second IMO GHG Study 2009 utilized one year (with no quarterly resolution). This study uses more parameter fields in IHSF than the Second IMO GHG Study 2009, although it should be noted that the data field quality is assumed to be the same between the two studies.

IHSF divides all ships into four groups: cargo-carrying, non-merchant, non-seagoing merchant, and work ships. Each ship group can have one to multiple ship classes, as presented in Table 2 below.

For the cargo-carrying group, ship classes are subdivided into subclasses based on Statcode3 designations and further subdivided by Statcode5 designations, as presented in Table 3. The cargo-carrying group is the most complex of the four IHSF groups in terms of classes and subclasses.

Table 2 – *IHSF ship groups and classes*

Ship group	Ship class
Cargo-carrying transport ships	1 Bulk carrier 2 Chemical tanker 3 Container 4 General cargo 5 Liquefied gas tanker 6 Oil tanker 7 Other liquids tanker 8 Ferry – passengers (pax) only 9 Cruise 10 Ferry – roll-on/passengers (ro-pax) 11 Refrigerated cargo 12 Roll-on/roll-off (ro-ro) 13 Vehicle
Non-merchant ships	14 Yacht 15 Miscellaneous – fishing[1]
Non-seagoing merchant ships	16 Miscellaneous – other[2]
Work ships	17 Service – tug 18 Offshore 19 Service – other

Notes: [1] Miscellaneous fishing vessels fall into the non-merchant ships and non-seagoing merchant ships categories.

[2] Miscellaneous other vessels fall into the non-seagoing merchant ships and work ships categories.

Table 3 – *Cargo-carrying category: class, subclass and StatCode5 designations*

Ship class	**Subclass**	**Statcode5 designations**	
Bulk carrier	Bulk Dry	A21A2BC	Bulk Carrier
		A21A2BG	Bulk Carrier, Laker Only
		A21A2BV	Bulk Carrier (with Vehicle Decks)
		A21B2BO	Ore Carrier
	Other Bulk Dry	A24A2BT	Cement Carrier
		A24B2BW	Wood Chips Carrier
		A24B2BW	Wood Chips Carrier, Self-unloading
		A24C2BU	Urea Carrier
		A24D2BA	Aggregates Carrier
		A24E2BL	Limestone Carrier
		A24G2BS	Refined Sugar Carrier
		A24H2BZ	Powder Carrier
	Self-discharging Bulk Dry	A23A2BD	Bulk Cargo Carrier, Self-discharging
		A23A2BD	Bulk Carrier, Self-discharging
		A23A2BK	Bulk Carrier, Self-discharging, Laker
	Bulk Dry/Oil	A22A2BB	Bulk/Oil Carrier (OBO)
		A22B2BR	Ore/Oil Carrier
Chemical tanker	Chemical	A12A2TC	Chemical Tanker
		A12B2TR	Chemical/Products Tanker
		A12E2LE	Edible Oil Tanker
		A12H2LJ	Fruit Juice Tanker
		A12G2LT	Latex Tanker
		A12A2LP	Molten Sulphur Tanker
		A12D2LV	Vegetable Oil Tanker
		A12C2LW	Wine Tanker
Container	Container	A33A2CR	Container Ship (Fully Cellular with Ro-Ro Facility)
		A33A2CC	Container Ship (Fully Cellular)
		A33B2CP	Passenger/Container Ship
General cargo	General Cargo	A31A2GA	General Cargo Ship (with Ro-Ro facility)
		A31A2GE	General Cargo Ship, Self-discharging
		A31A2GO	Open Hatch Cargo Ship
		A31A2GT	General Cargo/Tanker
		A31A2GX	General Cargo Ship
		A31B2GP	Palletised Cargo Ship
		A31C2GD	Deck Cargo Ship
	Other Dry Cargo	A38A2GL	Livestock Carrier
		A38B2GB	Barge Carrier
		A38C2GH	Heavy Load Carrier
		A38C3GH	Heavy Load Carrier, semi submersible
		A38C3GY	Yacht Carrier, semi submersible
		A38D2GN	Nuclear Fuel Carrier
		A38D2GZ	Nuclear Fuel Carrier (with Ro-Ro facility)
	Passenger/General Cargo	A32A2GF	General Cargo/Passenger Ship

Ship class	Subclass	Statcode5 designations	
Liquefied gas tanker	Liquefied Gas	A11C2LC	CO_2 Tanker
		A11A2TN	LNG Tanker
		A11B2TG	LPG Tanker
		A11B2TH	LPG/Chemical Tanker
Oil tanker	Oil	A13C2LA	Asphalt/Bitumen Tanker
		A13E2LD	Coal/Oil Mixture Tanker
		A13A2TV	Crude Oil Tanker
		A13A2TW	Crude/Oil Products Tanker
		A13B2TP	Products Tanker
		A13A2TS	Shuttle Tanker
		A13B2TU	Tanker (unspecified)
Other liquids tanker	Other Liquids	A14H2LH	Alcohol Tanker
		A14N2LL	Caprolactam Tanker
		A14F2LM	Molasses Tanker
		A14A2LO	Water Tanker
Ferry – pax only	Passenger	A37B2PS	Passenger Ship
Cruise	Passenger	A37A2PC	Passenger/Cruise
Ferry – ro-pax	Passenger/Ro-Ro Cargo	A36B2PL	Passenger/Landing Craft
		A36A2PR	Passenger/Ro-Ro Ship (Vehicles)
		A36A2PT	Passenger/Ro-Ro Ship (Vehicles/Rail)
Refrigerated cargo	Refrigerated Cargo	A34A2GR	Refrigerated Cargo Ship
Ro-ro	Ro-Ro Cargo	A35C2RC	Container/Ro-Ro Cargo Ship
		A35D2RL	Landing Craft
		A35A2RT	Rail Vehicles Carrier
		A35A2RR	Ro-Ro Cargo Ship
Vehicle	Ro-Ro Cargo	A35B2RV	Vehicles Carrier

For each ship class a capacity bin system was used to further aggregate ships by either their physical size or cargo-carrying capacity based on the following metrics: deadweight tonnage (dwt), twenty-foot equivalent units (TEU), cubic metres (cbm), gross tonnage (gt), or vehicle capacity, as presented in Table 4. The capacity bins are the same for all ships in a class. Wherever possible, the size bins are aligned to the Second IMO GHG Study 2009, although because there are some differences in the class definitions, there are also a few differences. It should be noted that the Third IMO GHG Study 2014 provides an improved and higher resolution by class/subclass/capacity bin than that used in the Second IMO GHG Study 2009.

Table 4 – *Ship class capacity bins*

Ship class	Capacity bin	Capacity units
Bulk carrier	0–9,999	dwt
	10,000–34,999	
	35,000–59,999	
	60,000–99,999	
	100,000–199,999	
	200,000–+	
Chemical tanker	0–4,999	dwt
	5,000–9,999	
	10,000–19,999	
	20,000–+	
Container	0–999	TEU
	1,000–1,999	
	2,000–2,999	
	3,000–4,999	
	5,000–7,999	
	8,000–11,999	
	12,000–14,500	
	14,500–+	
Cruise	0–1,999	gt
	2,000–9,999	
	10,000–59,999	
	60,000–99,999	
	100,000–+	
Ferry – pax only	0–1,999	gt
	2,000–+	
Ferry – ro-pax	0–1,999	gt
	2,000–+	
General cargo	0–4,999	dwt
	5,000–9,999	
	10,000–+	
Liquefied gas tanker	0–49,999	cubic metres (cbm)
	50,000–199,999	
	200,000–+	
Oil tanker	0–4,999	dwt
	5,000–9,999	
	10,000–19,999	
	20,000–59,999	
	60,000–79,999	
	80,000–119,999	
	120,000–199,999	
	200,000–+	
Other liquids tankers	0–+	dwt
Refrigerated cargo	0–1,999	dwt
Ro-ro	0–4,999	gt
	5,000–+	

Ship class	Capacity bin	Capacity units
Vehicle	0–3,999	vehicles
	4,000–+	
Miscellaneous – fishing	All sizes	gt
Miscellaneous – other	All sizes	gt
Offshore	All sizes	gt
Service – other	All sizes	gt
Service – tug	All sizes	gt
Yacht	All sizes	gt

It should be noted that because the basic method in Section 1.2 performs all calculations on a "per ship" basis and minimizes the use of average assumptions applied across populations of ships, there is a lesser need than in the Second IMO GHG Study 2009 for the bins used to be representative of technical or operational homogeneity.

Estimating ship activity over the course of a year using AIS data

The first stage in the bottom up model is the pre-processor and multi-AIS merger phase where the ship activity of a ship throughout the year is generated from AIS data. The following section discusses the source data used in this phase and the individual steps involved.

Sources and spatial and temporal coverage

The deployment of the AIS technology has only been enforced in the last 10 years (IMO, 2002) and in the intervening years its coverage has greatly increased. Due to its creation as a collision detection system, receivers were largely deployed around port facilities and in traffic-dense areas resulting in a lack of cover on the open ocean. In recent years, with the emergence of its use in other applications (e.g. security of ships in piracy zones), there has been greater demand for deployment of receivers globally. As a result, spatio-temporal coverage of the technology is ever increasing. The consortium has a high level of confidence in this coverage for the latter years of the study (i.e. 2011 and 2012) but decreasing confidence for previous years. Although S-AIS, which provides open ocean coverage, is available from 2010, it has only limited coverage for that year, but improves greatly in 2011 and 2012. The different AIS sources used in this study are outlined in Table 5. The quality provided by this coverage is discussed in greater detail in Annex 5.

Table 5 – *Number of processed messages (in millions) in 2007–2012 for each terrestrial and satellite data sets. EMSA LRIT data were used for QA/QC of the bottom-up emissions estimation only*

	Kystverket	**exactEarth**	**Marine Traffic**	**EMSA (AIS)**	**IHS**	**Civic exchange**	**Starcrest compiled**	**EMSA (LRIT)**
Receiver type	Satellite	Satellite	Terrestrial	Terrestrial	Terrestrial	Terrestrial	Terrestrial	Satellite
Area	Global	Global	Global, coastal	EU, coastal	Global, coastal	Hong Kong	New York Area	Global
2012	162.3	519.0	1 731.0	1 308.0	–	1.4	–	9.9
2011	142.0	159.0	1 769.0	1 100.0	–	1.3	–	9.9
2010	–	34.4	334.5	893.7	–	–	1.5	22.3
2009	–	–	–	–	96.0	–	–	7.0
2008	–	–	–	–	73.0	–	–	–
2007	–	–	–	–	4.7	–	–	–

Pre-processing AIS data

The first stage is to parse all the terrestrial AIS (T-AIS) and S-AIS data to create consistent individual data files for each MMSI, as the MMSI is the key unique identification in AIS. Each source of AIS data needs to be parsed separately into a universal format to allow combined processing in later stages. Since AIS data was provided in various formats, a pre-processor subprogram was used for the processing of all AIS data (see Figure 1 for a display of the user interface of the pre-processor). Together with this, there were requirements from the data providers that all ship locations be anonymized before the data was shared. This restricted the parsed data to the following fields:

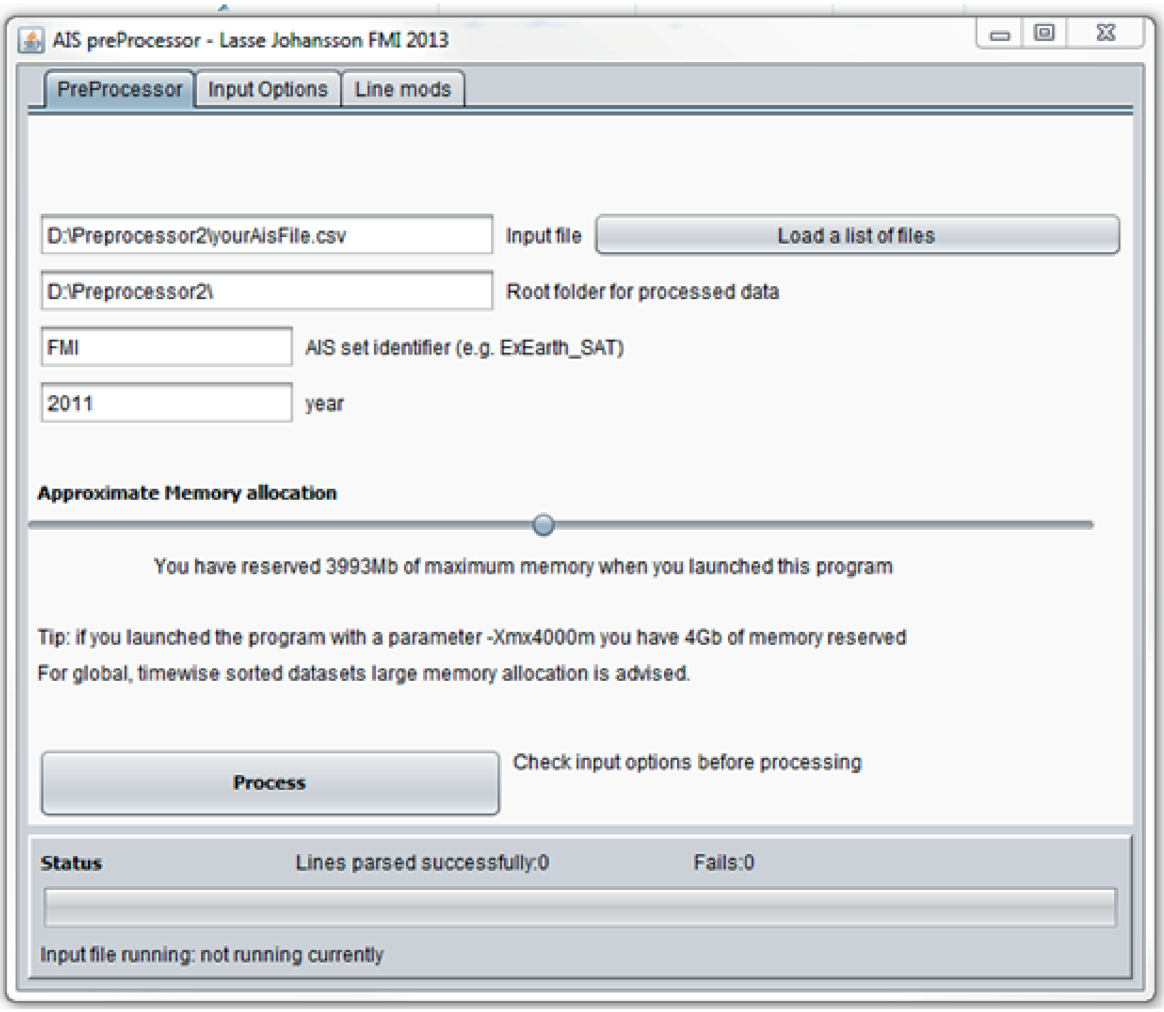
- MMSI
- IMO unique code
- Time of message
- Speed over ground
- Draught

The pre-processor facilitated the consortium partners to define their AIS data structure (e.g. time stamp pattern, field indices). While most (typically more than 99%) of the AIS data lines are successfully converted into the common selected format, the remaining non-relevant, false messages are removed from the set. Such messages may contain the following:

- Incorrectly formatted dates;
- Dynamic messages with no longitude, latitude or speed information;
- Messages without nine-digit numerical MMSI codes; valid MMSI codes are in the format MIDXXXXXX where the first three digits represent the Maritime Identification Digits (MID) and X is any figure from 0 to 9 (ITU, 2012).

Besides the task of parsing the information from one format to other, the pre-processor adds a region identifier as an additional field into the output while the precise coordinates are omitted. To achieve this, the pre-processor used locations defined by polygons (in the format of GIS shapefiles) which were obtained from Marine Regions (2014) to define the different sea regions shown in Figure 2.

Additionally, the pre-processor adds a speed-over-ground estimate (knots) for processed LRIT data. LRIT data was not used to generate activity estimates, but as a validation data set. It is explored in greater detail in Annex 3. The speed estimate generated for LRIT is based on the ship coordinates and the time difference between two consecutive messages, since ship speed is not included in an LRIT message.



D:\Preprocessor2\yourAisFile.csv Input file

D:\Preprocessor2\ Root folder for processed data

FMI AIS set identifier (e.g. ExEarth_SAT)

2011 year

Approximate Memory allocation

You have reserved 3993Mb of maximum memory when you launched this program

Tip: if you launched the program with a parameter -Xmx4000m you have 4Gb of memory reserved

For global, timewise sorted datasets large memory allocation is advised.

Check input options before processing

Status Lines parsed successfully:0 Fails:0

Input file running: not running currently

Figure 1: *Stand-alone pre-processor program with a graphic user interface. The pre-processor has been programmed with Java*

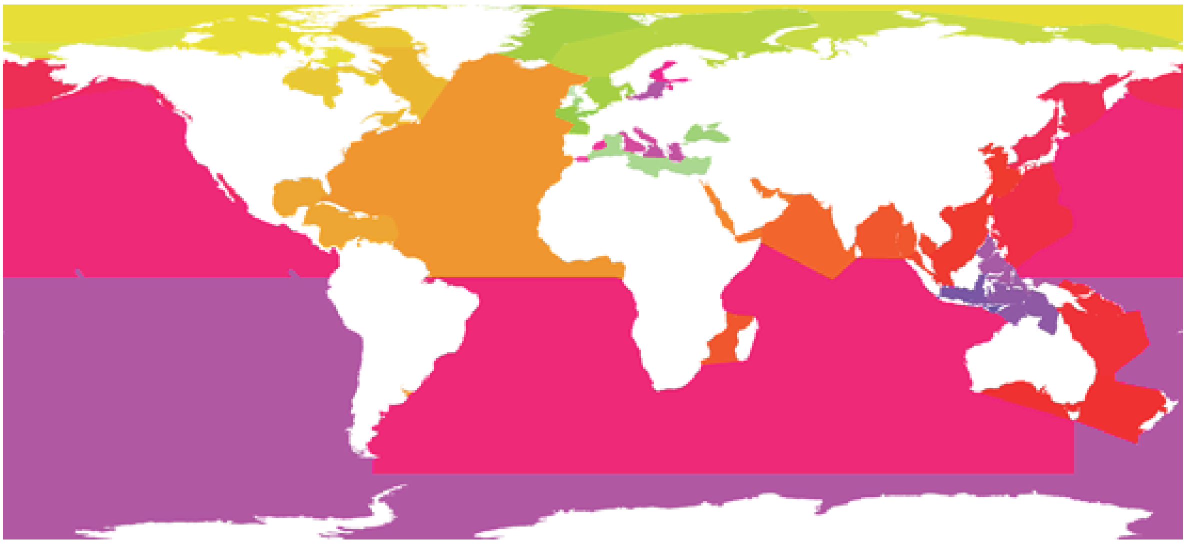


Figure 2: *Sea region definition illustration. GIS shapefile has been read by the pre-processor. The resolution of the sea region mapping is 0.1 × 0.1 degrees*

There are 102 different sea regions, as displayed in Figure 2. In the instance where a sea region is not found for any coordinate pair, a valid sea region (1-102) is searched from the nearby cells with a search radius of 0.2 degrees. If a valid region is still not found then the region indicator is set to have the value of 0.

ECA mapping

Certain areas of the world have special regulations that affect the maximum allowed fuel sulphur content. As fuel switching can occur in these areas to comply with these regulations, it was important to capture when ships were in the affected regions. While the northern European ECA can be identified as a combination of discrete sea regions, the North American ECA (NA-ECA) is a more complex subset of the Atlantic Sea, the Caribbean Sea and the Pacific. Using the geographical mapping of NA-ECA, EPA (2013), a custom polygon was added in the sea region identifier system (see Figure 3).

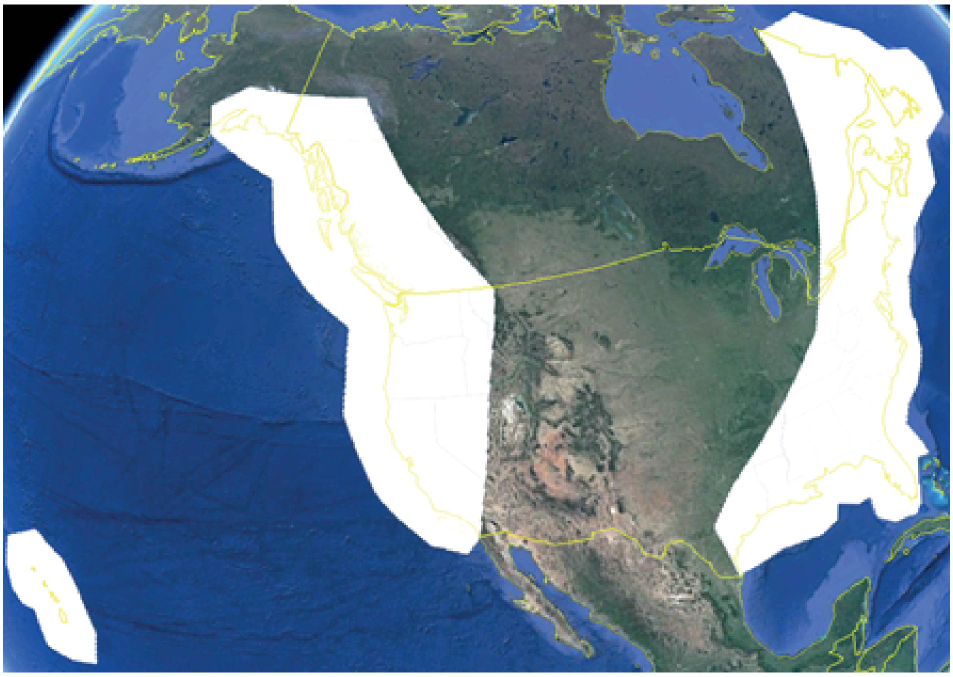


Figure 3: *NA-ECA polygons drawn with Google Earth 2014*

Outputs from pre-processing of raw AIS data

Following the parsing of the raw AIS messages, static and dynamic messages were merged to result in a "complete" activity report for that ship at that time stamp. As highlighted above, static messages and dynamic messages are linked through the MMSI number, with all information in a static message being associated with all the following dynamic messages until the next static message is received and so forth. This results in an array of tuples (ordered list of elements) containing MMSI number, IMO number, time, speed, draught and message source region.

The 2012 and 2007 combined AIS data sets are shown in Figure 4.

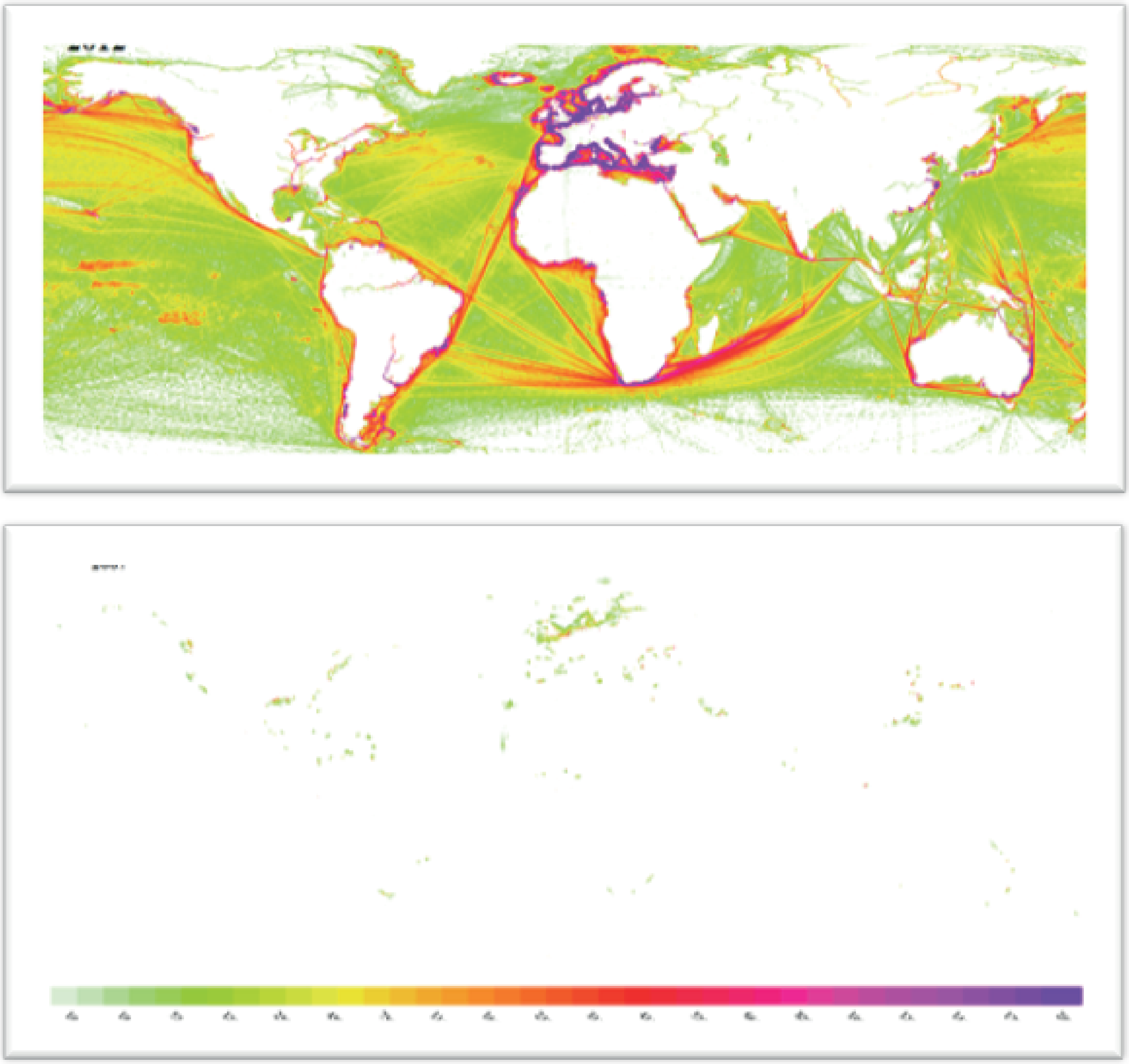


Figure 4: *Geographical distribution of AIS messages processed by the pre-processor for 2007 and 2012. All available AIS data sets have been combined. Unit: total number of messages per grid cell with an area of 0.2 × 0.2 degrees. Both plots are the same scale*

Multi-MMSI merging

On conversion of all the raw AIS data into a universal format for combined processing, the next stage is the generation of a complete annual data set for each ship. As a single ship may have had multiple MMSIs associated with it during a 12-month period (e.g. if the ship is reflagged, it is assigned a new MMSI), the initial merging process involves combining all ship-specific messages into a single IMO file. Activity reports from all AIS sources are merged and sorted chronologically. IMO numbers are mapped to their associated MMSI according to the most recently reported IMO number for that ship. As discussed in the main report, IMO numbers are only reported in the static message and therefore do not appear in every activity report. The data is then split into respective IMO ship activity reports, which could potentially have multiple MMSIs associated with the ship in any given year. The corollary applies with MMSIs potentially being spread across more than one ship if the MMSI has been reassigned within a year. Note that each year is processed separately with the starting IMO number for a particular MMSI being set as the first reported IMO number for that year.

If no IMO number was reported in any activity report for a particular MMSI, the ship is stored linked to its MMSI number. This results in two data-set groups: one with a series of ships saved under their IMO number and one with a series of ships stored under their MMSI.

Following the merging of the T-AIS and S-AIS data sources, the data is resampled to hourly estimators for each variable of interest: speed, draught and region. An aggregation time period of one hour was selected. The uncertainty within this hourly estimate for speed estimated is dealt with later, in Annex 3.

Each field is resampled uniquely:

- Speed: The estimate of the speed at any time period is calculated as a time-weighted average of reported speed within that period. The weighting is the elapsed time to the next reported message. Figure 5 shows an example of this.
- Draught: The draught is taken as the maximum reported draught within that period. As per IMO number, the draught is only reported in the static message, which appears less frequently. Thus, the effect of error in estimation is low. Moreover, the draught does not have the range of uncertainty that speed has across the hour and is typically only altered at the beginning of new voyages.
- Region classification: It is possible that a ship can be located in more than one region within the resampling period, if the ship crosses a region boundary within that period. In order to rationalize the data, the region of the ship is taken as the first reported region in that time period. As the regions are large and the region indicator is only used to understand the global geographical coverage of the data sets, it was assumed that this approach would not bias the overall coverage results as the number of ships crossing boundaries at each hourly interval is small in comparison with those located wholly within a region for the full hour duration.
- Organization flag: This is simply a coverage flag used to note from what data source the ship was picked up. For the resampling of this variable, the first recorded activity report in the hour was taken as the hourly resampled value. This variable is shown in the plot in Figure 6.

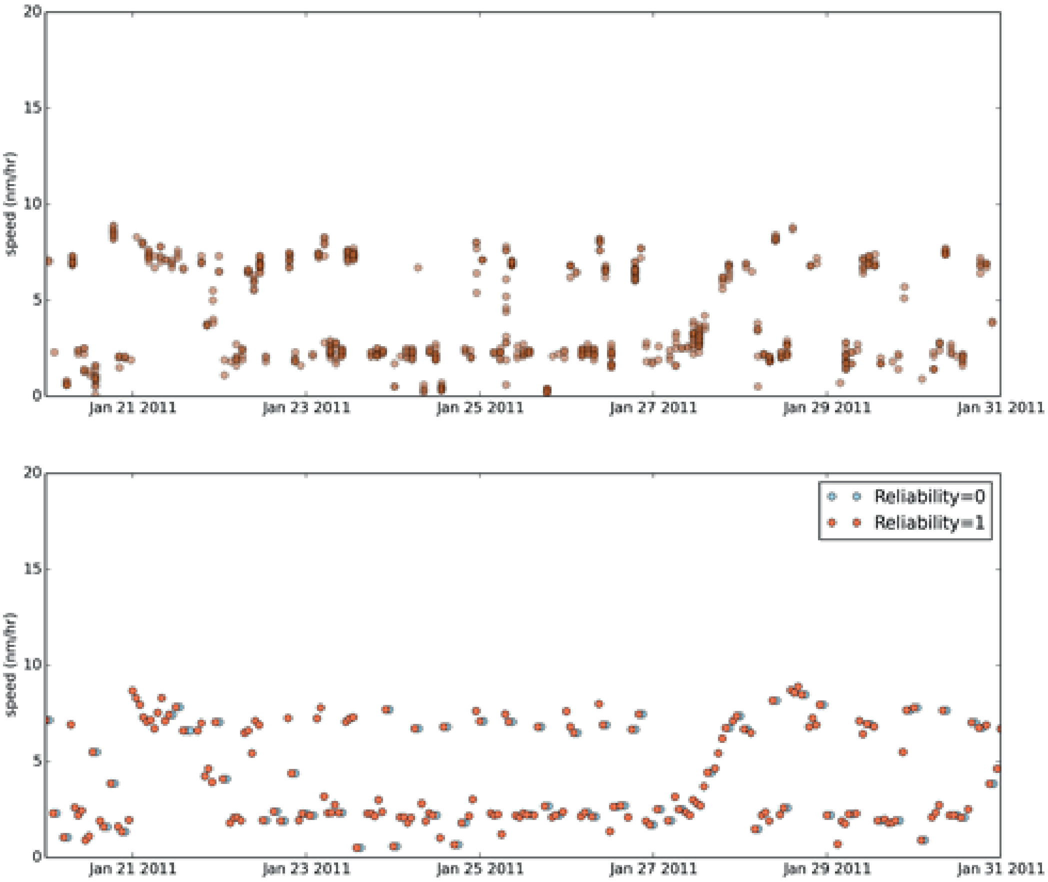


Figure 5: *Top plot shows the reported speed for an indicative ship between 15 January 2011 and 31 January 2011, each message with an opacity of 50% so that density is apparent. The lower plot shows the same ship with the speeds resampled. A reliability of 0 indicates that there was no activity report for that resampled hour*

On completion of the resampling, the data sets are matched to their respective ship technical characteristics and the data anonymized by removing the IMO and MMSI codes.

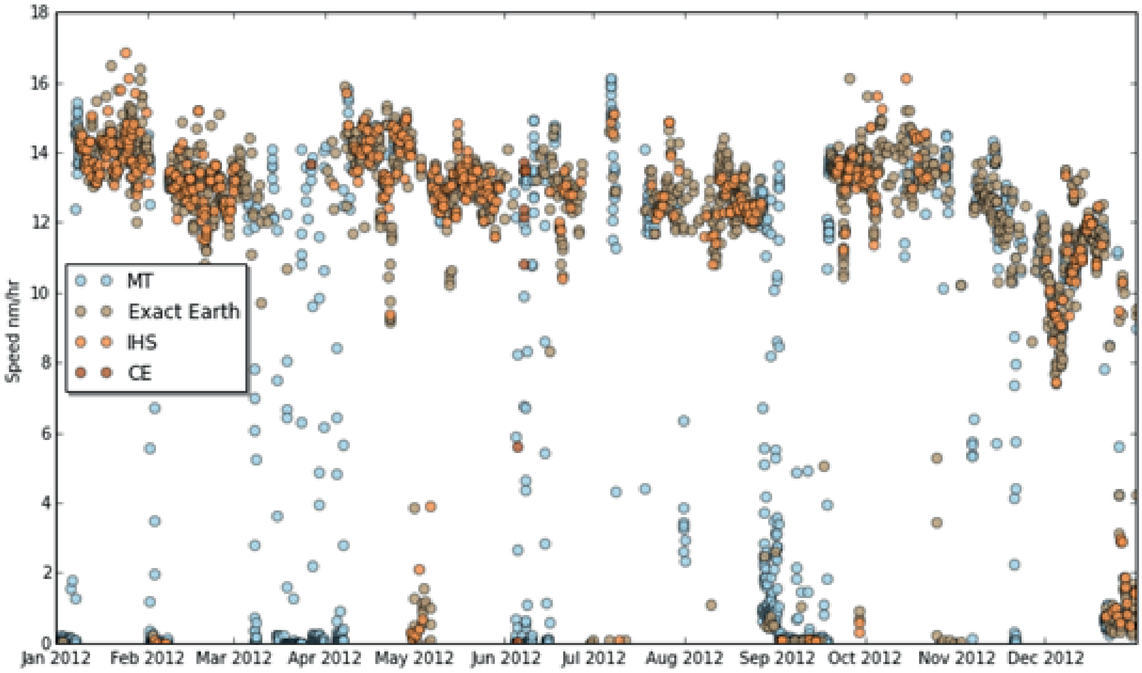


Figure 6: *Example plot of coverage indicated by source of data*

Extrapolating ship annual profile to generate complete annual operational profiles

As discussed above, the coverage of activity reports varies temporally and spatially, with significant improvements in later years. However, to determine the emissions for the global fleet over the whole year, a complete hourly data set of speed and draught for each ship is required.

This is done by correcting for biases in each year of data. A linear extrapolation is not suitable in most cases as the data is often biased towards shore-based data, particularly in years 2007 to 2009 which do not have satellite data and are therefore naturally biased towards shore-based reports. Together with this, satellite data will be bunched around the period that the ship is in range of the satellite.

As a result a method was developed that disaggregated the full year activity reports into discrete trips comprising a port phase, a transition phase and a voyage phase. Each trip is considered discretely with infilling of missing data drawn from in-phase samples.

The algorithm defines the phases as below:

- Port/anchor phase: Any activity report with a speed of less than 3 nm/hr. This is consistent with the definition of days at port used throughout this report.
- Voyage phase: Characterized by a speed over ground above a calculated threshold and a standard deviation of less than 2 nm/hr within a six-hour rolling window. This threshold is the 90% percentile of speeds reported above 3 nm/hr.
- Transition phase: This is defined as the period when a ship is transiting in and out of port or anchor. It consists of the remaining activity reports that have not been classified as port or voyage.

The phases are displayed visually in Figure 7 for an example ship.

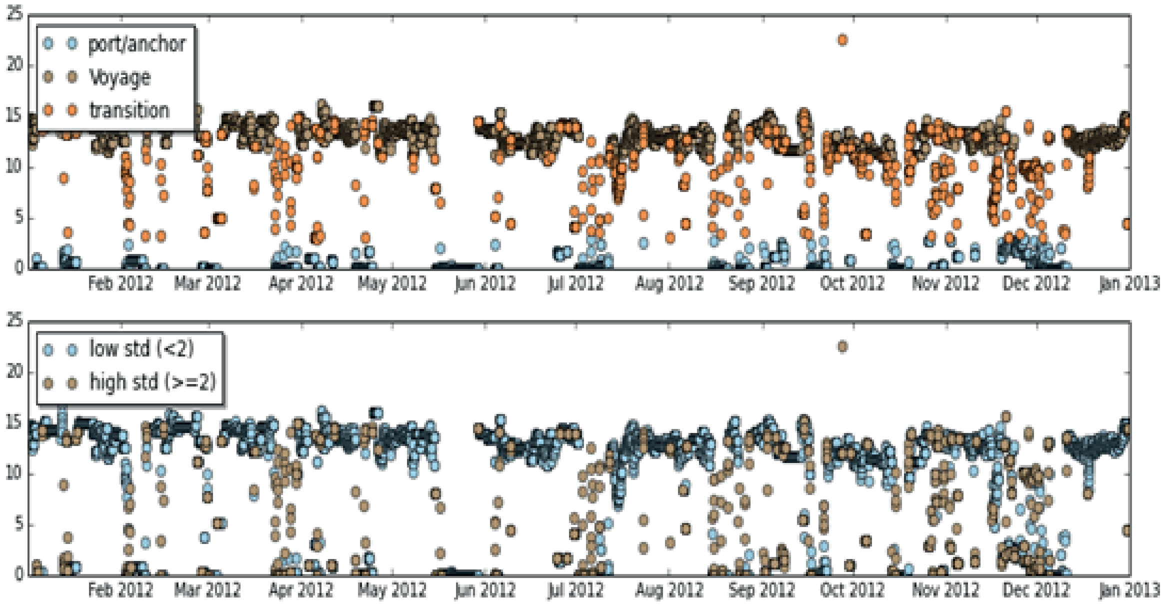


Figure 7: *Characterization of ship phases used in the extrapolation algorithm for an example very large crude carrier (VLCC) in 2012. The top plot shows the phase labels for each data point at given speeds (y-axis) and the lower plot classifies the data into high and low standard deviation of speed within a six-hour window*

The process of extrapolation follows the steps below:

- Speeds greater than 1.5 times the design speed of the ship are removed.
- Each hour where an activity report exists is classified as one of the phases indicated above.
- The activity data set is split by port activity, resulting in a sequence of discrete journeys.
- An acceptable missing period threshold is calculated as the median port-to-port time bounded by 6 and 72 hours.
- Where the contiguous missing periods are less than the missing period threshold, the intervening hours are randomly sampled from the set of reported speeds for that phase.
- Where the missing periods are greater than the missing period threshold, the whole voyage to which the contiguous missing periods belongs is stripped out and replaced with randomly sampled speeds from the full set of reported speeds.
- A reliability indicator is applied to each data point. Data points that are based on actual reports and those classified in step 4 are set as 1 and those sampled in step 5 are set as 0.

Naturally, the accuracy of the extrapolation would be improved by leveraging the ship location information. However, as discussed in earlier sections, the location information was removed at the pre-processing phase.

An example of the extrapolation process is displayed in Figure 8. The first column displays a snapshot of the speed time series for an example ship, followed by speed distribution for days at port and days at sea respectively. The final column displays the histogram plot for the speed in each state. The first row displays the raw data with the speed forward filled from the last activity report. The bar plots and the histogram are based on the combined data set. The middle row displays only those data points for which there was an activity report. The final row displays the extrapolated speed indicated by a reliability indicator. The plot labels indicate the respective captured points (i.e. there are a total of 8,785 points in the year, of which 2,245 contained actual activity reports. Following application of the extrapolation algorithm, 7,170 were classified as having a reliability of 1).

In the Figure 8 example, there were many activity reports missing in August; the contiguous missing period was below the acceptable missing period threshold resulting in those missing data points being resampled from in-phase activity reports. However, for the period from 17 July to 31 July, the missing data points were beyond the acceptable missing period threshold and thus the speed was sampled from the full activity report data set. This results in data points being selected from across all three phases and the resulting data points appearing more random. The overall effect of the days at sea and the days at port can be seen in the histograms in the third column.

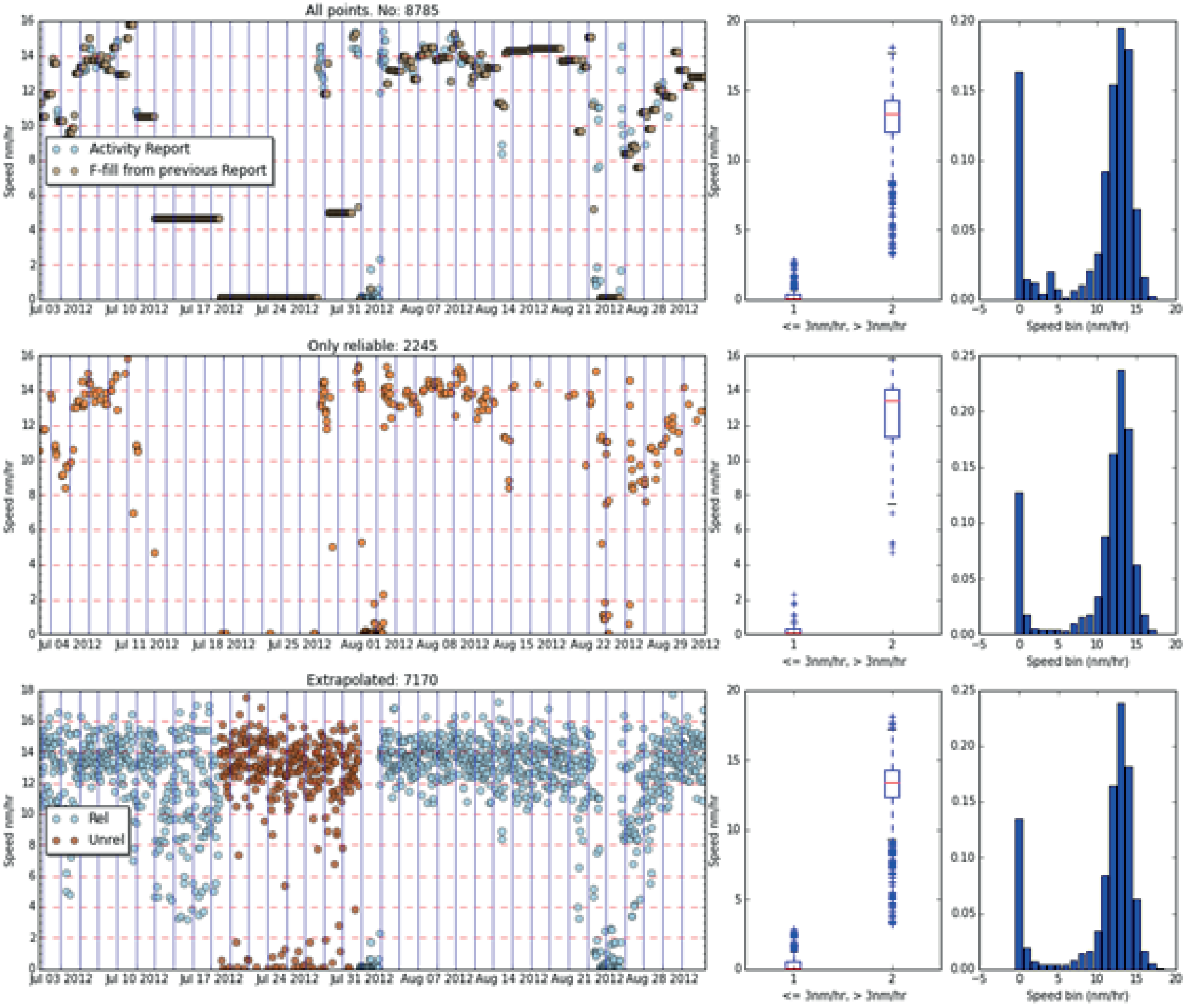


Figure 8: *Illustration of the extrapolation process*

The application of the above method was considered acceptable for 2010 to 2012 AIS data sets. However, for previous years no satellite data was available, which would inevitably lead to bias, notwithstanding the bias correction within the extrapolation algorithm. The adopted extrapolation method discussed above or a linear extrapolation would particularly affect larger ships that would be out of range for greater periods of the year. Therefore, for the years 2007 to 2009, following the application of the extrapolation method, the data sets were further adjusted to align with an external source for days at sea. This was applied using "best available" data, as follows:

- In 2007 and 2008, the extrapolation algorithm is calibrated to the days at sea reported in the Second IMO GHG Study 2009 for the year 2007 (it is assumed that 2007 and 2008 saw similar operation).
- In 2009, the extrapolation algorithm is calibrated to the days at sea as analysed from LRIT data in this year (see Annex 3 for greater discussion).

This had the dual effect of correcting the bias towards days in port (observed if only shore-based AIS data is used) but also provided comparability with the Second IMO GHG Study 2009 estimates for emissions for the year 2007. Limited analysis of the quality of these assumptions is carried out in Section 1.4 (due to limitations in the availability of noon report data in these earlier years of the study), but extensive analysis of the assumption is carried out in Section 1.5 to test the consequence of missing AIS data on the uncertainty of the inventory.

Assumptions for auxiliary and boiler power demands

Ship technical data are required to estimate ship emissions in the bottom-up model. The primary source of technical data used for this study is the IHSF ship registry database. Ship technical data utilized from the IHSF data sets included: Statcode3, Statcode5, gt, dwt, length, beam, max draught, ship speed, installed main engine power, engine revolutions per minute (RPM), various cargo capacity fields, date of build, keel laid date, propulsion type, number of screws, and main engine fuel consumption and stroke type. In addition to technical data, the IHSF data set includes a ship status field that provides an indication if a ship is active, laid up, being built, etc. The consortium had access to quarterly IHSF data sets from 2007 to 2012. Each year's specific data was utilized for the individual annual estimates.

It should be noted that the data sets do not provide complete coverage for all ships and all fields needed. In cases where data are missing, values are estimated either from interpolation or from referencing another publicly available data source. The details of the approach taken for the missing data and the technical and operational data themselves are further discussed in Section 1.4.3 and in Annex 3.

For auxiliary engine operational profiles, neither IHSF nor the other ship-characteristic data services provide auxiliary engine or auxiliary boiler utilization data, by ship mode. In the Second IMO GHG Study 2009, auxiliary loads were estimated by assuming the number and load of auxiliary engines operated, by ship class, and basing the rated auxiliary engine power on the limited data provided in IHSF. To improve on this approach, the consortium used data from Starcrest's Vessel Boarding Program (VBP) (Starcrest, 2013), which had been collected at the Port of Los Angeles, the Port of Long Beach, the Port Authority of New York & New Jersey, the Port of Houston Authority, the Port of Seattle and the Port of Tacoma. The VBP data set includes over 1,200 ships of various classes. Starcrest has collected data on-board ships for over 15 years specifically related to estimating emissions from ships and validating its models. Auxiliary load (in kW) are recorded for at-berth, at-anchorage, manoeuvring, and at-sea ship modes. The ship classes that have been boarded as part of VBP include:

- bulk carrier
- chemical tanker
- cruise ship
- oil tanker
- general cargo ship
- container ship
- refrigerated cargo ship.

For container and refrigerated cargo ships, ship auxiliary engine and boiler loads (kW), by mode, were developed based on the VBP data set and averages by ship class and bin size were used. This approach assumes that the ships boarded are representative of the world fleet for those same classes.

For bulk carriers, chemical tankers, cruise ships, general cargo ships and oil tankers, a hybrid approach was used combining VBP data, data collected from the Finnish Meteorological Institute (FMI), and the Second IMO GHG Study 2009 approach. The prior study's approach was based on average auxiliary engine rating (kW), assumption of number of engines running expressed in operational days per year (if greater than 365, it was assumed that more than one engine was running), a single load factor for each ship class and capacity bins. The hybrid method was used for ships boarded as part of VBP, but was considered not to be a robust enough to use on its own. VBP data were used to compare estimated at-berth loads and the ratios between various modes and to review the results for reasonableness of the estimates. The resulting ship-weighted auxiliary loads estimated from this approach are presented in Table 6.

Table 6 – *Ship-weighted auxiliary engine loads, by mode, for selected ship classes, with VBP data*

Ship class	Capacity bin	ME to aux ratio	# aux engines	# of aux running	Load factor (LF)	Ship-weighted average auxiliary engine load (kW)		
						At berth	Manoeuvring	At sea
Bulk	0–34,999	5.50	3	1.16	0.6–0.7	280	310	190
	35,000–59,999	5.50	3	1.10	0.6–0.7	370	420	260
	60,000–+	5.50	3	1.23	0.6–0.7	600	680	420
Chemical tanker	0–4999	2.40	3	1.10	0.5	160	110	80
	5,000–19,999	2.40	3	1.10	0.5	490	330	230
	20,000–+	2.40	3	1.23	0.5	1,170	780	550
Cruise	0-9,999	2.50	3	2	0.7	450	580	450
	10,000–99,999	2.50	5	4	0.7	4,200	5,460	4,200
	100,000+	2.50	6	4	0.7	11,480	14,900	11,480
General cargo	0–4,999	3.30	3	1.12	0.5–0.6	120	90	60
	5,000–9,999	3.30	3	1.04	0.5–0.6	330	250	170
	10,000–+	3.30	3	1.12	0.5–0.6	970	730	490
Oil tanker	0–4,999	3.75	3	1.16	0.5	250	375	250
	5,000–9,999	3.75	3	1.16	0.5	375	563	375
	10,000–19,999	3.75	3	1.16	0.5	625	938	625
	20,000–59,999	3.75	3	1.16	0.5	750	1,125	750
	60,000–79,999	3.75	3	1.16	0.5	750	1,125	750
	80,000–119,999	3.75	3	1.16	0.5	1,000	1,500	1,000
	120,000–199,999	3.75	3	1.16	0.5	1,250	1,875	1,250
	200,000–+	3.75	3	1.16	0.5	1,500	2,250	1,500

For ship classes not previously boarded by VBP, data collected by FMI was used to determine the ratio between main engines and auxiliary engines; the number of engines assumed to be installed and running was derived from either the Second IMO GHG Study 2009 or professional judgement. This information was used for the various ship classes and size bins to develop ship-weighted average auxiliary engine loads in kW. Consistent with the approach of the Second IMO GHG Study 2009, these loads are applied across all operational modes. The estimated average auxiliary engine loads for ship classes using FMI data is presented in Table 7.

Table 7 – *Ship-weighted auxiliary engine loads for selected ship classes, with FMI data*

Ship class	Capacity bin	ME to aux ratio	# engines	# of engines running	Load factor (LF)	Ship-weighted auxiliary load (kW)
Ferry – pax only	0–1,999	7.6	2	1	0.6	185
Ferry – pax only	2,000–+	3.0	3	1	0.6	525
Ferry – ro-pax	0–1,999	4.9	2	1	0.6	105
Ferry – ro-pax	2,000–+	4.9	3	1	0.6	710
Liquefied gas tanker	0–49,999	2.9	3	1.10	0.5	240
Liquefied gas tanker	49,999–+	2.9	3	1.23	0.5	1,710
Miscellaneous – fishing	1	1.5	2	1	0.7	200
Miscellaneous – other	1	2.2	2	1	0.7	190
Offshore	1	2.5	3	1	0.6-.07	320
Service – other	1	2.2	3	1	0.5-0.7	220
Service – tug	1	10.2	2	1	0.5	50
Yacht	1	7.2	2	1	0.7	130

The auxiliary engine loads by mode used in this study are presented in Table 8.

Table 8 – *Auxiliary engine loads, by ship class and mode*

Ship class	**Capacity bin**	**Auxiliary engine load (kW)**			
		At berth	**At anchorage**	**Manoeuvring**	**At sea**
Bulk carrier	0–9,999	280	190	310	190
	10,000–34,999	280	190	310	190
	35,000–59,999	370	260	420	260
	60,000–99,999	600	420	680	420
	100,000–199,999	600	420	680	420
	200,000–+	600	420	680	420
Chemical tanker	0–4,999	160	80	110	80
	5,000–9,999	490	230	330	230
	10,000–19,999	490	230	330	230
	20,000–+	1,170	550	780	550
Container	0–999	340	300	550	300
	1,000–1,999	600	820	1,320	820
	2,000–2,999	700	1,230	1,800	1,230
	3,000–4,999	940	1,390	2,470	1,390
	5,000–7,999	970	1,420	2,600	1,420
	8,000–11,999	1,000	1,630	2,780	1,630
	12,000–14,500	1,200	1,960	3,330	1,960
	14,500–+	1,320	2,160	3,670	2,160
General cargo	0–4,999	120	60	90	60
	5,000–9,999	330	170	250	170
	10,000–+	970	490	730	490
Liquefied gas tanker	0–49,999	240	240	360	240
	50,000–199,999	1,710	1,710	2,565	1,710
	200,000–+	1,710	1,710	2,565	1,710
Oil tanker	0–4,999	250	250	375	250
	5,000–9,999	375	375	563	375
	10,000–19,999	625	625	938	625
	20,000–59,999	750	750	1,125	750
	60,000–79,999	750	750	1,125	750
	80,000–119,999	1,000	1,000	1,500	1,000
	120,000–199,999	1,250	1,250	1,875	1,250
	200,000–+	1,500	1,500	2,250	1,500
Other liquids tankers	0–+	500	500	750	500
Ferry – pax only	0–1,999	186	186	186	186
	2,000–+	524	524	524	524
Cruise	0–1,999	450	450	580	450
	2,000–9,999	450	450	580	450
	10,000–59,999	3,500	3,500	5,460	3,500
	60,000–99,999	11,480	11,480	14,900	11,480
	100,000–+	11,480	11,480	14,900	11,480
Ferry – ro-pax	0–1,999	105	105	105	105
	2,000–+	710	710	710	710
Refrigerated bulk	0–1,999	1,080	1,170	1,150	1,170
Ro-ro	0–4,999	800	600	1,700	600
	5,000–+	1,200	950	2,720	950

Ship class	**Capacity bin**	**Auxiliary engine load (kW)**			
		At berth	**At anchorage**	**Manoeuvring**	**At sea**
Vehicle	0–+	800	500	1,125	500
	4,000–+	800	500	1,125	500
Yacht	0–+	130	130	130	130
Service – tug	0–+	50	50	50	50
Miscellaneous – fishing	0–+	200	200	200	200
Offshore	0–+	320	320	320	320
Service – other	0–+	220	220	220	220
Miscellaneous – other	0–+	190	190	190	190

Similar to auxiliary engine loads, there is no commercial data source that provides information regarding auxiliary boiler loads by operational mode. Auxiliary boiler loads were developed using VBP data and based on the professional judgement of the members of the consortium. Auxiliary boiler loads are typically reported in tons of fuel per day, but these rates have been converted to kW (Starcrest, 2013). Boilers are used for various purposes on ships and their operational profile can change by mode. The following auxiliary boiler profiles were used for this study:

- The study assumes that in at-sea operational mode, ships are meeting their steam requirements through economizers which scavenge heat from the main engine exhaust and use that heat to produce steam. There are exceptions to this assumption, with regards to tankers: we assumed, to be conservatively high, that boilers would be needed on oil tankers during at-sea operations to heat their cargo for the larger ship capacity bins (greater than 20,000 dwt).
- The study assumes that liquefied gas carriers will have additional steam requirements during at-sea operations.
- The study assumes that oil tankers and liquefied gas tankers will use steam plants to drive the cargo discharge pumps while at berth.
- The study assumes that the “Ferry – pax only”, “Ferry – ro-pax” and non-cargo ship categories do not have boiler loads, consistent with the Second IMO GHG Study 2009.

The auxiliary boiler loads by mode used in this study are presented in Table 9.

Table 9 – *Auxiliary boiler loads, by ship class and mode*

Ship class	**Capacity bin**	**Auxiliary boiler load (kW)**			
		At berth	**At anchorage**	**Manoeuvring**	**At sea**
Bulk carrier	0–9,999	50	50	50	0
	10,000–34,999	50	50	50	0
	35,000–59,999	100	100	100	0
	60,000–99,999	200	200	200	0
	100,000–199,999	200	200	200	0
	200,000–+	200	200	200	0
Chemical tanker	0–4,999	125	125	125	0
	5,000–9,999	250	250	250	0
	10,000–19,999	250	250	250	0
	20,000–+	250	250	250	0

Ship class	**Capacity bin**	**Auxiliary boiler load (kW)**			
		At berth	**At anchorage**	**Manoeuvring**	**At sea**
Container	0–999	120	120	120	0
	1,000–1,999	290	290	290	0
	2,000–2,999	350	350	350	0
	3,000–4,999	450	450	450	0
	5,000–7,999	450	450	450	0
	8,000–11,999	520	520	520	0
	12,000–14,500	630	630	630	0
	14,500–+	700	700	700	0
General cargo	0–4,999	0	0	0	0
	5,000–9,999	75	75	75	0
	10,000–+	100	100	100	0
Liquefied gas tanker	0–49,999	1,000	200	200	100
	50,000–199,999	1,500	300	300	150
	200,000–+	3,000	600	600	300
Oil tanker	0–4,999	500	100	100	0
	5,000–9,999	750	150	150	0
	10,000–19,999	1,250	250	250	0
	20,000–59,999	1,500	300	300	150
	60,000–79,999	1,500	300	300	150
	80,000–119,999	2,000	400	400	200
	120,000–199,999	2,500	500	500	250
	200,000–+	3,000	600	600	300
Other liquids tankers	0–+	1,000	200	200	100
Ferry – pax only	0–1,999	0	0	0	0
	2,000–+	0	0	0	0
Cruise	0–1,999	250	250	250	0
	2,000–9,999	250	250	250	0
	10,000–59,999	1,000	1,000	1,000	0
	60,000–99,999	500	500	500	0
	100,000–+	500	500	500	0
Ferry – ro-pax	0–1,999	0	0	0	0
	2,000–+	0	0	0	0
Refrigerated bulk	0–1,999	270	270	270	0
Ro-ro	0–4,999	200	200	200	0
	5,000–+	300	300	300	0
Vehicle	0–+	268	268	268	0
	4,000–+	268	268	268	0
Yacht	0–+	0	0	0	0
Service – tug	0–+	0	0	0	0
Miscellaneous – fishing	0–+	0	0	0	0
Offshore	0–+	0	0	0	0
Service – other	0–+	0	0	0	0
Miscellaneous – other	0–+	0	0	0	0

Assumptions for main and auxiliary fuel type

The approach to defining the type of fuel used employs a definition according to the area that the ship is operating in:

1. Outside ECAs: HFO/MDO/MGO average annual sulphur content is based on the IMO sulphur-monitoring programme findings for fuel oils for 2007 to 2012.
2. Inside ECAs: A sulphur content corresponding to the sulphur limit required in the ECA is assumed in both main engines and auxiliary engines and boilers.

The iterative process which is used to allocate a specific fuel type (HFO, MDO or LNG) to a specific ship type and size category is described in greater detail in Section 1.4.

Assumptions for hull fouling and deterioration over time

The hull condition can have a considerable impact on the power requirements of a ship owing to fouling, which works to increase the hull's frictional resistance. At low Froude number (low speeds or long ship lengths), the frictional resistance is the largest component of drag, and increases in hull roughness therefore have a larger effect relative to other components of resistance. The effects of deterioration, which could include engine wear and changes to plating and propulsor over time, are considered small relative to the effects of hull fouling and so are not included explicitly in the calculations at this point, but are the subject of ongoing research which may update the bottom-up model and its results in due course.

Owing to the number of factors involved in quantifying hull surface properties, there is a large degree of uncertainty surrounding the values that should be used for the amplitude of initial hull roughness and the subsequent increase per year. Fouling depends on ship type, speed, trading pattern and distances travelled, fouling patterns, dry-dock interval, ports visited and their cleaning/fouling class, sea temperatures, polishing (wear-off) rate of anti-fouling paint, thickness of anti-fouling paint and type of anti-fouling paint.

To ensure an initial inclusion of the impact of fouling on fuel consumption in this study, initial amplitude of hull surface roughness of 150 μm is assumed. A model by Doulgeris, Korakianitis et al. (2012) assumes clean hull roughness amplitude of 120 μm; a model by Carlton (2007) assumes a value of 130 μm. Carlton (2007) provides quantifications for change in roughness over time for different coatings. This work compares well with Doulgeris, Korakianitis et al. (2012), who assumed an increase in annual average hull roughness amplitude of 30 μm from initial amplitude of 120 μm, leading to an annual hull resistance increase of 2%.

On the assumption that maintenance takes place every five years to restore initial hull roughness, an average increase in total resistance of 9% (constant in time) is applied for all ships. However, there is considerable uncertainty in this assumption. Many ships may dock and repaint with higher frequency than five years, may use a higher performance coating or may undertake cleaning/scrubbing in the interim between dry docking, all of which would reduce the average increase in total resistance.

Assumptions for the impact of weather on fuel consumption

The weather impact parameter aims to quantify the added resistance in waves and the wind resistance and to therefore determine the extra load on the propeller and the additional power requirements from the engine in realistic operating conditions. In ship design it is common practice to include a sea margin (typically of between 10% and 30%) based on experience of the power requirements for maintaining the speed of similar ships operating on similar routes. The actual figure depends on ship type, hull geometry, sea keeping characteristics and environmental conditions. However, this represents the upper bound of the power required to overcome wind and waves, as the ship will be sailing in conditions where the full margin is required for only some of its operating time. To estimate the impact of weather on the CO_2 emissions of shipping, added resistance is estimated for the range of environmental conditions that are encountered over the period of operation (one year).

Methods for estimating added resistance fall into four categories: approximate, theoretical (i.e. strip theories from the ships motion in calm water plus superposition theory and a known wave energy spectrum), model experimental and computer-aided numerical approaches. However, the accuracy of the method used needs to be traded off against the availability of data describing the wind and wave environment that the ship has experienced over the period of operation. While it is theoretically possible to match the routing data in AIS with historical meteorological data to produce an estimate of weather impacts experienced on a ship-by-ship, voyage-by-voyage basis, the level of detail for input to the calculation and the computational resources required to apply this to the world fleet over the course of a year is not feasible within this project.

Consequently, the approach taken here is to apply findings from other more detailed studies. Work by Prpić-Oršić and Faltinsen (2012) undertook a detailed modelling of the effect of weather on fuel consumption for an S-175 container ship in the North Atlantic using state-of-the-art models for ship added resistance. Their calculations revealed that this ship type had, on average over the voyages, a 15% increment in fuel consumption over the calm water fuel consumption.

Whilst simplistic, this same assumption is applied as a starting assumption for the average increase in resistance for all oceangoing ship types (as classified according to the Second IMO GHG Study 2009) in this study. A lower value of 10% is applied as the added resistance of coastal shipping, as it is expected that they would experience, on average, less extreme environmental conditions.

Activity and fleet data merger

The activity and ship technical data merger is conducted using scripts that match the activity file's IMO or MMSI numbers with the corresponding ship in the appropriate annual IHSF file. Due to constraints imposed by the consortium members' pre-existing licensing agreements for both activity and ship technical data, during the merger process the ship identification fields (IMO and MMSI numbers) are removed to make the merged file anonymous at the ship level. A unique reference number is generated for each observed ship along with a merged activity and ship technical data file structure for each year. If a ship is observed in the activity data but not matched to the IHSF data set, the ship's activity data is returned unchanged. The ship status field is utilized for both observed and unobserved ships in the cargo-carrying ship type. The process is illustrated in Figure 9.

Figure 9: *Activity and ship technical and operational data merger process*

For unobserved cargo-carrying ship types, technical data is generated such that emissions can be estimated based on activity data surrogates from the same subclass and capacity bin. For the other ship types, ship class average values are used for estimating emissions and gap filling is conducted on a ship class basis.

It should be noted that due to license terms (from the providers of both technical data and AIS data), the data outputs depicted in Figure 9 are available to the consortium members only and during the duration of the study only. At the end of the study, they will be destroyed.

Bottom-up model calculation procedure

The bottom-up method combines both activity data (derived from AIS and LRIT raw data sources) and technical data (derived from IHSF and a series of empirical and literature-derived assumptions).

The model has been written in the programming language Matlab in order to take advantage of the data handling, statistical and modelling functionality and run-time management offered by this commercial software. The model is composed of a main programme (Run) which calls a number of subroutines as listed in Table 10. Each ship has a maximum of 8,760 different activity observations per year, and with approximately 60,000 ships included in a given year's fleet, the run-time of the model is significant on conventional hardware (hours).

The model can perform calculations for ships only for which there are both activity and IHSF technical data available; these are referred to as “matched ships”. Procedures for estimating the fuel demands and emissions of ships that are not matched are described in the section on fleet estimation.

Table 10 – *Description of bottom-up model subroutines and calculation stages*

Subroutine	**Description**
Read_fleet	Reads in and formats data from the database structure containing ship technical characteristics
Read_status	Reads in and formats data from the database structure containing ship quarterly status definition
Emissions_in	Reads in the emissions factor data for all engine types, fuel types and emissions species
Type_size_match	Reads in additional assumptions characterizing aggregate ship type and size fleets
EF_match	For each matched ship, looks up the machinery specification to identify the appropriate emissions factors from Emissions_in
Active_calcs	For each matched ship, uses the data describing hourly observations of a ship’s activity in a series of subroutines to estimate hourly power demands, fuel consumption and emissions
Power_at_op	Calculates the power demanded from main engine, auxiliary engine and boiler for each hour of observed and extrapolated activity
Emissions_at_op	Calculates the fuel consumed and emissions (nine species) for each hour of observed and extrapolated activity
Assemble	Calculates a series of annual and quarterly statistics to characterize activity, power, fuel use and emissions for each matched ship
Output	Structures and writes the databases produced in Assemble for producing aggregate statistics, performing QA/QC, and undertaking uncertainty analysis

Algorithms for reading in and formatting input databases do not manipulate the data and therefore are not described in greater detail here. However, there are a number of subroutines that perform operations on the activity data, technical data or both, and for transparency the method used in those steps is described in greater detail below.

Powering subroutine: *Power_at_op*

This subroutine estimates the main, auxiliary and boiler power output in a given hour of operation. The main engine’s power output is dominated by the propulsion requirements of the ship, which in turn is dominated by the operation (speed, draught) and condition (hull condition, environmental conditions). The auxiliary and boiler power demands are a function of service loads (including cargo operations), and vary depending on the cargo carried, the operation of the main machinery and the mode of operation (e.g. whether the ship is at berth, at anchor, at sea, etc.).

Key assumptions

Some ships have shaft generators, which produce electrical power for auxiliary systems from the propeller shaft. This represents main engine power output that would be additional to the propulsion power demand and would be expected to reduce the power output of the auxiliary machinery. There is no data in the IHSF database that could be used to reliably determine whether a ship is equipped with a shaft generator, and so an assumption was applied that for all ships, only the main engine produces propulsion power and only auxiliary engines produce service power. This assumption should not significantly impact the total power produced, but because main engines/shaft generators and auxiliary engines have different specific fuel consumptions and emissions factors, there will be an effect on these calculations which is discussed in greater detail in Sections 1.5 and 2.5.

A number of ships recover energy from waste heat (either exhaust, jacket waste heat or cooling water waste heat). This recovered energy can be used to provide both propulsion and service power supply, which reduces the power demands on the main engine, auxiliary engines and boiler to produce a given level of performance/service. The assumption applied for these calculations is that the majority of these reductions occur in the auxiliary and boiler systems, and that any reductions in their power demands are already factored in to the empirically derived power outputs. For the small number of ships that use waste-heat recovered energy for propulsion, this will be misrepresented by the model as written. The consequence can be observed in the discussion on quality of the bottom-up model in Section 1.4.

Main engine power output

In steady state (constant speed), the thrust produced by the engine and propeller is in equilibrium with forces opposing the ship's motion. These forces include both hydrodynamic and aerodynamic resistance. Both forces are modified by the weather; e.g. sailing into headwinds or head seas (waves) increases resistance. In both calm and rough weather, total resistance is dominated by hydrodynamic resistance, which in turn is dominated by viscous (friction) and wavemaking resistance.

Naval architects have progressed methods for estimating resistance from ship characteristics for a ship in ideal conditions (negligible wind and waves, clean hull), which reveal that in these conditions, resistance is strongly related to the speed of the hull through the water. However, in operation, a hull rarely stays "clean" and the surface properties are modified over time as coatings deteriorate, macro- and microfouling grows on the hull and the plating deforms through wear and tear. This modification of surface properties can have a significant impact on viscous resistance and needs to be taken into account in any calculation of operational fuel consumption.

Further influences to a ship's resistance and propulsion are its draught and trim, which are in turn determined by the ship's loading condition (the amount and distribution of cargo and variable loads). A greater draught will increase the wetted surface area of the hull and typically increase the resistance (although both bulbous bow and propeller performance can sometimes counteract this trend of increased power demand with increasing draught). The approximation used in this model is to represent the effect of draught through the use of the Admiralty formula, which assumes that power is related to displacement to the power 0.66.

The formulated equation to encapsulate all of these effects on resistance and therefore main engine power is given in equation (1).

$$P_t = \frac{P_{ref}\left(\frac{t_t}{t_{ref}}\right)^{\left(\frac{2}{3}\right)}\left(\frac{V_t}{V_{ref}}\right)^n}{\eta_w \eta_f} \qquad \text{Eq. (1)}$$

In equation (1), P_t, V_t and t_t are respectively the instantaneous power, speed and draught at time t, P_{ref} is the reference power at speed V_{ref} and draught t_{ref} (both taken from IHSF). n is an index that represents the relationship between speed and power, and η_w is the modification of propulsion efficiency due to weather and η_f is the modification of propulsion efficiency due to fouling (discussed above). For the bottom-up model, the same assumptions have been used as in the Second IMO GHG Study 2009: that $n = 3$, an assumption discussed in greater detail in Section 1.5, and evaluated with respect to quality in Section 1.4.

Auxiliary engine and boiler power demands

The power outputs required by both the auxiliary engine and the boiler are both found using look-ups from input tables described above in the section "Assumptions for auxiliary and boiler power demands". The corresponding mode is calculated for each ship and each hour of operation, from its instantaneous observed speed.

Emissions subroutine: *Emissions_at_op*

The emissions produced by machinery are a function of the amount of fuel consumed and the specifics of that fuel's combustion. The former (fuel consumed) is found from the power, SFOC and time, and the latter is found from the use of an emissions factor – in the case of CO_2, a carbon factor. The calculation of SFOC and emissions factors is detailed in Section 2 and Annex 6. Given this information, the formulation for this model's calculation of emissions of main, auxiliary and boiler machinery is given in equation (2).

$$CO_2 = P_t \times sfc \times C_f \times t \qquad \text{Eq. (2)}$$

In equation (2), P_t is the instantaneous power output at time t (obtained from *Power_at_op*), *sfc* is the specific fuel consumption (for a given engine with a given fuel at a given load factor), C_f is the carbon factor (for a given fuel), and t is the length of time the instantaneous power was observed to be constant. The values of C_f specific to different fuels are reported in Section 2.2 along with the other emissions species.

The *sfc* is found from the combination of a default assumption for a given engine type, size and age, sfc_e and a modifying factor obtained from a look-up table to account for variations in *sfc* as a function of fuel type and engine load factor.

$$sfc = sfc_e \times f_e \qquad \text{Eq. (3)}$$

The assumptions for sfc_e are described in detail in Section 2 and the associated Annex 6. f_e is estimated from manufacturers' data, as described in Section 2.

Aggregation by ship type and size

As discussed in Section 1.2, the activity and fleet data merger matches the IHSF fleet data to the AIS data, determining whether there is a match by ship and whether the activity data is of good or poor quality. Good quality activity data is currently defined as having day coverage of 10% or greater, although this assumption will be tested for its impact on quality and uncertainty in Sections 1.4 and 1.5. The matched data is filtered for good quality, creating a per-ship profile. The values in the per-ship profile are averaged across ship type and size bins to create an aggregate ship type profile.

Fleet estimate assembly

Further estimation is required for unmatched ships within both a ship type and size category. The aggregate average ship type and size profile is used to estimate the speed and draught profile, and this is then deployed with the ship's technical specification to calculate fuel use and emissions. This assumes that the mean speed and draught for the ship type and size bin is representative of all ships within that type and size bin. Once this step is completed, the per-ship profile is merged with the backfilled ships and the same aggregation by ship type and size bin category is performed, this time with the complete fleet of in-service ships. The effect of the uncertainty in the operational profile of the unmatched ships on the total inventory emissions is considered further in the uncertainty analysis.

Annex 2

Details for Section 1.3: inventory results

The following tables detail the data characterizing the activity, energy demand and emissions specifics of each of the ship type and size fleets within the shipping industry analysed using the bottom-up method, for each of the years of the study (2007–2012). The tables are the equivalent to the data in Table 14 in the main report, which lists the same fields for 2012.

2011 Detailed Results

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Bulk carrier	0–9,999	dwt	1,283	605	0.47	5,194	1,843	11.6	177	9.7	1.2	0.5	0.1	7,077
	10,000–3,4999	dwt	2,328	2,004	0.86	27,366	6,637	14.5	178	11.6	3.6	0.5	0.1	29,371
	35,000–59,999	dwt	2,650	2,423	0.91	51,195	8,922	14.9	187	12.2	5.1	0.7	0.1	47,873
	60,000–99,999	dwt	1,951	1,823	0.93	76,913	10,384	14.7	194	12.3	6.3	1.1	0.3	45,596
	100,000–199,999	dwt	1,084	1,006	0.93	167,167	16,402	15.1	203	12.2	9.6	1.1	0.2	35,873
	200,000–+	dwt	206	196	0.95	244,150	19,877	14.6	204	12.4	12.2	1.1	0.2	8,738
Chemical tanker	0–4,999	dwt	1,594	823	0.52	3,937	1,773	12.0	163	9.9	1.0	0.2	0.2	6,955
	5,000–9,999	dwt	884	778	0.88	8,931	3,707	13.5	170	10.8	1.9	0.6	0.4	7,819
	10,000–19,999	dwt	1,033	954	0.92	17,884	5,833	14.3	188	12.0	3.6	0.6	0.3	14,520
	20,000–+	dwt	1,410	1,275	0.90	42,782	9,398	15.0	182	12.6	5.2	1.4	0.4	29,961
Container	0–999	TEU	1,154	945	0.82	9,676	5,912	16.2	197	12.6	3.0	2.4	0.6	14,772
	1,000–1,999	TEU	1,277	1,172	0.92	20,723	12,443	19.3	206	14.4	5.8	2.2	0.4	32,935
	2,000–2,999	TEU	724	666	0.92	35,764	21,668	21.6	222	16.0	10.3	3.0	0.4	30,695
	3,000–4,999	TEU	944	864	0.92	53,951	35,980	23.8	241	16.9	16.3	3.8	0.5	59,865
	5,000–7,999	TEU	576	545	0.95	76,981	55,592	25.2	246	17.2	23.0	4.0	0.6	49,192
	8,000–11,999	TEU	260	236	0.91	108,236	68,779	25.4	250	17.4	28.9	4.3	0.6	27,195
	12,000–14,500	TEU	50	47	0.94	164,333	77,563	27.1	240	16.9	30.9	5.2	0.8	5,291
	14,500–+	TEU	–	–	–	–	–	–	–	–	–	–	–	0
General cargo	0–4,999	dwt	12,187	4,760	0.39	2,405	1,180	11.2	167	8.8	0.6	0.1	0.0	28,339
	5,000–9,999	dwt	2,936	2,268	0.77	8,441	3,405	13.5	178	10.3	1.7	0.4	0.1	19,682
	10,000–+	dwt	2,108	1,776	0.84	22,011	7,171	15.4	181	12.1	3.7	1.3	0.1	32,360
Liquefied gas tanker	0–49,999	cbm	1,088	833	0.77	7,240	3,870	13.9	186	12.0	2.7	0.6	0.4	12,206
	50,000–199,999	cbm	448	416	0.93	68,019	22,327	18.5	262	15.1	19.1	4.0	0.5	29,658
	200,000–+	cbm	45	38	0.84	121,270	37,358	19.3	297	16.6	34.4	3.9	1.0	5,504

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Oil tanker	0–4,999	dwt	3,761	1,419	0.38	2,781	1,415	11.2	145	8.9	0.8	0.6	0.2	19,110
	5,000–9,999	dwt	681	529	0.78	9,005	3,134	12.7	155	9.3	1.3	1.0	0.3	5,331
	10,000–19,999	dwt	215	172	0.80	20,338	5,169	13.5	159	9.8	2.0	1.6	0.4	2,602
	20,000–59,999	dwt	681	623	0.91	43,467	8,570	14.9	169	11.9	4.1	2.0	0.6	13,819
	60,000–79,999	dwt	397	356	0.90	72,401	12,091	15.3	177	12.4	5.9	1.9	0.6	10,118
	80,000–119,999	dwt	878	795	0.91	106,477	13,518	15.0	180	11.9	6.2	2.6	0.8	25,786
	120,000–199,999	dwt	417	380	0.91	154,878	17,849	15.1	206	12.2	9.2	3.1	1.0	17,114
	200,000–+	dwt	563	534	0.95	304,656	26,710	16.0	222	12.9	15.8	3.7	1.1	35,284
Other liquids tankers	0–+	dwt	152	28	0.18	740	594	9.8	103	8.8	0.4	1.3	0.4	1,046
Ferry – pax only	0–1,999	gt	3,051	928	0.30	702	1,991	22.6	180	14.4	0.9	0.4	0.0	12,299
	2,000–+	gt	72	37	0.51	1,730	6,785	16.8	219	13.8	4.9	1.0	0.0	1,335
Cruise	0–1,999	gt	201	72	0.36	2,306	1,219	12.6	119	8.8	0.4	1.0	0.5	1,204
	2,000–9,999	gt	72	54	0.75	4,847	4,549	15.6	160	10.2	1.5	1.0	0.4	636
	10,000–59,999	gt	116	99	0.85	4,312	19,479	19.7	209	14.0	9.9	8.9	1.4	7,131
	60,000–99,999	gt	83	75	0.90	8,369	52,920	22.0	261	15.8	31.5	25.8	0.6	14,690
	100,000–+	gt	46	44	0.96	12,527	72,663	22.1	264	16.4	47.1	26.0	0.5	10,365
Ferry – ro-pax	0–1,999	gt	1,617	574	0.35	896	1,530	13.0	177	8.6	0.7	0.2	0.0	4,507
	2,000–+	gt	1,216	917	0.75	3,459	15,357	21.4	199	14.2	6.4	1.4	0.0	28,789
Refrigerated bulk	0–1,999	dwt	1,126	802	0.71	5,538	4,877	16.0	184	13.6	3.4	2.3	0.4	21,212
Ro-ro	0–4,999	dwt	1,323	461	0.35	1,930	1,751	10.9	158	9.2	1.2	2.4	0.3	16,469
	5,000–+	dwt	443	391	0.88	11,286	11,526	17.8	206	14.4	7.2	3.7	0.4	15,349
Vehicle	0–3,999	vehicle	300	254	0.85	9,683	8,714	18.1	228	14.4	6.0	1.6	0.3	7,247
	4,000–+	vehicle	500	474	0.95	19,948	13,937	19.8	259	15.8	9.2	1.5	0.3	16,913
Yacht	0–+	gt	1,694	929	0.55	2,424	3,137	16.6	82	11.2	0.7	0.2	0.0	5,215
Service – tug	0–+	gt	14,221	4,204	0.30	1,342	2,437	11.9	102	7.2	0.6	0.1	0.0	30,601

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. deadweight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Miscellaneous – fishing	0–+	gt	22,428	2,796	0.12	281	945	11.5	175	7.7	0.4	0.4	0.0	57,894
Offshore	0–+	gt	6,324	4,511	0.71	3,016	4,560	13.9	113	8.3	0.9	0.8	0.0	30,078
Service – other	0–+	gt	2,863	2,347	0.82	4,735	3,782	12.7	122	8.0	1.0	0.4	0.0	12,812
Miscellaneous – other	0–+	gt	3,301	55	0.02	339	1,994	12.6	127	8.9	1.0	0.4	0.0	14,757

* indicates the use of weighted averaging (weighted by days at sea for each individual ship).

2010 Detailed Results

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption (‘000 tonnes)			Total CO_2 emissions (’000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Bulk carrier	0–9,999	dwt	1,276	637	0.50	3,313	1,687	12.1	174	9.9	1.1	0.5	0.1	6,171
	10,000–34,999	dwt	2,374	2,122	0.89	28,455	7,112	15.8	179	11.6	3.4	0.5	0.1	26,464
	35,000–59,999	dwt	2,487	2,389	0.96	54,546	9,548	16.3	188	12.2	4.6	0.7	0.1	38,531
	60,000–99,999	dwt	1,868	1,833	0.98	81,713	10,989	15.7	180	12.3	5.4	1.1	0.3	37,696
	100,000–199,999	dwt	1,008	994	0.99	198,060	18,997	17.4	179	12.7	8.1	1.1	0.3	27,299
	200,000–+	dwt	211	210	1.00	284,595	22,740	16.9	177	12.8	10.2	1.1	0.3	7,014
Chemical tanker	0–4,999	dwt	1,581	850	0.54	2,153	1,392	12.2	163	9.9	0.8	0.2	0.2	5,646
	5,000–9,999	dwt	892	807	0.90	8,082	3,573	14.5	170	11.0	1.8	0.5	0.4	6,926
	10,000–19,999	dwt	1,018	967	0.95	16,800	5,797	15.6	183	12.1	3.3	0.5	0.3	12,094
	20,000–+	dwt	1,446	1,381	0.96	45,789	10,035	16.3	179	12.7	5.2	1.3	0.3	28,668
Container	0–999	TEU	1,211	1,023	0.84	9,080	6,182	17.1	191	12.7	3.2	0.8	0.2	14,334
	1,000–1,999	TEU	1,313	1,264	0.96	21,520	13,156	20.2	201	14.5	5.8	2.1	0.4	32,336
	2,000–2,999	TEU	759	725	0.96	37,478	22,640	22.4	214	16.2	10.5	3.0	0.4	31,332
	3,000–4,999	TEU	949	922	0.97	58,072	39,328	25.8	230	17.2	16.0	3.7	0.5	55,792
	5,000–7,999	TEU	564	564	1.00	81,168	59,115	26.6	228	17.5	21.8	4.0	0.6	44,706
	8,000–11,999	TEU	242	241	1.00	119,058	76,538	28.3	238	17.9	27.6	4.2	0.6	23,008
	12,000–14,500	TEU	37	36	0.97	283,558	131,829	43.7	241	17.0	24.5	4.2	0.6	2,434
	14,500–+	TEU	0	0	0.00	0	0	0.0	0	0.0	–	–	–	0
General cargo	0–4,999	dwt	13,021	5,204	0.40	1,913	1,107	11.6	161	8.8	0.6	0.1	0.0	26,176
	5,000–9,999	dwt	3,009	2,381	0.79	7,534	3,471	14.2	180	10.4	1.7	0.4	0.1	18,893
	10,000–+	dwt	2,225	1,865	0.84	23,156	7,910	16.9	172	12.2	3.6	1.2	0.1	30,504
Liquefied gas tanker	0–49,999	cbm	1,102	872	0.79	7,081	3,908	14.6	181	11.9	2.4	0.6	0.4	10,950
	50,000–199,999	cbm	464	449	0.97	72,093	23,748	19.7	230	14.5	15.0	4.1	0.6	24,433
	200,000–+	cbm	45	45	1.00	135,581	41,767	21.5	251	15.5	22.8	4.0	1.1	3,691

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Oil tanker	0–4,999	dwt	3,910	1,450	0.37	1,933	1,236	11.4	140	9.0	0.7	0.6	0.2	16,768
	5,000–9,999	dwt	666	520	0.78	7,258	3,058	13.7	144	9.6	1.2	0.9	0.2	4,228
	10,000–19,999	dwt	227	175	0.77	16,019	4,956	14.2	139	10.2	2.0	1.5	0.4	2,355
	20,000–59,999	dwt	744	679	0.91	46,793	9,389	16.3	162	12.0	3.9	1.9	0.6	13,516
	60,000–79,999	dwt	405	389	0.96	78,219	12,831	16.3	172	12.5	5.8	1.9	0.6	9,733
	80,000–119,999	dwt	895	869	0.97	115,036	14,483	16.1	178	12.3	6.5	2.5	0.8	25,477
	120,000–199,999	dwt	423	410	0.97	169,810	19,500	16.5	186	12.7	9.1	3.1	1.0	16,199
	200,000–+	dwt	578	550	0.95	335,961	29,110	17.4	187	13.3	14.4	3.7	1.2	31,835
Other liquids tankers	0–+	dwt	168	33	0.20	778	614	10.2	50	7.2	0.1	1.1	0.4	831
Ferry – pax only	0–1,999	gt	3,117	901	0.29	103	1,907	23.2	158	14.6	0.7	0.3	0.0	9,973
	2,000–+	gt	75	42	0.56	1,761	6,974	17.6	141	12.7	3.4	0.9	0.0	839
Cruise	0–1,999	gt	203	65	0.32	177	987	12.7	88	8.3	0.2	0.9	0.5	968
	2,000–9,999	gt	78	60	0.77	1,169	4,557	16.2	174	10.8	2.1	1.0	0.4	823
	10,000–59,999	gt	126	117	0.93	4,616	19,902	20.6	212	14.3	10.5	8.7	1.3	7,398
	60,000–99,999	gt	83	81	0.98	8,630	54,568	22.7	252	15.8	31.6	25.8	0.6	13,919
	100,000–+	gt	44	43	0.98	12,200	80,601	24.3	268	16.9	47.4	24.4	0.5	9,311
Ferry – ro-pax	0–1,999	gt	1,670	592	0.35	400	1,552	13.5	170	9.0	0.7	0.2	0.0	4,433
	2,000–-+	gt	1,286	1,049	0.82	3,242	15,658	22.1	188	14.8	6.8	1.3	0.0	29,838
Refrigerated bulk	0–1,999	dwt	1,226	874	0.71	5,705	5,165	16.7	184	13.7	3.6	2.3	0.4	22,414
Ro-ro	0–4,999	dwt	1,319	469	0.36	1,168	1,701	11.5	154	9.4	1.3	2.2	0.3	14,591
	5,000–+	dwt	488	450	0.92	12,109	12,180	18.9	190	14.4	6.7	3.5	0.4	14,501
Vehicle	0–3,999	vehicle	328	283	0.86	10,459	9,705	20.3	218	14.6	6.0	1.4	0.3	6,808
	4,000–+	vehicle	527	493	0.94	21,335	15,369	22.1	244	16.1	9.1	1.4	0.3	15,946
Yacht	0–+	gt	1,568	896	0.57	146	2,942	17.4	71	11.1	0.4	0.2	0.0	3,175
Service – tug	0–+	gt	14,046	3,997	0.28	105	2,288	12.0	100	7.0	0.4	0.1	0.0	20,793

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption (‘000 tonnes)			Total CO_2 emissions (’000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Miscellaneous – fishing	0–+	gt	23,518	3,671	0.16	153	929	11.5	173	7.7	0.4	0.4	0.0	57,749
Offshore	0–+	gt	6,280	4,400	0.70	1,468	4,554	14.7	114	8.4	0.8	0.6	0.0	25,848
Service – other	0–+	gt	2,992	2,348	0.78	2,345	3,505	13.0	116	8.0	0.8	0.4	0.0	10,471
Miscellaneous – other	0–+	gt	3,465	44	0.01	29	1,905	12.7	110	7.9	0.4	0.3	0.0	8,531

* indicates the use of weighted averaging (weighted by days at sea for each individual ship).

2009 Detailed Results

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler'	
Bulk carrier	0–9,999	dwt	1,196	533	0.45	3,309	1,689	11.8	154	10.2	1,058.9	492.0	74.9	5,835
	10,000–34,999	dwt	2,241	2,034	0.91	26,915	6,896	15.3	184	12.0	3,844.0	483.3	68.0	28,702
	35,000–59,999	dwt	2,171	2,106	0.97	50,143	8,917	15.4	202	12.6	5,690.7	664.4	121.9	41,069
	60,000–99,999	dwt	1,691	1,657	0.98	77,454	10,450	15.1	226	13.0	8,522.5	1,047.0	209.6	49,201
	100,000–199,999	dwt	796	791	0.99	174,314	16,420	15.5	243	13.3	14,176.9	1,021.0	185.1	36,336
	200,000–+	dwt	168	166	0.99	272,464	21,553	16.4	285	13.0	18,441.8	942.9	134.8	9,496
Chemical tanker	0–4,999	dwt	1,547	819	0.53	2,480	1,384	12.0	153	10.3	833.0	185.6	191.2	5,605
	5,000–9,999	dwt	830	783	0.94	9,114	3,624	14.3	170	11.5	2,019.6	547.9	369.3	7,122
	10,000–19,999	dwt	929	913	0.98	16,650	5,730	15.3	164	12.5	3,121.8	543.5	371.2	11,049
	20,000–+	dwt	1,342	1,321	0.98	44,203	9,796	15.9	180	13.1	5,894.3	1,333.4	351.2	30,146
Container	0–999	TEU	1,202	1,081	0.90	9,059	6,117	16.9	183	13.2	3,136.7	836.4	169.4	14,896
	1,000–1,999	TEU	1,299	1,282	0.99	21,440	13,120	20.1	185	15.1	5,719.6	2,100.9	412.2	32,292
	2,000–2,999	TEU	762	752	0.99	37,550	22,613	22.4	217	16.8	11,432.2	2,968.3	428.0	33,759
	3,000–4,999	TEU	882	874	0.99	56,648	37,734	25.0	238	17.6	17,693.1	3,734.6	537.6	57,338
	5,000–7,999	TEU	520	514	0.99	79,317	57,944	26.0	266	19.2	32,751.6	3,772.4	460.8	58,162
	8,000–11,999	TEU	206	204	0.99	114,387	73,942	27.3	283	19.9	44,799.5	3,968.4	450.0	29,992
	12,000–14,500	TEU	13	13	1.00	187,649	91,187	29.2	299	17.4	37,762.8	4,748.0	674.0	1,636
	14,500–+	TEU	0	0	0.00	0	0	0.0						0
General cargo	0–4,999	dwt	12,940	5,386	0.42	1,915	1,102	11.4	175	9.2	636.8	142.0	0.0	30,090
	5,000–9,999	dwt	2,898	2,418	0.83	7,433	3,424	13.9	184	10.9	1,886.5	409.0	105.0	20,675
	10,000–+	dwt	2,125	1,888	0.89	22,274	7,670	16.5	200	12.6	4,499.3	1,160.0	127.9	35,927
Liquefied gas tanker	0–49,999	cbm	1,050	840	0.80	6,567	3,663	14.1	175	12.2	2,435.6	589.4	406.1	10,863
	50,000–199,999	cbm	443	436	0.98	69,596	22,561	19.3	204	14.6	12,437.1	4,189.3	594.1	21,056
	200,000–+	cbm	39	38	0.97	141,887	43,662	23.4	225	16.7	22,139.4	3,749.2	1,007.2	2,952

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Oil tanker	0–4,999	dwt	3,708	1,249	0.34	1,815	1,134	11.3	102	9.4	490.1	627.0	184.5	14,575
	5,000–9,999	dwt	555	403	0.73	6,938	2,953	13.0	128	9.9	1,181.8	955.2	265.8	3,952
	10,000–19,999	dwt	218	176	0.81	15,622	4,881	13.9	113	10.2	1,646.7	1,549.9	439.7	2,219
	20,000–59,999	dwt	707	659	0.93	44,340	8,929	15.6	166	12.4	4,469.3	1,921.0	615.7	14,471
	60,000–79,999	dwt	396	376	0.95	75,368	12,423	15.7	193	13.2	8,116.5	1,840.1	577.5	12,252
	80,000–119,999	dwt	834	817	0.98	111,331	14,000	15.7	175	12.9	7,675.6	2,516.5	810.5	27,224
	120,000–199,999	dwt	400	390	0.98	163,045	18,676	16.1	214	13.2	12,405.4	3,013.8	942.5	19,029
	200,000–+	dwt	558	551	0.99	317,023	27,254	16.5	232	14.3	22,478.5	3,551.9	1,082.2	44,756
Other liquids tankers	0–+	dwt	164	25	0.15	691	563	9.6	65	7.0	131.0	1,167.4	417.5	858
Ferry – pax only	0–1,999	gt	3,028	799	0.26	201	1,911	23.0	103	17.8	774.0	335.1	0.0	10,153
	2,000–+	gt	75	36	0.48	1,738	6,863	17.1	128	13.5	2,643.8	928.8	0.0	777
Cruise	0–1,999	gt	203	59	0.29	176	969	12.7	76	9.0	225.9	988.0	493.9	1,028
	2,000–9,999	gt	75	57	0.76	1,180	4,547	16.1	191	11.0	2,024.4	985.5	366.6	747
	10,000–59,999	gt	125	116	0.93	4,624	20,154	20.3	208	14.8	10,510.4	8,888.2	1,292.5	7,553
	60,000–99,999	gt	77	76	0.99	8,500	53,263	22.3	246	16.1	28,374.4	26,307.1	626.4	13,037
	100,000–+	gt	38	38	1.00	11,610	76,730	23.5	262	16.8	43,021.4	25,366.1	538.7	7,811
Ferry – ro-pax	0–1,999	gt	1,634	495	0.30	400	1,541	13.4	87	10.8	533.4	187.6	0.0	3,485
	2,000–-+	gt	1,273	987	0.78	3,201	15,541	22.0	193	17.0	9,095.6	1,333.6	0.0	38,412
Refrigerated bulk	0–1,999	dwt	1,221	903	0.74	5,591	5,036	16.3	146	13.6	2,758.7	2,220.3	447.1	20,234
Ro-ro	0–4,999	dwt	1,277	455	0.36	1,675	1,819	11.6	152	9.7	1,221.9	2,301.7	296.7	14,538
	5,000–+	dwt	486	456	0.94	11,718	11,352	18.0	222	14.5	7,624.9	3,447.8	350.7	16,758
Vehicle	0–3,999	vehicle	349	311	0.89	10,494	9,458	20.1	226	14.8	6,116.9	1,420.7	286.5	7,724
	4,000–+	vehicle	516	507	0.98	20,862	14,945	21.8	238	16.2	8,779.1	1,472.6	282.7	15,710
Yacht	0–+	gt	1,436	768	0.53	322	2,835	16.7	37	12.2	273.5	243.0	0.0	2,304
Service – tug	0–+	gt	13,462	3,673	0.27	275	2,329	12.0	61	7.8	295.7	92.8	0.0	16,504

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Miscellaneous – fishing	0–+	gt	23,421	2,806	0.12	151	911	11.5	94	8.8	287.2	327.3	0.0	44,452
Offshore	0–+	gt	5,671	3,883	0.68	1,758	4,317	14.4	71	9.2	609.4	595.8	0.0	20,399
Service – other	0–+	gt	3,286	2,186	0.67	2,089	2,702	12.4	74	8.8	528.8	412.1	0.0	9,153
Miscellaneous – other	0–+	gt	3,755	158	0.04	78	2,010	13.1	90	9.0	759.9	358.8	0.0	13,178

* indicates the use of weighted averaging (weighted by days at sea for each individual ship).

2008 Detailed Results

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Bulk carrier	0–9,999	dwt	1,151	470	0.41	3,100	1,654	11.6	173	10.3	1.2	0.5	0.1	6,328
	10,000–34,999	dwt	2,177	1,993	0.92	25,515	6,633	14.7	251	12.2	5.7	0.5	0.0	40,377
	35,000–59,999	dwt	2,030	1,957	0.96	48,249	8,611	15.0	249	12.7	7.3	0.6	0.1	48,479
	60,000–99,999	dwt	1,616	1,593	0.99	75,867	10,261	14.9	265	13.1	10.0	1.0	0.2	54,465
	100,000–199,999	dwt	724	718	0.99	165,582	15,500	14.7	273	13.2	16.0	1.0	0.1	37,983
	200,000–+	dwt	129	128	0.99	252,904	19,666	15.6	268	12.5	15.8	1.0	0.2	6,422
Chemical tanker	0–4,999	dwt	1,514	769	0.51	2,163	1,364	12.1	166	10.5	1.0	0.2	0.2	6,023
	5,000–9,999	dwt	728	682	0.94	8,164	3,602	14.4	227	11.8	2.9	0.5	0.3	7,803
	10,000–19,999	dwt	770	747	0.97	16,737	5,838	15.7	233	12.8	4.8	0.5	0.3	12,314
	20,000–+	dwt	1,177	1,154	0.98	43,482	9,859	15.9	241	13.6	8.8	1.3	0.2	35,333
Container	0–999	TEU	1,200	1,082	0.90	9,284	6,187	17.0	178	13.2	3.0	0.8	0.2	14,564
	1,000–1,999	TEU	1,275	1,253	0.98	21,824	13,367	20.3	179	15.2	5.8	2.2	0.4	32,098
	2,000–2,999	TEU	745	733	0.98	37,556	22,678	22.3	178	16.7	9.5	3.1	0.5	29,362
	3,000–4,999	TEU	797	779	0.98	56,036	37,246	24.7	253	18.1	20.9	13.3	2.8	60,102
	5,000–7,999	TEU	484	472	0.98	80,503	58,986	26.5	246	19.7	32.6	3.8	0.5	53,345
	8,000–11,999	TEU	172	172	1.00	117,315	76,127	28.4	250	20.3	41.3	4.1	0.6	22,853
	12,000–14,500	TEU	8	8	1.00	163,136	83,302	25.7	249	19.2	44.0	5.1	0.7	1,237
	14,500–+	TEU	0	0	0.00	0	0	0.0	0	0.0	–	–	–	0
General cargo	0–4,999	dwt	12,990	5,283	0.41	1,904	1,081	11.4	169	9.2	0.6	0.1	0.0	29,685
	5,000–9,999	dwt	2,763	2,288	0.83	7,321	3,445	14.0	258	11.3	2.9	0.4	0.1	27,708
	10,000–+	dwt	2,006	1,780	0.89	21,444	7,416	15.9	251	12.9	6.1	1.2	0.1	43,905
Liquefied gas tanker	0–49,999	cbm	1,021	804	0.79	6,544	3,643	14.1	174	12.2	2.7	0.6	0.4	11,423
	50,000–199,999	cbm	415	408	0.98	69,872	22,749	19.7	247	15.0	16.1	4.0	0.5	23,043
	200,000–+	cbm	21	20	0.95	188,232	61,990	33.4	225	17.5	20.1	3.0	0.8	1,212

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Oil tanker	0–4,999	dwt	3,722	1,133	0.30	1,909	1,172	11.3	158	9.6	0.8	0.6	0.1	17,211
	5,000–9,999	dwt	527	367	0.70	6,857	2,925	13.2	166	10.1	1.5	0.9	0.2	4,090
	10,000–19,999	dwt	227	177	0.78	16,073	5,115	14.3	163	10.8	2.6	1.6	0.4	2,961
	20,000–59,999	dwt	714	664	0.93	44,502	9,023	15.8	227	12.7	6.5	1.8	0.6	18,408
	60,000–79,999	dwt	358	341	0.95	74,030	11,962	15.5	224	13.4	9.9	1.8	0.5	12,841
	80,000–119,999	dwt	773	755	0.98	109,452	13,925	15.7	244	13.2	11.7	2.3	0.7	33,550
	120,000–199,999	dwt	369	363	0.98	156,778	17,912	15.5	258	13.6	16.5	2.9	0.9	22,222
	200,000–+	dwt	526	519	0.99	312,723	26,450	16.4	262	14.6	27.1	3.4	1.0	48,545
Other liquids tankers	0–+	dwt	165	26	0.16	775	606	10.0	76	7.7	0.3	1.1	0.4	866
Ferry – pax only	0–1,999	gt	2,988	620	0.21	162	1,877	22.8	207	18.7	1.7	0.3	0.0	17,961
	2,000–+	gt	80	35	0.44	1,643	6,587	16.9	207	13.1	4.0	0.9	0.0	1,152
Cruise	0–1,999	gt	194	50	0.26	241	1,048	13.0	165	9.3	0.5	0.9	0.4	1,045
	2,000–9,999	gt	78	57	0.73	1,174	4,366	15.9	205	11.4	2.5	1.0	0.4	920
	10,000–59,999	gt	129	123	0.95	4,687	19,888	20.3	213	14.8	10.2	8.9	1.3	7,874
	60,000–99,999	gt	77	75	0.97	8,810	55,376	22.9	230	16.3	27.1	26.6	0.7	12,834
	100,000–+	gt	31	30	0.97	11,088	74,258	22.8	265	17.1	45.4	25.6	0.5	6,754
Ferry – ro-pax	0–1,999	gt	1,633	395	0.24	1,000	1,599	13.4	188	11.8	1.6	0.2	0.0	8,533
	2,000–-+	gt	1,263	909	0.72	3,400	15,520	21.8	201	17.2	9.7	1.3	0.0	39,746
Refrigerated bulk	0–1,999	dwt	1,243	930	0.75	5,681	5,095	16.5	155	13.7	3.0	2.3	0.4	20,898
Ro-ro	0–4,999	dwt	1,224	396	0.32	1,310	1,803	11.6	164	9.9	1.3	2.2	0.3	13,901
	5,000–+	dwt	472	449	0.95	11,399	11,050	17.7	215	14.4	7.2	3.6	0.4	16,021
Vehicle	0–3,999	vehicle	347	308	0.89	9,315	8,345	17.9	263	14.9	7.3	1.4	0.2	9,390
	4,000–+	vehicle	468	464	0.99	20,306	14,114	20.7	282	16.7	11.8	1.4	0.2	18,706
Yacht	0–+	gt	1,263	610	0.48	461	2,814	16.9	95	12.7	0.7	0.2	0.0	3,813
Service – tug	0–+	gt	12,618	2,969	0.24	243	2,253	12.0	167	8.5	0.9	0.1	0.0	41,321

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Miscellaneous – fishing	0–+	gt	23,622	2,177	0.09	149	908	11.5	217	9.4	0.8	0.3	0.0	80,361
Offshore	0–+	gt	5,140	3,292	0.64	1,666	4,115	14.4	200	9.7	2.0	0.8	0.0	39,293
Service – other	0–+	gt	3,014	1,879	0.62	1,941	2,643	12.2	136	9.1	1.0	0.4	0.0	13,128
Miscellaneous – other	0–+	gt	3,902	140	0.04	101	1,957	12.7	135	8.3	0.8	0.4	0.0	14,454

* indicates the use of weighted averaging (weighted by days at sea for each individual ship).

2007 Detailed Results

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Bulk carrier	0–9,999	dwt	1,136	382	0.34	3,001	1,601	11.6	168	10.3	1.2	0.5	0.1	6,053
	10,000–34,999	dwt	2,115	1,916	0.91	25,405	6,631	14.6	245	12.2	5.6	0.5	0.0	38,324
	35,000–59,999	dwt	1,911	1,849	0.97	47,402	8,494	14.9	248	12.7	7.3	0.6	0.1	45,407
	60,000–99,999	dwt	1,532	1,511	0.99	75,373	10,204	14.9	258	13.0	9.9	1.0	0.2	50,373
	100,000–199,999	dwt	694	688	0.99	166,172	15,516	14.8	271	12.8	15.1	1.0	0.2	34,187
	200,000–+	dwt	102	100	0.98	247,529	18,925	15.6	267	11.5	13.3	1.0	0.2	4,319
Chemical tanker	0–4,999	dwt	1,481	680	0.46	2,032	1,303	12.0	170	10.6	1.0	0.2	0.2	6,014
	5,000–9,999	dwt	650	602	0.93	7,633	3,418	13.8	225	11.9	3.1	0.5	0.3	7,263
	10,000–19,999	dwt	636	619	0.97	16,200	5,688	15.3	232	12.9	5.1	0.5	0.3	10,804
	20,000–+	dwt	1,057	1,037	0.98	42,758	9,631	15.8	242	13.7	9.0	1.3	0.2	32,561
Container	0–999	TEU	1,138	1,015	0.89	8,976	6,004	16.7	178	13.3	3.1	0.9	0.2	14,177
	1,000–1,999	TEU	1,159	1,142	0.99	21,644	13,153	20.0	180	15.2	6.0	2.2	0.4	29,855
	2,000–2,999	TEU	691	684	0.99	36,869	22,228	21.9	178	16.8	9.9	3.2	0.5	28,440
	3,000–4,999	TEU	726	720	0.99	56,198	37,068	24.7	257	18.6	22.8	3.6	0.5	58,439
	5,000–7,999	TEU	436	432	0.99	79,567	58,342	26.3	248	20.6	37.2	3.8	0.5	54,287
	8,000–11,999	TEU	135	135	1.00	116,415	76,214	28.2	249	21.3	48.0	4.1	0.5	20,417
	12,000–14,500	TEU	7	7	1.00	245,802	125,669	38.4	249	20.6	46.6	4.1	0.6	889
	14,500–+	TEU	0	0	0.00	0	0	0.0	0	0.0	–	–	–	0
General cargo	0–4,999	dwt	12,931	4,934	0.38	1,796	1,053	11.3	170	9.3	0.6	0.1	0.0	29,888
	5,000–9,999	dwt	2,658	2,146	0.81	7,214	3,416	13.9	257	11.4	3.0	0.4	0.1	27,187
	10,000–+	dwt	1,912	1,672	0.87	21,106	7,424	15.8	250	12.9	6.3	1.2	0.1	43,063
Liquefied gas tanker	0–49,999	cbm	985	707	0.72	6,027	3,452	13.9	174	12.4	2.8	0.6	0.4	11,265
	50,000–199,999	cbm	380	374	0.98	68,516	22,601	19.5	240	14.8	15.8	4.0	0.6	21,027
	200,000–+	cbm	4	4	1.00	410,794	149,277	78.0	250	15.4	6.3	1.1	0.3	96

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. dead-weight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Oil tanker	0–4,999	dwt	3,703	887	0.24	1,759	1,110	11.2	158	9.7	0.8	0.6	0.1	17,566
	5,000–9,999	dwt	497	310	0.62	6,735	2,836	13.0	162	10.3	1.5	0.9	0.2	3,849
	10,000–19,999	dwt	228	168	0.74	15,910	5,069	14.0	161	10.8	2.6	1.5	0.4	2,907
	20,000–59,999	dwt	709	644	0.91	42,177	8,702	15.4	211	12.7	6.4	1.8	0.5	17,592
	60,000–79,999	dwt	347	329	0.95	74,629	11,973	15.7	220	13.4	10.2	1.8	0.5	12,341
	80,000–119,999	dwt	741	717	0.97	107,004	13,507	15.3	241	13.3	12.0	2.3	0.7	32,893
	120,000–199,999	dwt	378	371	0.98	156,240	17,787	15.4	255	13.7	17.1	2.9	0.9	23,099
	200,000–+	dwt	518	511	0.99	304,950	25,549	16.0	267	14.6	27.5	3.5	1.0	49,848
Other liquids tankers	0–+	dwt	163	16	0.10	798	612	9.9	183	9.0	0.6	1.2	0.4	1,113
Ferry – pax only	0–1,999	gt	2,974	450	0.15	143	1,824	22.7	205	18.9	1.7	0.3	0.0	18,639
	2,000–+	gt	80	27	0.34	1,574	7,020	16.5	109	11.4	2.1	0.7	0.0	516
Cruise	0–1,999	gt	182	43	0.24	189	1,017	12.8	142	9.4	0.5	0.9	0.3	873
	2,000–9,999	gt	78	60	0.77	1,155	4,289	15.7	177	10.9	2.0	1.0	0.3	735
	10,000–59,999	gt	127	120	0.94	4,629	19,222	19.9	224	14.7	10.3	9.0	1.3	8,028
	60,000–99,999	gt	73	72	0.99	8,663	54,947	22.8	227	16.4	28.2	26.7	0.7	12,188
	100,000–+	gt	28	28	1.00	11,262	74,422	22.9	264	16.9	43.0	25.7	0.6	5,947
Ferry – ro-pax	0–1,999	gt	1,611	306	0.19	317	1,484	13.2	185	11.0	1.1	0.2	0.0	6,085
	2,000––+	gt	1,248	809	0.65	3,068	15,126	21.5	195	17.4	10.0	1.3	0.0	40,092
Refrigerated bulk	0–1,999	dwt	1,237	932	0.75	5,500	5,060	16.3	148	13.6	2.9	2.3	0.4	20,513
Ro-ro	0–4,999	dwt	1,194	332	0.28	1,212	1,803	11.6	157	10.2	1.5	2.1	0.3	13,637
	5,000–+	dwt	470	432	0.92	11,401	10,985	17.8	216	14.6	7.6	3.5	0.4	16,121
Vehicle	0–3,999	vehicle	334	289	0.87	8,935	8,079	17.5	262	14.9	7.4	1.4	0.2	9,227
	4,000–+	vehicle	422	417	0.99	19,364	13,869	20.5	282	16.8	12.2	1.4	0.2	17,393
Yacht	0–+	gt	1,120	453	0.40	115	2,597	16.6	94	12.6	0.7	0.2	0.0	3,276
Service – tug	0–+	gt	12,079	2,182	0.18	84	2,158	11.9	168	8.6	1.0	0.1	0.0	41,172

Ship type	Size category	Units	Number active		Decimal AIS coverage of in-service ships	Avg. deadweight (tonnes)	Avg. installed power (kW)	Avg. design speed (knots)	Avg. days at sea	Avg.* sea speed (knots)	Avg.* consumption ('000 tonnes)			Total CO_2 emissions ('000 tonnes)
			IHSF	AIS							Main	Auxiliary	Boiler	
Miscellaneous – fishing	0–+	gt	23,658	1,699	0.07	101	880	11.4	216	9.7	0.9	0.3	0.0	86,119
Offshore	0–+	gt	4,761	2,545	0.53	1,032	3,864	14.1	195	9.7	2.0	0.6	0.0	36,037
Service – other	0–+	gt	2,681	1,546	0.58	1,786	2,624	12.2	137	9.4	1.1	0.4	0.0	12,430
Miscellaneous – other	0–+	gt	4,027	58	0.01	34	1,905	12.6	119	8.7	0.9	0.3	0.0	15,300

* indicates the use of weighted averaging (weighted by days at sea for each individual ship).

Annex 3

Details for Section 1.4: bottom-up QA/QC

Activity estimate quality of spatial coverage

It can be seen from Table 5 that the amount of messages per year usable for the bottom-up emissions study is the largest in 2012, including sets from two different satellite sources (Kystverket, exactEarth) and several terrestrial sources. The total number of AIS-messages successfully processed (all years) is over 8.3 billion. However, this number may include duplicate messages, especially near European coastal regions. The annual number of messages is significantly smaller for 2007–2009 and for these years there were no S-AIS sources available.

The effect of the increase in messages is that coverage increases both temporally and geographically from 2007 to 2012. This section focused specifically on the geographical coverage.

Figure 10 and Figure 12 show the coverage of the AIS and LRIT data sets respectively with the same scale to facilitate comparability through the period. Most noticeable is that from 2010 to 2012 there are marked improvements, particularly over ocean regions owing to the inclusion of S-AIS. Europe is very well covered in all years, but particularly from 2010 onwards. Marine Traffic and IHS are global coverage terrestrial AIS sources, with the former substituting for the latter from 2010 onwards, resulting in what appears to be consistently improved shore-based message reception.

The 2012 and 2011 AIS data set provides good global coverage, with shipping routes clearly noticeable at this scale.

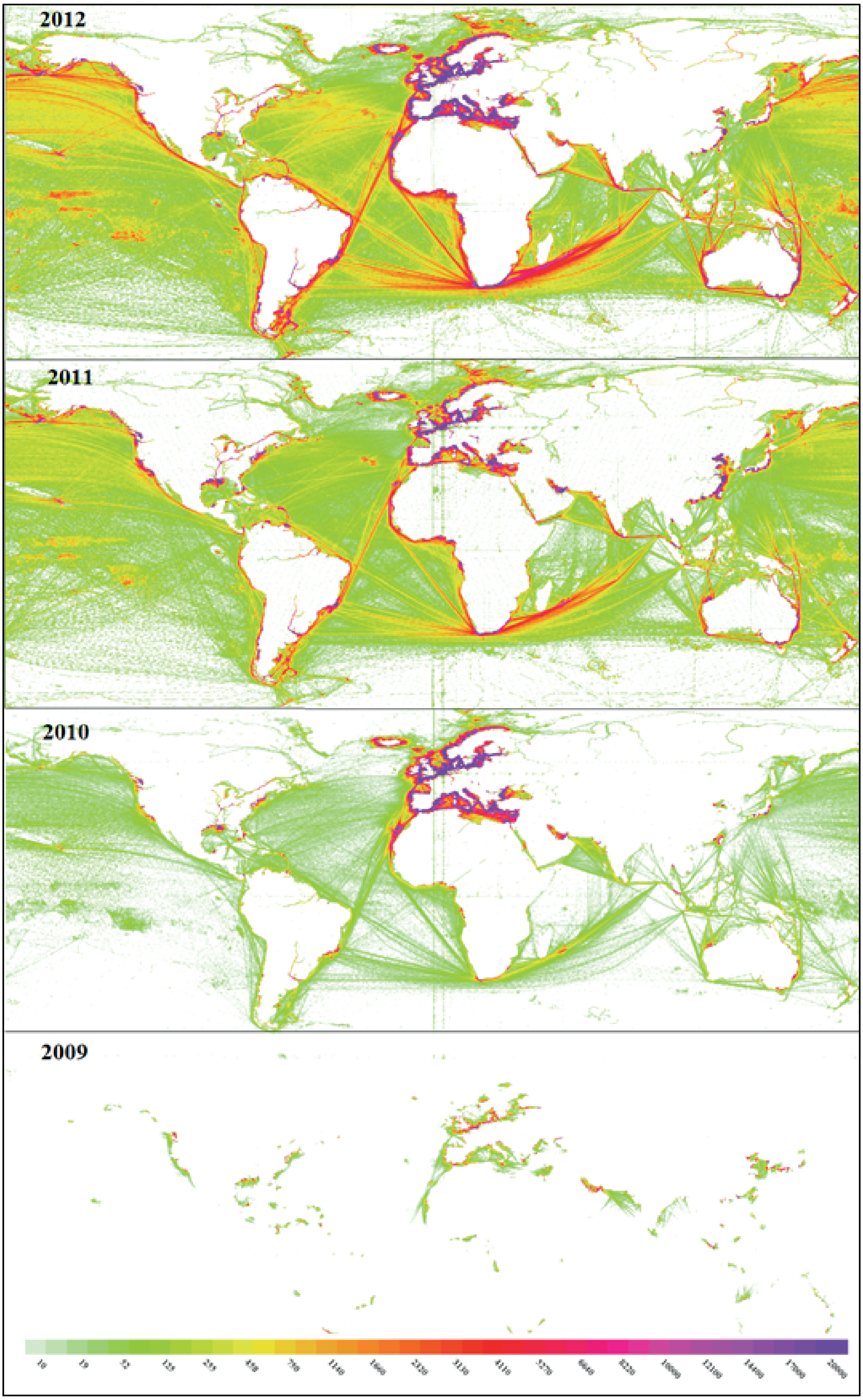


Figure 10: *Geographical distribution of AIS messages processed by the pre-processor for 2009–2012. All available AIS data sets (both satellite and terrestrial) have been combined. Unit: total number of messages per grid cell with an area of 0.2 × 0.2 degrees*

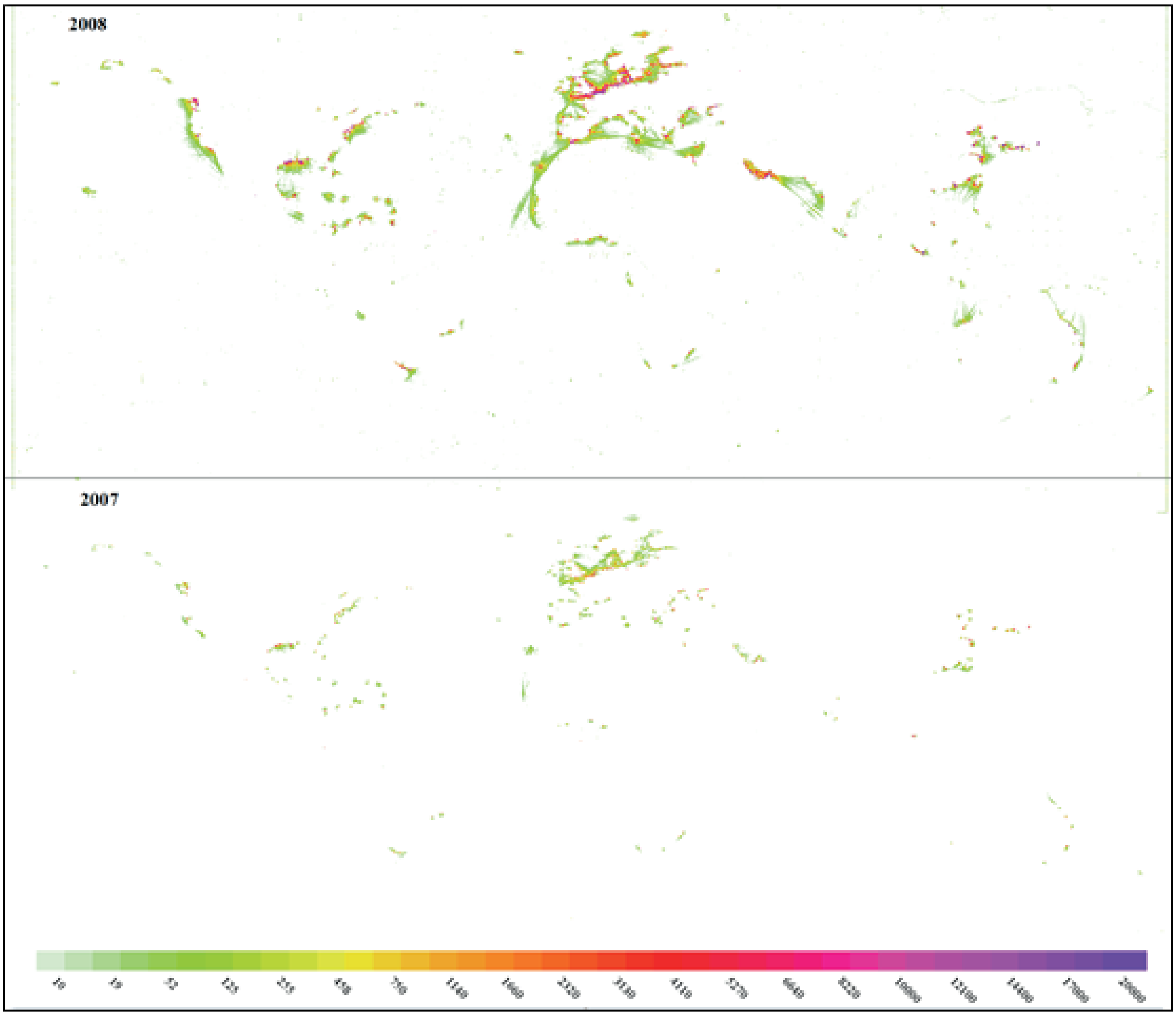


Figure 11: *Repeat plots for 2008 and 2007 as for Figure 4 with the same scale*

As discussed in Annex 1, LRIT data was processed in a way consistent with AIS sources. LRIT as a data source is discussed in more detail in the following section on temporal coverage. Comparing LRIT with AIS coverage, it is immediately apparent that the coverage is adequate for LRIT in the North Atlantic and Indian Ocean but poor in the Pacific. For the most part, it is suitable as a corroborating data set for coastal regions. The major areas of traffic highlighted by LRIT are the European sea area, the Far East (Singapore, China, Japan and the Republic of Korea) and the shipping lane connecting them. These areas and routes are well covered in AIS from 2010. There are no regions identified by LRIT that are not covered adequately by the 2010 to 2012 data sets.

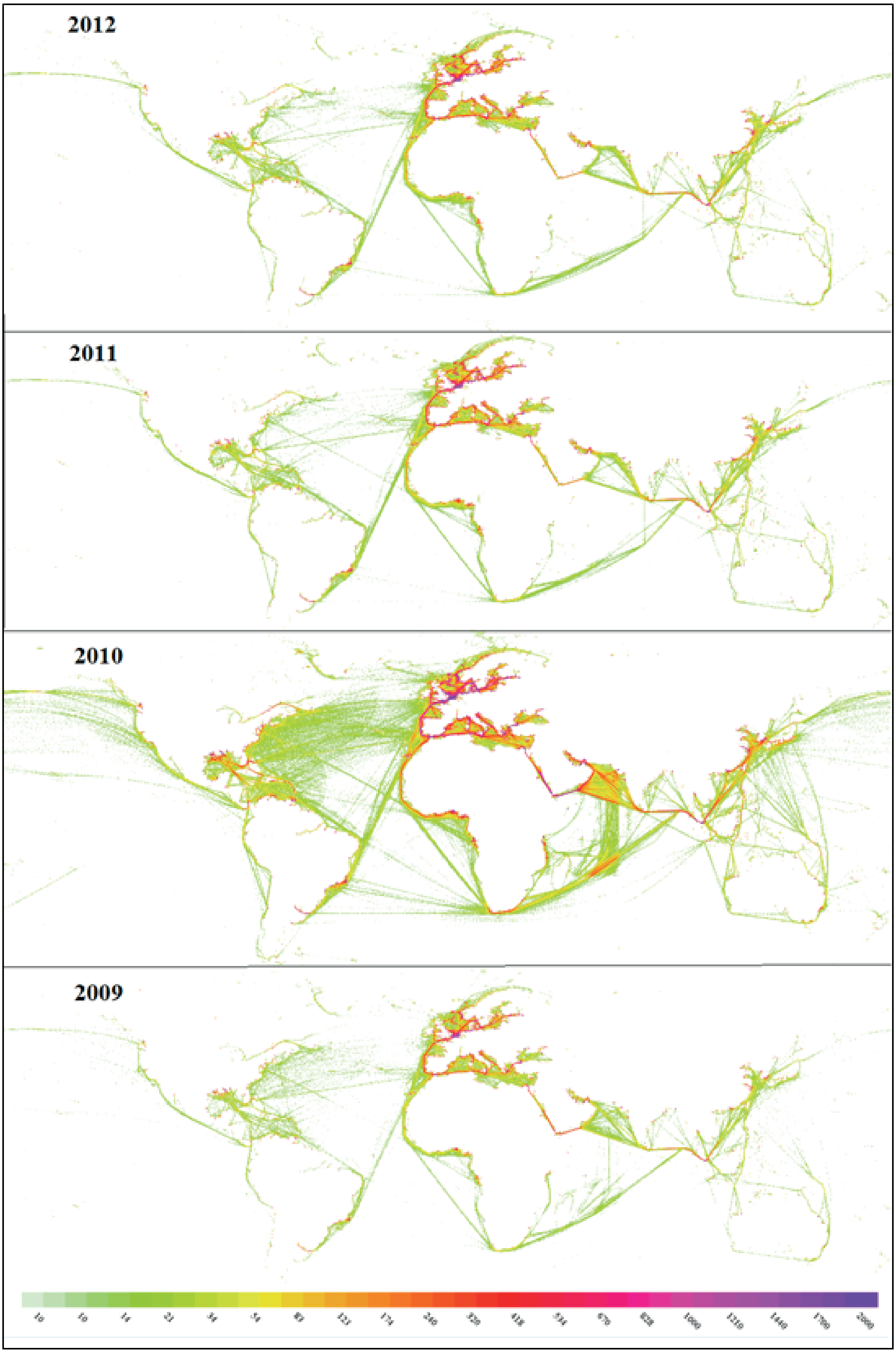


Figure 12: *Geographical distribution of LRIT messages processed by the pre-processor for 2009–2012. Unit: total number of messages per grid cell with an area of 0.2 × 0.2 degrees*

Further examination of specific regions can be found in Figure 13, which shows the average volume of AIS activity reports for a region reported by a very large crude carrier (VLCC). Note that it is not the volume of reports that is important, but the change in the volume, as one would expect the volume of messages to vary across regions. It is also important to note that while the regions at which ships call varies from year to year, any bias is assumed to be removed through the sample size selection and the ship categories selected.

The reduction in the Persian Gulf and Singapore Strait regions following 2009 is due to the change in data set from IHS to other terrestrial data sets. Notwithstanding this reduction, the coverage remains significant, but for some coastal regions 2010 has the poorest coverage. However, this improves significantly in 2011. For ocean regions, the coverage dramatically improves from 2010 onwards.

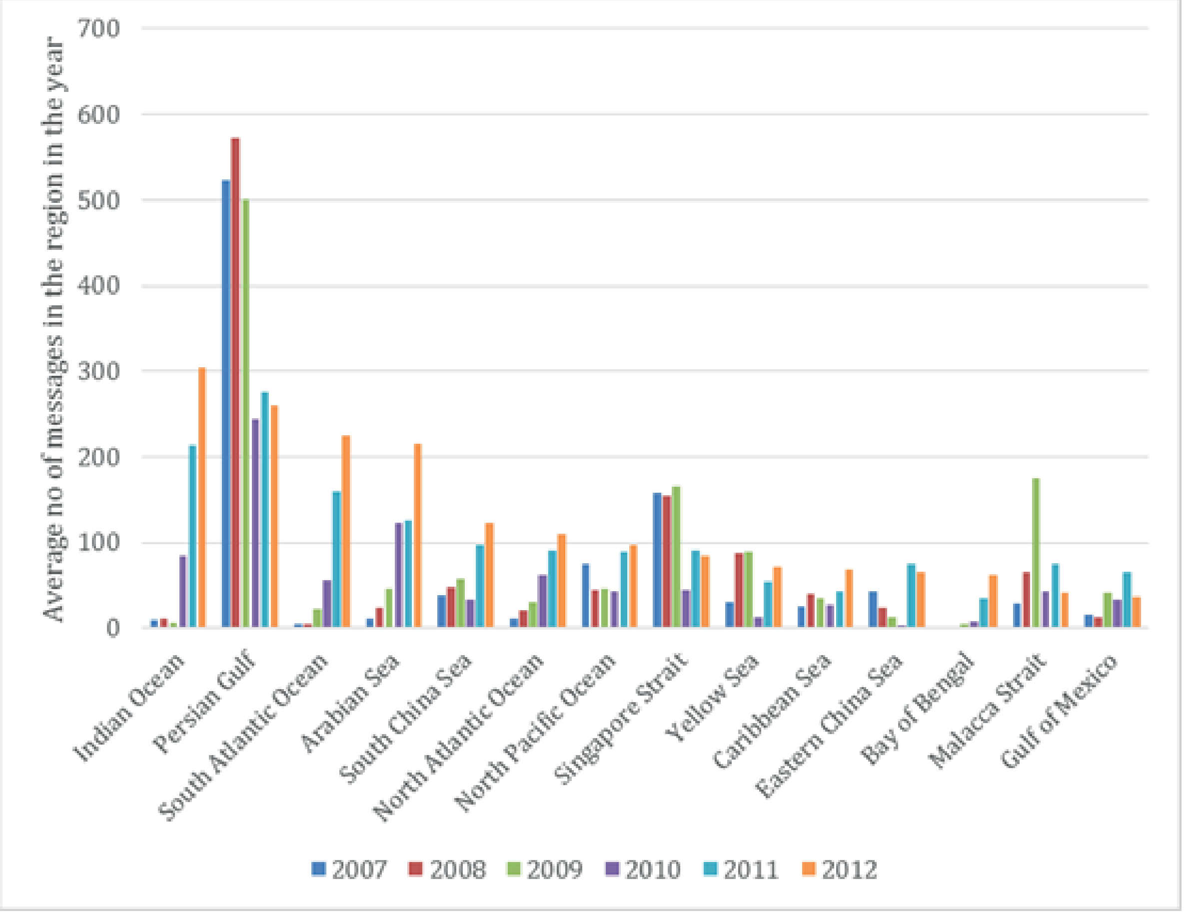


Figure 13: *The average volume of AIS activity reports for a region reported by a ship for up to 300 randomly selected VLCCs from 2007 to 2012*

Figure 14 shows a similar plot but in this instance is focused on the largest bulk carrier category. It shows a message that is consistent with Figure 13, with consistent coverage around China and highly improved coverage in ocean areas over time.

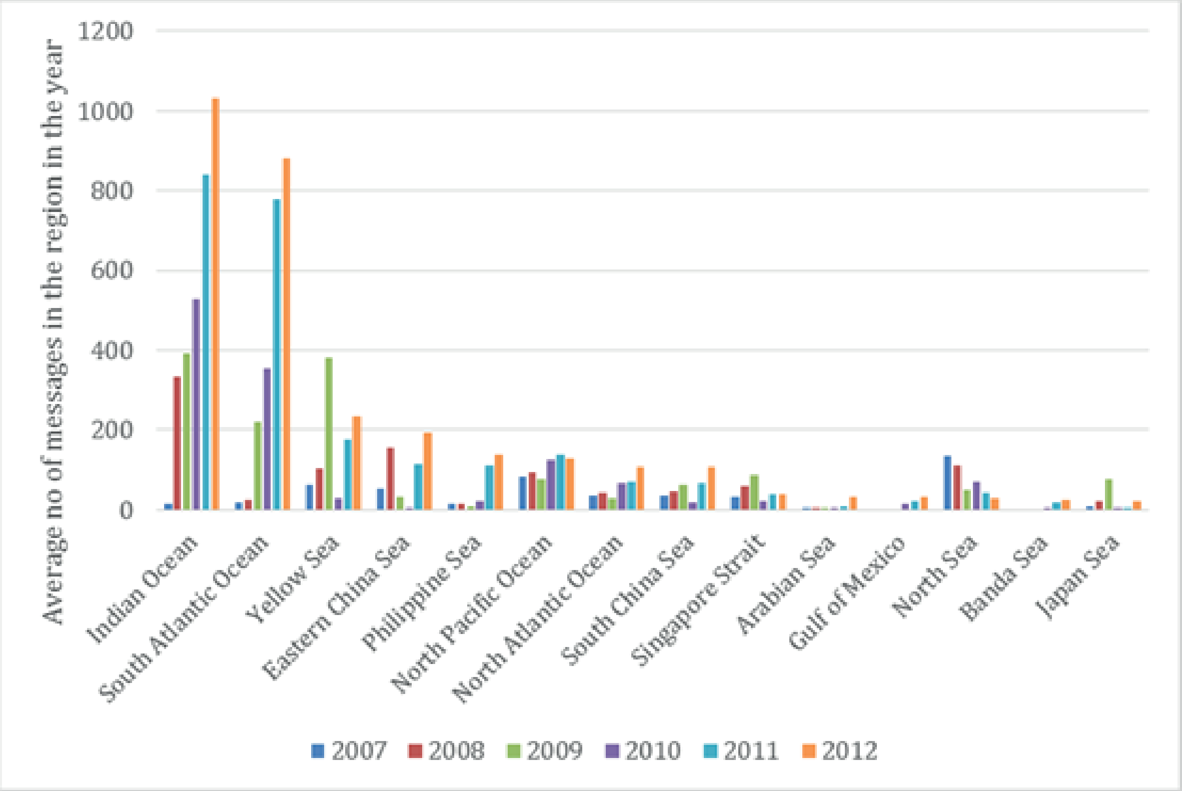


Figure 14: *The average volume of AIS activity reports for a region reported by a ship for up to 300 randomly selected Capesize bulk carriers from 2007 to 2012*

In summary, the coverage of AIS in 2011 and 2012 can be considered to be very rich. There are no areas identified in this analysis for which there is no coverage available, although the volume of reports in some areas has decreased with a drop in coverage in some coastal regions from 2009 to 2010, but this greatly improves in the following years.

Activity estimates temporal coverage QA/QC

To test and verify the number of days at sea and the speed profiles derived from the AIS data, results are compared to LRIT data. LRIT data complements AIS data by providing an independent data source against which the quality of the AIS data can be tested. Under LRIT, ships must send position reports to their flag administration at least four times a day, or every six hours. The transmission process is different to that of AIS so that LRIT is not subject to the same constraints that can limit AIS coverage. In particular, recording of AIS messages depends on the ship being located in the field of view of either a land- or a space-based AIS receiver and the successful reception of the message by that receiver. LRIT messages are not recorded by the same receivers and coverage by LRIT is therefore largely independent of coverage by AIS data.

The data sets hold LRIT messages from 6,441 distinct ships in 2009, from 8,716 ships in 2010, 8,127 in 2011, and 8,838 in 2012 (see Table 5). If four position reports per day are considered full coverage, this would correspond to 1,460 messages (1,464 in 2012) per year per ship. Table 11 shows the mean number of LRIT reports per ship. In 2010–2012, most ships came close, with more than four reports per day from very few ships and with fewer than four reports per day from some ships. In 2009, there were fewer reports per ship as LRIT was still coming into operation during that year. There are different reasons why there may be fewer than 1,460 (1,464) reports per year from a ship. For example, some reports might be lost and, of course, ships entering into service in a given year would not have the full number of reports in that year. It could also be the case that ships are laid up and inactive for some part of the year, and the LRIT signal is only transmitted at times when the ship is active/in service.

Table 11 – *Mean number of messages by ship for LRIT ships used in the analysis*

	2012	2011	2010	2009
Mean no. of messages	1,194	1,161	1,118	342

In summary, the data do not fulfil the assumption of four reports per day exactly. However, for the most part, the assumption that the data includes one LRIT position report every six hours per ship is met reasonably well. To quantify the latter point, the fraction of time intervals between consecutive LRIT messages in the range from five to seven hours is shown for each ship category in Figure 15: the majority of LRIT reports are recorded at a frequency of about one every six hours, with most consistency in 2012.

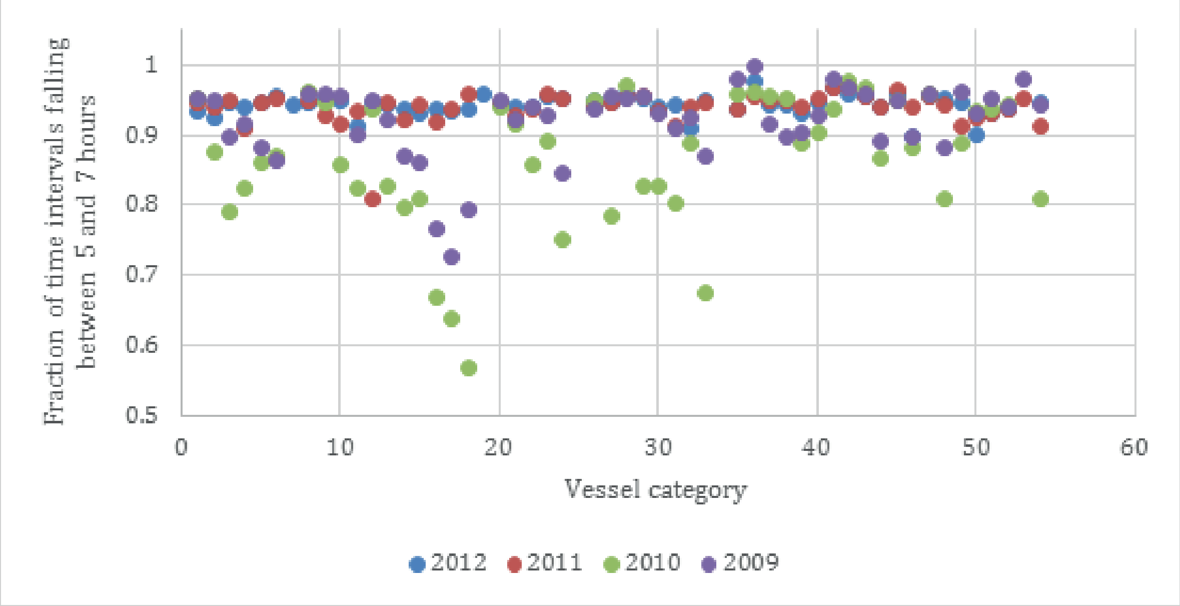


Figure 15: *Fraction of time intervals between consecutive messages that fall between five and seven hours for each ship type and size category*[1]

The key point is that coverage of LRIT position reports is largely independent of coverage of AIS reports. Therefore, the LRIT data can shed light on the validity or otherwise of the days at sea and speed profiles estimated from extrapolated AIS data.

The LRIT data contain six parameters: a unique ship identification number (Ref_ID) (generated in the merging and anonymization process with fleet technical data), a time stamp, speed, draught, region and organization source identification. In this section, Ref_ID, time and speed are the only variables used. The original, raw LRIT data contain geographical location. That information has been stripped out of the data used for this report and replaced with the speed, which is calculated as the great circle distance between the geographical locations given in the LRIT report and in the consecutive one, divided by the time difference between the reports. For a ship travelling at constant speed over the open oceans, the resulting speed value is accurate. For a ship that changes its course within the time interval between consecutive position reports, its speed is underestimated.

In order to compare ship activity estimated from AIS and LRIT data, respectively, the ships appearing in the LRIT data are matched to the AIS data and to entries in the ship fleet database, from which the ship category to which they belong is determined. Table 12 shows how many of the ships identified in the LRIT data are also found in both the AIS data and the ship database.

Table 12 – *AIS to LRIT ship mapping (number of ships)*

	2009	2010	2011	2012
LRIT ships	6,441	8,716	8,127	8,838
LRIT ships matched to AIS	6,402	8,640	7,261	8,776
Three-way matches (LRIT, AIS and IHS ship parameters)	5,283	8,562	7,261	7,322

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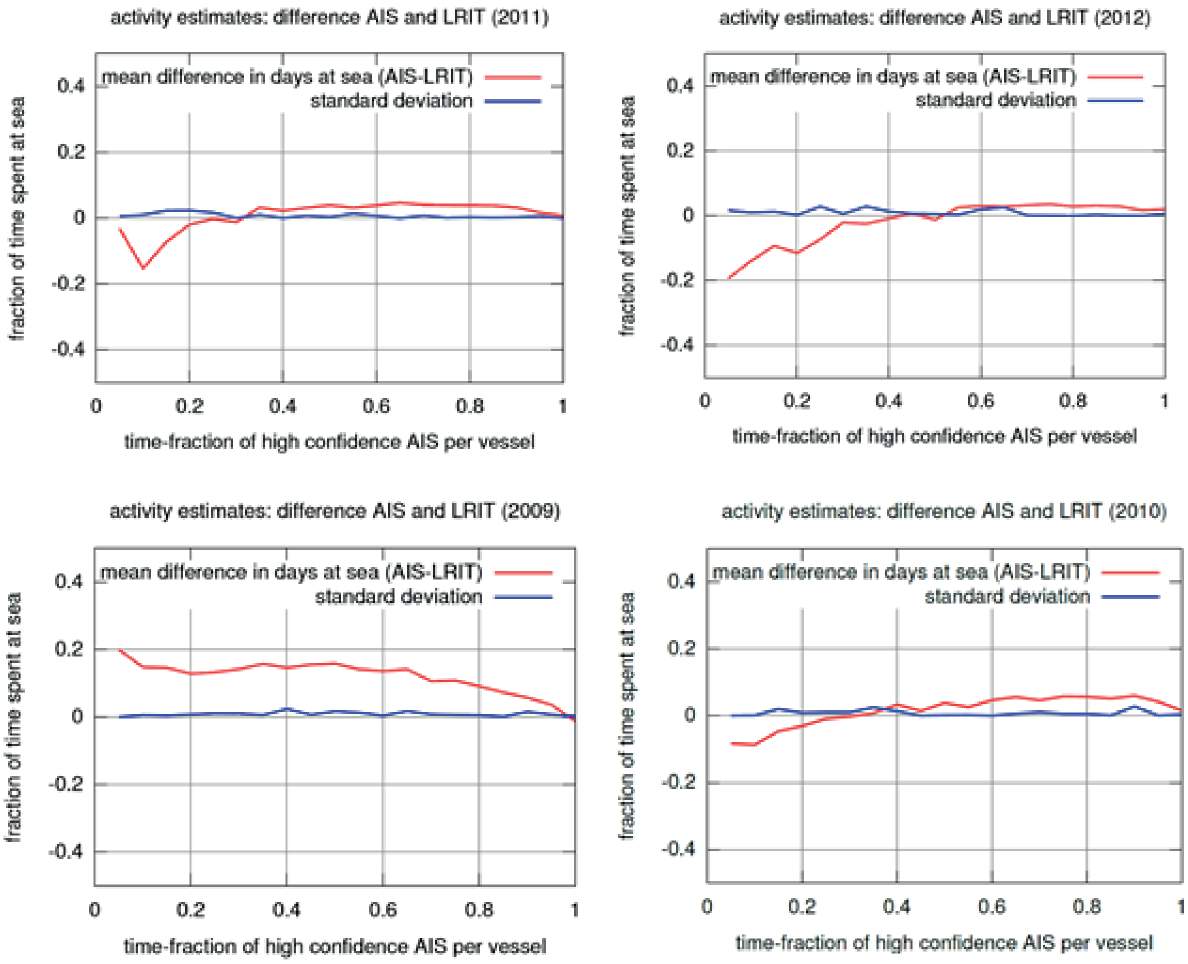
[1] 1–6: bulk carrier; 7: combination carrier; 8–11: chemical tanker; 12–19: container; 20–22: general cargo; 23–25: liquefied gas tanker; 26–33: oil tanker; 34: other liquids tanker; 35–36: ferry – pax only; 37–41: cruise; 42–43: ferry – ro-pax; 44: refrigerated cargo; 45–46: ro-ro; 47–48: vehicle; 49: yacht; 50: service – tug; 51: miscellaneous – fishing; 52: offshore; 53: miscellaneous – other; 54: service – other.

Every LRIT report is labelled "at sea" if the stored speed value is greater than or equal to 3.0 knots. If the speed value is below 3.0 knots, the LRIT report is labelled "in port". The same criteria are applied to the corresponding AIS data. The AIS data are in the format of hourly messages that include a reliability flag, set to 1 if the AIS data at that time are reliable and to 0 if they rely more heavily on the extrapolation algorithm. To investigate any bias that may be introduced by accounting for the cases of low AIS coverage, time spent at sea according to LRIT data is compared to time spent at sea according to AIS data, for ships that are more or less well observed in the AIS data. To this end, for each ship in each year, the parameter of AIS coverage is defined as the ratio of AIS messages with reliability of 1 to all AIS messages.

The plots in Figure 16 show the comparisons over each year for the estimates of days at sea. Perfect agreement would result in a value of 0 for the mean difference in days at sea. For 2010 to 2012, with good AIS coverage, there is convergence between LRIT and AIS days at sea, with a slightly higher value for AIS. However, in each year, as AIS coverage deteriorates, AIS underestimates the number of days at sea compared to LRIT for all years.

For the comparison in 2009, it should be noted that the extrapolation algorithm applies a correction factor to the AIS data in order to attempt to correct for the expectation of bias when shore-based AIS data is used. For the comparison shown in Figure 16, the correction factor used is derived from the days at sea reported in the Second IMO GHG Study 2009 for the year 2007. The poor quality observed in that comparison, showing that AIS consistently overestimates days at sea relative to the LRIT data, reflects the inadequacy of the assumption that Second IMO GHG Study 2009 data (for 2007) is representative of the activity of shipping in 2009. Whether this is because the Second IMO GHG Study 2009 data is inaccurate, or cannot be assumed approximately constant over the period 2007–2009, cannot be identified. However, following observation of the poor quality of the starting assumption, the assumptions were revised, and the extrapolation algorithm uses the LRIT data to calibrate observed days at sea in 2009, rather than the Second IMO GHG Study 2009 data, and this definition is provided in Annex 1. This assumption is tested in the uncertainty section to determine the effect on final results.



activity estimates: difference AIS and LRIT (2011)

activity estimates: difference AIS and LRIT (2012)

activity estimates: difference AIS and LRIT (2009)

activity estimates: difference AIS and LRIT (2010)

Figure 16: *Plots of difference in fraction of time spent at sea for all ships, with increasing high-confidence AIS count over the year. For each ship in one of these 5%-wide bins, the difference between fraction of time at sea between AIS and LRIT is calculated. The mean of this difference per bin is plotted in red, and the standard deviation of the difference in each bin is plotted in blue*

Speed is also compared from AIS-derived estimates to the LRIT estimates. During the processing and extrapolating from AIS data, the AIS data are resampled to hourly bins. This introduces uncertainty into the estimate of the speed of the ship, as the ship speed is not constant throughout the hour. To highlight this uncertainty, Figure 17 shows the distribution of the difference between reported speed and resampled speed for a ship travelling at its average speed.

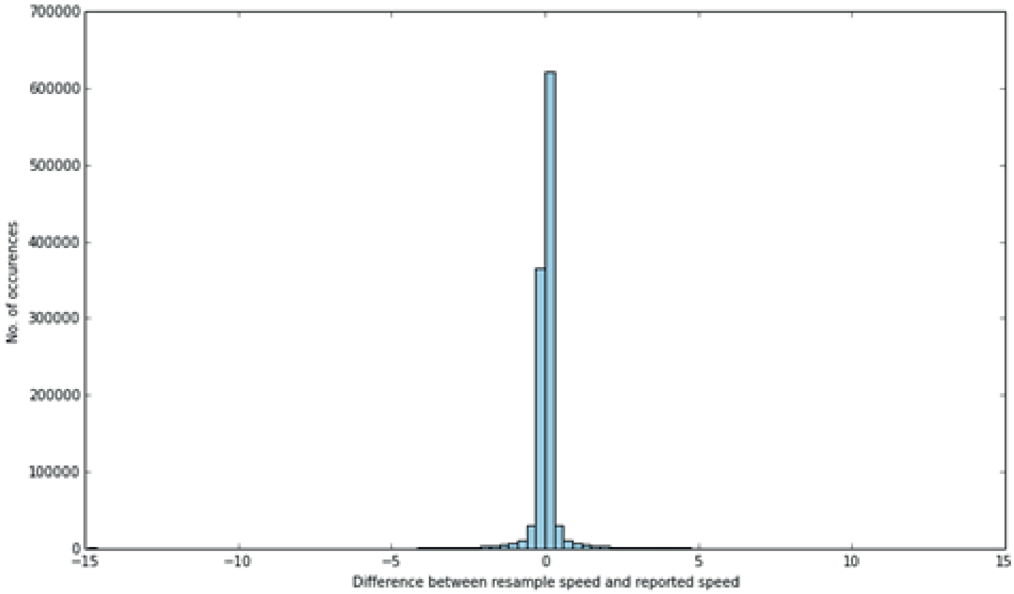


Figure 17: *Distribution of difference between resampled hourly speeds and the reported speed within the hour sampled across 10 VLCCs in 2011. The standard deviation was calculated as 0.75 nm/hr*

Similarly, Figure 18 shows the distribution of speed change for a time difference of two hours.

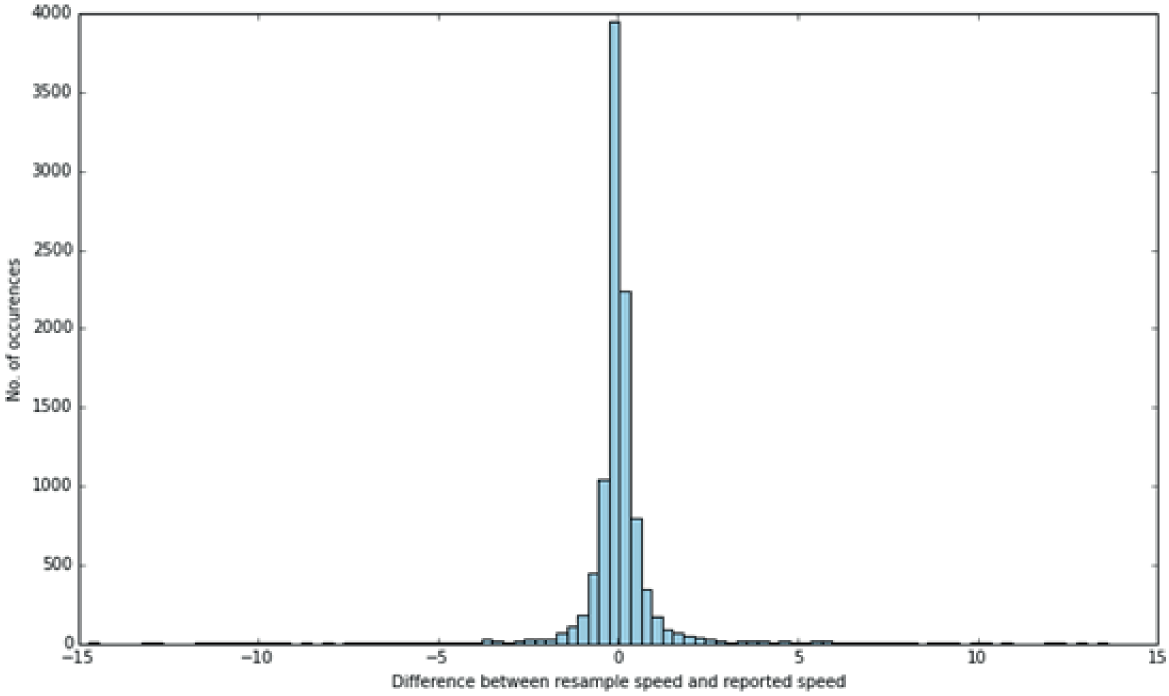


Figure 18: *Distribution of difference between reported speeds when the time difference in reporting is within two hours (sampled as message from 105 minutes to 120 minutes from the original message) for all VLCCs captured in AIS. The standard deviation of the sample was 1.85 nm/hr*

Figure 19 shows the comparison of LRIT speed and AIS-derived mean speed at sea for each ship category. In most cases and years, AIS-derived speed is higher than that provided by LRIT. This is not unsurprising as the LRIT speed is calculated from shortest path between points, which is not necessarily the route the ship will have taken. Moreover, there will most likely be bias towards reported shore-side speeds, which are typically lower. The extreme outliers occur when there is a low count of LRIT messages for ships within a type and size category. Notwithstanding the extreme outliers, there is generally good agreement between the speed estimates. From 2009 to 2012, the number of categories where the difference in mean category speed is less than 1 is 19, 34, 33 and 37 respectively. The differences observed in 2009 are attributable to the fact that there is no satellite-derived activity data in this year.

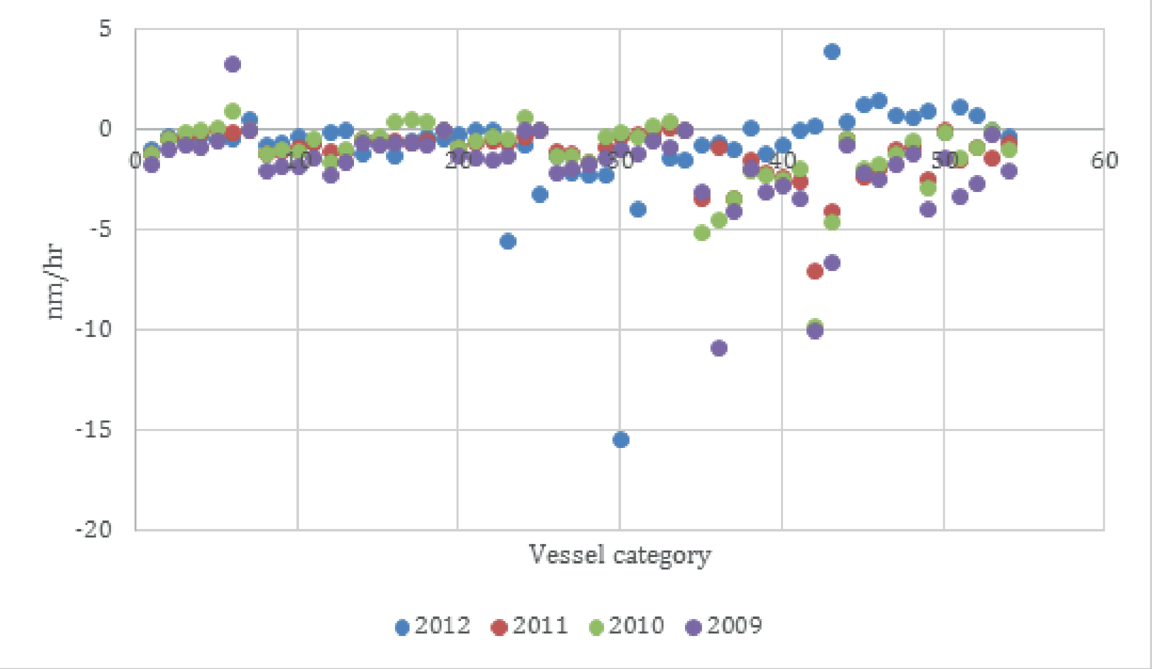


Figure 19: *Difference between average speed at sea for each ship size and type category. Negative values indicate that LRIT data provides a lower estimate of speed than the extrapolated AIS data*

In summary, there is good confidence about the days at sea and speed estimates for 2010 to 2012, both regarding a lack of bias and convergence in estimates of these variables when there is high confidence in the AIS extrapolation. However, for 2009 and for low-confidence AIS extrapolation estimates (less than 40%), bias is evident, tending to increase the days-at-sea percentage.

Fleet technical data quality

Evaluating the technical fields from 2007 to 2012 used for estimating ship emissions, the fields with over 99% coverage over the study time frame include Statcode3, Statcode5, gt, propulsion type, number of screws and date of build. The fields with the poorest coverage (under 50%) over the study time frame include length, main engine (ME) fuel consumption and total fuel consumption. It should be noted that the IHSF database did not include keel laid date until 2012. A qualitative field quality was initially assigned based on consortium members' evaluation/use of fields in previous projects and input from IHS Maritime. The qualitative designations include "representative" and "speculative". "Representative" designates that, based on previous work with this field on other projects, the field is generally found to be representative of the actual ship characteristic and reliably reported across numerous ships. "Speculative" designates that, based on previous work with this field on other projects, the field is generally found to be inconsistent with the actual ship characteristic and/or not reliably reported across numerous ships. Again, at this time the quality designations are based on the past experience and judgement of the consortium for a particular field, with input from IHS Maritime.

A comparison was conducted for the 2007 to 2012 observed cargo-carrying ships (identified with AIS and S-AIS activity), which showed improvements in the coverage of several of the fields. Fields in which coverage is improving are beam and RPM, while dwt, maximum draught, ship speed, and installed ME power had similar coverage across the study time frame. The coverage of the cargo-carrying fleet with respect to the various fields utilized for this study is presented in Table 13.

Table 13 – *Analysis of 2011 and 2012 observed cargo-carrying fleet*

	% IHSF coverage						Qualitative field quality
Field	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	
Statcode3	100%	100%	100%	100%	100%	100%	Representative
Statcode5	100%	100%	100%	100%	100%	100%	Representative
gt	100%	100%	100%	100%	100%	100%	Representative
dwt	99.1%	98.9%	98.7%	98.3%	98.0%	98.1%	Representative
length	30.5%	31.9%	38.9%	40.6%	39.7%	43.2%	Speculative
beam	77.6%	79.8%	86.6%	86.6%	88.9%	93.5%	Speculative
max draught	99.0%	98.7%	98.7%	98.6%	98.3%	98.5%	Representative
ship speed	90.2%	88.1%	89.1%	89.6%	87.7%	93.3%	Representative
installed ME power	99.3%	99.2%	99.3%	99.4%	99.0%	99.1%	Representative
RPM	55.6%	61.9%	79.9%	90.0%	90.3%	91.6%	Speculative
ME consumption	35.0%	32.9%	31.0%	28.8%	27.1%	24.7%	Speculative
total consumption	33.0%	31.0%	28.9%	26.5%	24.8%	22.3%	Speculative
propulsion type	100%	100%	100%	100%	100%	99.1%	Representative
number of screws	100%	100%	100%	100%	100%	100%	Representative
date of build	100%	100%	100%	100%	100%	100%	Representative
keel laid date	na	na	na	na	na	91.9%	Representative

An evaluation of the cargo capacity fields was also conducted for the 2011 and 2012 IHSF data sets. TEU capacity coverage for the container subclass was nearly 100% for both years, but reefer slot capacity coverage was less than 1% in both years. There was 100% coverage for cbm capacity for the liquefied gas carrier subclass in both years. There was over 90% coverage for vehicle capacity for auto carriers (pure car carriers) in both years, but there was less than 55% coverage for vehicle capacity for all the rest of the ro-ro cargo subclass.

Noon report data for activity and fuel consumption quality assurance

Description of noon report data

Noon reports are records kept by the crew of a ship with the information used for a variety of management processes both on board and ashore. There is no standard report format, but most operators collect very similar data, and in most cases the reporting frequency (every day at noon when at sea) is the same. In some cases, per-voyage aggregate data only is available. The data used in this report, and the ship types that it includes, have been generously donated by the operators listed in Table 14. The composition of the fleets used (number of ships by ship type category), after filtering out ships where noon report coverage over the entire quarter is incomplete, is listed in Table 15. The total number of observations is approximately 60,000 days' operation.

Table 14 – *List of operators and their fleets (number of ships) used in this analysis*

Operator	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Gearbulk	0	0	0	0	0	63
V.Ships	2	2	5	11	14	42
Shell	0	0	0	0	61	0
Carbon Positive	16	18	18	26	46	65
Totals	**18**	**20**	**23**	**37**	**121**	**170**

Table 15 – *List of ship types (number of ships) used in this analysis*

Ship Type	2007	2008	2009	2010	2011	2012
Bulk carrier	3	3	6	9	39	52
Chemical tanker	0	0	3	1	17	1
Container	1	1	0	4	4	10
General cargo	0	0	0	0	0	57
Liquefied gas tanker	1	3	2	7	17	10
Oil tanker	11	11	12	16	54	40
Service – tug	0	0	0	0	5	0
Miscellaneous – fishing	0	0	0	0	2	0
Offshore	0	0	0	0	1	0

The total number of ships for which data has been collected represents approximately 1% of the total number of ships in the fleet, and approximately 2% of the total fuel consumption of the fleet.

Noon report data contains inherent uncertainties because measurement on board ships is of variable quality depending on the techniques used. Many noon reports (including many of those used in this study) are populated using tank soundings which can have high measurement error (see Aldous et al., 2013). To address this issue, we have discussed quality procedures with the companies from which the data is collected (many of which have processes in place to assure the quality of the data). Furthermore, we have aggregated the data to quarterly totals (main engine and auxiliary engine fuel consumed, days at sea and in port, and distance travelled) and averages (speed, draught and tonne-per-day fuel consumption). This process of aggregation controls for the uncertainty in daily observations, providing there is no systemic bias in the reporting of any of the data. While systemic bias (e.g. consistent under-reporting of fuel consumed by the crew) cannot be ruled out, the magnitude of the error that this could create is not considered likely to be large relative to the level of assurance that is sought from these comparisons.

Method of processing noon report data in preparation for comparison against bottom-up model output

The noon report data for each ship was aggregated per quarter, and summary statistics on activity and fuel consumption were output for comparison with the bottom-up method.

Only ships for which the noon report data are fully populated for a full quarter (plus or minus five days) is suitable for comparison; incomplete quarters are filtered out. Obvious outliers, usually due to human error in the reporting, are identified manually and removed.

There are a small number of observations for which ship speed and distance travelled is logged but fuel consumption is not recorded. In this instance, the fuel consumption is filled in by conditional mean imputation: fuel consumption is predicted based on information from fully observed variables (ship speed, loading condition and weather) through multiple regressions. Filtering for part days precedes the regression in order to avoid skewness arising from manoeuvring/in-port operations. If none of the coefficients from the regression are found to be statistically significant, simply the mean at-sea fuel consumption for that ship is used. Overall, this approach introduces additional uncertainty in the comparison, but since fuel consumption is compared on an aggregate basis, on balance this is an improvement. Only a small number of observations are adjusted in this way (approximately 2.3% of all observations).

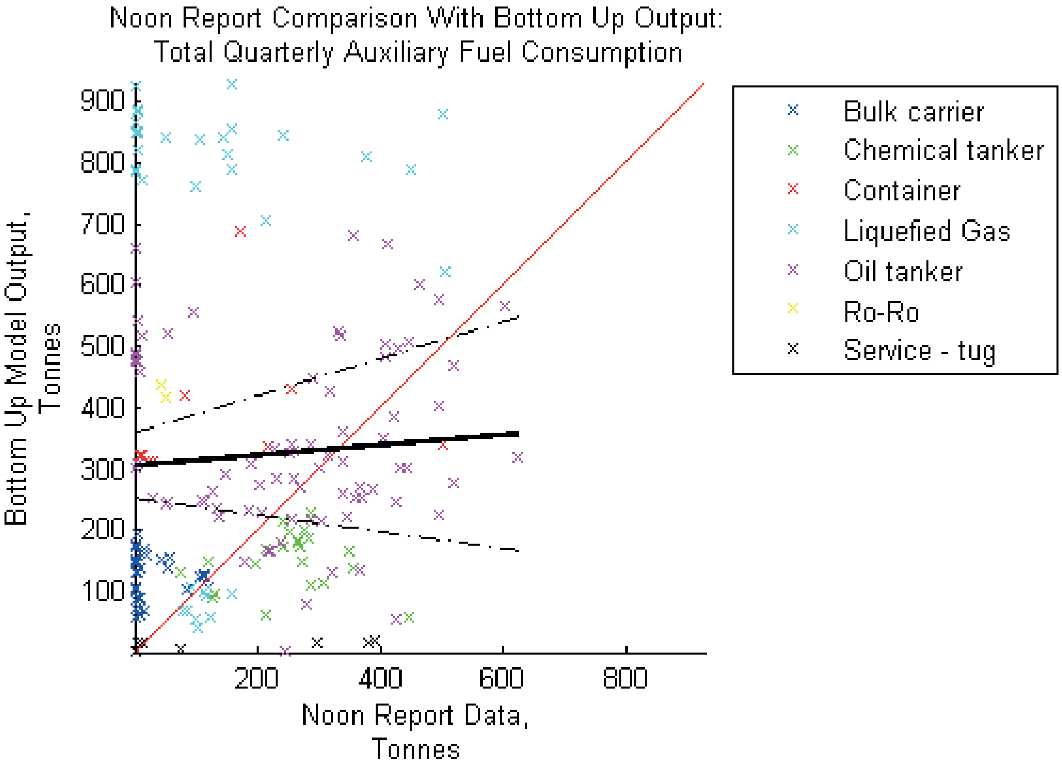
Where a time and distance travelled is logged but there is no speed recorded, the speed is calculated from these two fields and filled in (0.3% of observations).

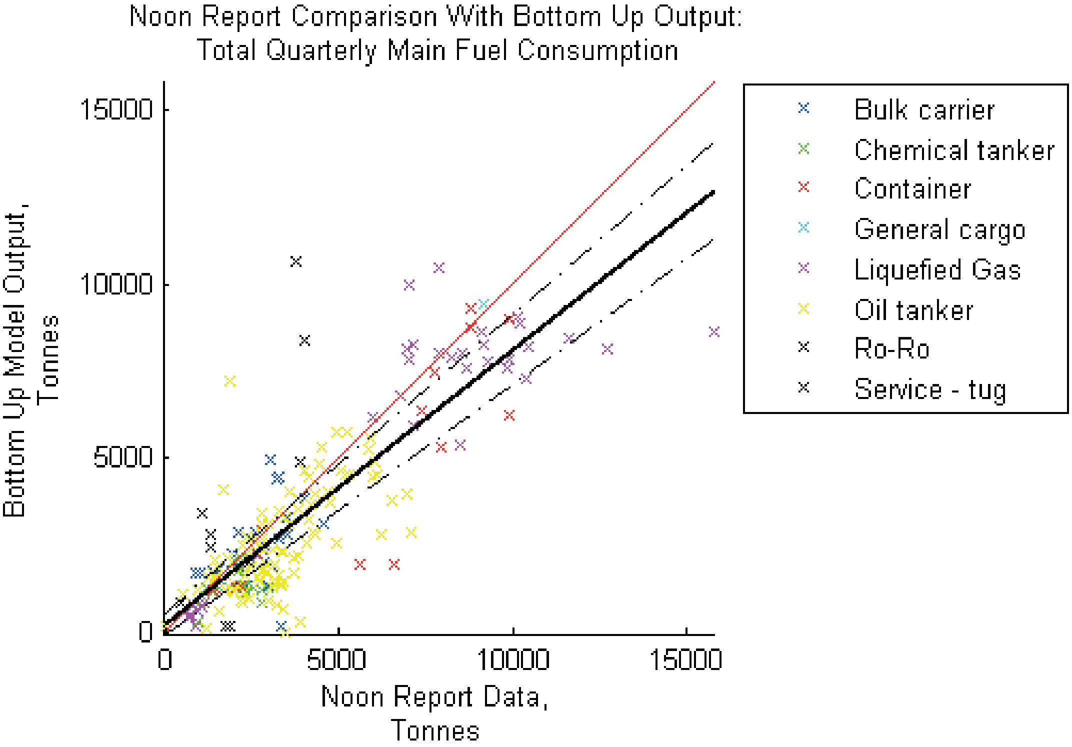
Generally, the noon report fuel consumption fields cover only days at sea; where End of Sea Passage (EOSP) or Free Away on Passage (FAP) are not explicitly defined in an "activities" field (or similar), port days are therefore calculated when zero monitored fuel consumption coincides with zero speed and distance travelled.

Fuel consumption associated with part days – i.e. on a day when the ship is leaving or arriving in port – is included in the per-quarter aggregates, and the hours' steaming during part days are included in the totals for time spent at sea. However, average at-sea ship speed is calculated from full days' steaming only, to ensure that manoeuvring activities do not skew the results.

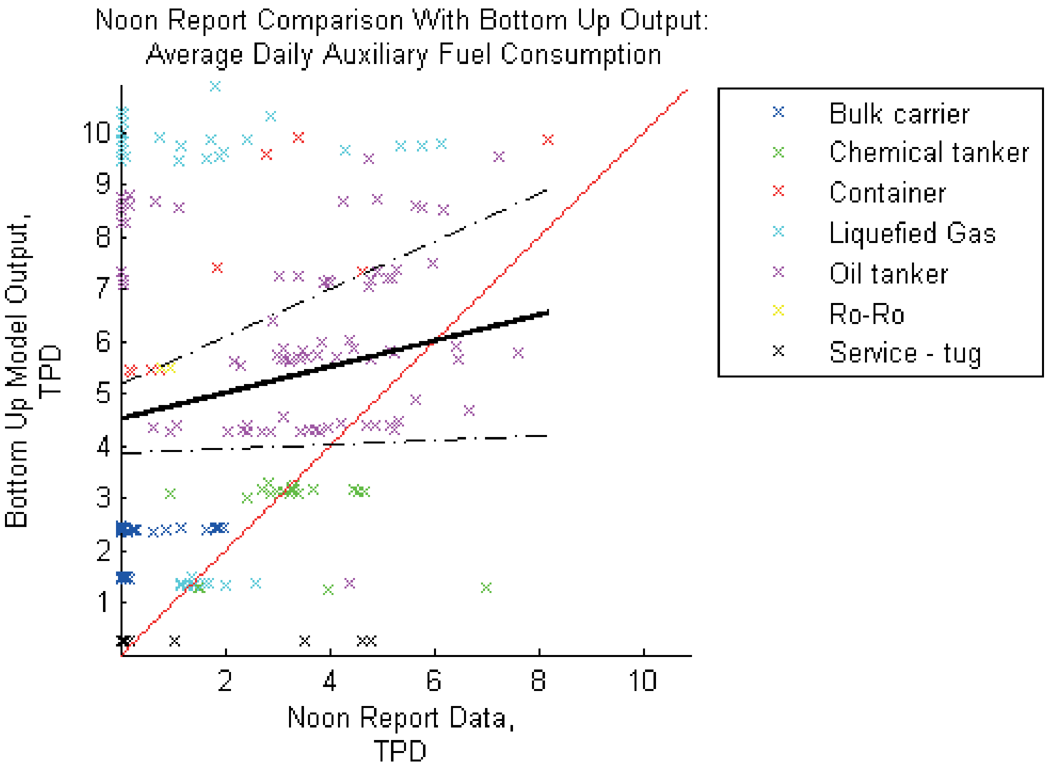
Results of noon report and bottom-up output quality assurance of activity estimate and fuel consumption (all years)

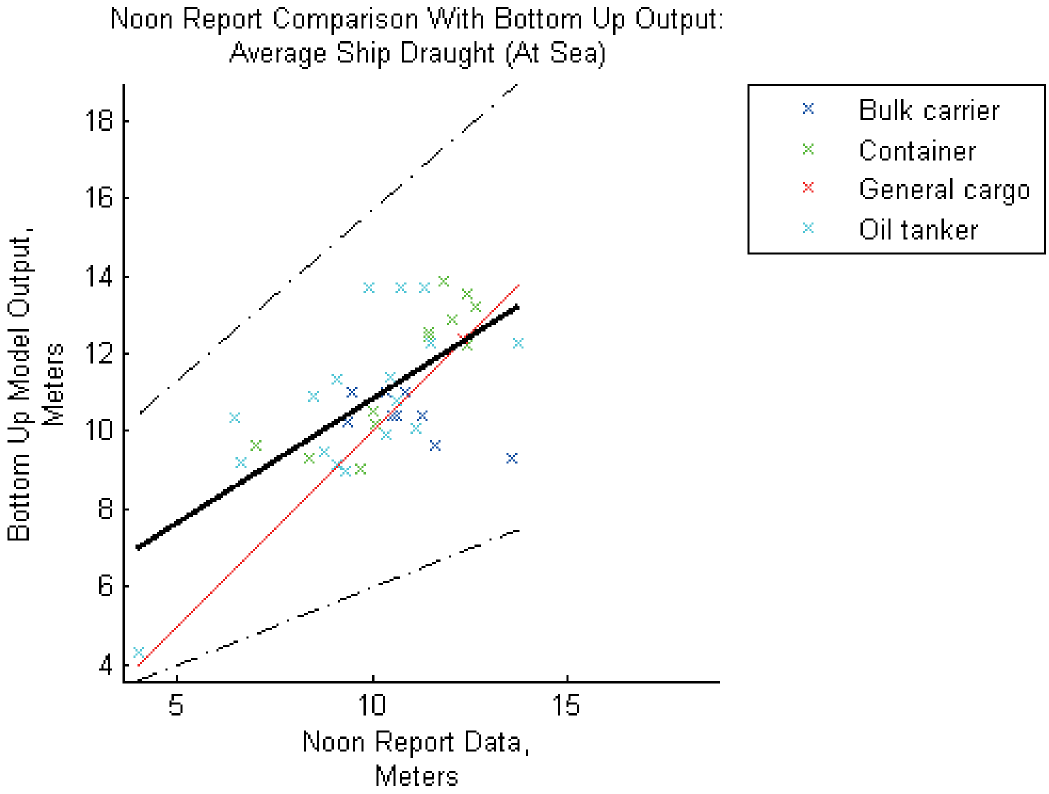
2011



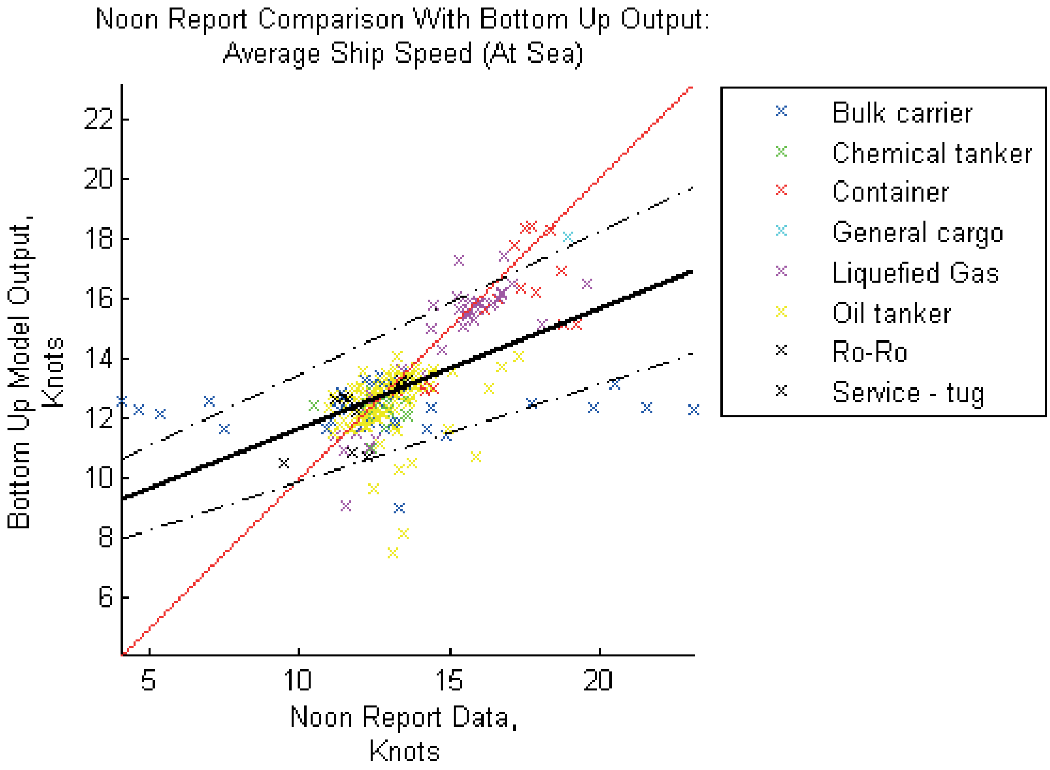


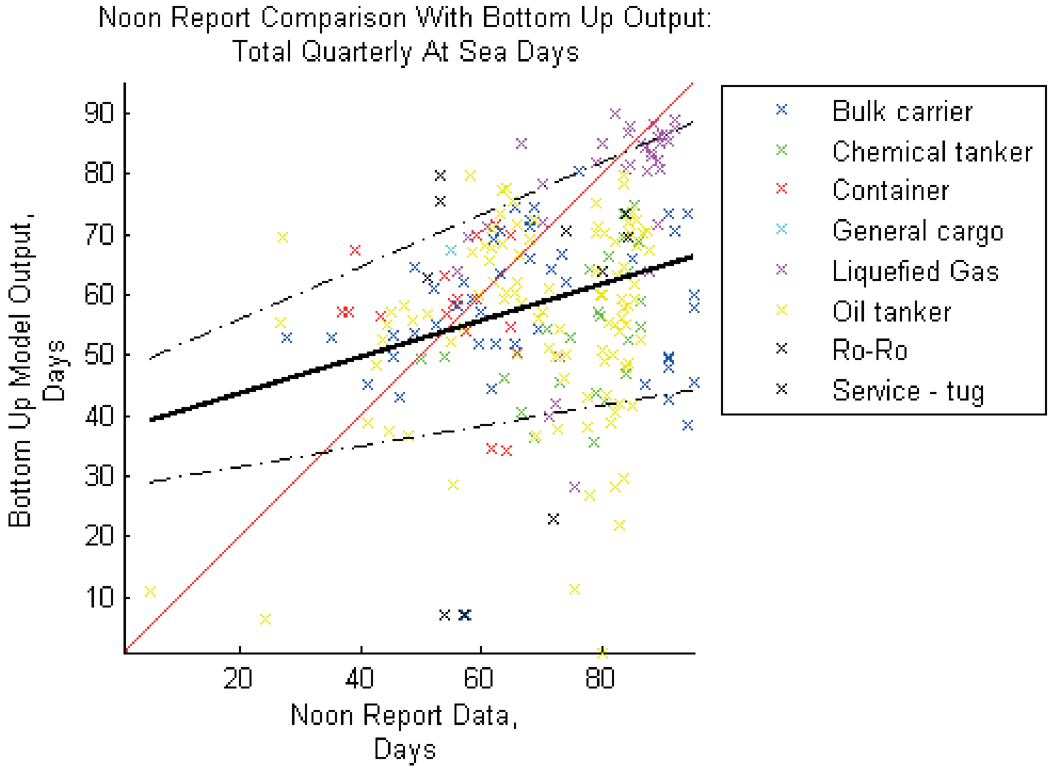
2011


Noon Report Comparison With Bottom Up Output:
Average Daily Auxiliary Fuel Consumption
Bottom Up Model Output,
TPD
Noon Report Data,
TPD
1
2
3
4
5
6
7
8
9
10
2
4
6
8
10
Bulk carrier
Chemical tanker
Container
Liquefied Gas
Oil tanker
Ro-Ro
Service - tug

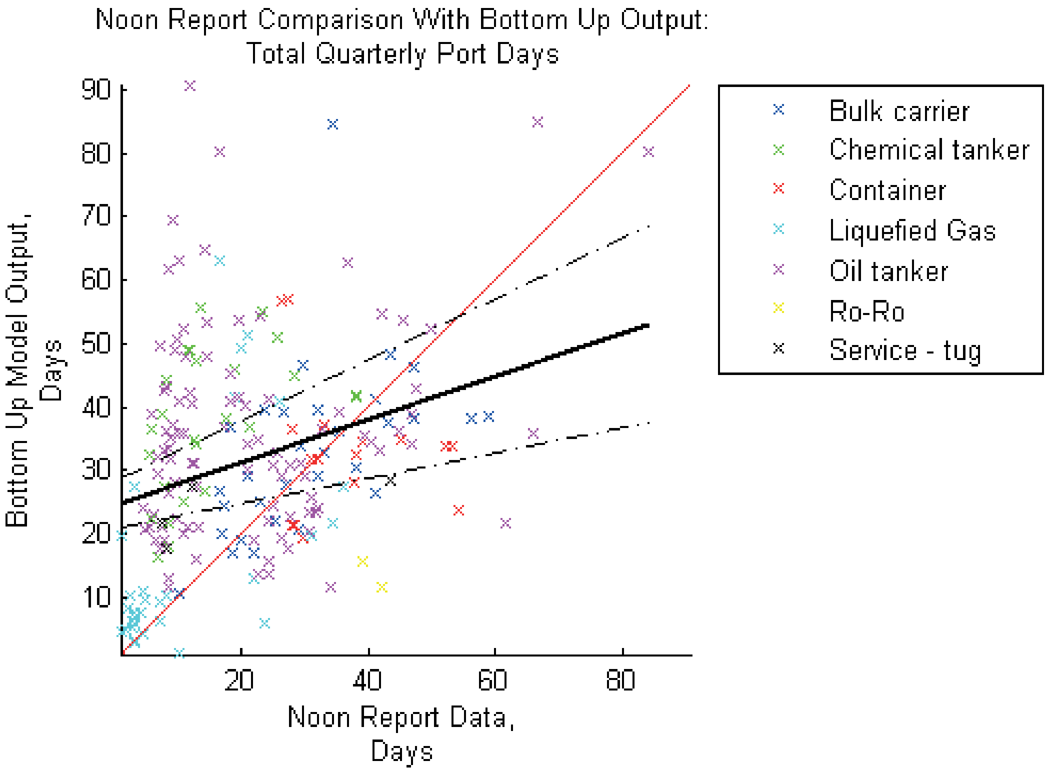

Noon Report Comparison With Bottom Up Output:
Average Ship Draught (At Sea)
Bottom Up Model Output,
Meters
Noon Report Data,
Meters
4
6
8
10
12
14
16
18
5
10
15
Bulk carrier
Container
General cargo
Oil tanker

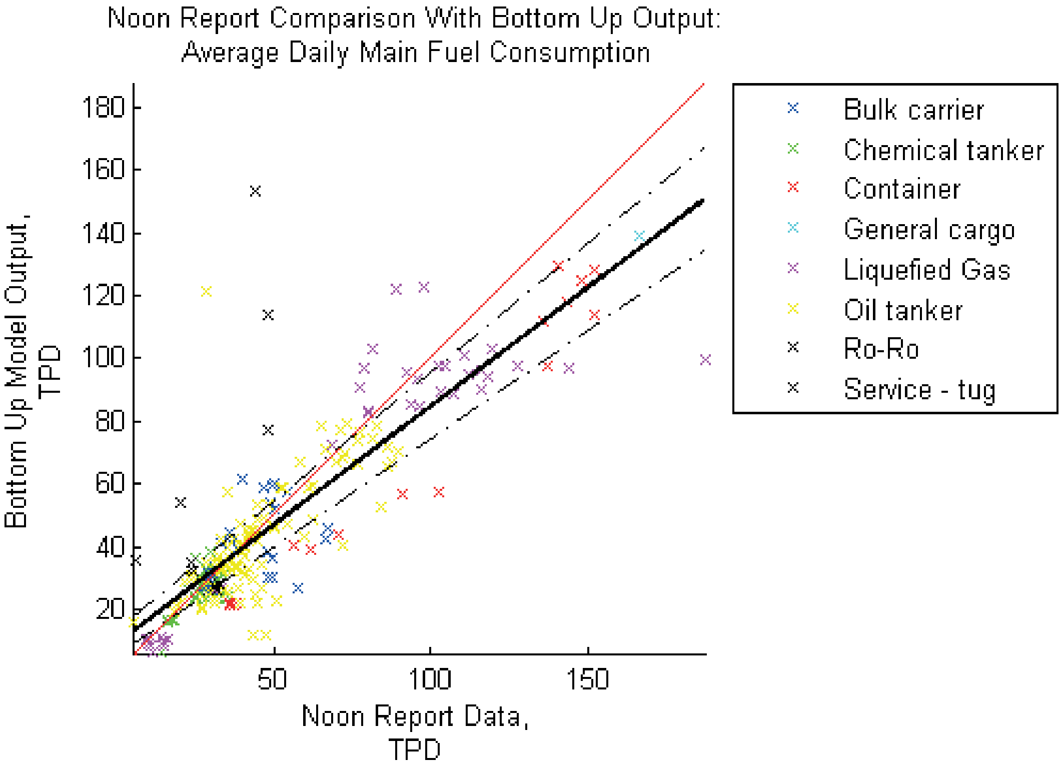
2011


Noon Report Comparison With Bottom Up Output:
Average Ship Speed (At Sea)
Bottom Up Model Output,
Knots
22
20
18
16
14
12
10
8
6
5
10
15
20
Noon Report Data,
Knots
Bulk carrier
Chemical tanker
Container
General cargo
Liquefied Gas
Oil tanker
Ro-Ro
Service - tug

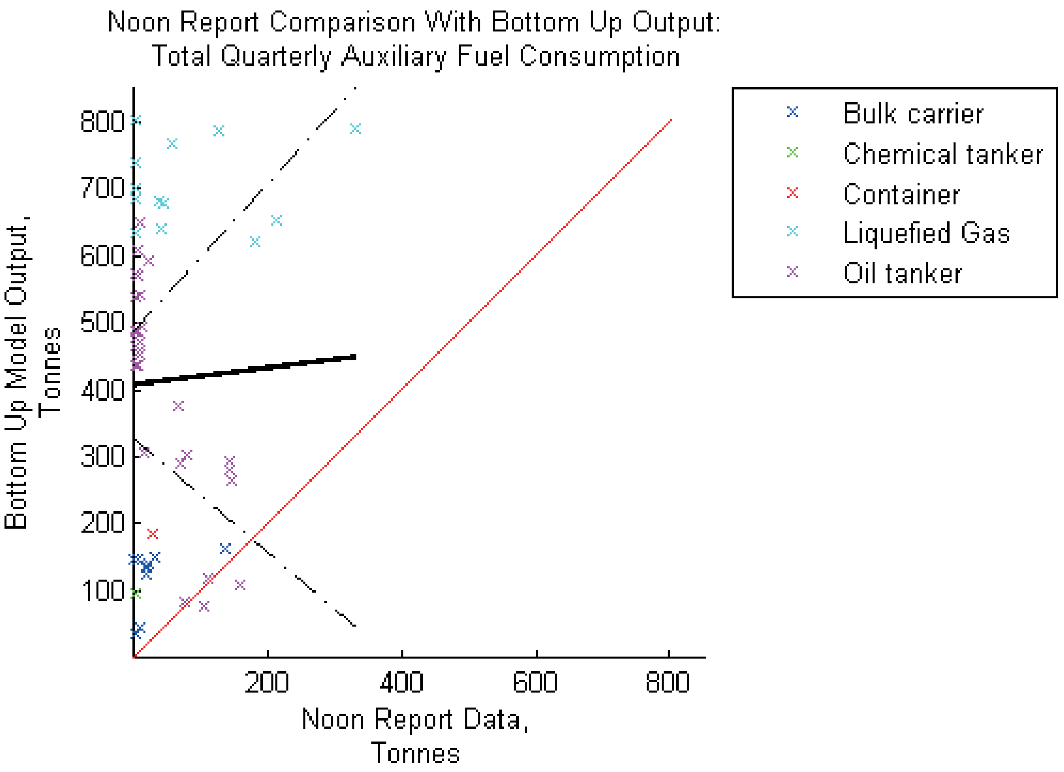

Noon Report Comparison With Bottom Up Output:
Total Quarterly At Sea Days
Bottom Up Model Output,
Days
90
80
70
60
50
40
30
20
10
20
40
60
80
Noon Report Data,
Days
Bulk carrier
Chemical tanker
Container
General cargo
Liquefied Gas
Oil tanker
Ro-Ro
Service - tug

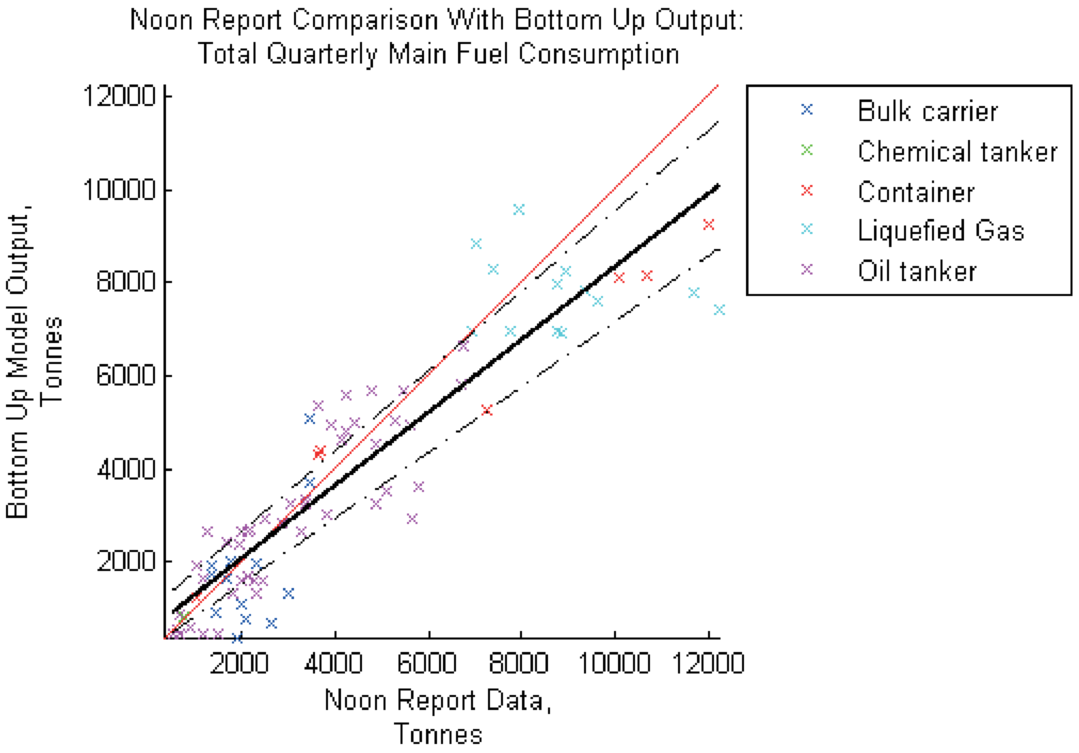
2011


Noon Report Comparison With Bottom Up Output:
Total Quarterly Port Days
Bottom Up Model Output,
Days
Noon Report Data,
Days
90
80
70
60
50
40
30
20
10
20
40
60
80
Bulk carrier
Chemical tanker
Container
Liquefied Gas
Oil tanker
Ro-Ro
Service - tug

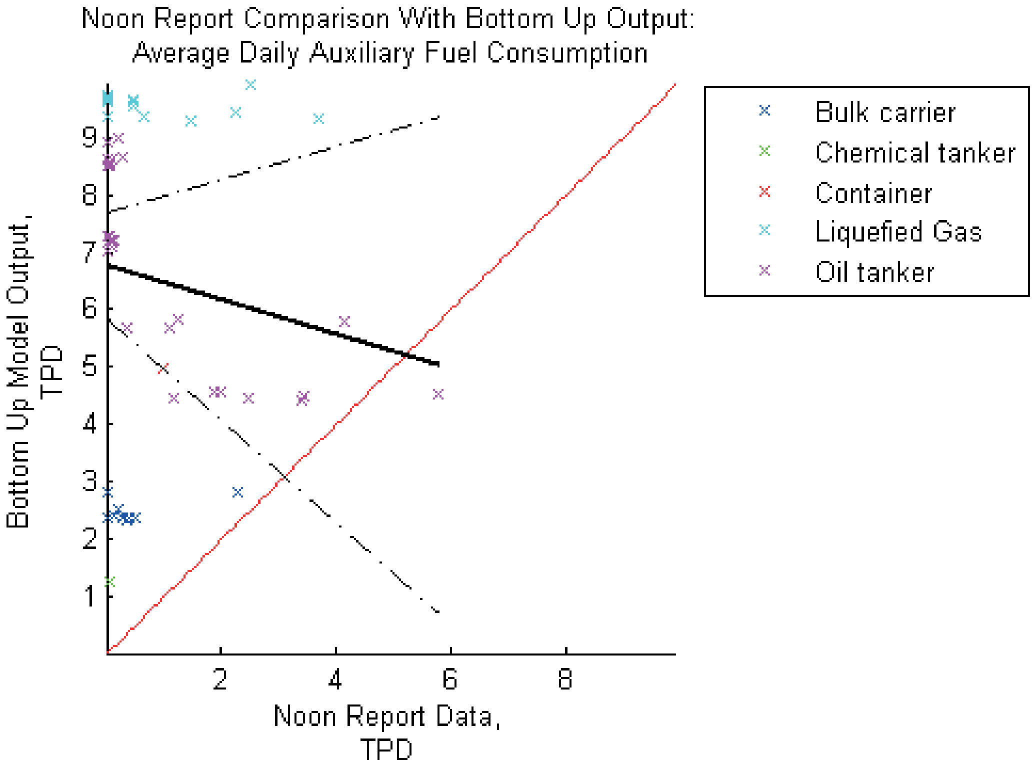

Noon Report Comparison With Bottom Up Output:
Average Daily Main Fuel Consumption
Bottom Up Model Output,
TPD
Noon Report Data,
TPD
180
160
140
120
100
80
60
40
20
50
100
150
Bulk carrier
Chemical tanker
Container
General cargo
Liquefied Gas
Oil tanker
Ro-Ro
Service - tug

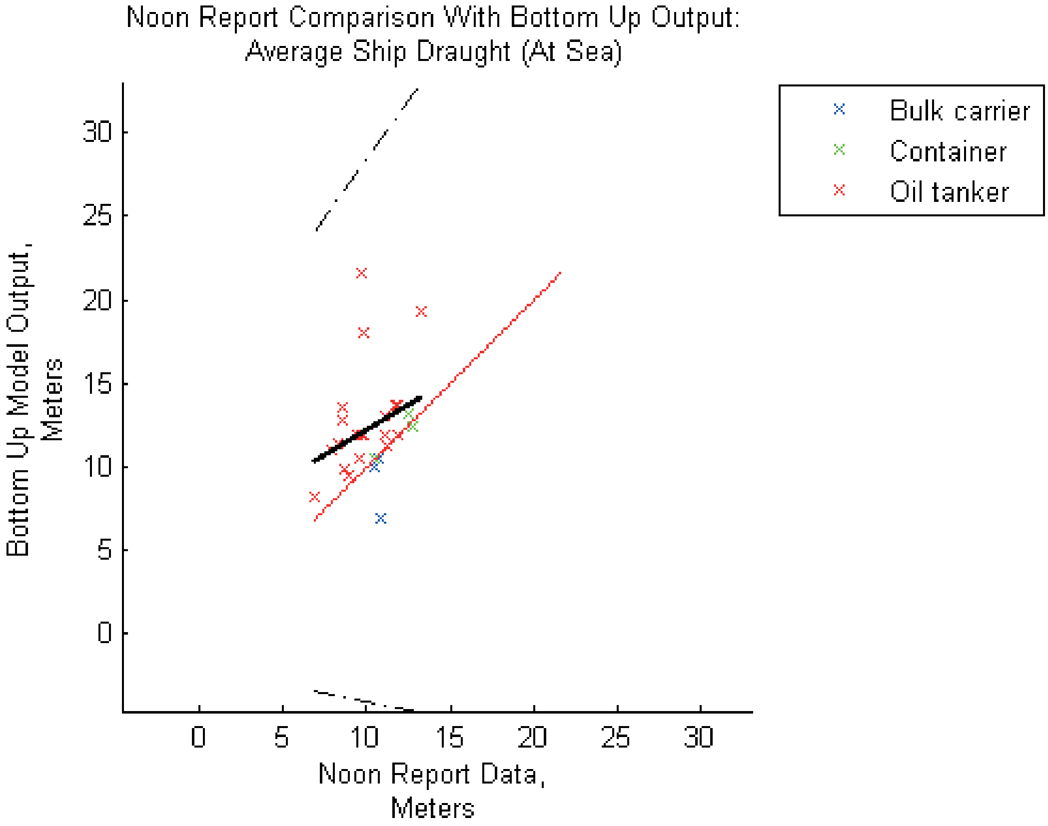
2010


Noon Report Comparison With Bottom Up Output:
Total Quarterly Auxiliary Fuel Consumption
Bottom Up Model Output,
Tonnes
100
200
300
400
500
600
700
800
200
400
600
800
Noon Report Data,
Tonnes
Bulk carrier
Chemical tanker
Container
Liquefied Gas
Oil tanker

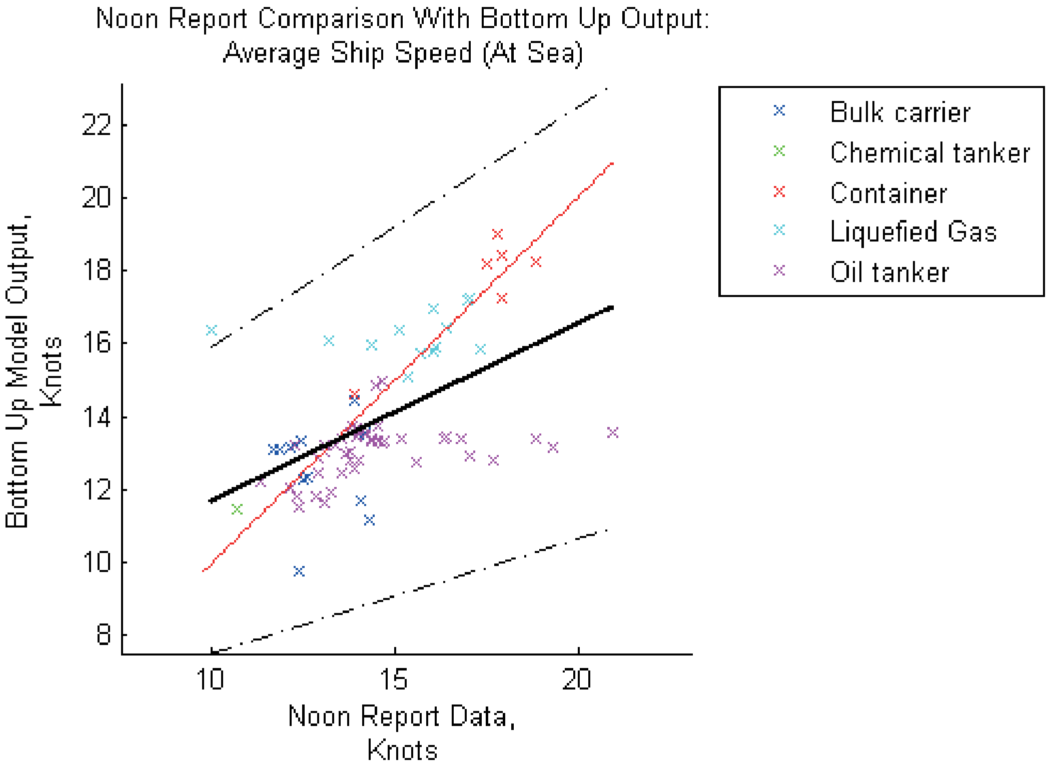

Noon Report Comparison With Bottom Up Output:
Total Quarterly Main Fuel Consumption
Bottom Up Model Output,
Tonnes
2000
4000
6000
8000
10000
12000
2000
4000
6000
8000
10000
12000
Noon Report Data,
Tonnes
Bulk carrier
Chemical tanker
Container
Liquefied Gas
Oil tanker

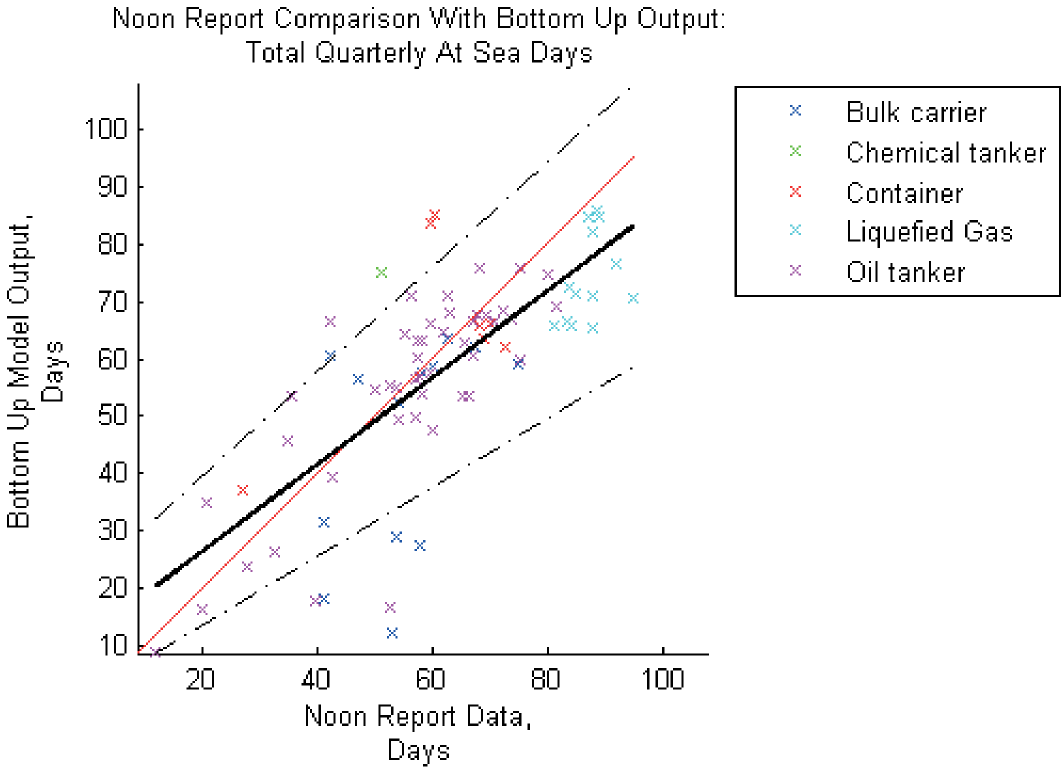
2010


Noon Report Comparison With Bottom Up Output:
Average Daily Auxiliary Fuel Consumption
Bottom Up Model Output,
TPD
Noon Report Data,
TPD
1
2
3
4
5
6
7
8
9
2
4
6
8
× Bulk carrier
× Chemical tanker
× Container
× Liquefied Gas
× Oil tanker

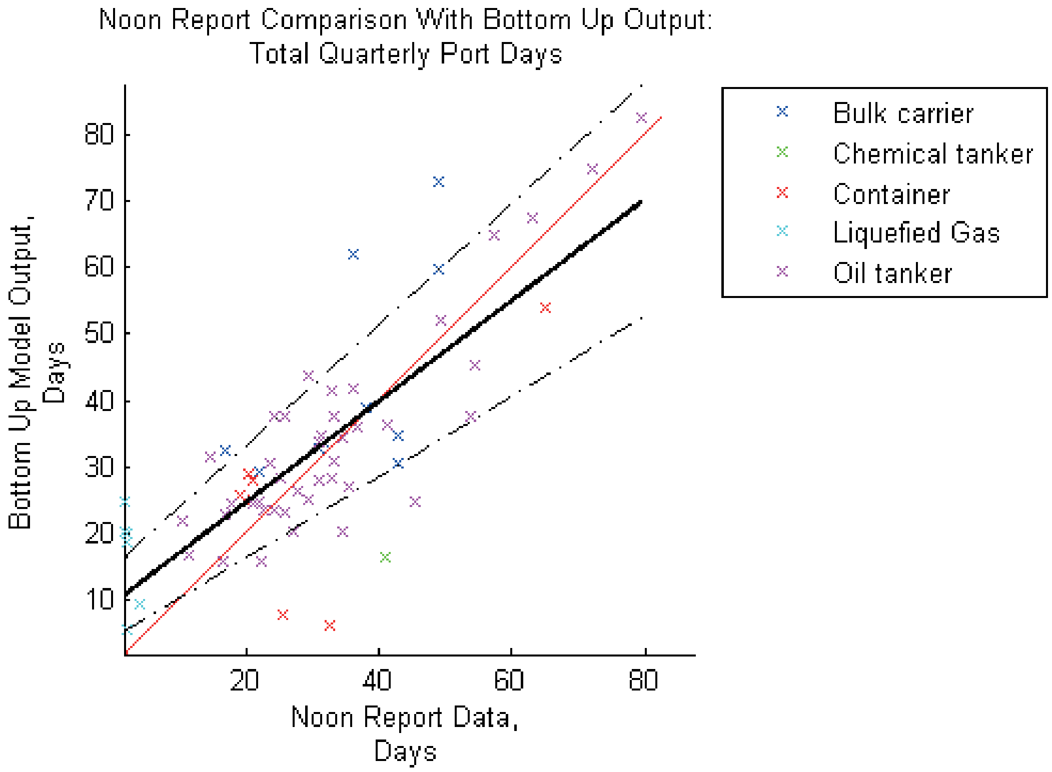

Noon Report Comparison With Bottom Up Output:
Average Ship Draught (At Sea)
Bottom Up Model Output,
Meters
Noon Report Data,
Meters
0
5
10
15
20
25
30
0
5
10
15
20
25
30
× Bulk carrier
× Container
× Oil tanker

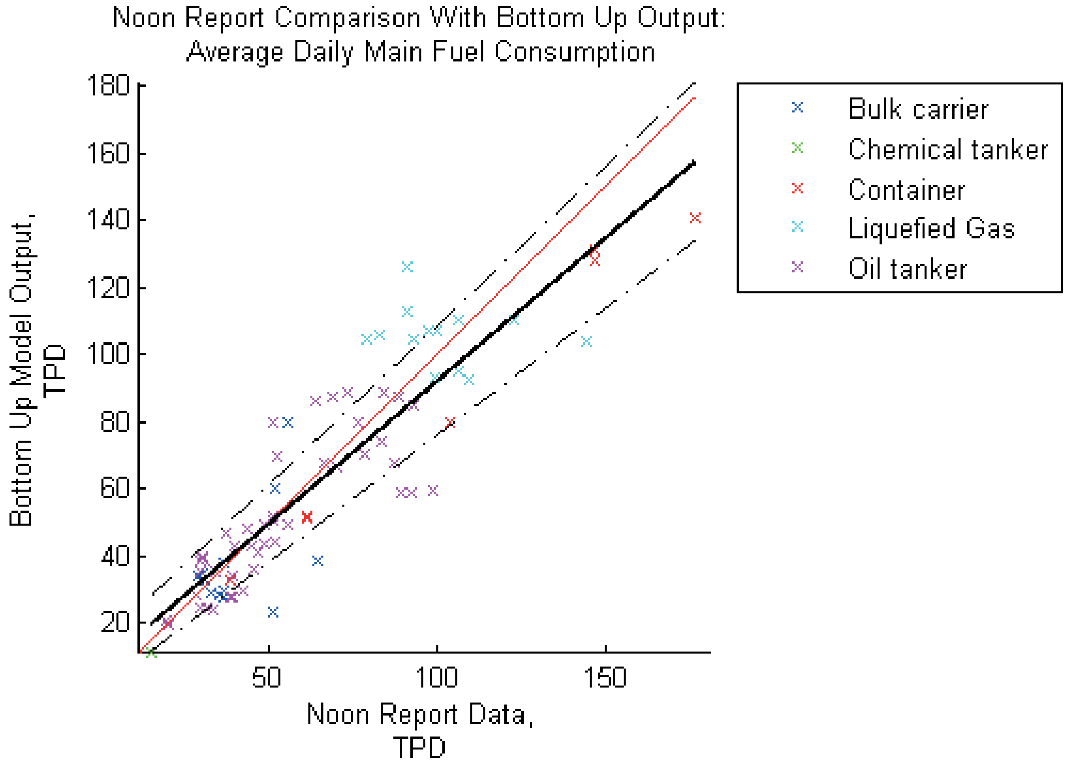
2010


Noon Report Comparison With Bottom Up Output:
Average Ship Speed (At Sea)
Bottom Up Model Output,
Knots
22
20
18
16
14
12
10
8
10
15
20
Noon Report Data,
Knots
Bulk carrier
Chemical tanker
Container
Liquefied Gas
Oil tanker

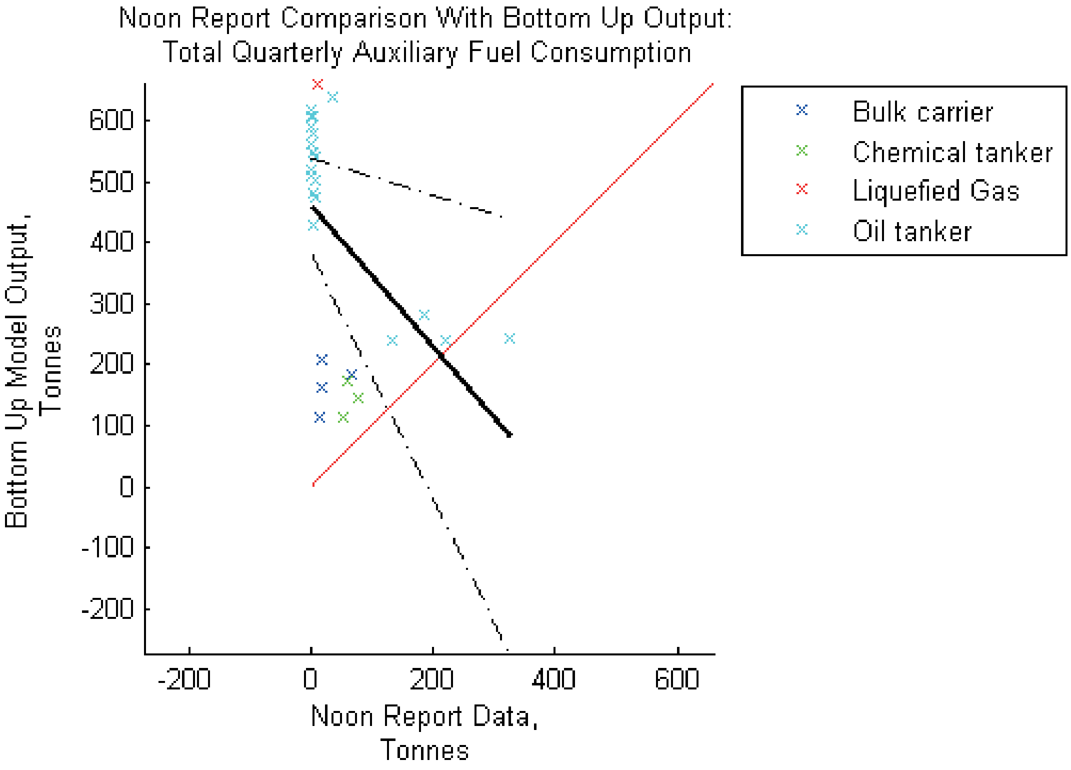

Noon Report Comparison With Bottom Up Output:
Total Quarterly At Sea Days
Bottom Up Model Output,
Days
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
Noon Report Data,
Days
Bulk carrier
Chemical tanker
Container
Liquefied Gas
Oil tanker

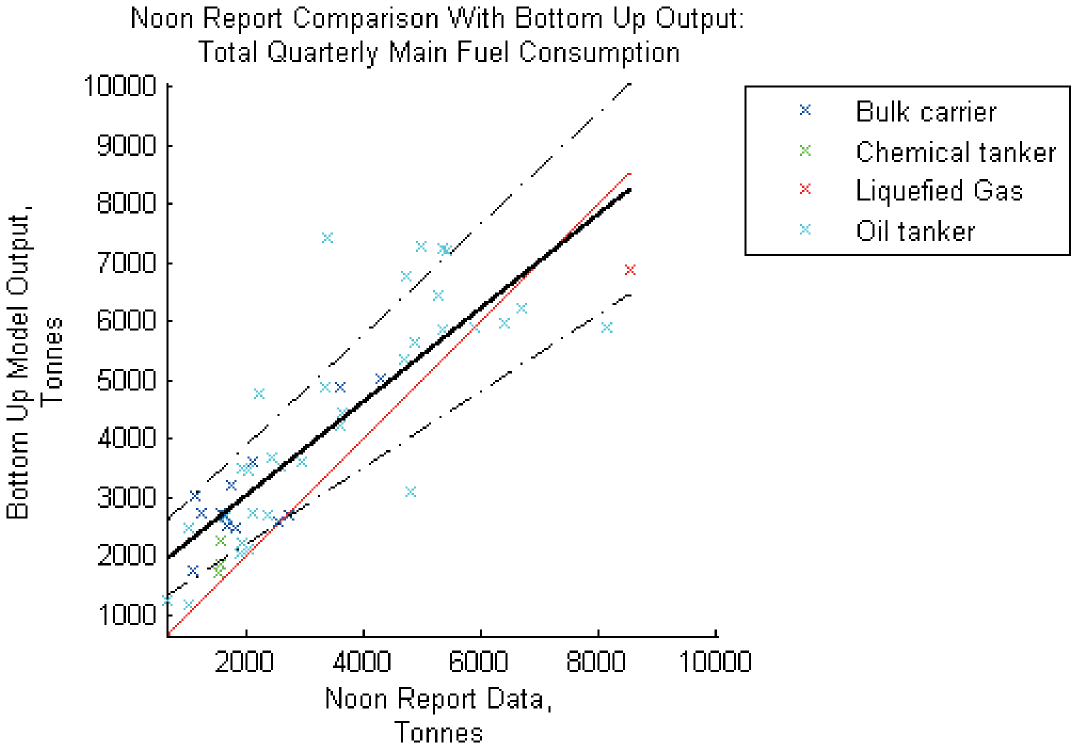
2010


Noon Report Comparison With Bottom Up Output:
Total Quarterly Port Days
Bottom Up Model Output,
Days
Noon Report Data,
Days
10
20
30
40
50
60
70
80
20
40
60
80
Bulk carrier
Chemical tanker
Container
Liquefied Gas
Oil tanker

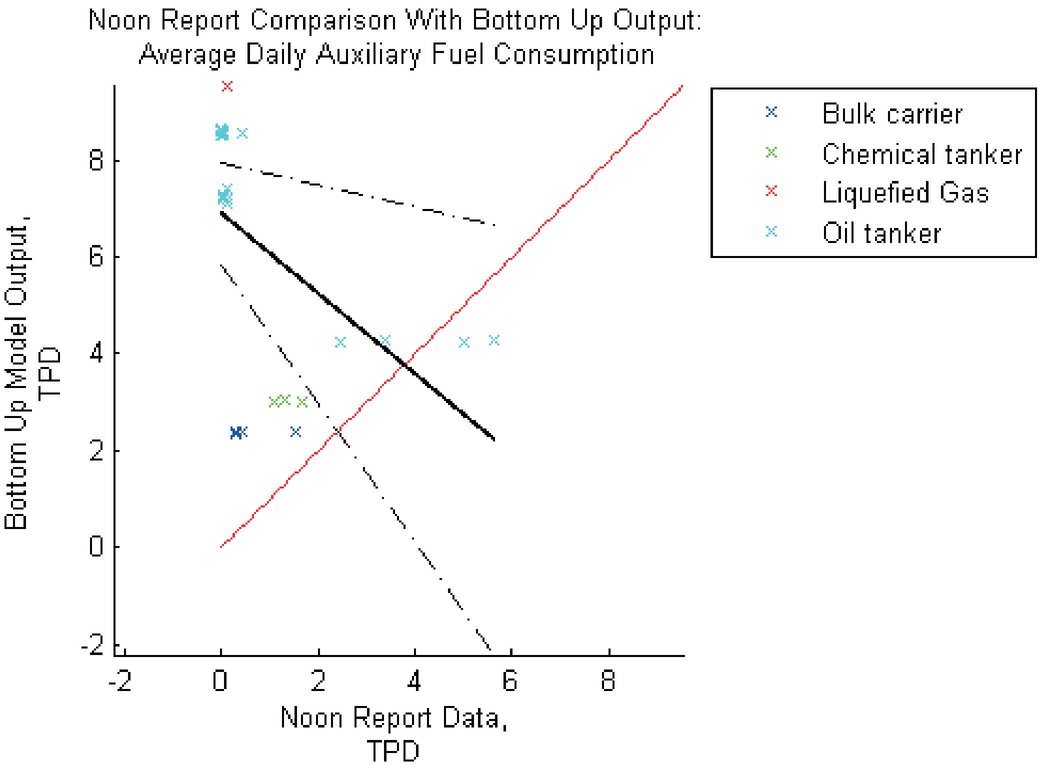

Noon Report Comparison With Bottom Up Output:
Average Daily Main Fuel Consumption
Bottom Up Model Output,
TPD
Noon Report Data,
TPD
20
40
60
80
100
120
140
160
180
50
100
150
Bulk carrier
Chemical tanker
Container
Liquefied Gas
Oil tanker

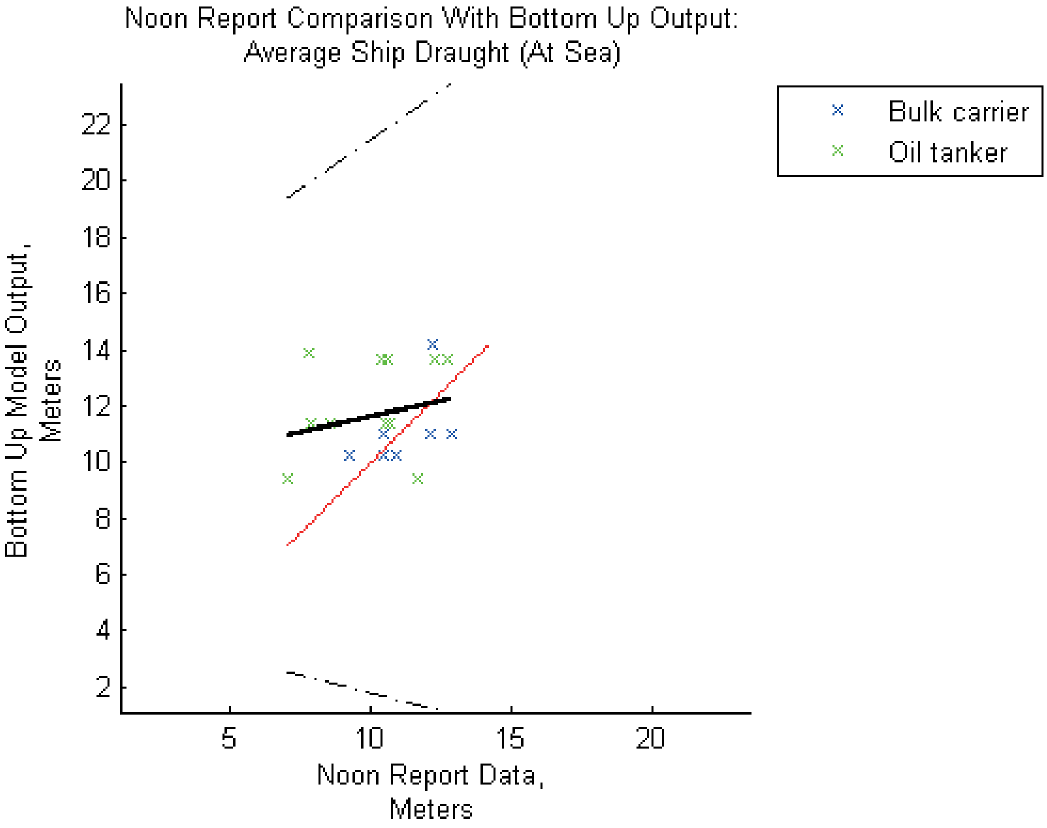
2009


Noon Report Comparison With Bottom Up Output:
Total Quarterly Auxiliary Fuel Consumption
Bottom Up Model Output,
Tonnes
600
500
400
300
200
100
0
-100
-200
-200
0
200
400
600
Noon Report Data,
Tonnes
Bulk carrier
Chemical tanker
Liquefied Gas
Oil tanker

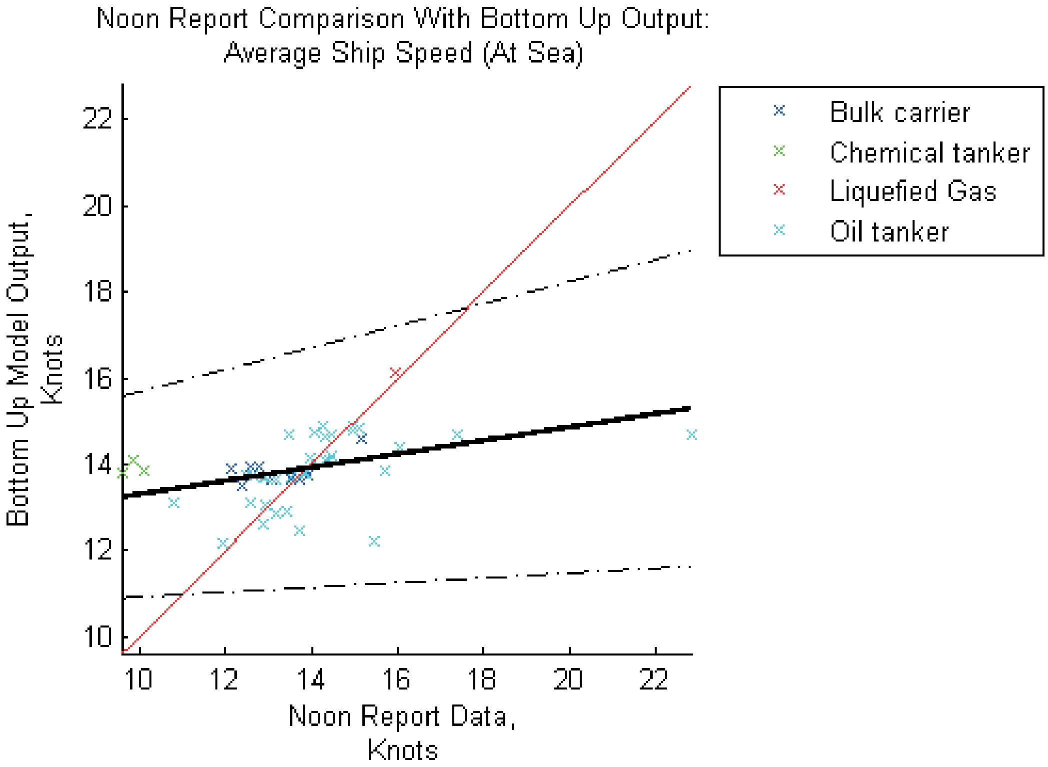

Noon Report Comparison With Bottom Up Output:
Total Quarterly Main Fuel Consumption
Bottom Up Model Output,
Tonnes
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
2000
4000
6000
8000
10000
Noon Report Data,
Tonnes
Bulk carrier
Chemical tanker
Liquefied Gas
Oil tanker

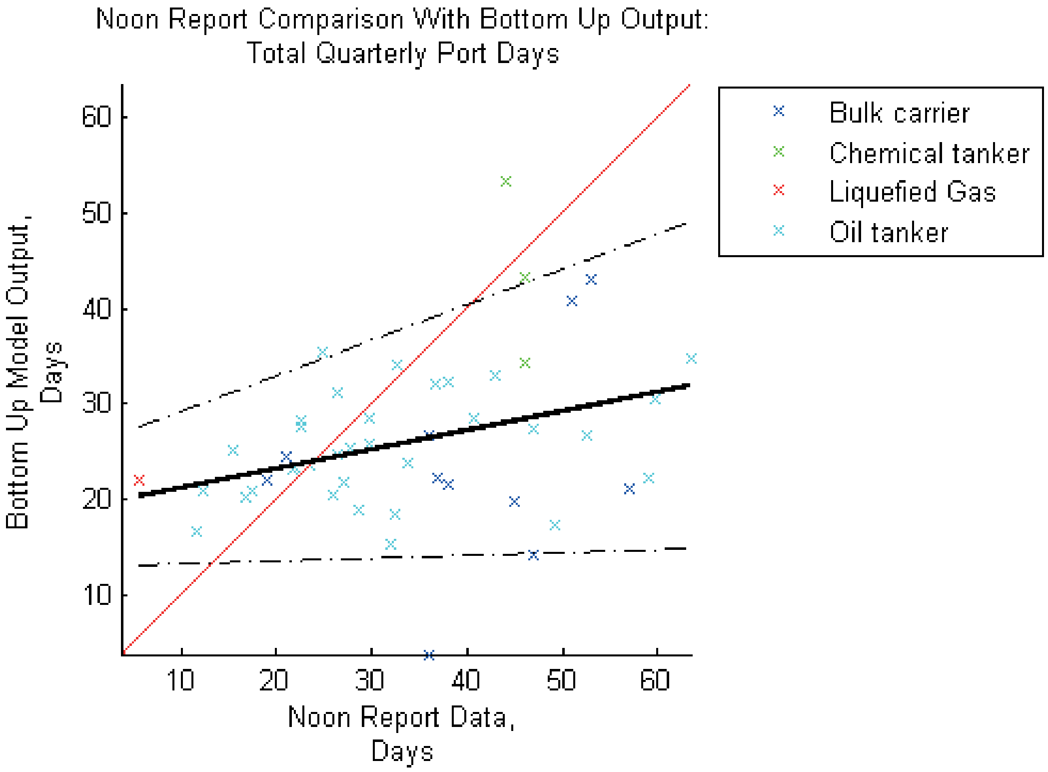
2009


Noon Report Comparison With Bottom Up Output:
Average Daily Auxiliary Fuel Consumption
Bottom Up Model Output,
TPD
Noon Report Data,
TPD
-2
0
2
4
6
8
Bulk carrier
Chemical tanker
Liquefied Gas
Oil tanker

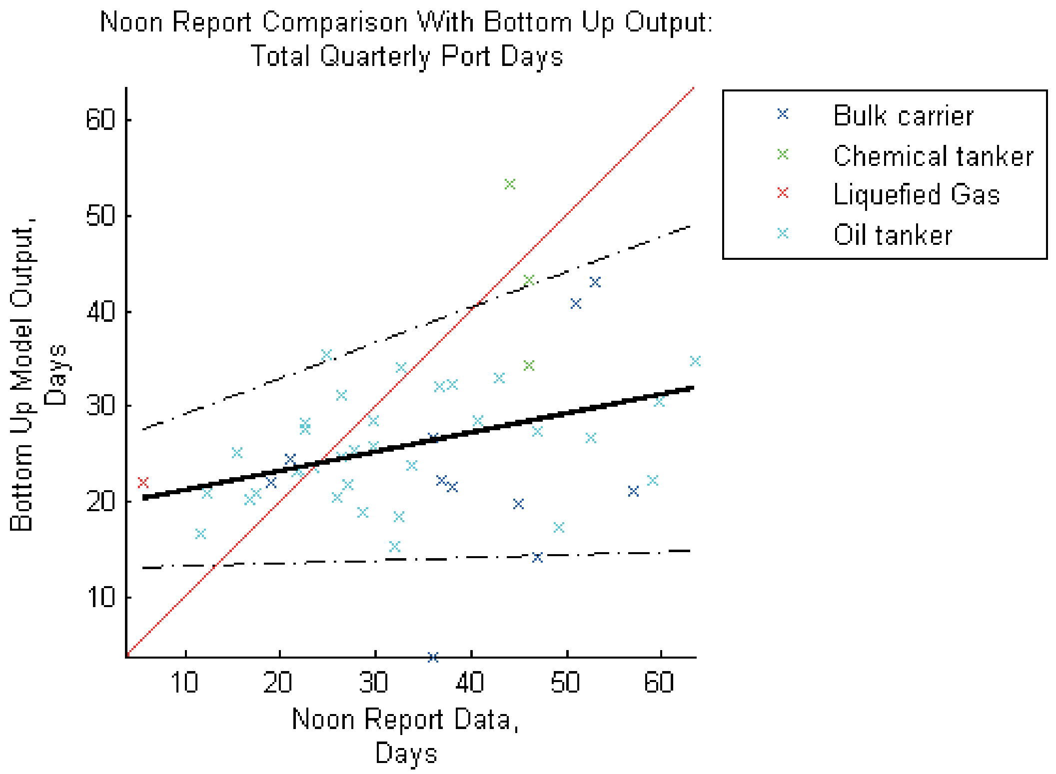

Noon Report Comparison With Bottom Up Output:
Average Ship Draught (At Sea)
Bottom Up Model Output,
Meters
Noon Report Data,
Meters
2
4
6
8
10
12
14
16
18
20
22
5
10
15
20
Bulk carrier
Oil tanker

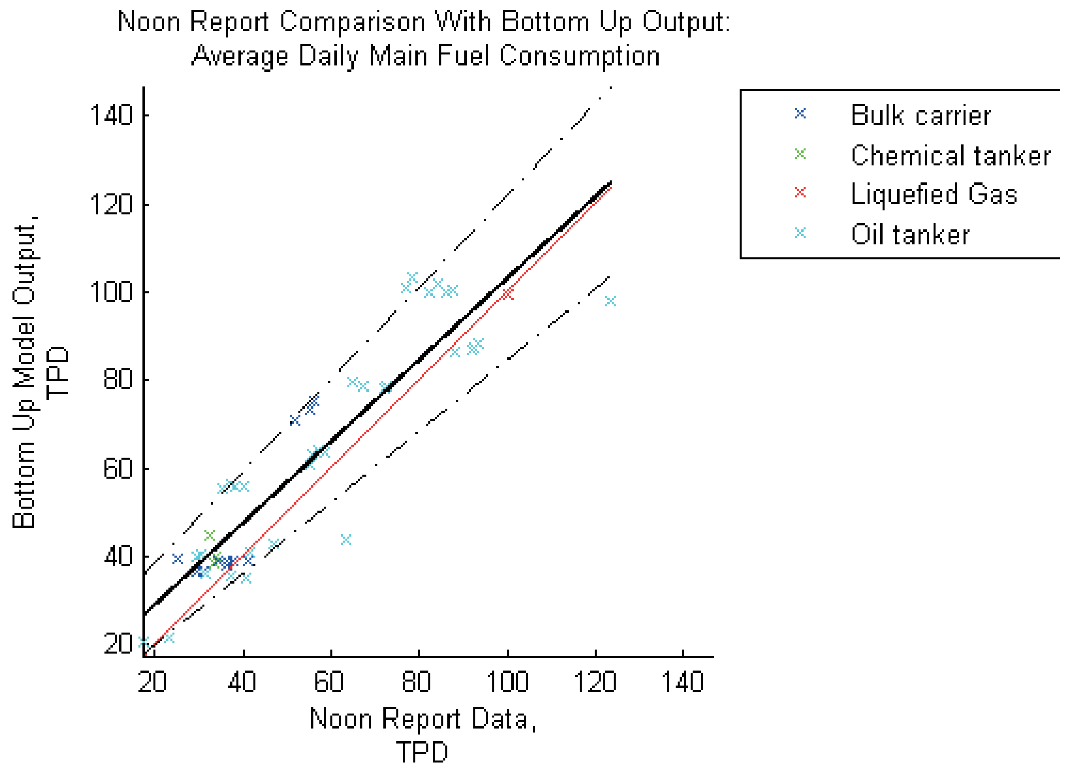
2009


Noon Report Comparison With Bottom Up Output:
Average Ship Speed (At Sea)
Bottom Up Model Output,
Knots
22
20
18
16
14
12
10
10
12
14
16
18
20
22
Noon Report Data,
Knots
Bulk carrier
Chemical tanker
Liquefied Gas
Oil tanker

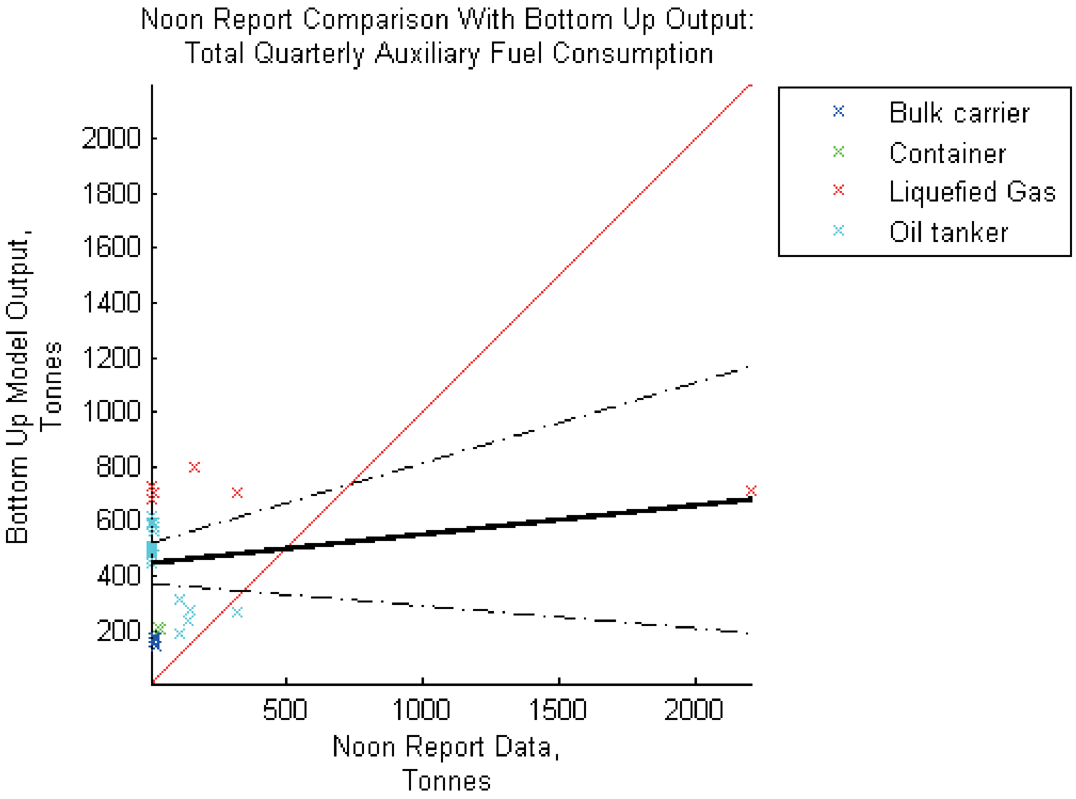

Noon Report Comparison With Bottom Up Output:
Total Quarterly Port Days
Bottom Up Model Output,
Days
60
50
40
30
20
10
10
20
30
40
50
60
Noon Report Data,
Days
Bulk carrier
Chemical tanker
Liquefied Gas
Oil tanker

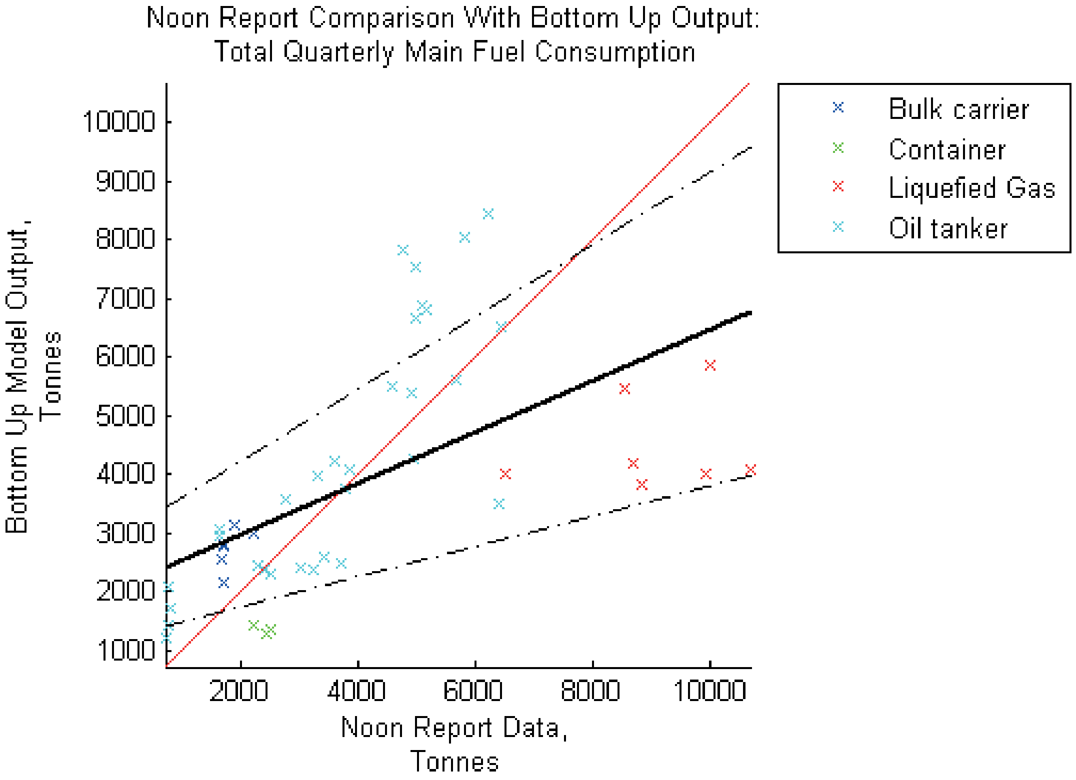
2009


Noon Report Comparison With Bottom Up Output:
Total Quarterly Port Days
Bottom Up Model Output,
Days
Noon Report Data,
Days
60
50
40
30
20
10
10
20
30
40
50
60
× Bulk carrier
× Chemical tanker
× Liquefied Gas
× Oil tanker

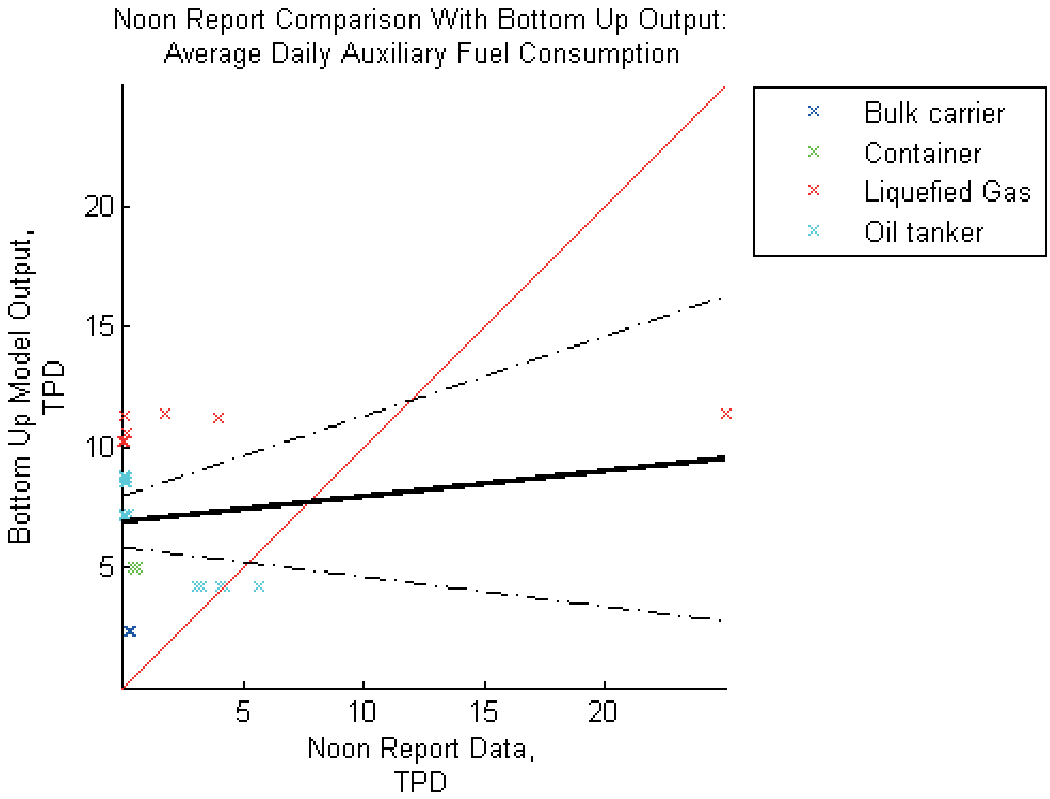

Noon Report Comparison With Bottom Up Output:
Average Daily Main Fuel Consumption
Bottom Up Model Output,
TPD
Noon Report Data,
TPD
140
120
100
80
60
40
20
20
40
60
80
100
120
140
× Bulk carrier
× Chemical tanker
× Liquefied Gas
× Oil tanker

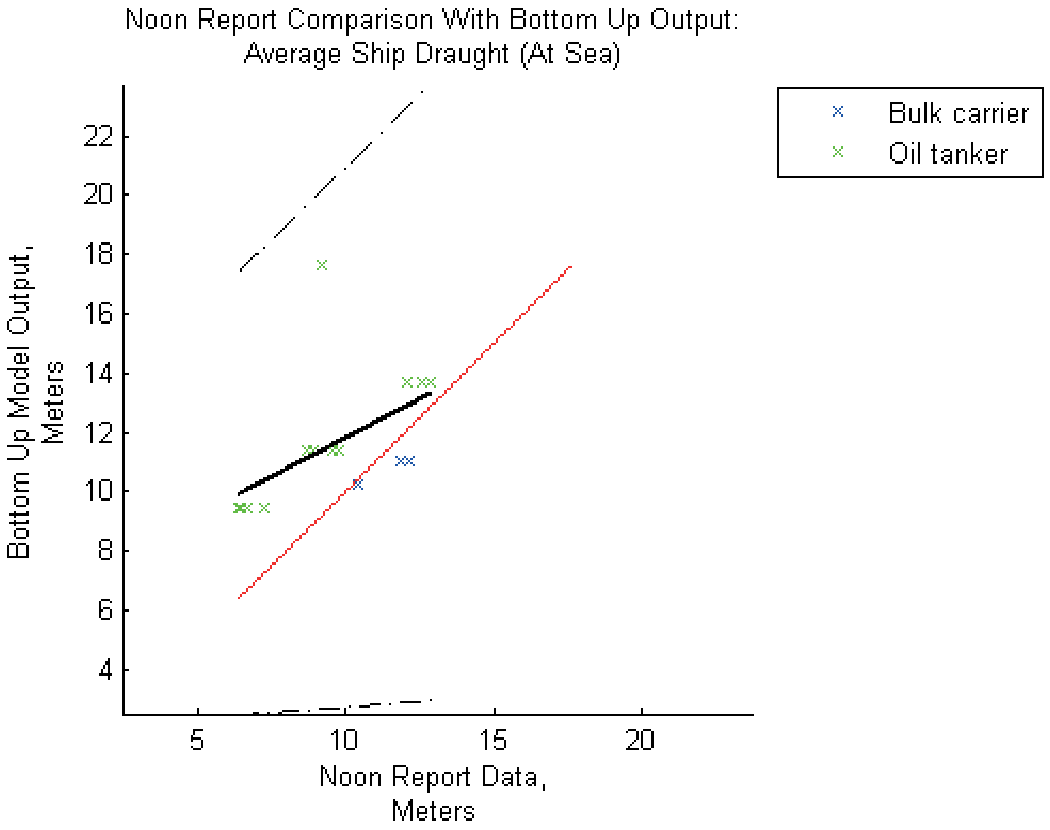
2008


Noon Report Comparison With Bottom Up Output:
Total Quarterly Auxiliary Fuel Consumption
Bottom Up Model Output, Tonnes
2000
1800
1600
1400
1200
1000
800
600
400
200
500
1000
1500
2000
Noon Report Data, Tonnes
Bulk carrier
Container
Liquefied Gas
Oil tanker

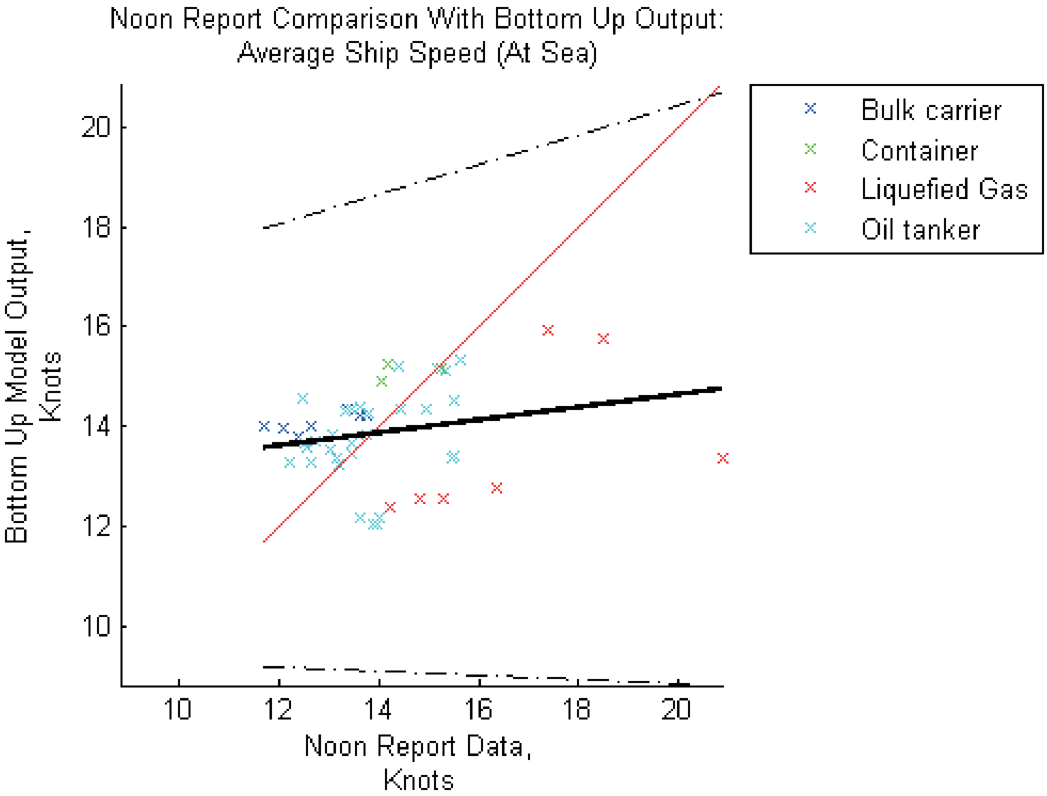

Noon Report Comparison With Bottom Up Output:
Total Quarterly Main Fuel Consumption
Bottom Up Model Output, Tonnes
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
2000
4000
6000
8000
10000
Noon Report Data, Tonnes
Bulk carrier
Container
Liquefied Gas
Oil tanker

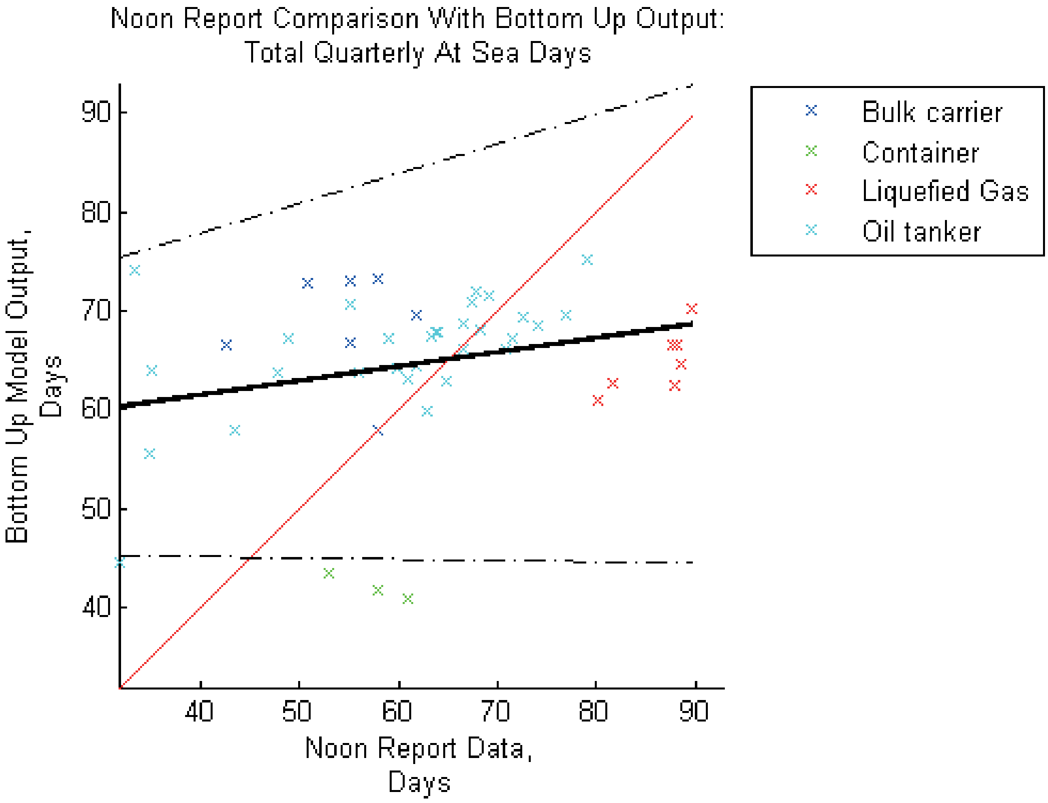
2008


Noon Report Comparison With Bottom Up Output:
Average Daily Auxiliary Fuel Consumption
Bottom Up Model Output,
TPD
Noon Report Data,
TPD
5
10
15
20
5
10
15
20
Bulk carrier
Container
Liquefied Gas
Oil tanker

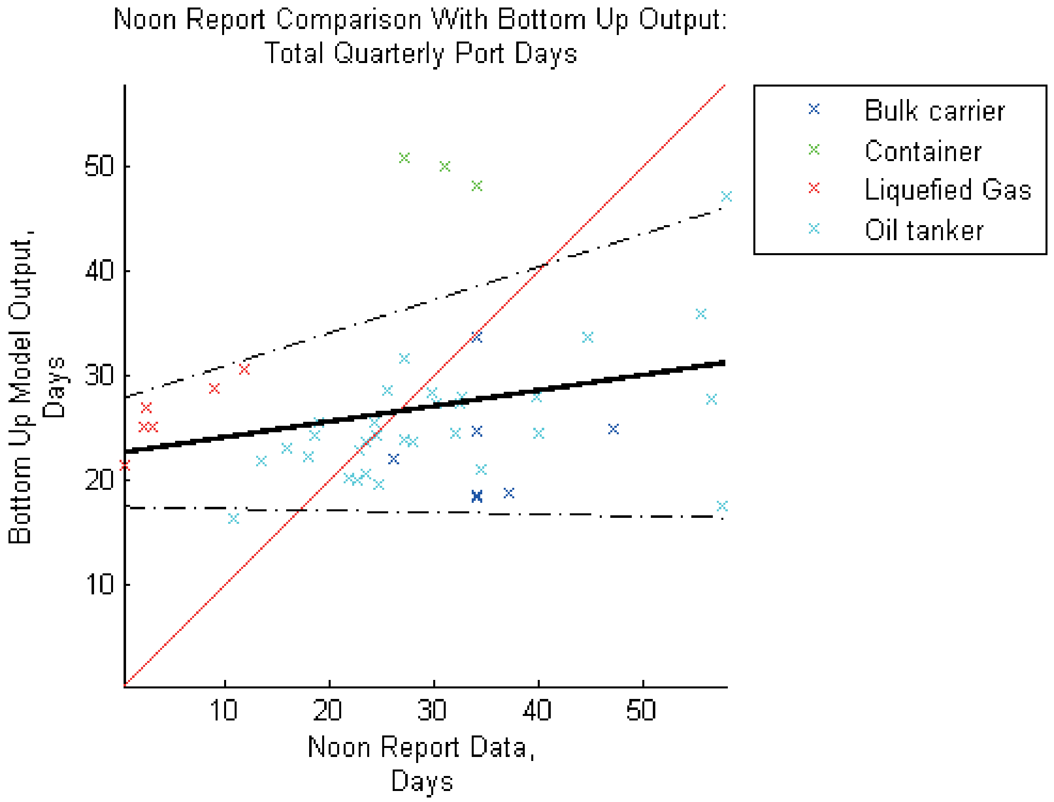

Noon Report Comparison With Bottom Up Output:
Average Ship Draught (At Sea)
Bottom Up Model Output,
Meters
Noon Report Data,
Meters
4
6
8
10
12
14
16
18
20
22
5
10
15
20
Bulk carrier
Oil tanker

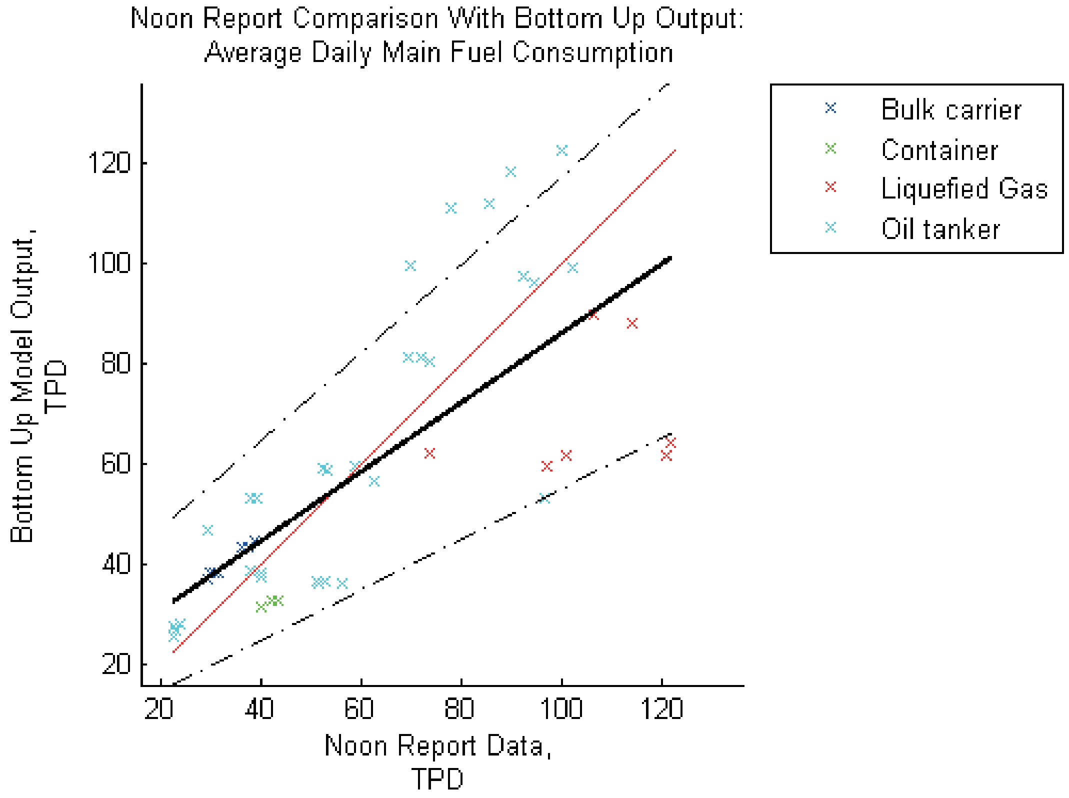
2008


Noon Report Comparison With Bottom Up Output:
Average Ship Speed (At Sea)
Bottom Up Model Output, Knots
Noon Report Data, Knots
10
12
14
16
18
20
Bulk carrier
Container
Liquefied Gas
Oil tanker

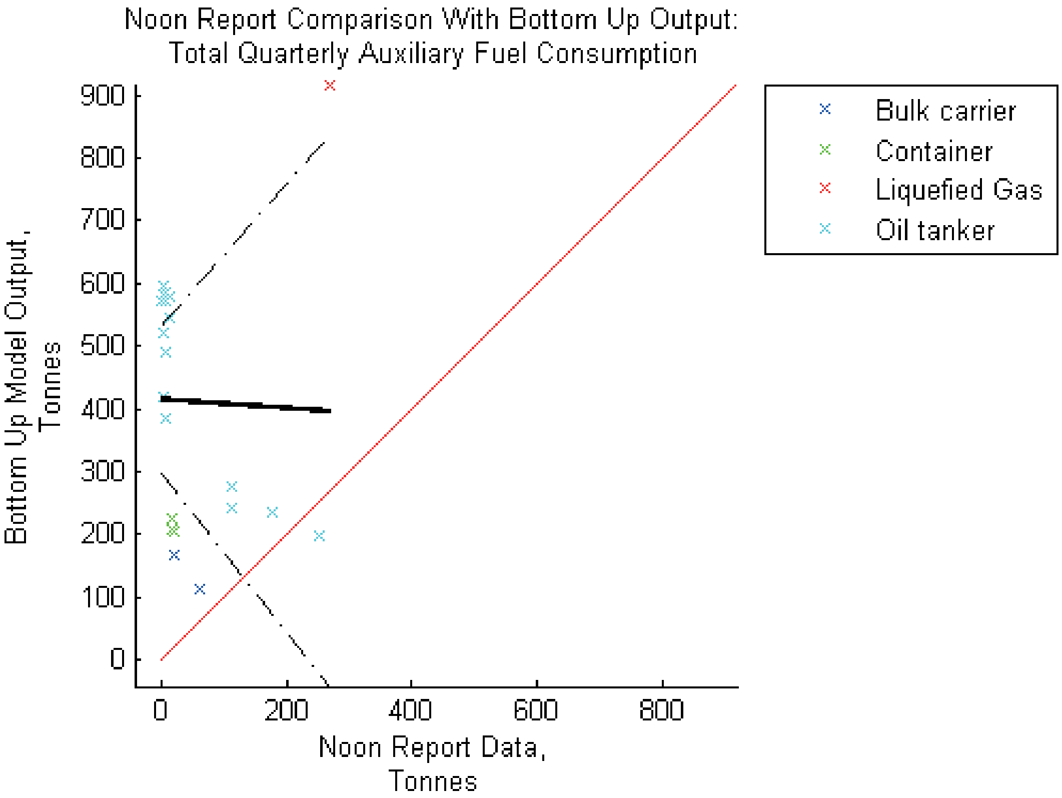

Noon Report Comparison With Bottom Up Output:
Total Quarterly At Sea Days
Bottom Up Model Output, Days
Noon Report Data, Days
40
50
60
70
80
90
Bulk carrier
Container
Liquefied Gas
Oil tanker

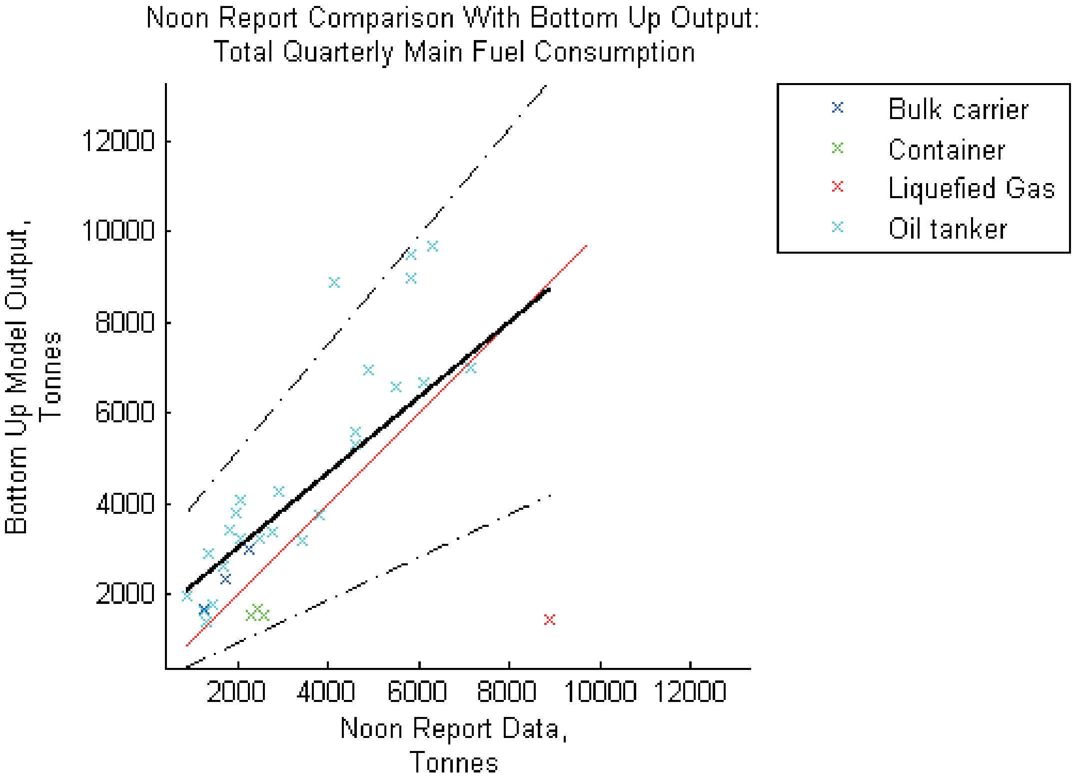
2008


Noon Report Comparison With Bottom Up Output:
Total Quarterly Port Days
Bottom Up Model Output,
Days
Noon Report Data,
Days
10
20
30
40
50
Bulk carrier
Container
Liquefied Gas
Oil tanker

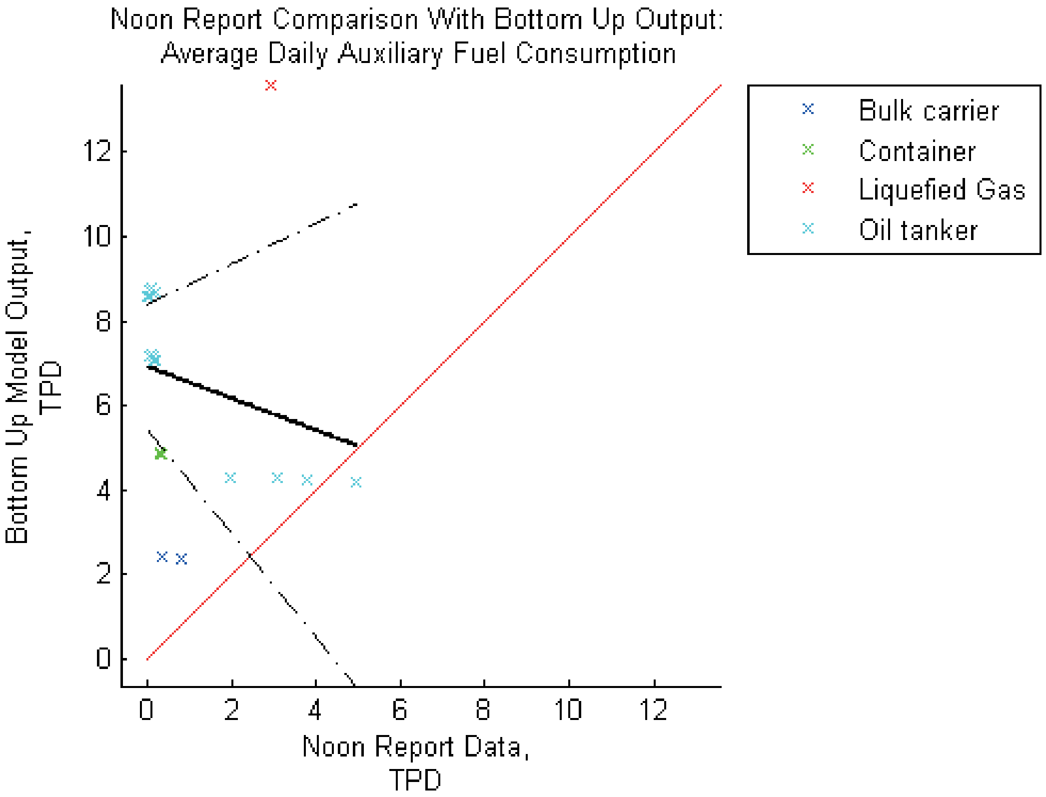

Noon Report Comparison With Bottom Up Output:
Average Daily Main Fuel Consumption
Bottom Up Model Output,
TPD
Noon Report Data,
TPD
20
40
60
80
100
120
Bulk carrier
Container
Liquefied Gas
Oil tanker

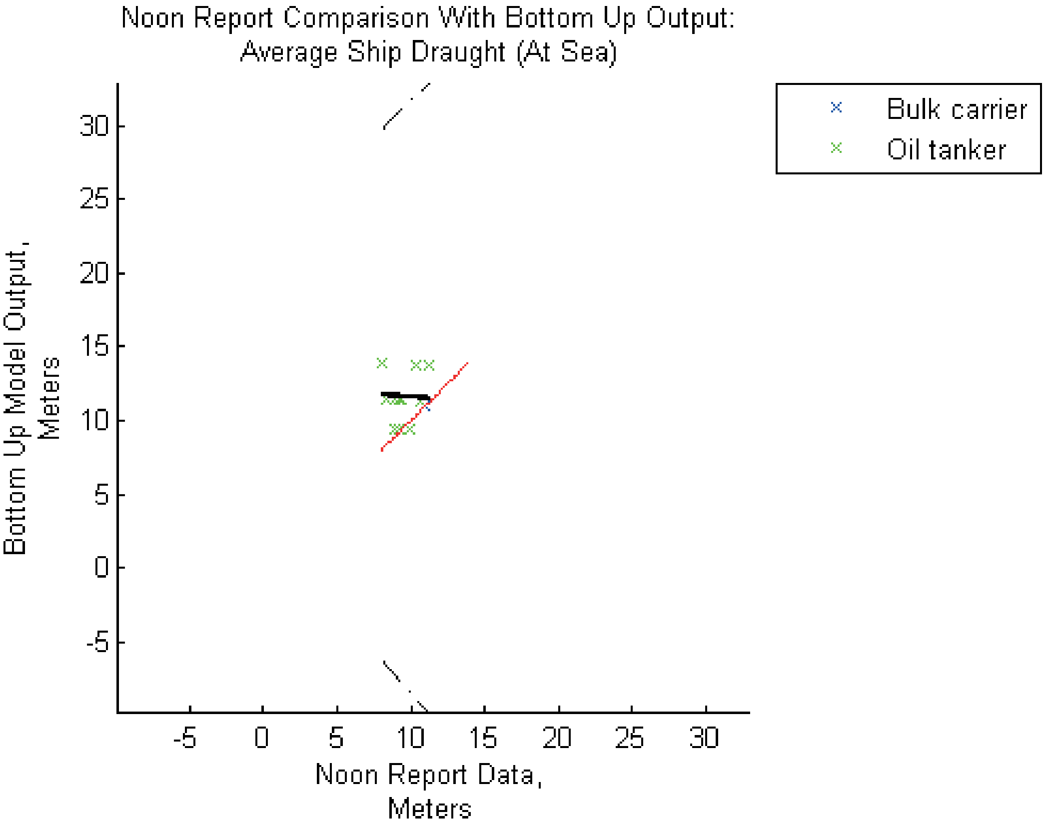
2007


Noon Report Comparison With Bottom Up Output:
Total Quarterly Auxiliary Fuel Consumption
Bottom Up Model Output,
Tonnes
900
800
700
600
500
400
300
200
100
0
0
200
400
600
800
Noon Report Data,
Tonnes
Bulk carrier
Container
Liquefied Gas
Oil tanker

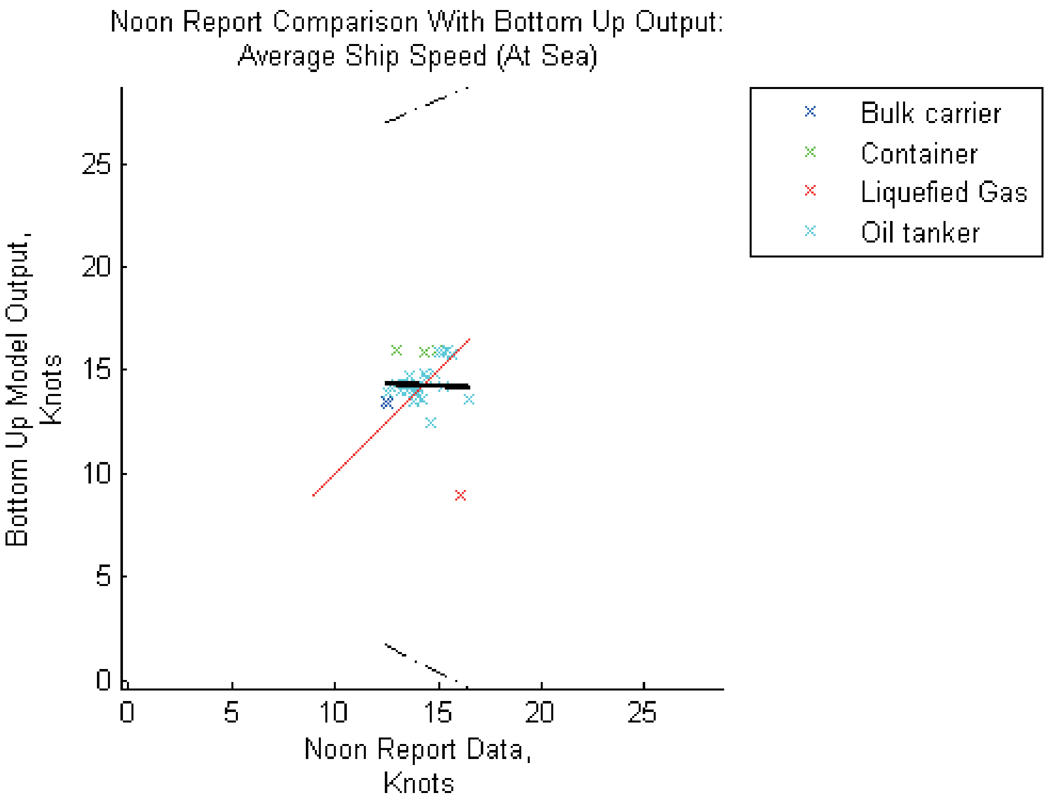

Noon Report Comparison With Bottom Up Output:
Total Quarterly Main Fuel Consumption
Bottom Up Model Output,
Tonnes
12000
10000
8000
6000
4000
2000
2000
4000
6000
8000
10000
12000
Noon Report Data,
Tonnes
Bulk carrier
Container
Liquefied Gas
Oil tanker

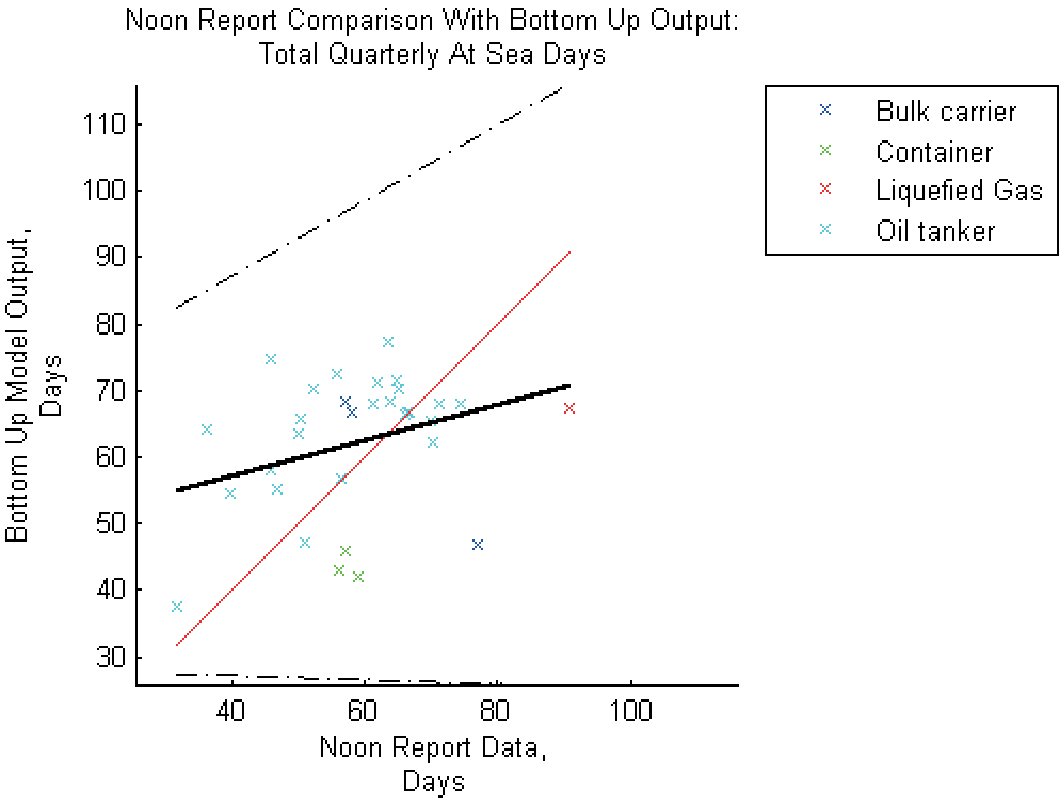
2007


Noon Report Comparison With Bottom Up Output:
Average Daily Auxiliary Fuel Consumption
Bottom Up Model Output, TPD
Noon Report Data, TPD
0
2
4
6
8
10
12
Bulk carrier
Container
Liquefied Gas
Oil tanker

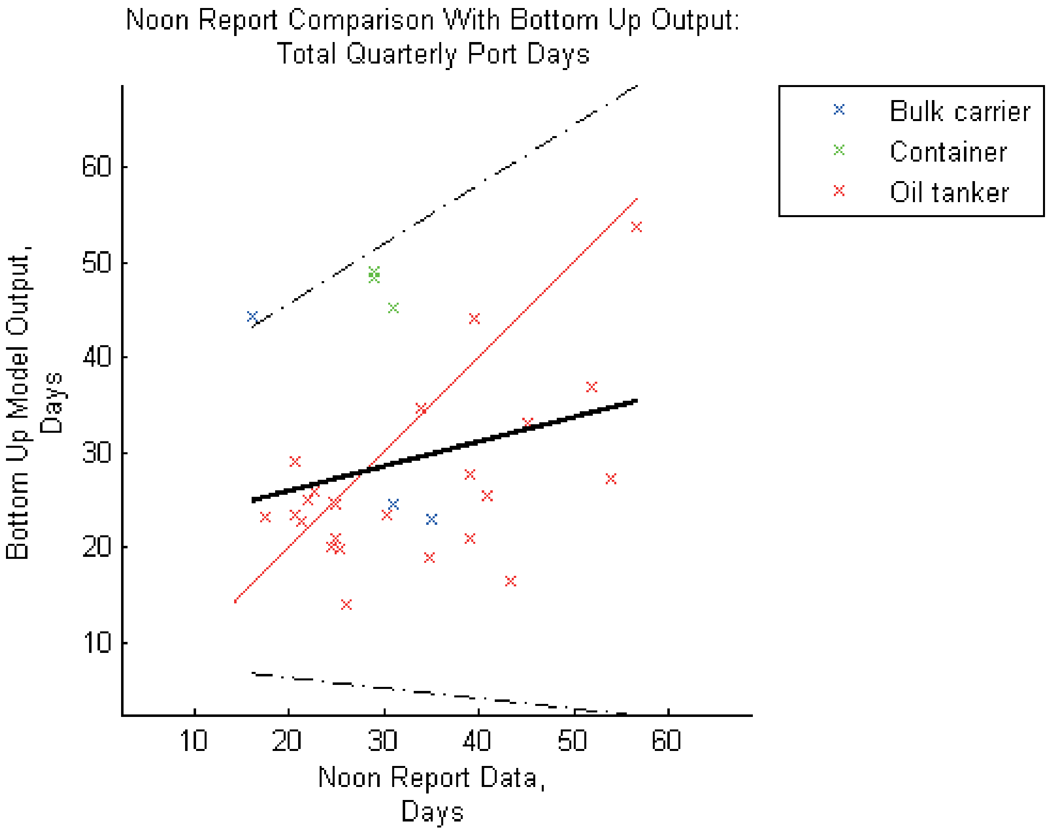

Noon Report Comparison With Bottom Up Output:
Average Ship Draught (At Sea)
Bottom Up Model Output, Meters
Noon Report Data, Meters
-5
0
5
10
15
20
25
30
Bulk carrier
Oil tanker

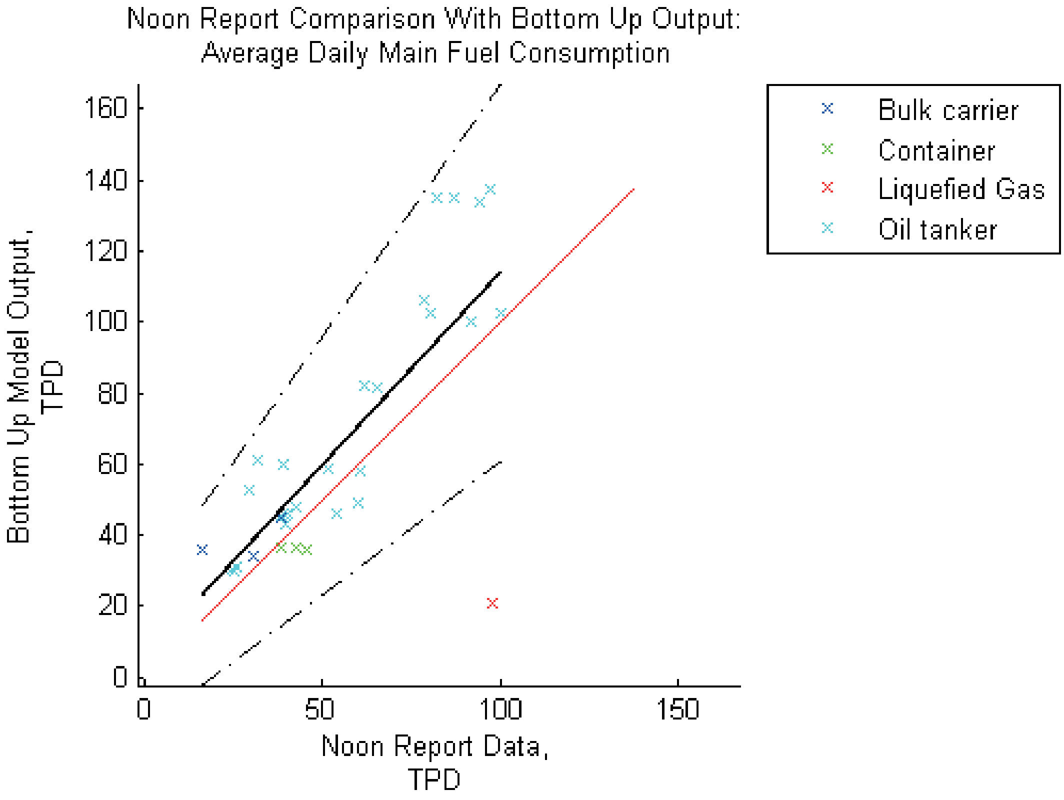
2007


Noon Report Comparison With Bottom Up Output:
Average Ship Speed (At Sea)
Bottom Up Model Output,
Knots
Noon Report Data,
Knots
0
5
10
15
20
25
Bulk carrier
Container
Liquefied Gas
Oil tanker


Noon Report Comparison With Bottom Up Output:
Total Quarterly At Sea Days
Bottom Up Model Output,
Days
Noon Report Data,
Days
30
40
50
60
70
80
90
100
110
Bulk carrier
Container
Liquefied Gas
Oil tanker

2007


Noon Report Comparison With Bottom Up Output:
Total Quarterly Port Days
Bottom Up Model Output,
Days
60
50
40
30
20
10
10
20
30
40
50
60
Noon Report Data,
Days
Bulk carrier
Container
Oil tanker


Noon Report Comparison With Bottom Up Output:
Average Daily Main Fuel Consumption
Bottom Up Model Output,
TPD
160
140
120
100
80
60
40
20
0
0
50
100
150
Noon Report Data,
TPD
Bulk carrier
Container
Liquefied Gas
Oil tanker

Annex 4

Details for Section 1.5.1: top-down uncertainty analysis

Organization of top-down uncertainty analysis

The top-down uncertainty section begins with a review of ongoing data accuracy efforts in which the International Energy Agency (IEA) has participated, and data accuracy reports produced by the Energy Information Administration (EIA), an energy statistics activity independent of IEA. We also summarize some additional literature that helps to understand uncertainty in energy statistics. We then summarize four specific sources of uncertainty in IEA data. With this information, we present our work to estimate possible sources and quantities of uncertainties that may adjust reported statistics. Our quantification of potential adjustments to fuel statistics distinguishes sources with the greatest impact on fuel statistic uncertainty – primary (or first-order) sources – from secondary and tertiary sources.

Ongoing data quality efforts related to uncertainty in fuel sales

The Joint Organisations Data Initiative (JODI) has worked since 2001 to produce a database to provide more transparency in oil market data. The data effort includes "the collection of monthly oil statistics from each organisation's member countries by means of a harmonised questionnaire on 42 key oil data points". More than 90 countries/economies, members of the six pioneer organizations (APEC, EUROSTAT, IEA, OLADE, OPEC and UNSD) participate in JODI-Oil, representing around 90% of global oil supply and demand. Among the important work this group is performing, JODI is engaged in data quality assessment. That work appears to be focused on uncertainties related to several elements, including:

1 data validation;

2 intercomparison with other energy statistics;

3 data collection; and

4 metadata.

While much of the current work seems to be engaging knowledge transfer through workshops and training exchanges, the group has produced two approaches to characterizing data participation and content quality. These are available in what JODI reports as smiley-face assessments, produced every six months since 2012 (Barcelona, 2012). Currently, these are qualitative assessments only, and could not be used in the quantitative uncertainty analysis required for this work.

Review of EIA accuracy analyses (estimation of percentage error)

EIA resources were evaluated for a) similarity to IEA statistics, and b) complementary data quality investigations. A discussion of the comparison of EIA similarity for fuel oil statistics was provided in the QA/QC section under Section 1.4. Here we discuss the EIA reports on data accuracy as independent and indirect evidence of sources and magnitude of uncertainty in top-down fuel consumption statistics.

A series of reports, entitled *Accuracy of Petroleum Supply Data*, exists for EIA statistics that identify types of error that may exist in US energy statistics (Heppner & French, 1996-2008; Heppner & Breslin, 2009). These include:

1. Sampling error (difference between the sample estimate and the population value): this arises because "surveys are administered to samples of the monthly populations to reduce respondent burden and to expedite the turnaround of data" (Heppner & Breslin, 2009).
2. Non-sampling error (two types):
   - a Random: "on average, and over time, values will be overestimated by the same amount they are underestimated. Therefore, over time, random errors do not bias the data, but they will give an inaccurate portrayal at any point in time" (Heppner & Breslin, 2009).
   - b Systematic: "a source of bias in the data, since these patterns of errors are made repeatedly."

The series of reports by EIA identified specific sources of uncertainty (non-sampling errors) that may include:

1. insufficient respondents coverage of target population;
2. nonresponse;
3. response error; and
4. errors due to lack of survey clarity.

The EIA report identifies imports and exports as statistics with greater uncertainty, similar to IEA. "Because of the irregularity of imports for crude oil and petroleum products, the magnitude and range of percent errors for both the MFW [monthly-from-weekly] and the PSM [petroleum supply monthly] imports numbers can be expected to be much larger and wider than for production and stocks" (Heppner & Breslin, 2009). No discussion assessing the accuracy of marine fuel statistics (domestic or international) is provided by EIA in these annual reports. However, fuel totals are expected to exhibit similar or greater uncertainty to imports, for reasons that IEA has identified in the QA/QC discussion.

For the Third IMO GHG Study 2014, the consortium specifically reviewed the 2009 report by Heppner and Breslin, because it was the most recent such report we had obtained, and because it reported the US imports percentage error for distillate and fuel oil in 2007 – a common year for both Second IMO GHG Study 2009 and Third IMO GHG Study 2014. (Each of these reports presents a running series of five years' data, so this report reported percentage error statistics on imports for 2003–2007.)

For US residual fuel oil imports, the EIA 2007 monthly-from-weekly (MFW) "range of percent errors was 57.38, ranging from −28.72 to 28.66 percent." This error is much larger than the range of percentage errors for production, or stocks, or even crude oil imports, which are all in the order of 10% or less. For example, "the 2007 range of the MFW percent errors [for fuel oil production], ranging between −5.16 and 3.86 percent, was 9.02", and "the 2007 range (2.02) of the PSM percent errors [for fuel oil stocks], ranging from −1.84 to 0.18 percent, was the smallest range over the 5-year period". The percentage error in monthly and annual statistics for US distillate fuel imports was smaller than fuel oil imports, but bigger than error ranges for distillate production, stocks, etc.

Analysis of US statistics provided two insights into our analysis of potential uncertainty in global top-down inventories for shipping. First, imports and exports are confirmed as important sources of uncertainty even for a nation with very good statistical data on its energy balances. Second, uncertainties surrounding different fuel types can be dissimilar. We do not take any of the specific US calculations on percentage error to represent global statistical error, nor do we imply that the analysis done by EIA represents IEA percentage error. Moreover, we recognize that maritime bunkers (indeed international bunkers for aviation and marine) are unaddressed in the US evaluation of accuracy of energy data. Combined, these two insights provide independent evidence that import and export statistics can jointly contribute uncertainty in energy balances, also identified as a potential uncertainty by IEA.

IEA sources of uncertainties that can be quantified for this work

As mentioned in Section 1.5.1 of the main report, IEA energy balance statistics represent the best available top-down numbers that include marine bunker fuels estimates on a global basis. We assess the quality of IEA by looking at possible sources of uncertainties, and by estimating the potential correction when it is feasible.

We identify four important sources of top-down marine fuel uncertainties:

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 non-shipping categories, e.g. export, agriculture, etc. In this case, marine fuels would be under-reported and other sectors may have their fuels over-reported.

3 Transfers category reporting: in accordance with IEA, this category comprises inter-product transfers, which result 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 under-reporting.

4 Data accuracy: IEA data may suffer a lack of intrinsic accuracy because of the ways in which the data are collected.

These sources of discrepancy are not mutually exclusive, and not all of them can be identified and quantified given available data at the national levels.

Estimates of potential adjustment to top-down statistics

Potential adjustments are evaluated by considering world energy statistical balances, and quantifying discrepancies in quantities most related to known top-down uncertainty. We quantify sector misallocation specifically for cumulative volumes that could be misallocated marine bunkers, in whole or in part.

Export-import misallocation

Some of energy allocation discrepancies can be identified through analysing IEA data in world balance format. We use these discrepancies to estimate potential corrections due to uncertainties that are under the category "other sector misallocation".

As acknowledged by IEA, the difference between total exports and imports (net difference at world scale) indicates a possible misallocation of bunkers into exports for some countries. By collecting IEA data in world balance format, this net difference at world scale can be used to identify an upper bound of potential correction. Given evidence that at least part of this discrepancy could be from a misallocation of marine fuels, we expect that the best estimation of this uncertainty would adjust the fuel sale data. In other words, if excess exports are not recorded as imports, then excess fuel deducted as exports could be sold as marine bunkers without record.

The net discrepancies reported by IEA as "Statistical differences" are calculated as total consumption minus total supply. Figure 20, Figure 21 and Figure 22 show the marine fuel sales data and both discrepancies over the period 1971–2011. The net statistical difference should be expected to be smaller than any single contributor to the net differences. This is because net statistic difference includes the export-import discrepancy, and all other discrepancies that may be additive or offsetting, including unquantified discrepancies (uncertainties) in marine bunker statistics.

The export-import discrepancies represent a larger fraction of marine fuel oil bunkers than distillate bunkers. Conversely, statistical differences are larger for distillate fuels than for fuel oil. These findings could be expected, given the larger presence of fuel oil in the maritime sector. For example, allocation of bunker sales as exports, if occurring equally frequently for all marine fuels, would produce a greater discrepancy for marine fuel oil. Moreover, given the greater world demand for distillate fuels (e.g. small statistical uncertainties in a larger fuel sector), statistical uncertainty could represent a larger fraction of distillate marine bunkers than import-export differences. Natural gas discrepancies vary around the zero value, and no international gas sales statistics exist; therefore, we will not quantify uncertainty for natural gas data.

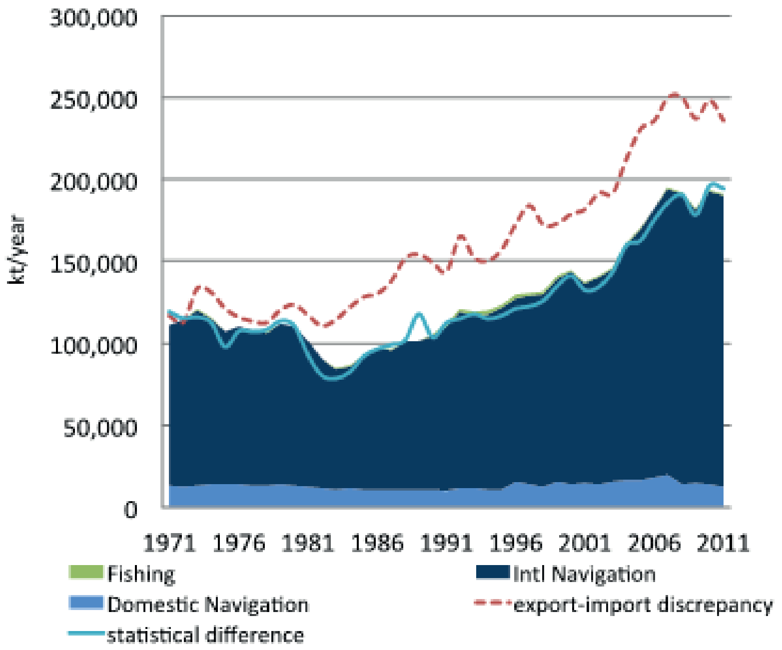


Figure 20: *Fuel oil shipping sales, export-import discrepancy and statistical difference at world balance*

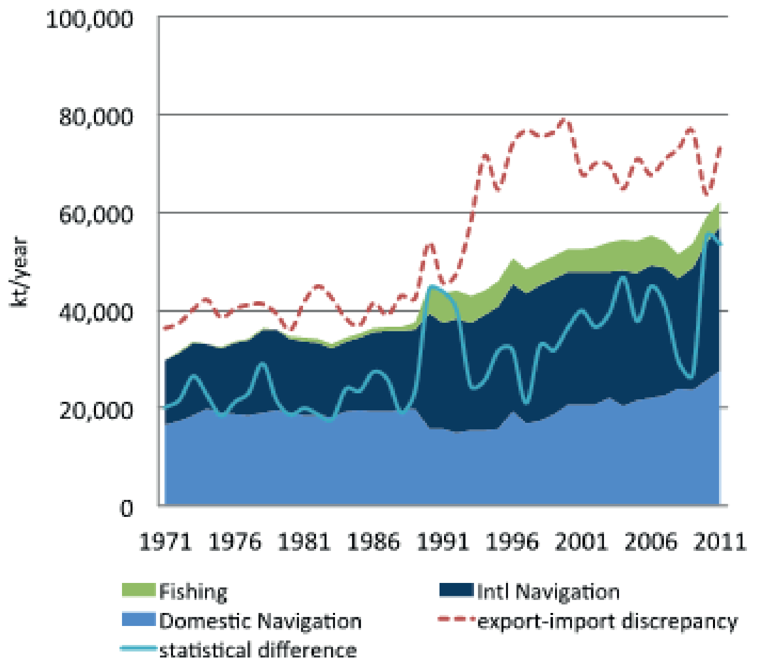


Figure 21: *Gas/diesel shipping sales, export-import discrepancy and statistical difference at world balance*

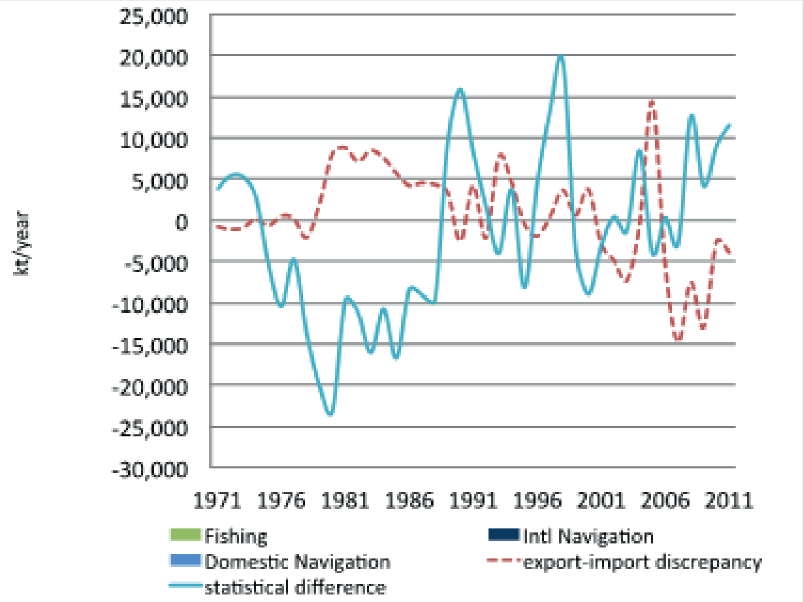


Figure 22: *World natural gas shipping sales, export-import discrepancy and statistical difference*

Transfers category reporting

The IEA "Transfers" category "… comprises … products transferred and recycled products. Products transferred are intended for oil products imported for further processing in refineries. Recycled products are finished products, which pass a second time through the marketing network …".

Given this definition, the net balance of inter-product transfers cannot be checked if equal to zero; however, the net balance of "Transfers" may be an indicator of a potential maximum discrepancy in the net balance of inter-product transfers figure.

We find that the world transfers balance also is greater than zero, meaning that net transfer statistics do not balance at the world scale – in other words, that additional fuel exists in the transfers data. If these transfers include significant volumes of fuel or other products that were later blended for marine bunkers, the statistical data could under-report marine bunkers consumption.

Our assessment indicates that the additional uncertainty contributed by such an allocation error would increase the export-import adjustment by approximately 10% to approximately 20% since 1998. Figure 23 illustrates the comparative impact on uncertainty of the observed export-import discrepancy and the observed transfers balance discrepancy.

Data accuracy

The accuracy of the data depends on different statistical approach on data collection, reporting and validation. For example, Marland (2008) reports that:

> "… the United States national calculation of CO_2 emissions has an uncertainty (at the 95% confidence level) of –1% to 6%, and Environment Canada reported a comparable value of –4% to 0%. Olivier and Peters (2002) estimated that emissions from Organisation for Economic Co-operation and Development (OECD) countries might have – on average – an uncertainty of 5% to 10%, whereas the uncertainty may be 10% to 20% for other countries. The International Energy Agency did not report the uncertainty of its emissions estimates but relied on Intergovernmental Panel on Climate Change (IPCC) methodologies and cited the IPCC estimate that 'for countries with good energy collection systems, this [IPCC Tier I method] will result in an uncertainty range of ±5%. The uncertainty range in countries with "less well-developed energy data systems" may be on the order of ±10%.'"

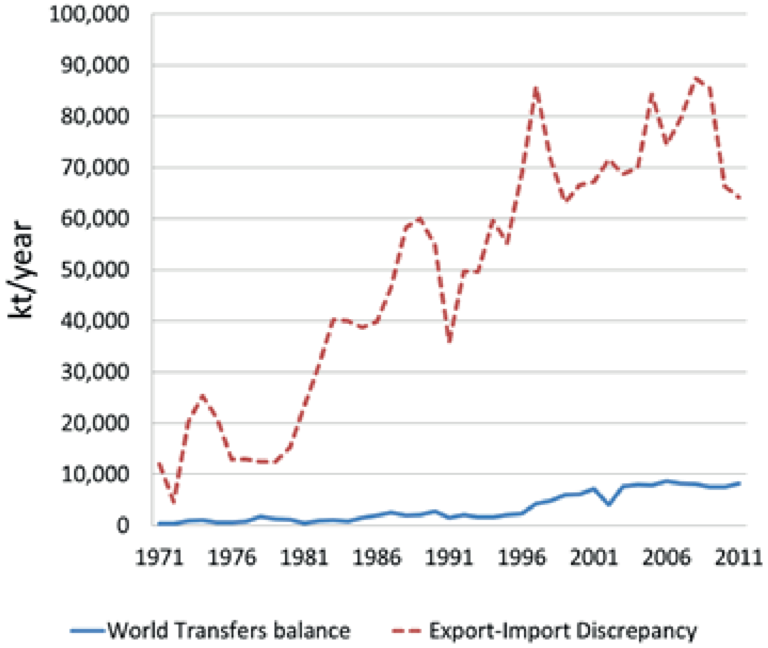


Figure 23: *Stacked graph showing sum of fuel transfer balance and export-import discrepancy*

Only qualitative assumptions on the possible percentage of accuracy within the marine sectors can be attempted based on the available literature. Le Quéré et al. (2009) used an uncertainty in CO_2 emissions of ±6% for global inventories, but that necessarily means that some sectors and nations can have greater than 6% uncertainty, especially smaller sectors; conversely, small percentage uncertainties in energy-consuming nations or sectors may represent very large volumes of fuel. Marland (2008) reported that these types of uncertainties and errors showed "no systematic bias, and the global totals were very similar". Relative differences were largest for countries with weaker national systems of energy statistics, and absolute differences were largest for countries with large emissions. Again, this literature did not assess marine fuel statistics specifically, but reported on overall energy balance integrity. Based on the literature, we cannot quantify the remaining accuracy of marine fuel consumption from top-down statistics.

Results of top-down uncertainty analysis

We present a modified estimate of top-down marine fuels totals by adding the fuel volumes attributed to export-import discrepancies for fuel oil and gas diesel and by adding the additional fuel volumes associated with the positive balance of world fuels transfers. These represent the primary and secondary sources of quantified uncertainty. We add these volumes to the sum of reported fuel sales for fuel oil and gas diesel, to assess the total additional fuel that may be considered part of the shipping demand for energy. Our logic in combining known and reported marine fuel consumption by international shipping, domestic shipping and fishing is as follows:

1. The uncertainty in allocation of marine fuels among international voyages, domestic shipping and fishing remains unquantified; we therefore produce an assessment of uncertainty in top-down estimates that is independent of the allocation uncertainty challenge.
2. The total marine fuels volumes reported in the Second IMO GHG Study 2009 included such a combined statistic, the consensus estimate for bounding 2007 bottom-up fuel consumption; our analysis is therefore consistent with that study.
3. This general summary of the quantified uncertainty in top-down fuel consumption serves important comparison tasks in this scope of work.

Figure 24 presents a time series of the quantified change in top-down fuel consumption by represented world net export-import discrepancies and world net fuel transfers balances in addition to the reported marine fuel totals for 1971–2011. Figure 25 and Table 16 present these results for 2007–2011.

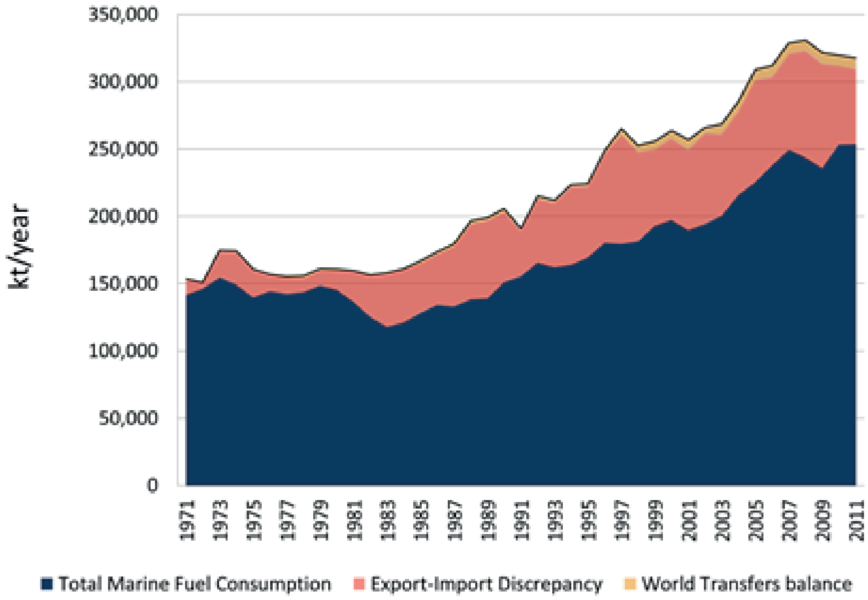


Figure 24: *Time series of adjustments due to primary and secondary sources of uncertainty*

Table 16 – *Results of quantitative uncertainty analysis on top-down statistics (million tonnes)*

Marine Sector	**2007**	**2008**	**2009**	**2010**	**2011**
Total marine fuel consumption (reported)	249.2	243.7	235.9	253.0	253.5
Adjustment for export-import discrepancy	71.5	79.4	78.0	59.0	56.0
Adjustment for fuel transfers balance	8.1	8.1	7.5	7.5	8.2
Adjusted top-down marine fuel estimate	**328.8**	**331.2**	**321.4**	**319.5**	**317.7**

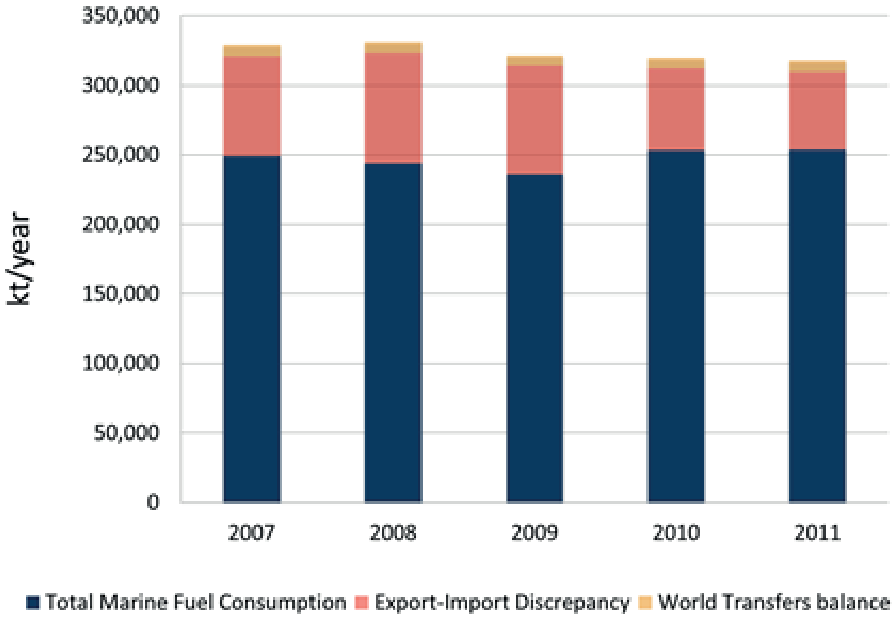


Figure 25: *Adjusted marine fuel sales based on quantitative uncertainty results (2007–2011)*

Export-import discrepancy represents the primary source of uncertainty, as measured by the quantity of adjustment that is supported by our analysis. This discrepancy exists because the total fuel volumes reported as exports exceed the total fuel volumes reported as imports. Evidence associating the export-import discrepancy with marine fuels includes the known but unquantified potential to misallocate bunker fuel sales as exports, as documented above. The magnitude of this error has increased during the period of globalization, particularly since the 1980s. This is evident in Figure 24, where the percentage of adjustment due to export-import discrepancies never exceeded 10% prior to 1980, but always exceeded 10% after 1980. In fact, the percentage adjustment due to export-import allocation uncertainty has never been lower than 22% since 1982. More recently, Table 16 and Figure 25 illustrate the top-down adjustment for 2007–2011. During these years, the average adjustment due to export-import allocation uncertainty averaged 28%.

The secondary source of uncertainty, measured by the quantity of adjustment that is supported by our analysis, derives from the excess balance of fuels that were transferred among domestic consumption sectors in national inventories. This discrepancy exists because deduction reclassification of energy products in one or more fuel sectors remains undocumented as an addition reclassification in another sector. In other words, fuel-transfer deductions appear to be blended into marine bunkers to meet ship/engine fuel quality specifications without accompanying documentation reclassifying them as added to the marine fuel sales volumes. The trend on this error only slightly increased from the 1970s to mid-1990s, and the magnitude of the error, as a percentage of marine fuel sales, never exceeded 2% until 1997. Since 1997, the contribution to uncertainty in marine fuel statistics has more than doubled; nonetheless, during the 2007–2011 period, the average impact on marine fuel statistics of approximately 3% still remains small compared to export-import allocation uncertainty.

Tertiary sources of uncertainty exist, including different statistical approaches on data collection, reporting and validation. These have been observed and reported in the Second IMO GHG Study 2009 (see Table 3.1 of that report). Data accuracy is an ongoing QA/QC effort by IEA and others to help minimize these sources of error and uncertainty. Our work for this update indicates three insights about the nature of uncertainties that we judge to be tertiary, or smaller than those discussed above.

1 The impact of these uncertainties cannot be shown to be consistently biased; in other words, the sign of a potential adjustment appears to vary from year to year;

2 Little evidence supports a cumulative effect on marine fuel sales statistics; in other words, the magnitude cannot be shown to be increasing or decreasing over time; and

3 No uncertainty adjustment can be quantified from the existing statistical differences.

The combined error in recent years associated with these uncertainties ranges from approximately 64 million tonnes to approximately 87 million tonnes of fuel, as indicated in Table 16 for 2007–2011. Incidentally, the 2007 calculated adjustment would reconcile within 1.2% of the top-down statistics with the activity-based estimate of 333 million tonnes reported in the Second IMO GHG Study 2009.

Uncertainty in top-down allocations of international and domestic shipping

We anticipate limited ability to evaluate or reduce allocation uncertainty within top-down fuel types. This could mean that a remaining key uncertainty for IMO will be the designation of top-down marine bunker sales as domestic or international, without additional empirical data. Options include:

1 Treating reported allocations in existing IEA statistics as certain, and using these to allocate the fuel adjustments quantified in this uncertainty analysis;

2 Recognizing that allocations in the statistics are also uncertain, and studying ways to adjust both reported fuel volumes and the adjustments quantified here using the same top-down assumptions, evidence and conclusions;

3 Treating as independent the marine fuel sales data and the adjustment quantified by uncertainty analysis using different top-down assumptions, evidence and conclusions; and

4 Coordinating top-down and bottom-up allocation approaches to leverage insights and produce mutually consistent allocation algorithms.

Annex 5

Details for Section 1.5.2: bottom-up inventory uncertainty analysis

Sources of uncertainty in the Second IMO GHG Study 2009

In the Second IMO GHG Study 2009, the method relied upon weighted average values for each ship/size category. As such, much of the uncertainty in that study was related to aleatory uncertainty. This limited the ability of that work to quantitatively characterize uncertainty, although some key aleatory uncertainties could be characterized with distributions around computed average values.

The Second IMO GHG Study 2009 relied upon a set of independent estimates to define a confidence range on the central estimate for fleetwide fuel use and emissions. It also discussed uncertainties in calculating total emissions (Second IMO GHG Study 2009, Table 3.1). It reported that a dominant source of uncertainty included assumptions about average main operating days, and that a secondary source of uncertainty was average main engine load. Both of these were applied in common to all ships in a type and size category. The study reported that better AIS collection and better quality control on AIS-reported speed were needed to reduce uncertainty. Lastly, the Second IMO GHG Study 2009 reported a number of uncertainties with auxiliary engine calculations.

Overview of sources of uncertainty in current work

Figure 26 illustrates where potential uncertainty is introduced into the bottom-up model for this update. Table 17 (adapted from Jalkanen et al., 2013) identifies examples of uncertainties and relates these to explicit QA/QC efforts that reduce uncertainty.

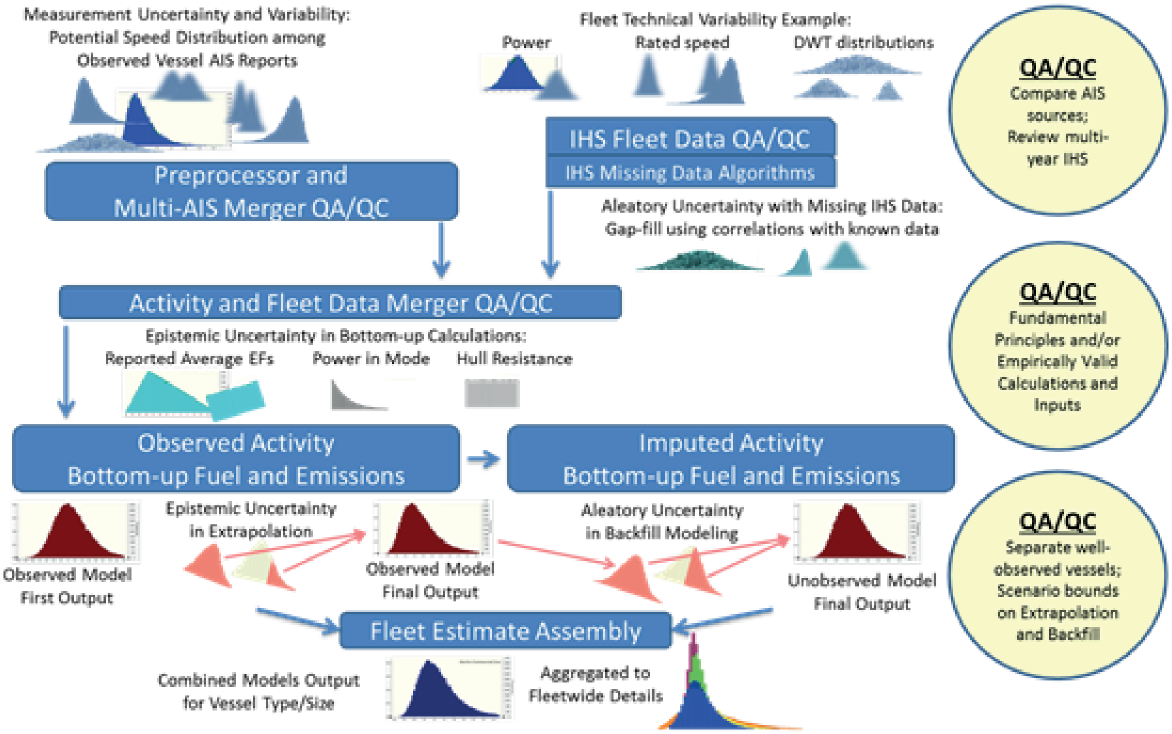


Figure 26: *Bottom-up model with overview of QA/QC and uncertainty characterization*

Table 17 – *Characterization of uncertainty in bottom-up model*

Modelling stage	**Uncertainty (examples)**	**QA/QC measures to reduce uncertainty**	**Remaining uncertainty**
Pre-processor and multi-AIS merger	Speed Draught Time observed	Variability in observed activity at individual ship	Measurement
IHSF fleet data	Gaps in data	Algorithm based on empirically valid data to gap-fill missing data	Aleatory
Activity and fleet data merger	All equations Load by mode SFOC by mode EFs Fuel properties	Empirical validation; fundamental principles; noon reports comparison	Epistemic Aleatory (aggregated measurement uncertainty)
Observed activity bottom-up fuel and emissions	Extrapolation of known activity to unobserved periods in a year	Select well-observed ships; Quantify percentage of year extrapolated	Epistemic Aleatory
Imputed activity bottom-up fuel and emissions	Backfill of ship profile for unobserved ships	Characterize ships subject to backfill Quantify backfill fleet	Epistemic Aleatory
Fleet estimate assembly	No new uncertainty		Propagated from prior steps

From both Figure 26 and Table 17, we have broken down the uncertainty in the total emissions estimate into three key interconnected components of uncertainty:

1 The uncertainty in the emissions from a ship in one hour:
  a When the ship is observed on AIS;
  b When the ship is not observed on AIS.
2 The uncertainty in the aggregation of (uncertain) hourly emissions (both observed and unobserved hours) into annual estimates for each ship.

3 The uncertainty in estimating the total annual emissions from the (uncertain) annual estimate of emissions for a fleet of ships.

The bottom-up model uses a mixture of look-up data related to a ship's specification (e.g. engine, age of ship), physics in closed-form equations (e.g. relationships between speed and power) and empirical data (e.g. emissions factors) in order to derive emissions. The multiple sources of uncertainty in both input parameters and the relationships embedded in the model itself (some of which – e.g. speed and power – are non-linear), in combination with the aggregation of multiple observations (by hour and by ships in the fleet), mean that characterization of uncertainty on input parameters does not map straightforwardly onto the uncertainty of the outputs (annual emissions by fleet of ships). However, there is established literature on this subject, which indicates that Monte Carlo simulation can be used to structure an estimate of the uncertainty of the bottom-up method's outputs from characterization of both the input and model uncertainties, and this literature was used to define the method employed in this study.

The following text in this annex outlines the approach taken to conduct a quantitative assessment of the uncertainty of the CO_2 emissions inventory by considering the input and model uncertainties at each of the three levels outlined above (hourly per ship, annual per ship and annual per fleet).

The characterization of uncertainty relies on knowledge about the measurement variable that is being used, and a benchmark or "the truth" to which that measurement is being compared. For many of the parameters that are needed, we have used the best available data in our bottom-up model, which limits the availability of data sets that can be used as proxy benchmarks and therefore comparators. Deeper insight or higher quality data sets that are available are typically available for only a sample of ships, and this adds a risk that the sample used could contain bias. The process of deriving quantitative estimates of uncertainty therefore has to be viewed as approximate and not definitive (there is uncertainty in the quantification of uncertainty). This section therefore lays out the thought processes and data used as clearly and comprehensively as possible and focuses on those sources of uncertainty judged to be of greatest significance to the overall estimate.

Uncertainty in the emissions from a ship in one hour

There are a number of sources of uncertainty in the estimate of the uncertainty of the emissions for a "given" ship in a "given" hour. These stem from uncertainty both in the technical parameters used to characterize the ship (its current specification in terms of hull and machinery, the condition of the hull, etc.) and in the operational specification (the weather the ship has encountered, its speed through water and draught). The descriptions that follow are not the only parameters that are uncertain, but they are all components of the equations in Section 1.2 which are the core of the calculation of fuel consumption and emissions, and therefore of the highest significance in influencing the uncertainty of the estimated emissions.

Estimate of uncertainty of the input parameters

Speed through the water uncertainty

A ship's aero- and hydrodynamic resistance and therefore power requirements are a function of ship speed (among other factors). Of these two sources of resistance, in calm weather it is the hydrodynamic resistance that dominates the total resistance and this is a function of a ship's speed through the water. The relationship is commonly approximated as a cubic (e.g. power is proportional to speed cubed), as described in Section 1.2. Consequently, small variations in ship speed are magnified into larger variations in power (and therefore fuel consumption and emissions). For periods of time when a ship is observed on AIS, the bottom-up method uses the ship's speed as reported in the AIS message (which is most commonly obtained from a ship's GPS, which measures speed over ground). For periods of time when the ship is not observed on AIS, the bottom-up method estimates the ship speed by extrapolating an operating profile based on the information gathered when the ship is observed (see Section 1.2). In relation to a ship's resistance, there are therefore three important and fundamental sources of uncertainty in the bottom-up method:

1 Uncertainty due to the approximation of a ship's speed through the water using a sensor measuring speed over ground;

2 Uncertainty in the speed over ground, estimated as an hourly average speed:

   a from the weighted averaging of one or more instantaneous reports of speed obtained from AIS;

b from the extrapolation of observed activity to estimate the operating parameters when the ship is not observed.

The first of these is a function of a relative speed between the water and the ground – e.g. tides and currents – and is therefore a function of the metocean conditions in which the ship is sailing. These conditions cannot be easily generalized; some ships may spend all their time operating in areas of high tidal flows and current (typically coastal shipping) and others may spend little time operating in such areas (typically, although not necessarily, when a ship is in the open ocean). To estimate the variability, we have used operator data supplied for a fleet of twenty ships (a mixture of bulk carriers and tankers with a variety of ship sizes) for which measurements of average speed through the water and average speed over ground were available, averaged over 24 hours. The ships are owned by a variety of companies but managed by the same company and have consistent data reporting mechanisms. In total they represent approximately 80 ship years of operation and data. Figure 27 displays the estimate of the probability density function of the difference between speed over ground and speed through the water. The average difference is −0.14 knots and the standard deviation is 0.95 knots. Implicit in this distribution is the measurement error associated with the speed logs used to obtain the speed through the water and the GPS used to obtain the speed over ground, but these are assumed to be negligible relative to the uncertainty in the difference between the two measurements.

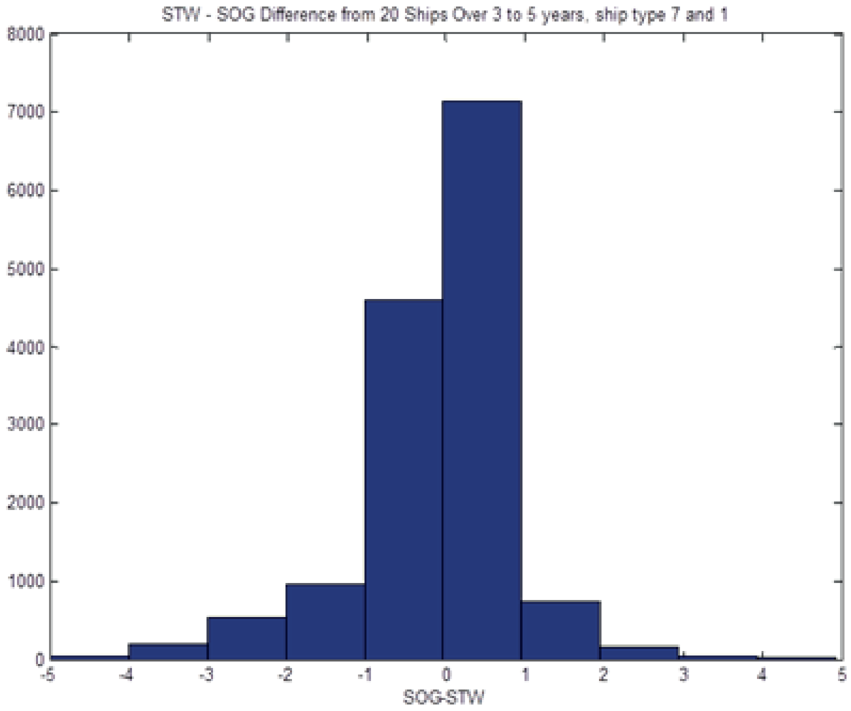


Figure 27: *Relationship between speed over ground and speed through the water*

From the analysis described above in the section "Activity estimates temporal coverage QA/QC", an estimate was found for the standard deviation of the uncertainty of speeds during an hour of operation. These values are:

- For an observed hour, 0.75 kt
- For an unobserved hour, 1.85 kt

Combining these sources of uncertainty, we can estimate the total uncertainty for the two types of observation (see Table 18).

Draught uncertainty

Draught influences the underwater hull surface area and hull form. It varies during the course of a voyage and from one voyage to another. The measurement of draught is obtained from the data reported in AIS messages (see Section 1.2). On some ships, the value is entered manually (from draught mark readings or a loading computer), and on others it is reported from sensors. As the value is entered manually and rarely audited for quality, it is possible that spurious or null returns may be observed in the raw data. For the purposes of estimating the uncertainty of this parameter, the comparison between the noon report and the reported AIS data has been used. The data for both observed and unobserved hours can be seen in Figure 28. The dotted black lines are the 95% confidence bounds around the best fit line. Reading from the chart, these confidence bounds imply that the standard deviation of the error between the bottom-up estimate of draught and the noon report value is approximately 10%. This value is used both for the observed and the unobserved hours.

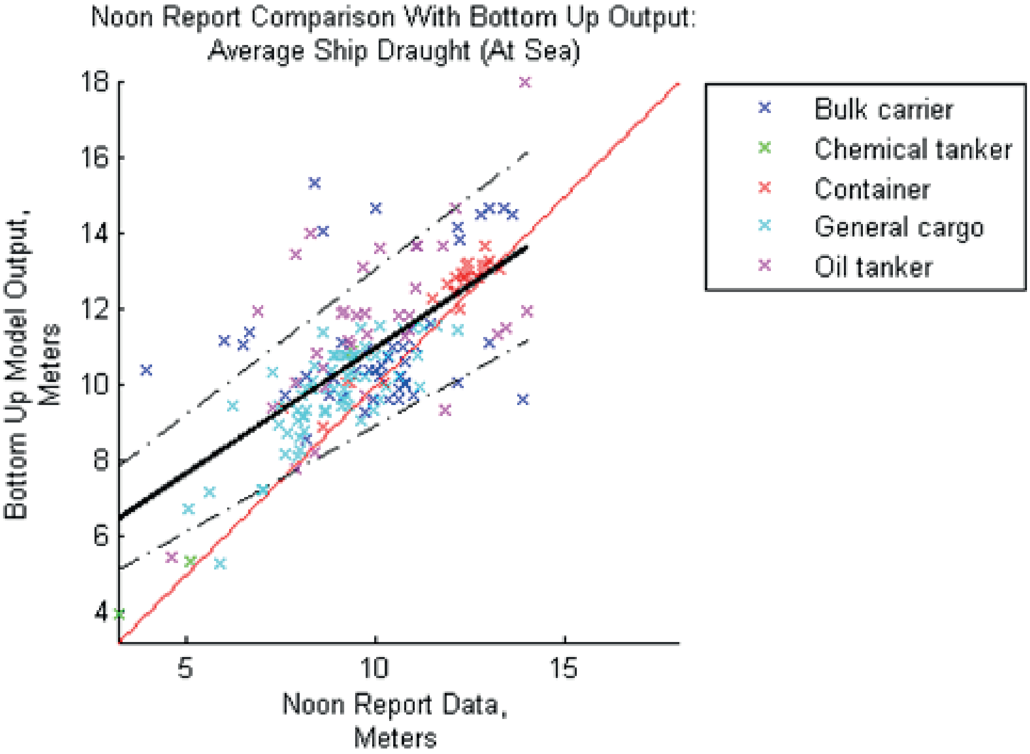


Figure 28: *Comparison between draught estimated in the bottom-up model from AIS data and reported in noon reports*

Ship specification uncertainty

Section 1.4 discusses the quality assurance of the ship specifications obtained from IHSF. This concludes that uncertainty exists, but cannot be easily quantified or characterized. A comprehensive data set describing the variability of fouling and weather for different ship types and sizes was also not available, leading to this uncertainty being omitted. An investigation was carried out into the variability of the power law relationship between a ship's resistance and its speed (see Annex 1, Powering subroutine: *Power_at_op*). This relationship is key to the bottom-up method's ability to accurately capture the slow-steaming phenomenon. Samples of ships from a number of ship types were taken, and parameters describing the ship's length, beam, draught, etc., were used in a calculation of resistance using the Holtrop-Mennen resistance regression formulae (Holtrop & Mennen, 1982). Figure 29 presents the outcome of the investigation, which shows for bulk carriers greater than 40,000 dwt that the use of a cubic relationship between speed and power is a high-quality assumption. For smaller ships, the assumption of a cubic appears less valid, and in particular for container ships. Drawing from this investigation and to ensure simplicity of analysis, the speed-resistance relationship is held as a cubic and no uncertainty is applied.

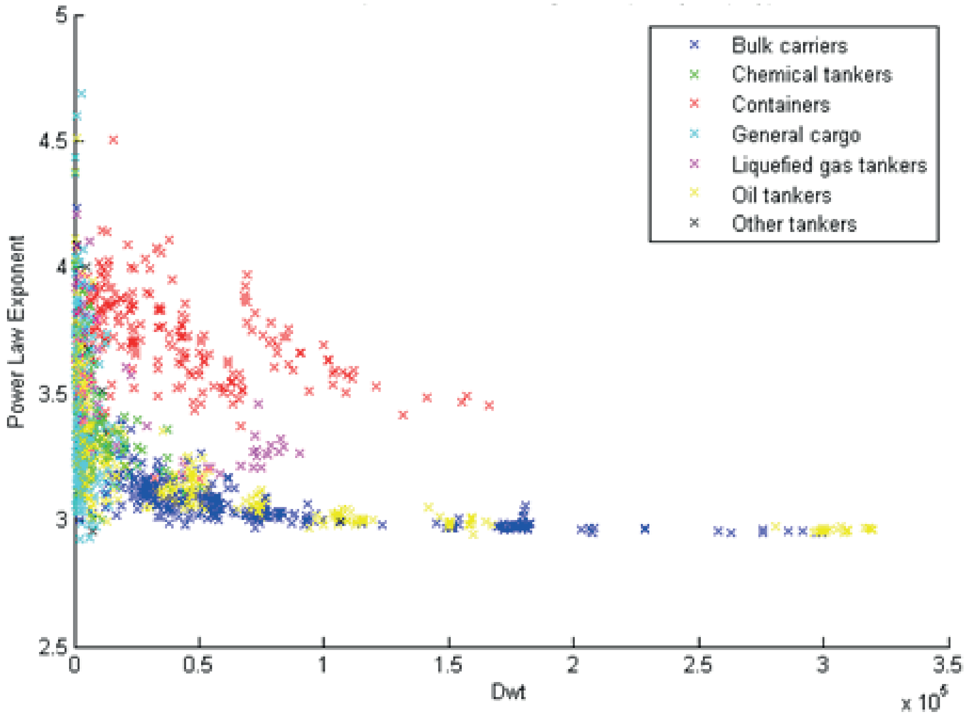


Figure 29: *Estimation of the power law relating deadweight to resistance for samples of different ship types*

Summary of input uncertainties used in the per-hour uncertainty analysis

Table 18 – *Summary table of uncertainty characterizations used*

	Input parameter	Hour when observed on AIS		Hour when not observed on AIS	
		Mean	**Standard deviation**	**Mean**	**Standard deviation**
Operation	Speed	Mean at-sea speed	11%	Mean at-sea speed	18%
	Draught	Mean at-sea draught	10% of mean	Mean at-sea draught	10% of mean
IHSF specification	Installed power	Known to exist, but not known in magnitude and so assumed to be deterministic			
	Reference (design) speed				
Other technical and operational assumptions	Fouling-added resistance	Equally uncertain, regardless of whether observed or unobserved; assumed here to be deterministic			
	Weather-added resistance				
	SFOC	Known to exist, but assumed to be deterministic in this calculation			
	C_f	Known to exist, but assumed to be deterministic in this calculation			
	n	Significant for smaller ships, but assumed to be deterministic for larger ships			
	Aux/boiler	Known to exist, but not known in magnitude and so assumed to be deterministic			

Uncertainty in the aggregation of hourly emissions into annual emissions

For periods of time during the year that a ship is not observed on AIS, we extrapolate from the measured activity data. This extrapolation introduces uncertainty, as this step requires that assumptions be made. The uncertainty analysis will propagate uncertain inputs at the per-ship-hour stage of the model into the per-ship-year stage of the model.

In addition to uncertainty in the speed, for times when the ship is not observed on AIS, there is also uncertainty about whether the ship is at sea or in port. The reliability of the extrapolation algorithm for estimating the annual days at sea at varying levels of AIS coverage reliability was examined in detail in Annex 3 (Activity estimates temporal coverage QA/QC). This analysis provides a derivation for the relationship between coverage and uncertainty in the days spent at sea, which, in combination with the per-hour uncertainty estimates, is applied to calculate the total uncertainty in the annual CO_2 emissions estimate.

Estimate of uncertainty of the input parameters and method

The assumptions used to estimate the uncertainty in the annual fuel consumption of an average ship in a given ship type and size category are listed in Table 19.

Table 19 – *Estimated parameters for the uncertainty in the inputs to the annual emissions calculation*

Period	**Input parameter**	**Mean**	**Standard deviation**
Per annum (observed and unobserved)	Ratio of days at sea to days at port per year	Taken from LRIT to AIS analysis derived relationship	
When observed on AIS	Average emissions per hour at sea	Read in from the per-hour uncertainty analysis	
	Average emissions per hour in port		
When not observed on AIS	Average emissions per hour at sea		
	Average emissions per hour in port		

Results

The output of the simulation of the per-year uncertainty analysis, using the outputs from the per-hour uncertainty analysis, can be seen in Figure 30 and Figure 31. Both plots depict the bulk carrier size category 60–99,999 dwt. The first of the two plots characterizes the uncertainty in 2007, a year when the average ship in that type and size category was observed on AIS for just 14% of the year. This contrasts with the second plot, which is calculated for 2012, when the AIS coverage of the average ship was 65% and the uncertainty greatly reduced.

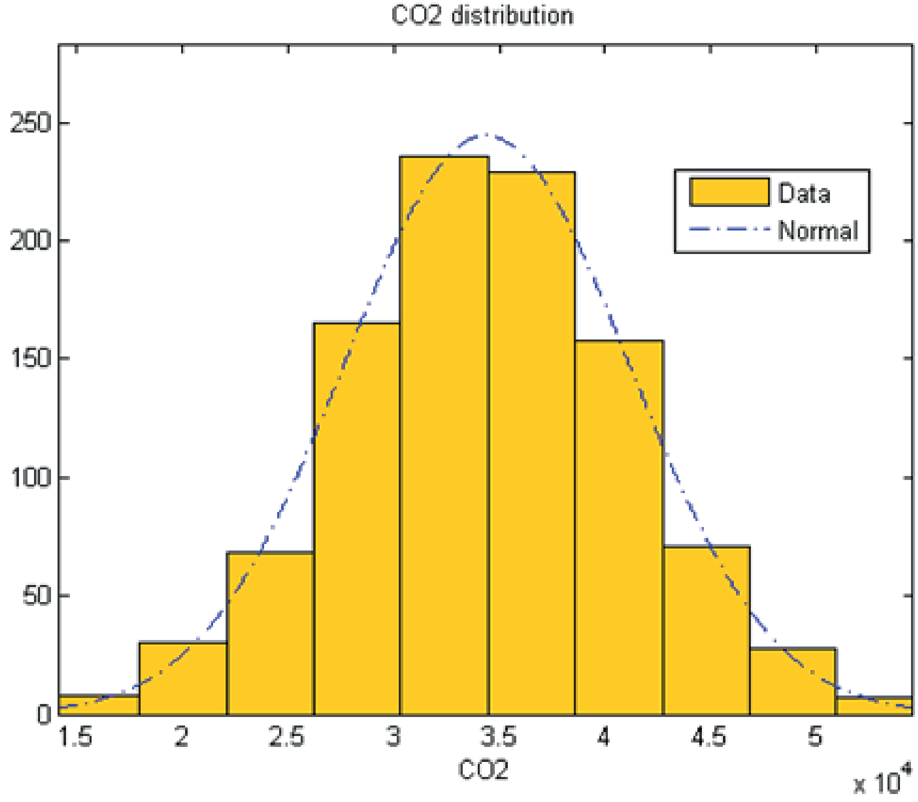


Figure 30: *Uncertainty around the annual emissions (x-axis is '00,000 tonnes of CO_2; y-axis is frequency) from a Monte Carlo simulation of an "average" Panamax bulk carrier (60,000–99,999 dwt capacity) in 2007*

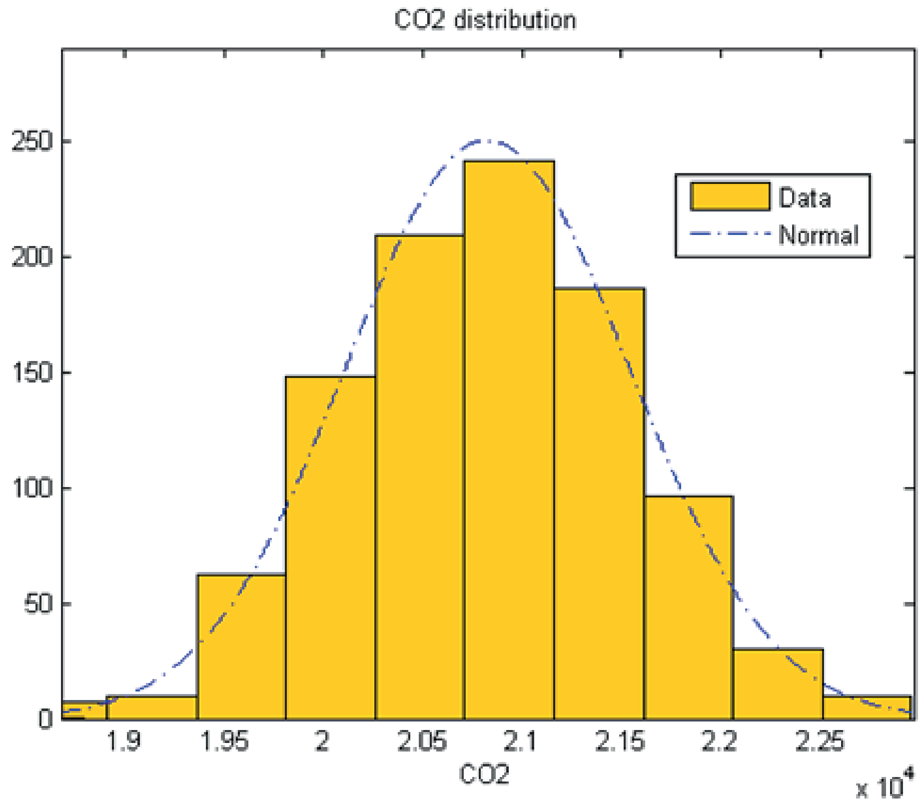


Figure 31: *Uncertainty around the annual emissions (x-axis is '00,000 tonnes of CO_2; y-axis is frequency) from a Monte Carlo simulation of an "average" Panamax bulk carrier (60,000–99,999 dwt capacity) in 2012*

Uncertainty in the aggregation of a fleet of ships' emissions

Activity for ships that are in service but not observed in AIS is imputed. Epistemic and aleatory uncertainty is introduced because the observed activity is propagated to the ships where imputed activity is used. The assumptions used to estimate the influence of the uncertainty associated with the imputed fleet, in combination with the uncertainty of the observed fleet, are listed in Table 20.

Table 20 – *Estimated parameters for the uncertainty in the inputs to the annual emissions calculation*

Per annum per ship	Input parameter	Mean	Standard deviation
A ship observed in AIS	CO_2 emissions per year	Read in from the per-year uncertainty analysis	
A ship not observed in AIS but identified as in service		Characteristics of an individual ship's fuel consumption are simulated from the distribution of the CO_2 emissions of the observed fleet of the same ship type and size The number of in-service ships is simulated as a uniform distribution with a minimum value of zero (i.e. none of the ships defined in IHSF as in service but not observed in AIS is active), with the maximum given by the difference between the size of the IHSF in-service fleet and the number of ships observed on AIS in that type and size category	

Results

Results are first calculated for each of the ship type and size categories and then aggregated to total uncertainty characterizations for international shipping and for total shipping. The upper and lower bounds applied to the Figures in Section 1.5.2 are obtained as the maximum and minimum values obtained from the Monte Carlo simulation. The statistics of the outputs to that simulation can also be approximated as normal distributions (similar to the uncertainties in the hourly aggregations), and Table 21 lists these for each of the ship type and size categories. The variation in uncertainty between ship types and sizes can be seen, with the lowest uncertainties (standard deviation of approximately 13% of mean) being for well observed (on AIS) fleets, and those fleets where the total number of ships listed in IHSF closely matches the number of ships observed on AIS (cruise ships, large vehicle carriers, large tankers and bulk carriers and large container ships). This contrasts with the smallest size general cargo fleet and the smallest tankers (both 0–5,000 dwt), which have standard deviations exceeding 20% of the mean estimate. The contrast is even more notable for certain categories of non-merchant shipping (e.g. "Miscellaneous – fishing" and "Miscellaneous – other": 37% and 56% respectively), which are poorly observed and poorly matched in IHSF, although in both cases these are ship types and sizes which are not categorized in this study as international shipping.

Table 21 – *Estimated characteristics of the uncertainty for individual ship type and size categories*

Ship type	Size category	Mean	Standard Deviation	Standard deviation as a % of mean
Bulk carrier	0–9,999	4,484,703	783,207	17%
	10,000–34,999	23,406,255	3,572,119	15%
	35,000–59,999	43,016,318	6,617,266	15%
	60,000-99,999	44,617,850	6,411,213	14%
	100,000–199,999	35,363,715	5,188,630	15%
	200,000–+	10,478,638	1,494,526	14%
Chemical tanker	0–4,999	4,493,655	679,510	15%
	5,000–9,999	7,007,269	956,839	14%
	10,000–19,999	12,117,662	1,744,680	14%
	20,000–+	29,614,933	4,314,846	15%
Container	0–999	12,289,773	1,599,989	13%
	1,000–1,999	30,532,084	3,913,000	13%
	2,000–2,999	24,649,848	3,352,376	14%
	3,000–4,999	52,578,459	6,509,096	12%
	5,000–7,999	42,436,722	5,480,776	13%
	8,000–11,999	30,009,753	3,925,368	13%
	12,000–14,500	8,614,072	1,120,637	13%
	14,500–+	776,608	105,888	14%
General cargo	0–4,999	17,993,881	3,891,076	22%
	5,000–9,999	15,937,373	2,326,828	15%
	10,000–+	26,463,128	3,720,868	14%
Liquefied gas tanker	0–49,999	10,477,872	1,501,513	14%
	50,000–199,999	28,390,114	3,641,861	13%
	200,000–+	5,313,632	697,094	13%
Oil tanker	0–4,999	11,244,284	2,391,743	21%
	5,000–9,999	4,339,055	580,383	13%
	10,000–19,999	2,038,769	260,104	13%
	20,000–59,999	12,307,094	1,696,973	14%
	60,000–79,999	9,870,325	1,326,081	13%
	80,000–119,999	25,724,409	3,405,958	13%
	120,000–199,999	16,846,138	2,271,416	13%
	200,000–+	35,612,562	4,762,621	13%
Other liquids tankers	0–+	631,061.4	222,835	35%
Ferry – pax only	0–1,999	8,065,654	1,839,021	23%
	2,000–+	937,766.4	142,744	15%

Ship type	Size category	Mean	Standard Deviation	Standard deviation as a % of mean
Cruise	0–1,999	765,518	201,026	26%
	2,000–9,999	541,192.7	69,983	13%
	10,000–59,999	6,777,427	814,564	12%
	60,000–99,999	15,272,130	1,847,344	12%
	100,000–+	10,858,883	1,327,775	12%
Ferry – ro-pax	0–1,999	3,196,211	728,938	23%
	2,000–+	25,101,829	3,483,843	14%
Refrigerated bulk	0–1,999	15,681,223	2,347,187	15%
Ro-ro	0–4,999	11,194,992	2,907,801	26%
	5,000–+	13,214,632	1,585,173	12%
Vehicle	0–3,999	6,049,479	791,876	13%
	4,000–+	17,618,246	2,094,463	12%
Yacht	0–+	2,903,868	506,778	17%
Service – tug	0–+	14,861,465	4,114,117	28%
Miscellaneous – fishing	0–+	31,227,450	11,465,708	37%
Offshore	0–+	24,875,547	4,053,364	16%
Service – other	0–+	10,982,136	1,989,317	18%
Miscellaneous – other	0–+	3,750,878	2,112,923	56%

Annex 6
Details for Section 2: other GHG emissions and relevant substances

Emissions factors

The emissions factors (EF) incorporated into this report build on and significantly improve and increase the resolution of the Second IMO GHG Study 2009 with the inclusion of IMO engine Tiers pre-2000, I and II, the introduction of fuel correction factors (FCFs) that allow for the estimate of various fuel types (HFO, IFO, MDO, MGO, LNG) with varying fuel sulphur contents, and the incorporation of load-adjusted emissions factors over the entire engine load range.

Method for selecting/developing baseline and actual emissions factors

Available emissions factors were reviewed by the EF working group and the following hierarchy was established:

- IMO-published emissions factors;
- EFs used by consortium members' work: these were reviewed, discussed, and the selected emissions factors unanimously agreed on.

The following pollutants were estimated as part of this study:

- carbon dioxide (CO_2)
- nitrogen oxides (NO_x)
- sulphur oxides (SO_x)
- particulate matter (PM)
- carbon monoxide (CO)
- methane (CH_4)
- nitrous oxide (N_2O)
- non-methane volatile organic compounds (NMVOC)

The following methodology was used to develop the baseline and actual emissions factors for this study:

1. Identify baseline emissions factors with the following hierarchy: IMO emissions factors; if none published, then consortium-recommended emissions factors from other studies that members are using in their published work. Emissions factors come in two groups: energy-based in g pollutant/kWh and fuel-based in g pollutant/g fuel consumed. The baseline fuel for the bottom-up emissions factors is defined as HFO fuel with 2.7% sulphur content.

2. Convert energy-based baseline emissions factors in g pollutant/kWh to fuel-based emissions factors in g pollutant/g fuel consumed, as applicable, using:

$$EF_{\text{baseline}}\ (\text{g pollutant})/(\text{g fuel})) = \frac{EF_{\text{baseline}}\ (\text{g pollutant})/\text{kWh})}{SFOC_{\text{baseline}}\ (\text{g fuel})/\text{kWh})} \qquad \text{Eq. (4)}$$

where

$EF_{baseline}$ = cited emissions factor

$SFOC_{baseline}$ = SFOC associated with the cited emissions factor

3 Use FCFs, as applicable, to adjust emissions factors for the specific fuel being used by the engine:

$$EF_{actual} \text{ (g pollutant)/(g fuel)} = EF_{baseline} \text{ (g pollutant)/(g fuel)} \times FCF \qquad \text{Eq. (5)}$$

Convert to kg pollutant/tonne fuel consumed (for presentation purposes)

4 Adjust EF_{actual} based on variable engine loads using SFOC engine curves and low load adjustment factors to adjust the SFOC.

Baseline emissions factors

Baseline emissions factors for main engines, auxiliary engines and auxiliary boilers are provided in this section. Certain emissions factors change based on fuel type (HFO, MDO, MGO) and sulphur content while others remain the same across various fuel types and are not affected by sulphur. The assumed fuel for the $EF_{baseline}$ presented in this section is HFO with 2.7% sulphur content. The baseline emissions factors and associated references are provided in Table 22.

Pollutant and fuel-specific notes are provided below:

CO_2 – The carbon content of each fuel type is constant and is not affected by engine type, duty cycle or other parameters when looking on the basis of kg CO_2 per tonne fuel. The fuel-based CO_2 emissions factors for main and auxiliary engines at slow, medium and high speeds are based on MEPC 63/23, annex 8 and include:

HFO $EF_{baseline}$ CO_2 = 3,114 kg CO_2/tonne fuel

MDO/MGO $EF_{baseline}$ CO_2 = 3,206 kg CO_2/ tonne fuel

LNG $EF_{baseline}$ CO_2 = 2,750 kg CO_2/ tonne fuel

It should be noted that CO_2 emissions are also not affected by sulphur content of the fuel burned. FCFs are not used for CO_2 as IMO has published specific EFs for each fuel type, which were used in this study directly.

CO, CH_4, NMVOC – Emissions of methane (CH_4) were determined by analysis of test results reported in IVL (2004) and MARINTEK (2010). Methane emissions factors for diesel-fuelled engines, steam boilers and gas turbines are taken from IVL (2004), which states that CH_4 emissions are approximately 2% magnitude of VOC. Therefore, the $EF_{baseline}$ is derived from multiplying the NMVOC $EF_{baseline}$ by 2%. The CH_4 emissions factor for LNG Otto-cycle engines is 8.5 g/kWh, which is on a par with the data of LNG engines (MARINTEK, 2010 and 2014). However, this value may be slightly low for older gas-fuelled engines, especially if run on low engine loads, and slightly high for the latest generation of LNG engines (Wartsila, 2011). This emissions factor was used in the bottom-up approach to determine the amount of methane released to the atmosphere from each of the vessels powered by LNG. It should be noted the LNG NMVOC emissions factor was conservatively assumed to be the same as the hydrocarbon emissions factor. All LNG engines have been modelled as low-pressure, spark injection Otto-cycle engines, which have low NO_x emissions. In the study period (2007–2012), the majority of LNG-fuelled vessels in the world fleet do not use diesel-cycle engines (DNV GL USA, 2013, a) and b)) and AIS/satellite AIS does not indicate which fuel a ship is burning. Further emissions testing on LNG engines in this area would help clarify the above assumptions. These pollutants are affected by neither fuel type nor fuel sulphur content and therefore FCFs are not used for these pollutants.

LNG – Emissions from LNG-fuelled Otto-cycle engines are different from LNG-fuelled diesel-cycle engines (e.g. NO_x reductions associated with LNG-fuelled Otto-cycle engines are not realized in LNG-fuelled diesel-cycle engines). In the study period (2007–2012), the majority of LNG-fuelled vessels in the world fleet do not use diesel-cycle engines (DNV GL USA (2013) a) and b)) and AIS/satellite AIS does not indicate which fuel a ship is burning. For the Third IMO GHG Study 2014, we assumed that LNG carriers operated Otto-cycle engines and burned boil–off, and therefore only LNG Otto-cycle emissions are used for ships designated as using LNG as a fuel. Depending on how many dual-fuel engines enter the world's fleet, future inventories may need to adjust to both LNG-fuelled Otto and diesel cycles.

Table 22 – *Baseline emissions factors*

Emission Species		Engine Speed or Type	EF Equation	Main SFOC g/kWh	Main EF g/kWh	Main EF g/g fuel	Main EF kg/tonne	Aux SFOC g/kWh	Aux EF g/kWh	Aux EF g/g fuel	Aux EF kg/tonne	Reference
CO_2		Slow	1	195	607	3.114	3,114	na	na	na	na	MEPC 63/23, Annex 8
		Medium	1	215	670	3.114	3,114	227	707	3.114	3,114	MEPC 63/23, Annex 8
		High	1	na	na	na	na	227	707	3.114	3,114	MEPC 63/23, Annex 8
		LNG (Otto)	1	166	457	2.750	2,750	166	457	2.750	2,750	MEPC 63/23, Annex 8
		Gas Turbine	1	305	950	3.114	3,114	na	na	na	na	MEPC 63/23, Annex 8
		Steam	1	305	950	3.114	3,114	na	na	na	na	MEPC 63/23, Annex 8
NO_x		Slow	na	195	18.1	0.093	92.82	na	na	na	na	ENTEC 2002
	T0	Medium	2	215	14.0	0.065	65.12	227	14.7	0.065	64.76	ENTEC 2002
		High	na	na	na	na	na	227	11.6	0.0511	51.10	ENTEC 2002
		Slow	na	195	17.0	0.09	87.18	na	na	na	na	IMO Standard
	TI	Medium	3	215	13.0	0.06047	60.47	227	13.0	0.05727	57.27	IMO Standard
		High	na	na	na	na	na	227	10.4	0.04581	45.81	IMO Standard
		Slow	na	195	15.3	0.07846	78.46	na	na	na	na	IMO Standard
	TII	Medium	na	215	11.2	0.05209	52.09	227	11.2	0.04934	49.34	IMO Standard
		High	na	na	na	na	na	227	8.2	0.03612	36.12	IMO Standard
		LNG (Otto)	na	166	1.3	0.00783	7.83	166	1.3	0.00783	7.83	Kristensen 2012
		Gas Turbine	na	305	6.1	0.020	20.00	na	na	na	na	IVL 2004
		Steam	na	305	2.1	0.00689	6.89	na	na	na	na	IVL 2004
SO_x		Slow	4	195	10.29	0.053	52.77	na	na	na	na	Mass balance
		Medium	4	215	11.35	0.053	52.79	227	11.98	0.053	52.78	Mass balance
		High	4	na	na	na	na	227	11.98	0.05	52.78	Mass balance
		LNG (Otto)	na	166	0.00269	0.00002	0.02	166	0.00269	0.00002	0.02	Kunz & Gorse 2013
		Gas Turbine	4	305	16.10	0.053	52.79	na	na	na	na	Mass balance
		Steam	4	305	16.10	0.053	52.79	na	na	na	na	Mass balance
PM		Slow	5	195	1.42	0.00728	7.28	na	na	na	na	USEPA 2007
		Medium	5	215	1.43	0.00665	6.65	227	1.44	0.00634	6.34	USEPA 2007
		High	5	na	na	na	na	227	1.44	0.00634	6.34	USEPA 2007
		LNG (Otto)	na	166	0.03	0.00018	0.18	166	0.03	0.00018	0.180	Kristensen 2012
		Gas Turbine	na	305	0.06	0.00020	0.20	na	na	na	na	IVL 2004
		Steam	na	305	0.93	0.00305	3.05	na	na	na	na	IVL 2004
CO		Slow	na	195	0.54	0.0028	2.77	na	na	na	na	Sarvi et al 2008
		Medium	na	215	0.54	0.0025	2.51	227	0.54	0.0024	2.38	Sarvi et al 2008
		High	na	na	na	na	na	227	0.54	0.00238	2.38	Sarvi et al 2008
		LNG (Otto)	na	166	1.30	0.00783	7.83	166	1.30	0.00783	7.83	Kristensen 2012
		Gas Turbine	na	305	0.10	0.00033	0.33	na	na	na	na	IVL 2004
		Steam	na	305	0.20	0.00066	0.66	na	na	na	na	IVL 2004
CH_4		Slow	6	195	0.012	0.00006	0.06	na	na	na	na	IVL 2004
		Medium	6	215	0.01	0.00005	0.05	227	0.008	0.00004	0.04	IVL 2004
		High	6	na	na	na	na	227	0.008	0.00004	0.04	IVL 2004
		LNG (Otto)	na	166	8.50	0.0512	51.2	166	8.50	0.0512	51.2	MARINTEK 2010
		Gas Turbine	6	305	0.002	0.00001	0.01	na	na	na	na	IVL 2004
		Steam	6	305	0.002	0.00001	0.01	na	na	na	na	IVL 2004
N_2O		Slow	7	195	0.031	0.00016	0.16	na	na	na	na	USEPA 2014
		Medium	7	215	0.034	0.00016	0.16	227	0.036	0.00016	0.16	USEPA 2014
		High	7	na	na	na	na	227	0.036	0.00016	0.16	USEPA 2014
		LNG (Otto)	7	166	0.018	0.00011	0.11	166	0.018	0.00011	0.11	Kunz & Gorse 2013
		Gas Turbine	7	305	0.049	0.00016	0.16	na	na	na	na	USEPA 2014
		Steam	7	305	0.049	0.00016	0.16	na	na	na	na	USEPA 2014
NMVOC		Slow	na	195	0.60	0.00308	3.08	na	na	na	na	ENTEC 2002
		Medium	na	215	0.50	0.00233	2.33	227	0.40	0.00176	1.76	ENTEC 2002
		High	na	na	na	na	na	227	0.4	0.00176	1.76	ENTEC 2002
		LNG (Otto)	na	166	0.50	0.00301	3.01	166	0.50	0.00301	3.01	Kristensen 2012
		Gas Turbine	na	305	0.10	0.00033	0.33	na	na	na	na	ENTEC 2002
		Steam	na	305	0.10	0.00033	0.33	na	na	na	na	ENTEC 2002

Equation 1	CO_2 g/kWh = 3.114 g CO_2/g fuel x SFOC g fuel/kWh
Equation 2	IMO Tier I NOx standard for engines speed (n) in rpm between $130 \leq n < 2{,}000$ (assumed 500 rpm) NOx g/kWh = 45 x $n^{-0.20}$
Equation 3	IMO Tier II NOx standard for engines speed (n) in rpm between $130 \leq n < 2{,}000$ (assumed 500 rpm) NOx g/kWh = 44 x $n^{-0.23}$
Equation 4	SOx g/kWh = SFOC g fuel/kWh x 2 x 0.97753 x % Fuel Sulfur Fraction where, 0.97753 is the fraction of fuel S converted to SOx and 2 is the ratio of molecular weight of SOx and S
Equation 5	For HFO fuel, PM g/kWh = 1.35 + SFOC g fuel/kWh x 7 x 0.02247 x (Fuel Sulfur Fraction – 0.0246) For MDO/MGO fuel, PM g/kWh = 0.23 + SFOC g fuel/kWh x 7 x 0.02247 x (Fuel Sulfur Fraction – 0.0024)
Equation 6	CH4 g/kWh = NMVOC EF g/kWh x 0.02
Equation 7	N_2O g/kWh = 0.16 x SFOC g fuel/kWh/1,000

Notes: Base fuel assumption: HFO 2.7% sulphur

SFOCs

To develop fuel-based baseline emissions factors in g pollutant/g fuel or kg pollutant/tonne fuel, the cited energy-based baseline emissions factor (g pollutant/kWh) needed to be divided by a related SFOC. In general, energy-based baseline emissions factors and SFOCs were derived from IVL (2004), which analysed ENTEC (2002). The exceptions to this rule are for LNG-powered engine and diesel-cycle NO_x emissions. The LNG SFOC used for this study was 166 grams of fuel/tonne fuel (Wärtsilä, 2014).

IMO has capped NO_x emission rates for Tier I and II engines through regulation and expressed the emission limits with energy-based emissions factors. Since there is no related SFOC, we used the SFOCs for NO_x, relating to diesel-cycle main and auxiliary engines, presented in Table 23. It should be noted that for the other pollutants, baseline emission factor related SFOCs were used to convert to the fuel-based baseline emissions factors, and that the efficiencies associated with Tier I and II engines is captured by the use of the tier-related SFOCs when estimating emissions over a given distance and/or time.

Table 23 – *IMO Tier I and II SFOC assumptions for NO_x baseline emissions factors*

Engine type	IMO Tier	Rated speed	SFOC g/kWh
Main	I	SSD	195
	I	MSD	215
	II	SSD	195
	II	MSD	215
Aux	I	MSD/HSD	227
	II	MSD/HSD	227

The baseline emission factor related SFOC to the energy-based baseline emissions factors depends on the rated speed of the engine, fuel type and if the engine is used for propulsion or auxiliary service. The related SFOCs associated with the energy-related baseline emissions factors are presented in Table 24.

Table 24 – *EF-related SFOCs used to convert energy-based baseline emissions factors to fuel-based*

Engine type	Rated speed	Fuel	SFOC g/kWh	Source
Main/SSD	SSD	HFO	195	IVL 2004
		MGO/MDO	185	IVL 2004
Main/MSD	MSD	HFO	215	IVL 2004
		MGO/MDO	205	IVL 2004
Main/HSD	HSD	HFO	215	IVL 2004
		MGO/MDO	205	IVL 2004
Aux MSD & HSD	MSD/HSD	HFO	227	IVL 2004
		MGO/MDO	217	IVL 2004
Gas turbine	all	HFO	305	IVL 2004
		MGO/MDO	300	IVL 2004
Steam boilers	na	HFO	305	IVL 2004
		MGO/MDO	300	IVL 2004
LNG (Otto cycle)	na	LNG	166	Wärtsilä 2014

It should be noted that for all pollutants (except NO_x and LNG-powered engines) the baseline emission factor related SFOCs were used to convert to the fuel-based baseline emissions factors and that the efficiencies associated with Tier I and II engines is captured by the use of the tier-related SFOCs when estimating emissions over a given distance and/or time.

Fuel correction factors – NO_x, SO_x, PM, N_2O

As stated above, FCFs are not used for CO_2, CO, CH_4 or NMVOC. FCFs are applied to a baseline emissions factor to adjust baseline emissions factors for changes in fuel type and/or sulphur content. The following tables provide examples of FCFs between fuel types and representative sulphur contents.

Base fuel:	HFO 2.7% sulphur content
Target fuel:	HFO and MDO with IMO annual sulphur contents (2007–2012)

Table 25 – *IMO annual average global sulphur contents*

Fuel type	% Sulphur content averages – IMO					
	2007	2008	2009	2010	2011	2012
Non-ECA Average HFO S%	2.42	2.37	2.60	2.61	2.65	2.51
Global Average MDO/MGO S%	0.15	0.15	0.15	0.15	0.14	0.14
Fuel type	**% Sulphur content ECA & base EF**					
	2007	**2008**	**2009**	**2010**	**2011**	**2012**
ECA S%	1.00	1.00	1.00	1.00	1.00	1.00
Base EF HFO S%	2.70	2.70	2.70	2.70	2.70	2.70

Table 26 – *NO_x FCFs – HFO global sulphur averages*

Engine type	2007	2008	2009	2010	2011	2012
HFO sulphur %	***2.42***	***2.37***	***2.60***	***2.61***	***2.65***	***2.51***
Main SSD	1.00	1.00	1.00	1.00	1.00	1.00
Main MSD	1.00	1.00	1.00	1.00	1.00	1.00
Aux MSD	1.00	1.00	1.00	1.00	1.00	1.00
Aux HSD	1.00	1.00	1.00	1.00	1.00	1.00
GT	1.00	1.00	1.00	1.00	1.00	1.00
ST	1.00	1.00	1.00	1.00	1.00	1.00

Table 27 – *NO_x FCFs – MGO global sulphur averages*

Fuel type	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
MDO/MGO sulphur %	***0.15***	***0.15***	***0.15***	***0.15***	***0.14***	***0.14***
Main SSD	0.94	0.94	0.94	0.94	0.94	0.94
Main MSD	0.94	0.94	0.94	0.94	0.94	0.94
Aux MSD	0.94	0.94	0.94	0.94	0.94	0.94
Aux HSD	0.94	0.94	0.94	0.94	0.94	0.94
GT	0.97	0.97	0.97	0.97	0.97	0.97
ST	0.95	0.95	0.95	0.95	0.95	0.95

Table 28 – *SO_x FCFs – HFO global sulphur averages*

Engine type	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
HFO sulphur %	***2.42***	***2.37***	***2.6***	***2.61***	***2.65***	***2.51***
Main SSD	0.90	0.88	0.96	0.97	0.98	0.93
Main MSD	0.90	0.88	0.96	0.97	0.98	0.93
Aux MSD	0.90	0.88	0.96	0.97	0.98	0.93
Aux HSD	0.90	0.88	0.96	0.97	0.98	0.93
GT	0.90	0.88	0.96	0.97	0.98	0.93
ST	0.90	0.88	0.96	0.97	0.98	0.93

Table 29 – *SO_x FCFs – MGO global sulphur averages*

Engine type	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
MDO/MGO sulphur %	***0.15***	***0.15***	***0.15***	***0.15***	***0.14***	***0.14***
Main SSD	0.05	0.05	0.05	0.05	0.05	0.05
Main MSD	0.05	0.05	0.05	0.05	0.05	0.05
Aux MSD	0.05	0.05	0.05	0.05	0.05	0.05
Aux HSD	0.05	0.05	0.05	0.05	0.05	0.05
GT	0.05	0.05	0.05	0.05	0.05	0.05
ST	0.05	0.05	0.05	0.05	0.05	0.05

Table 30 – *PM FCFs – HFO global sulphur averages*

Engine type	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
HFO sulphur %	***2.42***	***2.37***	***2.60***	***2.61***	***2.65***	***2.51***
Main SSD	0.94	0.93	0.98	0.98	0.99	0.96
Main MSD	0.93	0.92	0.98	0.98	0.99	0.96
Aux MSD	0.93	0.92	0.98	0.98	0.99	0.95
Aux HSD	0.93	0.92	0.98	0.98	0.99	0.95
GT	0.91	0.89	0.97	0.97	0.98	0.94
ST	0.91	0.89	0.97	0.97	0.98	0.94

Table 31 – *PM FCFs – MGO global sulphur averages*

Engine type	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
MDO/MGO sulphur %	***0.15***	***0.15***	***0.15***	***0.15***	***0.14***	***0.14***
Main SSD	0.14	0.14	0.14	0.14	0.14	0.14
Main MSD	0.14	0.14	0.14	0.14	0.14	0.14
Aux MSD	0.14	0.14	0.14	0.14	0.14	0.14
Aux HSD	0.14	0.14	0.14	0.14	0.14	0.14
GT	0.13	0.13	0.13	0.13	0.12	0.12
ST	0.13	0.13	0.13	0.13	0.12	0.12

The actual bottom-up emissions factors (assumed at 75% engine load) for all non-sulphur-dependent pollutants are presented in Table 32 and SO_x and PM are presented in Table 33 (see Table 22 for more details). As noted above, SO_x and PM emissions factors vary depending on the sulphur content of the fuels consumed. MEPC annual reports from the sulphur monitoring programme were used to determine the average sulphur content for both HFO and MDO/MGO fuels from 2007 to 2012. For regional variations driven by regulation (ECAs), the fuel sulphur content is assumed to be equivalent to the minimum regulatory requirement (see the description in Section 1.2 of how shipping activity is attributed to different global regions). All bottom-up emissions factors are further adjusted by engine load based on the activity data.

Table 32 – *Emissions factors for bottom-up emissions due to the combustion of fuels*

Emissions species	**Marine HFO emissions factor (g/g fuel)**	**Marine MDO emissions factor (g/g fuel)**	**Marine LNG emissions factor (g/g fuel)**
CO_2	3.11400	3.20600	2.75000
CH_4	0.00006	0.00006	0.05120
N_2O	0.00016	0.00015	0.00011
NO_x Tier 0 SSD	0.09282	0.08725	0.00783
NO_x Tier 1 SSD	0.08718	0.08195	0.00783
NO_x Tier 2 SSD	0.07846	0.07375	0.00783
NO_x Tier 0 MSD	0.06512	0.06121	0.00783
NO_x Tier 1 MSD	0.06047	0.05684	0.00783
NO_x Tier 2 MSD	0.05209	0.04896	0.00783
CO	0.00277	0.00277	0.00783
NMVOC	0.00308	0.00308	0.00301

Table 33 – *Year-specific bottom-up emissions factors for SO_x and PM*

	% Sulphur content averages – IMO[1]					
Fuel type	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Average Non-ECA HFO S%	2.42	2.37	2.6	2.61	2.65	2.51
SO_x EF (g/g fuel)						
Marine fuel oil (HFO)	0.04749	0.04644	0.05066	0.05119	0.05171	0.04908
Marine gas oil (MDO)	0.00264	0.00264	0.00264	0.00264	0.00264	0.00264
Natural gas (LNG)	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002
PM EF (g/g fuel)						
Marine fuel oil (HFO)	0.00684	0.00677	0.00713	0.00713	0.00721	0.00699
Marine gas oil (MDO)	0.00102	0.00102	0.00102	0.00102	0.00102	0.00102
Natural gas (LNG)	0.00018	0.00018	0.00018	0.00018	0.00018	0.00018

[1] Source: MEPC annual reports on sulphur monitoring programme

Annex 7
Details for Section 3

The emissions projection model

The model used to project emissions starts with a projection of transport demand, building on long-term socioeconomic scenarios developed for IPCC. Taking into account developments in fleet productivity and ship size, it projects the fleet composition in each year. Subsequently, it projects energy demand, taking into account regulatory and autonomous improvements in efficiency. Together with the fuel mix, fuel consumption is calculated which, in combination with emissions factors, yields the emissions. Emissions are presented both in aggregate and per ship type and size category.

A schematic presentation of the emissions projection model is shown in Figure 32.

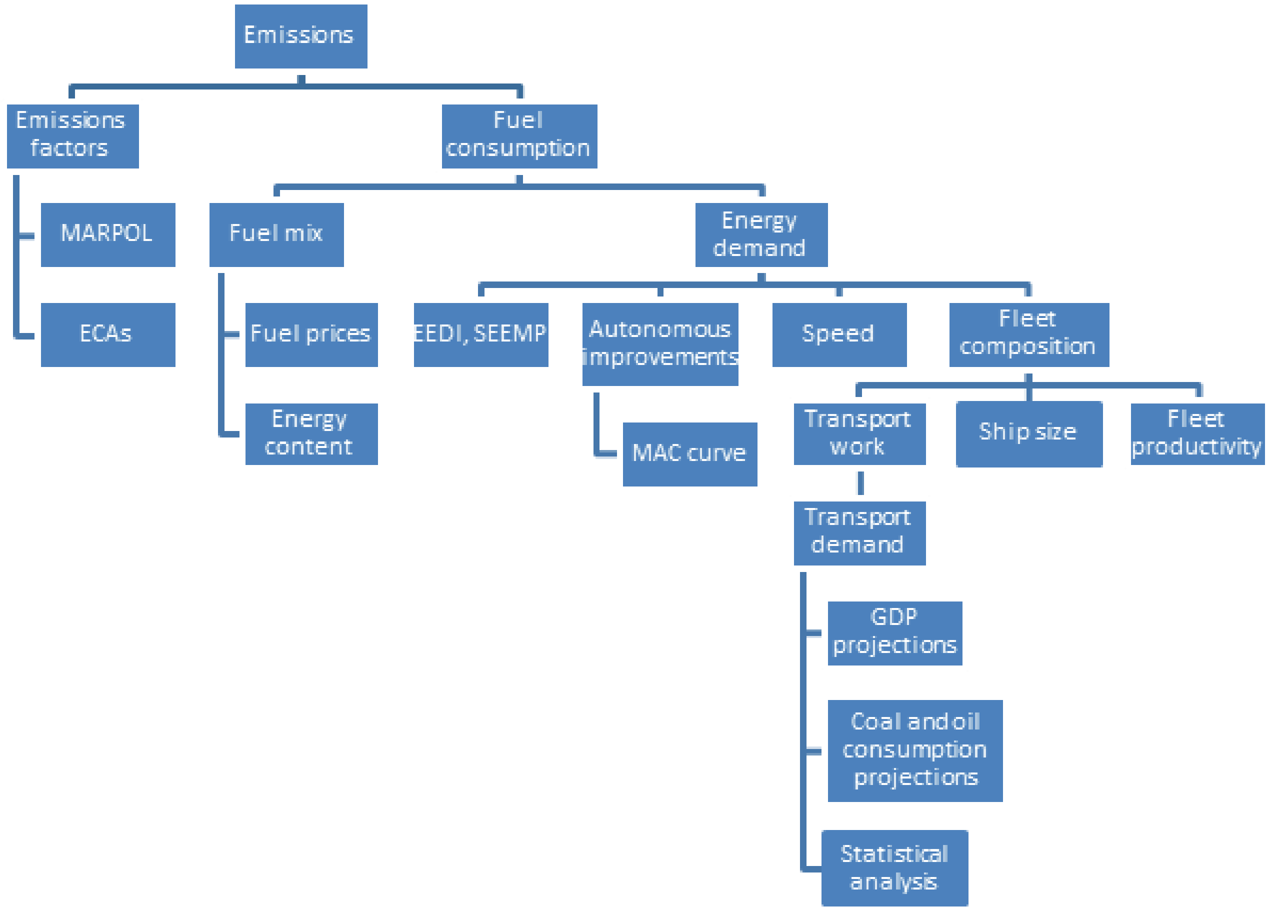


Figure 32: *Schematic presentation of the emissions projection model*

Each of the factors is described in more detail below.

Analysis of historical transport work data

Introduction

Historical data on seaborne trade from a number of different cargo types from 1970 to 2012 have been used to project future trade in terms of three different types of cargo, and total seaborne trade (TST) to 2050 using a non-linear regression model. The model used is a Verhulst model of the sigmoid curve type, which simulates the three typical phases of economic markets: emergence, maturation and saturation.

Methodology

Global data on seaborne transport are produced on a routine basis 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 (e.g. UNCTAD, 2013). The UNCTAD secretariat kindly provided annual data back to 1970. These data were in tonne-miles, which are more satisfactory than transport volume in tonnes (although highly correlated) since this is a better measure of transport work performed.

The data included the following cargo types: crude oil, other oil products, iron ore, coal, grain, bauxite and alumina, phosphate and other dry cargos. By interpretation, these categories can be usefully combined into total oil, coal, total (non-coal) bulk dry goods and total dry goods, which approximate into three different ship types – tankers, bulk raw material ships and container (and other) ships – but discriminating between fossil fuel transport and non-fossil fuel transport.

Data for bauxite and alumina and for phosphate were only available from 1987 onwards, so have been backfilled in a simplistic manner; bauxite and alumina from a simple linear trend, and phosphate as an average of the 1987 to 2008 data, as the time series appears to be stationary.

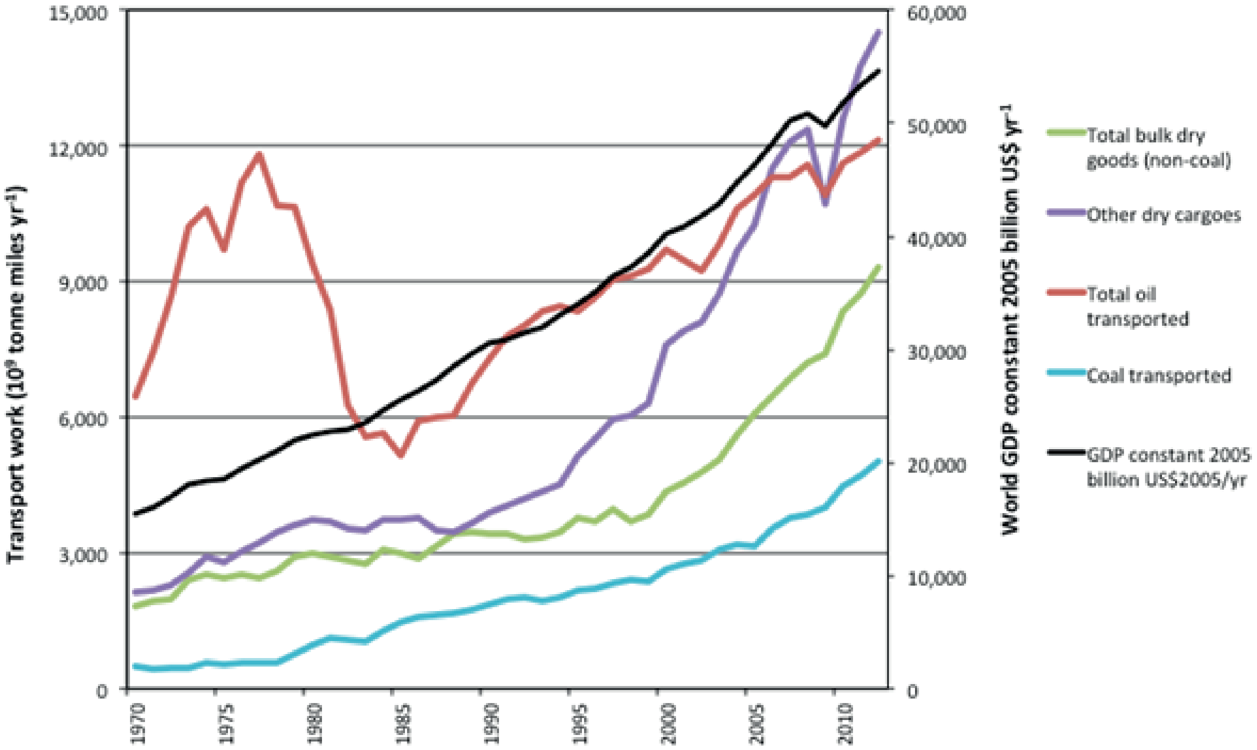


Figure 33: *Transport work for all categories of cargo, provided by UNCTAD, from 1970 to 2012 in billion tonne-miles; also illustrated with global GDP (right-hand axis) in US$ billion (constant 2005 prices)*

From Figure 33 it is apparent why previous studies (Eyring et al., 2005; Eide et al, 2007; Buhaug et al., 2009) have used TST data from 1985 on only; there is an extreme excursion of TST over the period 1970 to 1985, which is entirely caused by crude oil seaborne trade and was driven by a number of 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 oversupply 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 unnavigable for some ships. Therefore, the period 1970 to 1985 is known to have a particular explicable data excursion for tonne-miles of crude oil, so that those data were excluded from the analysis.

Historical data on global GDP were obtained and GDP projection data for the five SSP scenarios obtained from the website of the International Institute for Applied Systems Analysis (IIASA). The GDP projection data are already shown in Chapter 3. For liquid fossil fuels (essentially, oil) and coal, relationships with historical global oil and coal consumption were constructed.

Previous studies, such as Eyring et al. (2005) and Eide et al. (2007), have based projections on linear regression models. Non-linear statistical models have been used for some time in long-term projections of aviation. Such models are often 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 econometric literature where the requirement is to simulate some form of market saturation (Jarne et al., 2005).

The sigmoid curve 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 first phase 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 future demand, t is time in years and a, b and c are model constants:

$$x = a/(1 + b \times \exp(- c \times t)) \qquad \text{Eq. (6)}$$

The constants a, b, and c are estimated from initial guesses of asymptote, intercept and slope, and solved by converged iterative solution. SPSS v19 provided a suitable program for this model.

Different ship types are quite different in size, power and market growth rates, so that individual models were derived for each transport type.

Results

The ratios of TST in tonne-miles to GDP for the four different cargo types (total oil, coal, total (non-coal) bulk dry goods and other dry goods) are shown in Figure 34.

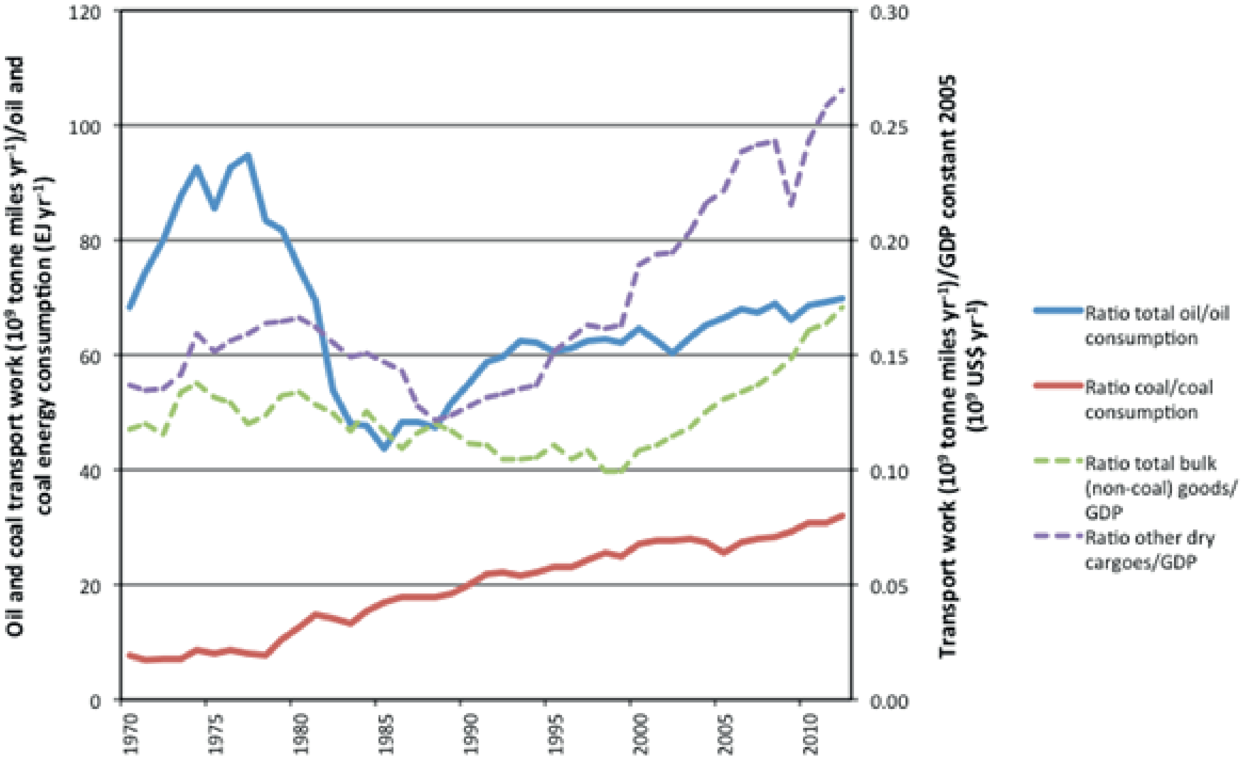


Figure 34: *Ratios of TST (different subtypes) in billion tonne-miles to historical global GDP in US$ (constant 2005 prices) and coal/oil consumption (from BP* Statistical Review*)*

Figure 34 shows a set of complex signals. The pattern of growth in oil transported between 1970 and 1985 has already been mentioned, and its reason for exclusion from the model construction. Statistically significant and robust Verhulst models were calculated for the four main cargo types, and the future ratios growth curves are shown, as calculated, in Figure 35.

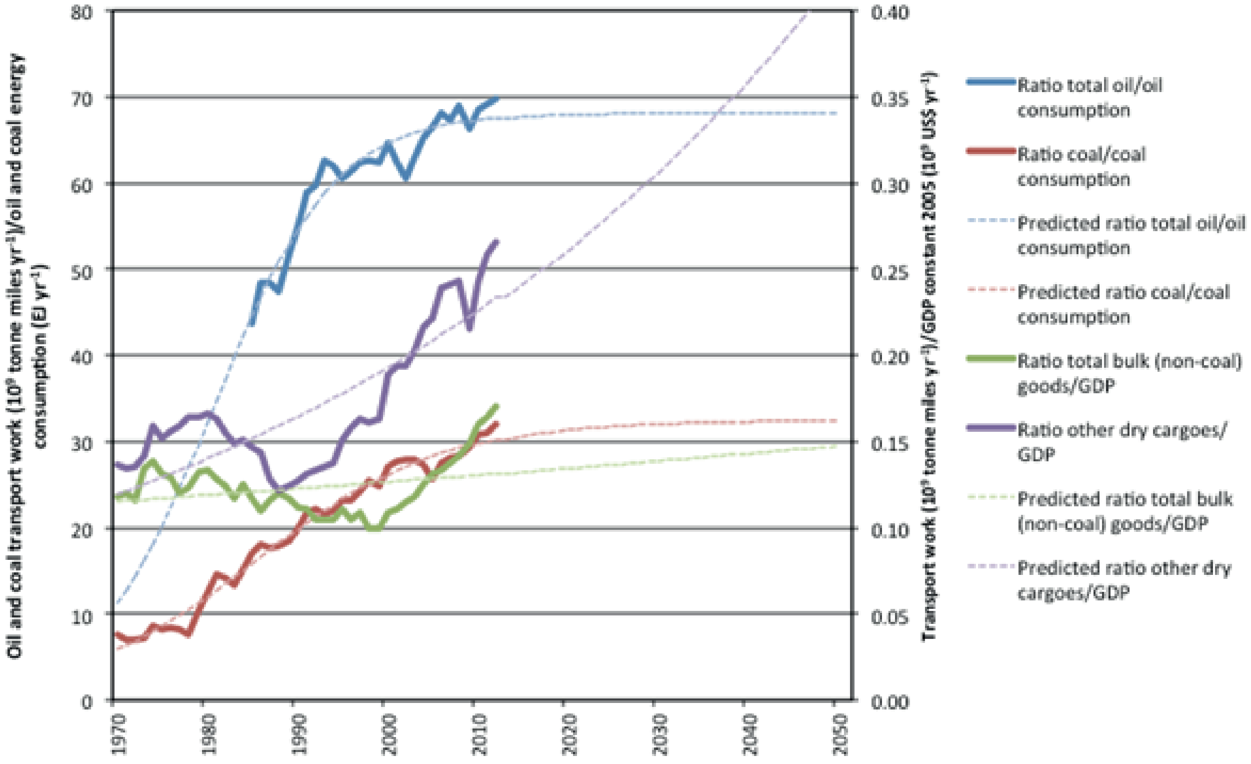


Figure 35: *Historical and modelled growth curves to 2050 for ratios of total oil, coal, total (non-coal) bulk dry goods and other dry cargoes*

Figure 35 shows that future growth rates of TST can be successfully modelled in a non-linear fashion, which is more realistic than the conventional linear model, by three different cargo types. This is a distinct advantage for the next step of assembling a simplified modelling system of future emissions.

Sensitivities

Removing the period 1970–1985 from the total oil model results in an early maturation of total oil. However, even when these data are included, despite the model not being as statistically robust, early maturation is still shown. The weakest model is that of the total (non-coal) bulk dry goods, as the ratio to GDP is almost constant over time, with only a weak linear or non-linear increase. However, while a linear model is statistically significant, it does not indicate growth (in ratio) much different to that of the non-linear model. The ratio of other dry cargoes also shows something of an excursion over the period 1970 to 1985; however, this is not as easy to explain (in terms of physical events/changes in the underlying data) from known causes as is the case for total oil. However, if this period is removed, the non-linear model indicates a growth in ratio twice that of the model that includes the entire data series. Given that the explanation for this excursion is less easy than that of total oil, a conservative approach has been adopted that includes the entire data series, resulting in a lower ratio projection. However, it should be remembered that in the projections, the proxy data (i.e. oil, coal consumption, GDP projections) are highly influential in the end ship traffic projections and, in the case of GDP, tend to dominate the calculations.

Fleet productivity projections

For the emissions projection, the development of the tonnage of the different ship types is determined by a projection of the productivity of the ships (highlighted red in the schematic presentation of the model structure), defined as transport work per deadweight tonne.

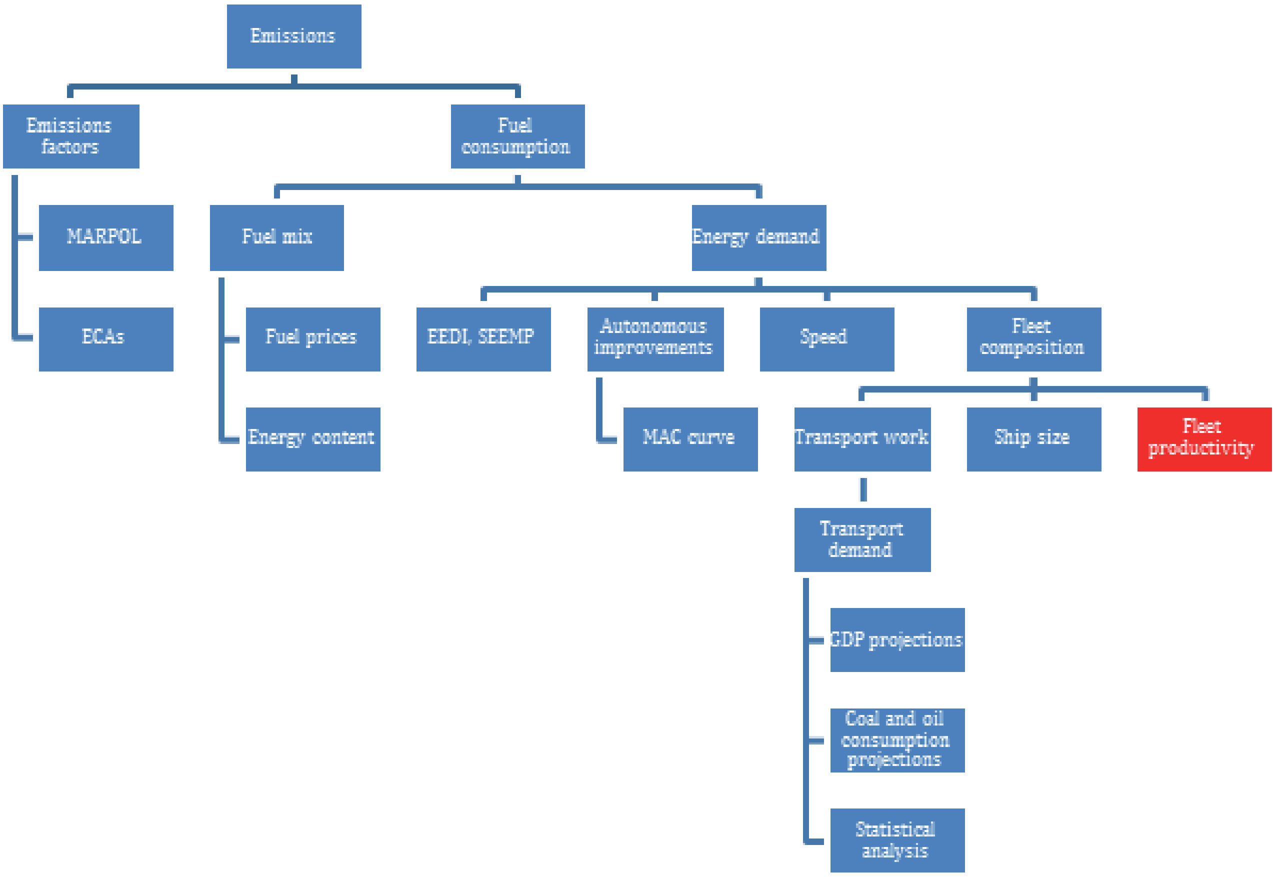


Figure 36: *The role of fleet productivity in the model structure*

More precisely, the fleet is assumed to grow if, given the projected productivity, the expected transport demand could not be met by the fleet. On the other hand, if, given the projected productivity, the expected transport demand could be met by a smaller fleet, the active fleet is not assumed to decrease. That means that ships are assumed to reduce their cargo load factor – i.e. become less productive – rather than being scrapped/laid up or reducing their speed.

The projection of ship productivity is based on historical productivity of the ship types.

Historical ship productivity

A look at the historical productivity of the total world fleet reveals that it has seen dramatic variations over the last five decades. During this period, the fleet's productivity peaked in the early seventies with 35,000 tonne-miles per dwt and reached a minimum in the mid-eighties with 22,000 tonne-miles per dwt (Stopford, 2009). Productivity then increased until 2005/2006 but was far from reaching the peak from the early seventies. Since then the productivity again shows a falling trend.

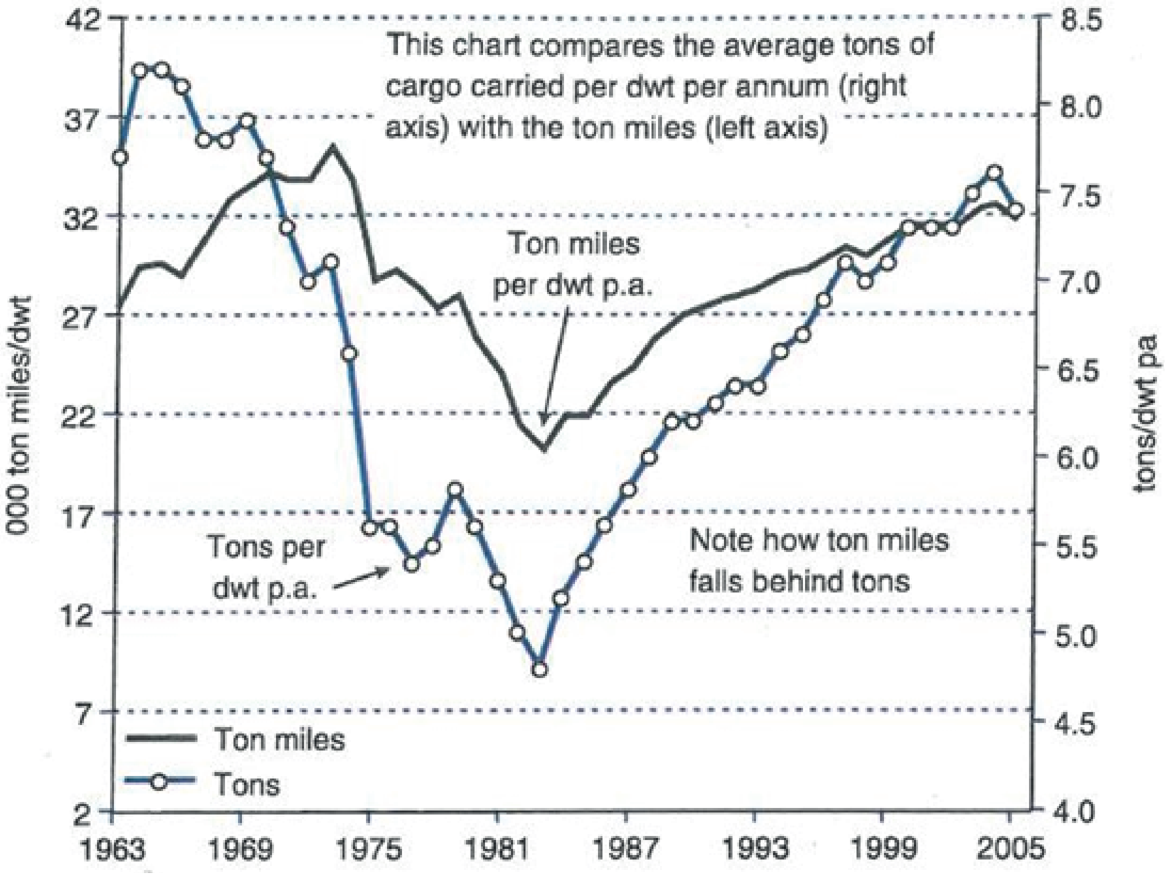


Figure 37: *Historical fleet productivity (Stopford, 2009)*

The historical productivity of the different ship types varies greatly.

Figure 38, Figure 39, and Figure 40 give the historical productivity of oil tankers, bulk carriers, container ships and liquefied gas tankers.

Two data sources have been used to determine these productivities:

1 Tonne-miles data for 1970–2008 provided by Fearnleys.

2 Tonne-miles data for 1999–2013 as published in the *Review of Maritime Transport* 2013 by UNCTAD.

3 Tonnage data (dwt) for 1979–2013 as provided to us by UNCTAD.

For oil tankers and bulk carriers, the historical productivity is determined for the period 1970–2013, where tonne-miles data from the two different sources had to be combined. As can be seen in Figure 38 and Figure 39, the productivities of the overlapping years match well.

For container ships and liquefied gas ships, the historical productivity is determined for the period 1999–2013.

Oil tankers

The average productivity of oil tankers has varied greatly in the last four decades (see Figure 38) with a maximum of 90,000 tonne-miles per dwt in the early seventies and a much lower peak at the beginning of the twentieth century (34,000 tonne-miles per dwt), and a minimum in the early eighties (18,000 tonne-miles per dwt). The fluctuation has therefore been stronger than for the world fleet as a whole.

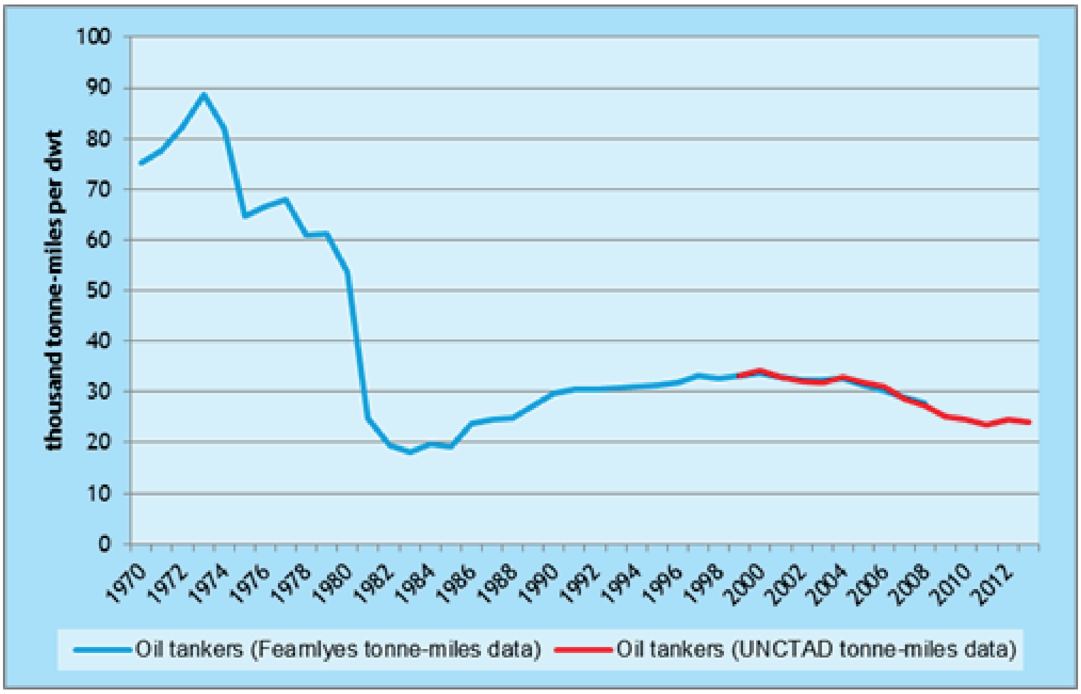


Figure 38: *Productivity of oil tankers measured in thousand tonne-miles per dwt, 1970–2013*

In 2012, we found the productivity of oil tankers to amount to 24,000 tonne-miles per dwt.

Dry bulk carriers

For dry bulk carriers, tonne-miles data are only available for the five main dry bulks (iron ore, coal, grain, bauxite and alumina, and phosphate rock), whereas the tonnage data is related to the total bulk carrier fleet. The productivity presented in Figure 39 is thus an underestimation of the productivity of dry bulk carriers. This, however, is not a problem for our tonnage projection: if it is assumed that the future tonne-miles related to the other bulks develop according to the tonne-miles of the five main dry bulks, the tonnage projection based on the underestimated productivity will still give a good tonnage projection for the dry bulk fleet.

The 2012 productivity value amounts to 23,000 tonne-miles per dwt.

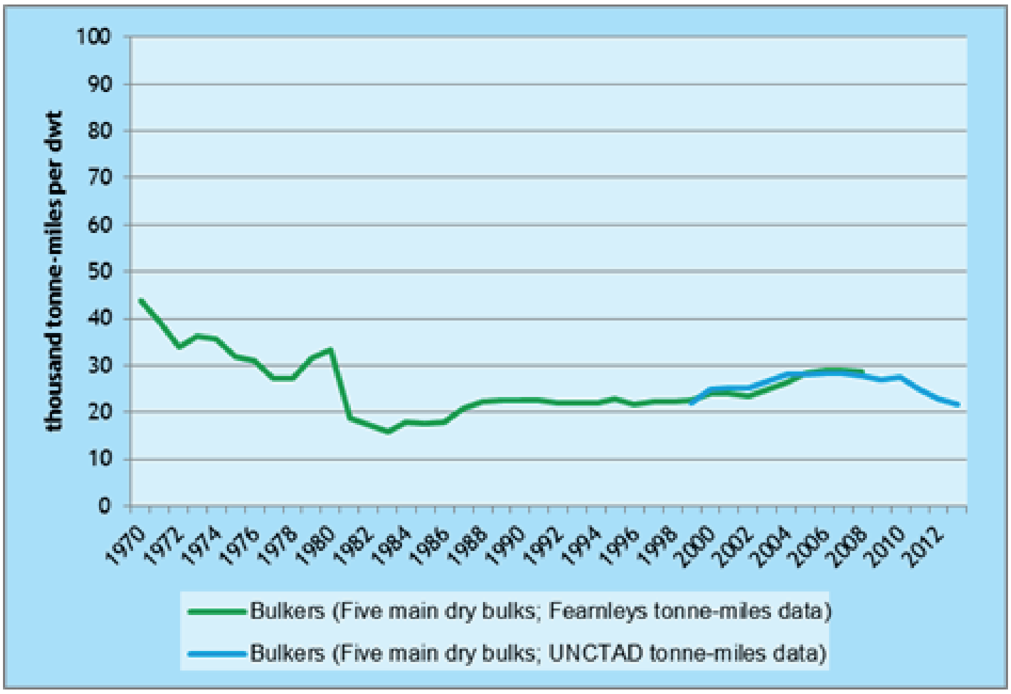


Figure 39: *Productivity of dry bulk carriers measured in thousand tonne-miles (five main dry bulks) per dwt (all bulk carriers), 1970–2013*

Container ships[1]

In the period 1999–2013, the productivity of container ships (see Figure 40) reached a maximum in 2005 with 53,000 tonne-miles per dwt – the supply side could probably only satisfy the high demand by sailing at high speeds and at high cargo load factors. The order placed for container ships in these years and the following economic downturn can explain the decrease of the productivity until 2009. The 2012 productivity amounts to 39,000 tonne-miles per dwt and is higher than the 2009 productivity of 37,000 tonne-miles per dwt.

Liquefied gas ships

In the period 1999–2013, the productivity of the liquefied gas tankers (see Figure 40) fluctuated between 22,000 and 30,000 tonne-miles per dwt and was thus less volatile than the productivity of the other ship types. In 2012, the productivity amounted to 24,000 tonne-miles per dwt.

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[1] The productivity of container ships is determined on the basis of tonne-miles data as published by UNCTAD in the *Review of Maritime Transport*. If the tonne-miles data has been determined by applying a default container weight factor to TEU-miles data, which is our understanding of the UNCTAD data, then it can be concluded that the development of the container ship tonne-miles as used in the emissions projection model is the same as the development in terms of TEU-miles.

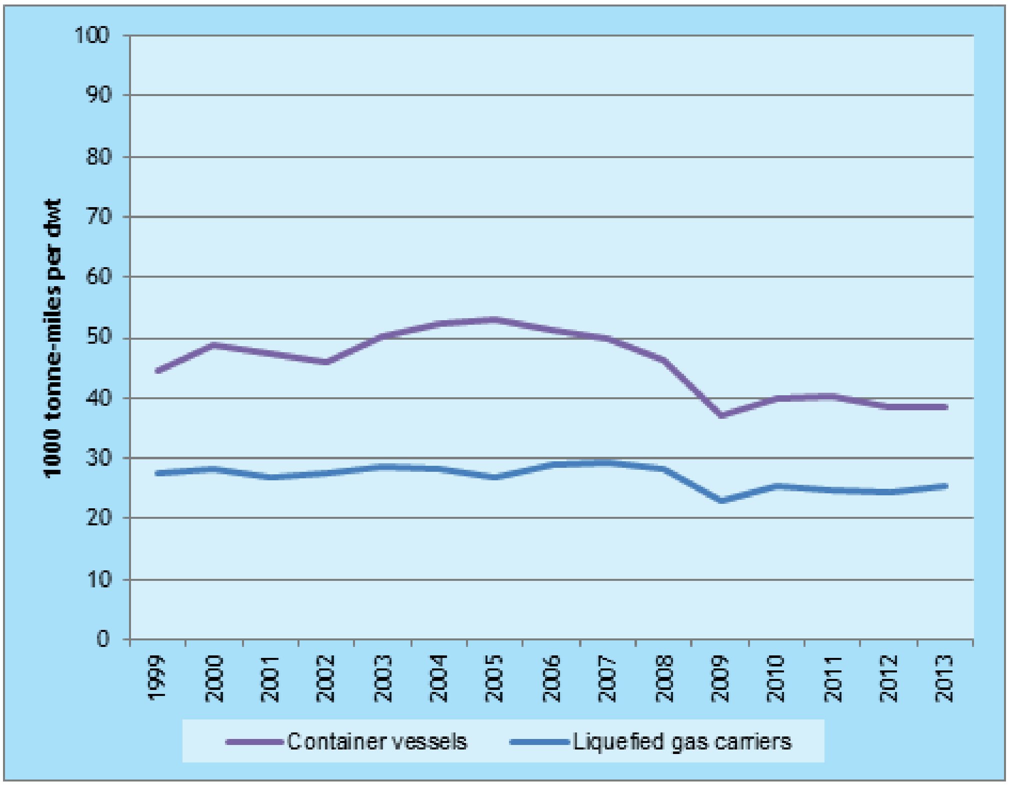

Figure 40: *Productivity of container and liquefied gas ships measured in thousand tonne-miles per dwt, 1999–2013*

Ship productivity projection

For all ship types, the 2012 productivity of the ship types is lower than the long-term historical average. We assume that this is caused by the business cycle, rather than by structural changes in the shipping market in the last year. Productivity cycles have appeared before. In liquid and dry bulk, they appear to have a length of 25–30 years. In container shipping, we do not have data for a sufficiently long period to determine the length of the cycle.

Based on this analysis, we assume future productivity development that converges towards the ship type's average productivity. We therefore assume that productivity reverts back to the 25-year[1] mean value within 10 years (i.e. by 2022).

The ship productivity indices used in the emissions projection model, which can be specified per five-year period, are given in Table 34.

Table 34 – *Ship type productivity indices used in emissions projection model*

	2012	2017	2022–2050
Liquid bulk ships	100	113	125
Dry bulk ships	100	102	104
Container ships	100	109	118
Liquefied gas carriers	100	106	113

Productivity of liquid bulk ships is therefore taken to be the same as for oil tankers, and that of dry bulk ships to be the same as for bulk carriers carrying the five main dry bulk goods.

For general cargo ships, since the data did not allow plausible historical productivity to be determined, we assume that the productivity of general cargo ships evolves according to the productivity of container ships in the model.

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[1] For container ships and liquefied gas ships, due to a lack of historical data, we take the average of the 1999–2013 period (i.e. a 14-year period).

Regarding passenger ships, productivity is kept constant.

Remarks/caveats

If, given the projected productivity, the expected transport demand could be met by a smaller fleet, the active fleet is not assumed to be reduced in the model, but the cargo load factor of the ships is assumed to decrease; i.e. ships become less productive. If ships are scrapped/laid up or slow down instead, projected emissions constitute an overestimation.

The historical ship productivity that serves as a basis for the projection of the future productivity development of the ships is based on data that has a different scope: the tonnage data provided to us by UNCTAD is given in terms of total tonnage, so does not differentiate between international and domestic shipping, whereas the tonne-miles data is related to international shipping only. Using this productivity metric to project the development of ships used for international shipping, we thus implicitly assume that the share of tonnage used for international shipping and domestic shipping does not change in the future.

Ship size projections

In the emissions projection model, the ship types are divided into the same ship size classes as in the emissions inventory model. For the emissions projection, the future number of ships per size category has to be determined.

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 2012. 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.

Depending on data availability, two alternative approaches to derive the future number of ships per size category have been applied (see Figure 41 for an illustration):

1 The total expected tonnage capacity of a ship type is first distributed over the ship size categories, and then, by means of the expected average ship size per category, the number of ships per category is derived; or

2 The total number of expected ships of a ship type is derived by first applying the expected average ship size of all ships of the type to the total expected tonnage capacity of that ship type, and subsequently the expected distribution of ships over the size categories in terms of numbers is applied.

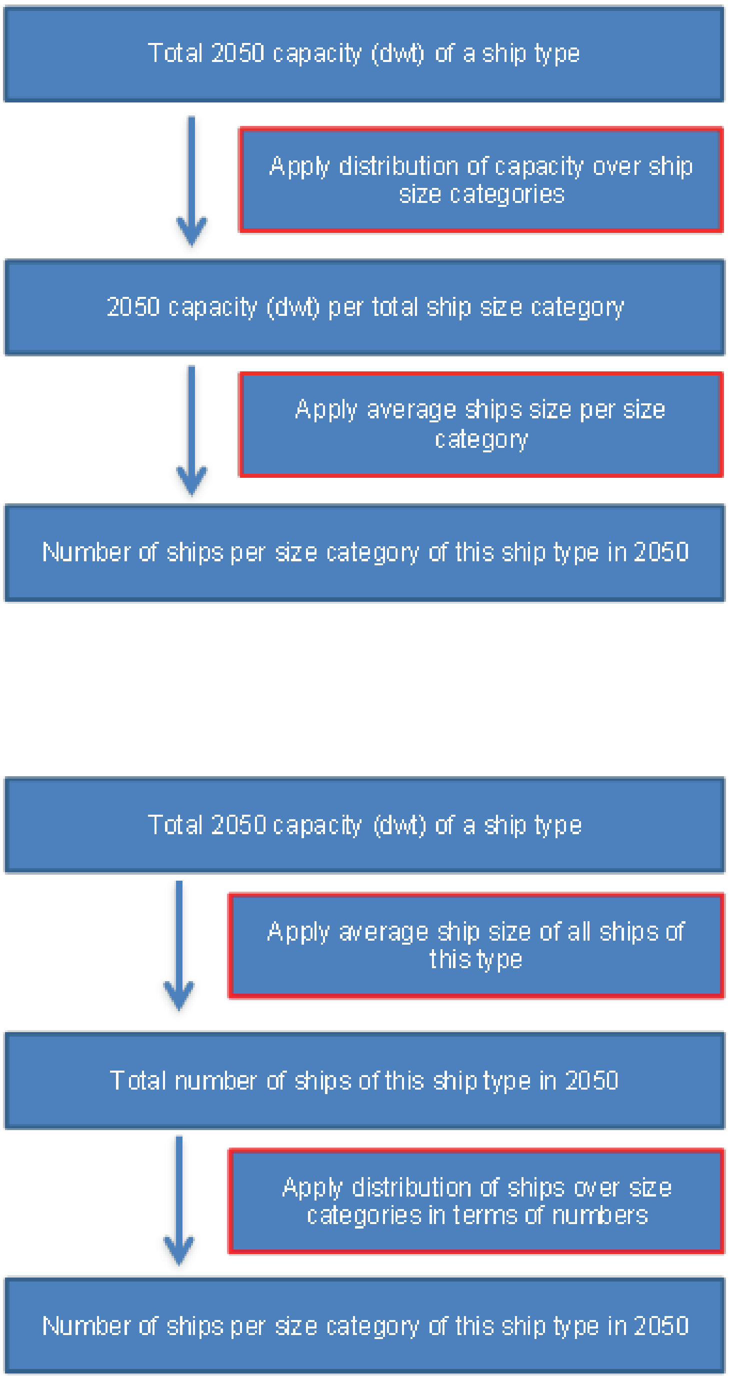


Figure 41: *First (upper chart) and second (lower chart) methodologies to determine the number of ships per size category in 2050*

From the emissions inventory, we know the following for each ship type for 2012:

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 (in terms of capacity or in terms of numbers) to develop until 2050. Historical developments of the distribution, expected structural changes in the markets and infrastructural constraints are taken into account. The average size of a ship per ship type, which is necessary for the first methodology, then follows.

We are aware that 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.

In the following, the derivation of the 2050 ship size distribution for the main ship types is presented. Table 35 presents an overview of the methodology that has been applied per ship type. The choice for the first or the second methodology (as illustrated in Figure 41) is solely based on data availability.

Table 35 – *Methodology applied for the projection of ship size distribution of the different ship types differentiated in the study*

Ship type	Methodology
Container	Second methodology
Bulk carrier	First methodology
Oil tanker	First methodology
Liquefied gas tanker	Second methodology
Chemical tanker	Same development is applied as derived for oil tankers
All other ship types	Distribution of the ships over the size categories in terms of the share of the capacity is assumed not to change

Container ships

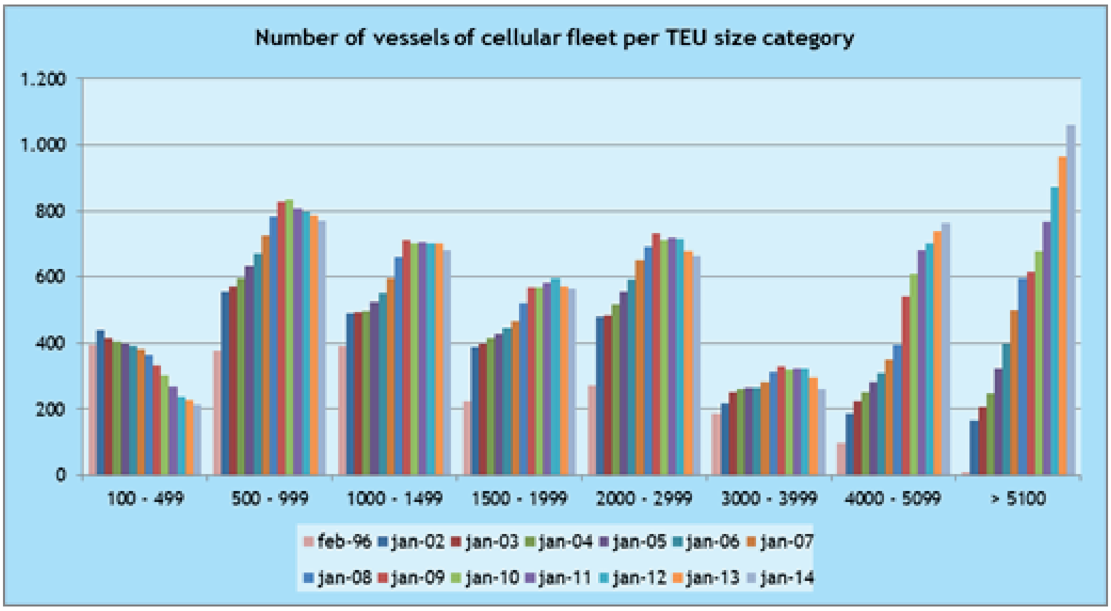
For container ships, we derive the number of ships per size category, applying the second methodology (see Figure 41).

The starting point of the analysis is the 2012 distribution of the container ships over the size categories, as determined in the emissions inventory (see Table 36).

Table 36 – *2012 distribution of container ships over the size categories in terms of numbers*

Size category	Distribution of ships in terms of numbers
0–999 TEU	22%
1,000–1,999 TEU	25%
2,000–2,999 TEU	14%
3,000–4,999 TEU	19%
5,000–7,999 TEU	11%
8,000–11,999 TEU	7%
12,000–14,500 TEU	2%
14,500–+ TEU	0.2%

In Figure 42, the development of the distribution of ships of the cellular fleet over the size categories is given for the period 1996–2014.



Source: Based on Alphaliner data collected from various sources

Figure 42: *Composition of global container fleet in the period 1996–2014 (beginning of year figures)*

Over this period the numbers of ships in the 500–999 TEU and 4,000–5,099 ranges have been relatively high, whereas the number of ships in the 3,000–3,999 TEU range has been relatively low.

Figure 42 also illustrates that over the last decade, the number of the smallest ships, in the 100–499 TEU range, has steadily decreased, whereas the number of the ships above 4,000 TEU has steadily increased. For all the others (the medium-sized ships), it holds that their numbers increased until the crises and decreased thereafter.

Owing to economies of scale, there has been a trend towards using larger ships. Ships of 10,000 TEU and above have replaced smaller ships, mainly in the range 2,800–5,000 TEU, and ships of 1,000–2,000 TEU have been mostly been displaced by 2,000–2,700 TEU ships (BRS, 2013). There is broad agreement among observers of the container fleet that "mid-size" ships (those in the 4,000–5,000 TEU range) are becoming almost obsolete as they are being replaced by more efficient larger ships.

In contrast, ships that are being used as regional network carriers or as feeders (ships of 2,800 TEU or less) have naturally not been replaced by ships of 10,000+ TEU.

About 93% of ships of 10,000+ TEU currently in operation are deployed in the East Asia–Europe trade lanes because they have the requisite volume scale, voyage length, channel depths and configuration of ports to support the use of such ships (U.S. DOT, 2013).

Nearly 55% of existing ships of 7,500–9,999 TEU in operation are also assigned to the East Asia–Europe trade, while another 22% are serving the East Asia–US West Coast markets. The remaining 23% are deployed mainly in the Far East–West Coast of South America trade and the Far East–Suez Canal–US East Coast corridor (U.S. DOT, 2013).

Regarding the development of the size of the container ships until 2050, we expect two main factors to have an impact: a further trend towards larger ships due to economies of scale, as well as infrastructural changes.

As mentioned above, there has been a trend towards building and utilizing larger ships in the container ship market. As a result of current infrastructural barriers, which can be expected to be removed by 2050, some trades can be expected to experience a catch-up effect in this regard:

- The Suez Canal can be used by container ships of up to 18,000 TEU, which is the size of the currently largest ships. This is not the case for the Panama Canal: a container ship of up to 5,000 TEU before expansion and probably up to 13,000 TEU after expansion will be able to transit the Panama Canal. This can be expected to lead to a greater number of large ships being used in the East Asia–US East Coast trade.

- The East Asia–US West Coast trade is, apart from the East Asia–Europe trade, the only trade that is currently ready for the 18,000 TEU size in terms of cargo volumes (ContPort Consult, 2013). So far, ship owners have been hesitant to utilize very large container ships due to the demand for a high sailing frequency combined with low terminal productivity at US ports (ContPort Consult, 2013). However, terminal productivity can be expected to increase until 2050, and more very large container ships can also expected to be utilized for this trade.

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 down 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 37 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.

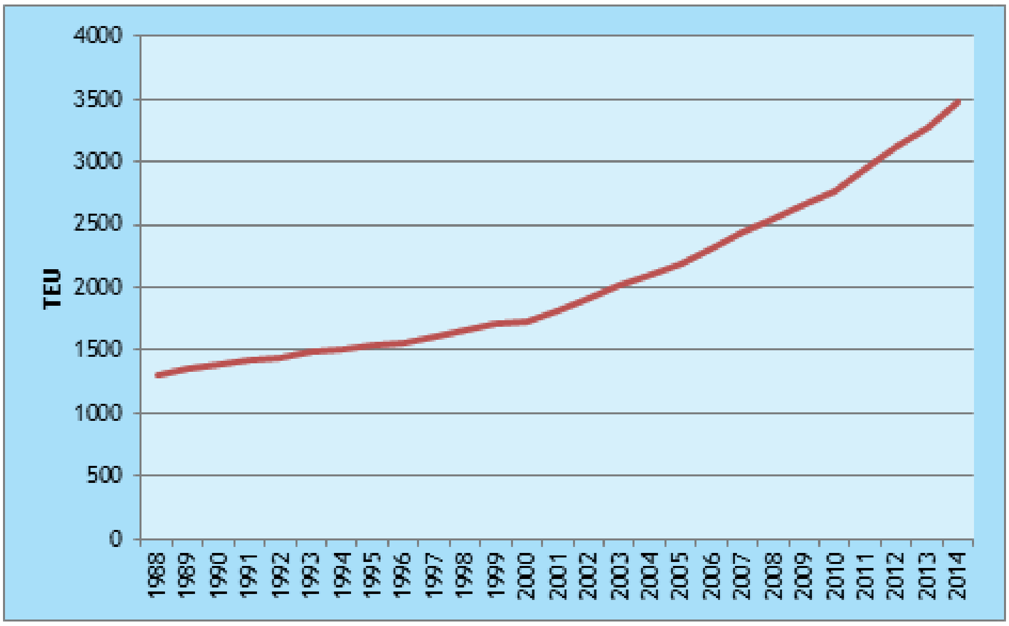
Table 37 – *Development of the distribution of container ships over size categories (in terms of numbers)*

Size category (TEU)	2012 distribution	Development until 2050	2050 distribution
0–999	22%	Very low share of 0–499 TEU does not change; high share of 500–999 TEU unchanged.	22%
1,000–1,999	25%	Trend that 1,000–1,999 TEU ships are replaced by 2,000–2,999 TEU ships continues.	20%
2,000–2,999	14%		18%
3,000–4,999	19%	Replaced by very large ships (14,500+ TEU) and by larger ships that can transit Panama Canal after expansion (probably 8,000–11,999 TEU and some 12,000–14,500 TEU).	5%
5,000–7,999	11%	Share as in 2012.	11%
8,000–11,999	7%	Share increases due to expansion of Panama Canal.	10%
12,000–14,500	2%	Share increases due to ongoing trend of using larger ships, replacing 3,000–4,999 TEU ships, and due to expansion of Panama Canal, replacing 3,000–4,999 TEU ships.	9%
14,500–+	0.2 %	Share increases due to ongoing trend of using larger ships, replacing 3,000–4,999 TEU ships.	5%

If the average ship size per size bin does not change compared to 2012, the average size of a container ship will be approximately 4,600 TEU or 55,000 dwt in 2050.

In Figure 43, the development of the average ship size of the cellular fleet is given for the period 1988–2014, showing a steady increase in the average size.

An average size of 4,600 TEU in 2050 means that this trend will slow down in the period until 2050.



Source: BRS (2009) and Alphaliner (various years)

Figure 43: *Historical development of average ship size of cellular fleet*

Oil tankers

For the oil tankers, we derive the number of ships per size category, applying the first methodology (see Figure 41) to derive the distribution of the capacity over the ship size categories as well as the expected average size of the ships per size category.

Tankers are usually divided in several size categories:

- Small
- Handysize
- Handymax
- Panamax
- Aframax
- Suezmax
- Very large crude carrier (VLCC)
- Ultra large crude carrier (ULCC).

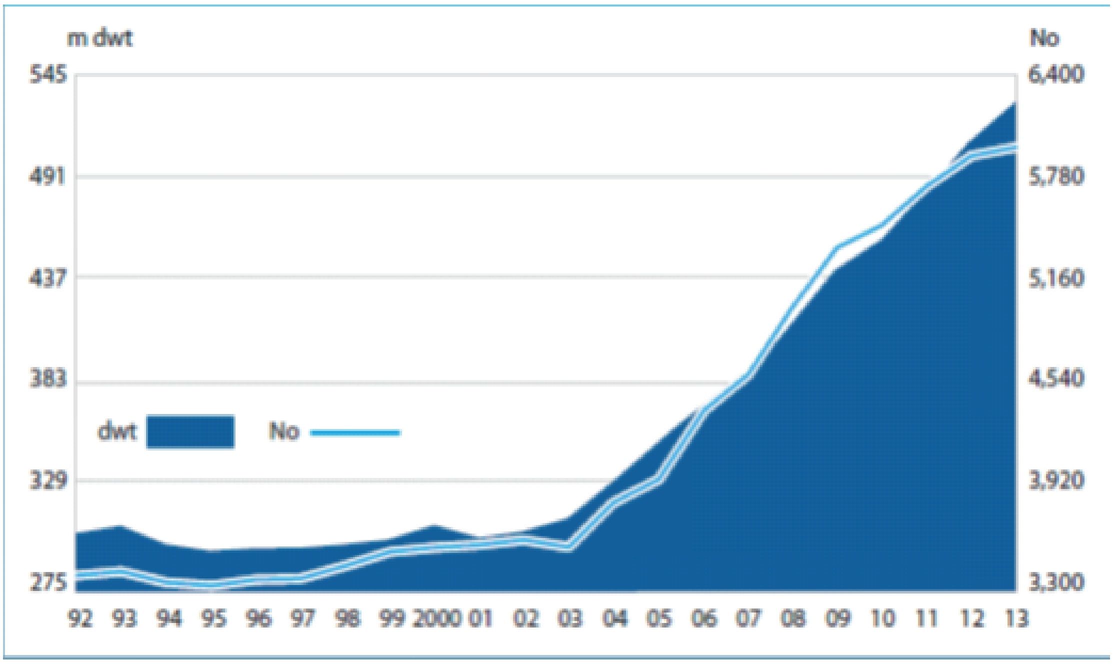
The sizes of these ships differ somewhat. For the purpose of our inventory model and ship projection model, the following bins have been defined:

Table 38 – *Size bins for tankers*

Capacity range (dwt)	**Size category**
0–4,999	Small
5,000–9,999	Small
10,000–19,999	Handysize
20,000–59,999	Handymax
60,000–79,999	Panamax
80,000–119,999	Aframax
120,000–199,999	Suezmax
200,000–+	VLCC, ULCC

ULCCs (>320,000 dwt) have been built in the 1970s and again in the 2000s, but they have never conquered a significant market share. They are currently predominantly used as floating storage units. We do not expect a breakthrough of larger tankers in the coming decades and will therefore not include them in our analysis.

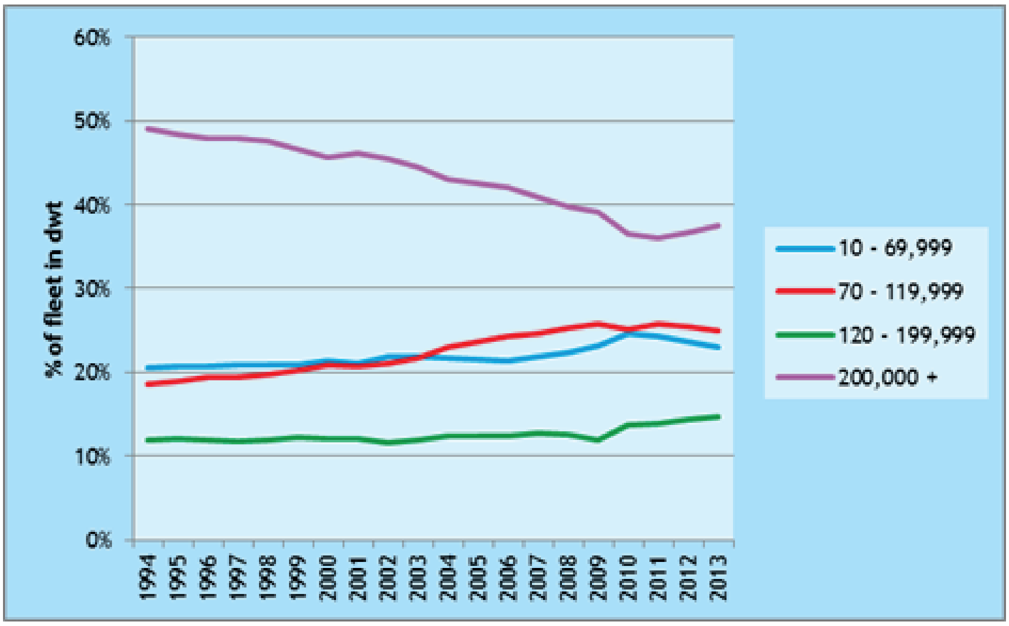
In the 1990s, the average size of tankers decreased as the total fleet capacity remained constant and the total number of ships grew, as shown in Figure 44. In the 2000s, the average size remained more or less stable, and in the last few years, the capacity of the fleet has increased at a higher rate than the number of ships, indicating an increase in the average size.

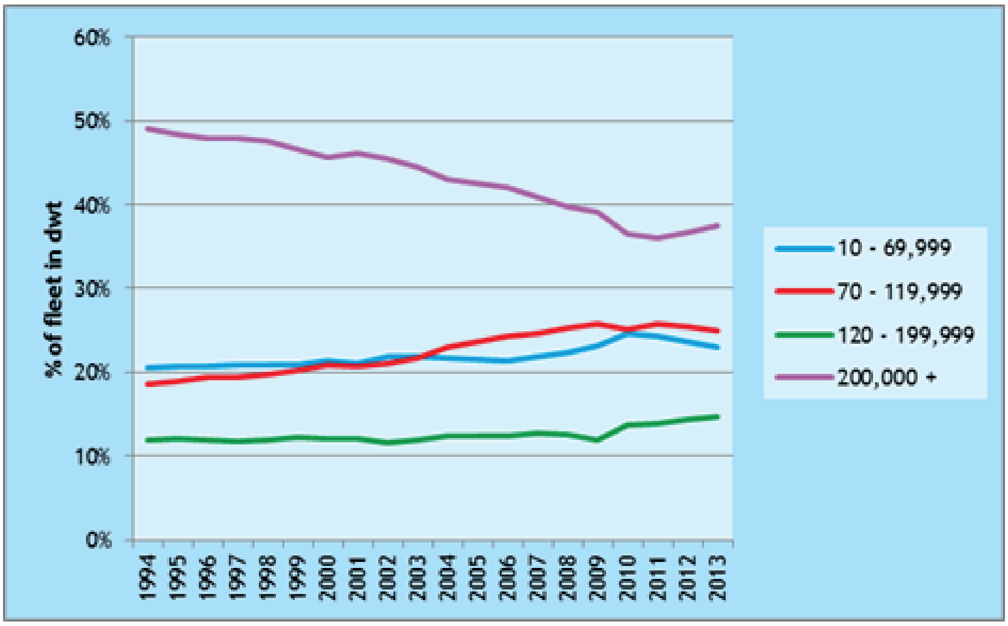


Source: Intertanko (2012)

Figure 44: *Projected tanker fleet development 1992–2013 (projection for 2012 and 2013)*

According to RS Platou (2014) (see Figure 45), there has been a shift from VLCCs towards other tanker sizes, mainly to tankers in the 70–120,000 dwt range (this is confirmed by Intertanko's annual report 2012/2013), although this shift seems to have come to a halt in 2012 and 2013. On the one hand, larger refineries (e.g. in Asia) could drive up the ship sizes again, but, on the other, a shift of production away from OPEC to countries that are unable to accommodate ships larger than Aframax might drive the size down again.





Source: RS Platou (2014)

Figure 45: *Capacity distribution of tankers over size categories (1994–2013)*

From the available evidence, we conclude that:

- The shift from VLCCs towards the other smaller tanker sizes seems to have come to a halt. It is uncertain whether the shift 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 39 – *Development of the distribution of oil tankers over size categories (in terms of capacity)*

Size categories of tankers used in update study (dwt)	Distribution in 2012	Development until 2050	Distribution in 2050
0–4,999	1%	None	1%
5,000–9,999	1%	None	1%
10,000–19,999	1%	None	1%
20,000–59,999	7%	None	7%
60,000–79,999	7%	None	7%
80,000–119,999	23%	None	23%
120,000–199,999	17%	None	17%
200,000–+	43%	None	43%

Dry bulk carriers

There is relatively little data available for the dry bulker fleet, and the available data only allows the application of the first methodology (see Figure 41).

Bulk carriers are traditionally divided into five size categories:

- Small
- Handysize
- Handymax
- Panamax
- Capesize

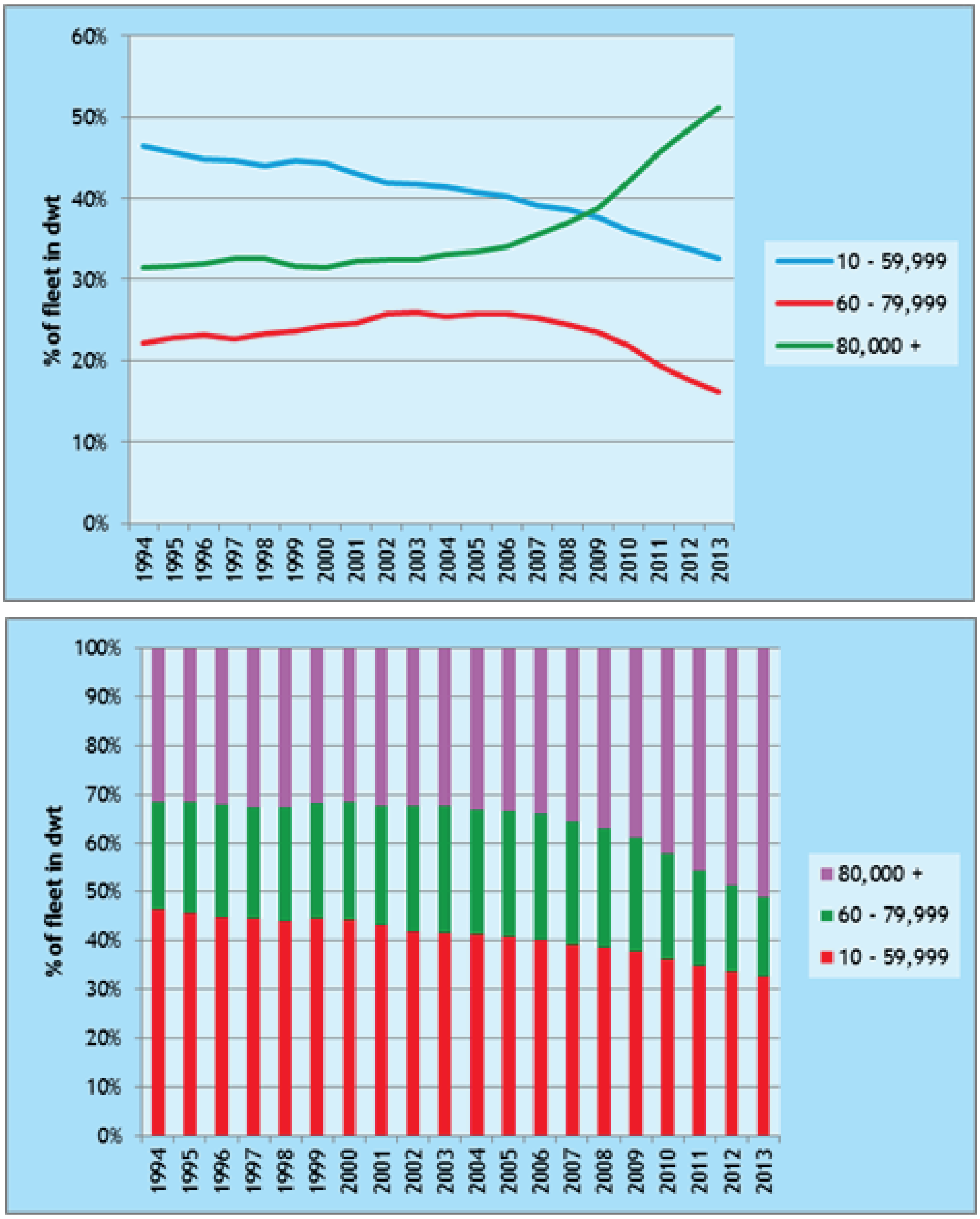
For the purpose of our inventory model and ship projection model, the following bins have been defined:

Table 40 – *Size bins for dry bulk carriers*

Capacity range (dwt)	Size category
0–9,999	Small
10,000–34,999	Handysize
35,000–59,999	Handymax
60,000–99,999	Panamax
100,000–199,999	Capesize
200,000–+	

Note that since the Capesize category does not have an upper capacity limit the last two capacity ranges are both classed as Capesize. Very large ore carriers (VLOCs) and ultra large ore carriers (ULOCs) fall into the last (200,000+ dwt) category.

RS Platou (2014) provides the distribution of the capacity (dwt) of the bulker fleet over three size ranges for the period 1994–2013 (see Figure 46).



Source: RS Platou (2014)

Figure 46: *Capacity distribution of bulker fleet over size categories (1994–2013)*

The capacity share of ships in the range 10,000–59,000 dwt decreased steadily in the period 1994–2013, from around 45% in 1994 to around 33% in 2013.

The capacity share of ships in the range 60,000–79,999 dwt increased from 30% in 1994 to 26% in 2006, and dropped afterwards to almost 15%.

The capacity share of bulk carriers of 80,000 dwt and above increased steadily in the period 1994–2013, from around 30% to around 50%, with the main growth having taken place from 2006.

The capacity share of ULOCs and VLOCs is not separately specified in this graph, but is part of the 80,000+ dwt range.

Regarding the development of the shares until 2050, we expect the expansion of the Panama Canal to have a major impact.

According to the *Review of Maritime Transport* (UNCTAD, 2013), the expansion aimed initially to attract shipments from Asia to the East Coast of the United States, but other goods and regions are emerging as potentially important users of the new canal. By allowing larger tonnage to pass, a number of markets, commodities and goods can be expected to benefit. Examples include the following:

a grain moving from the United States East/Gulf Coast ports to Asia;

b soybean moving from developing America to Asia;

c coal and iron-ore shipments from Colombia, the Bolivarian Republic of Venezuela and Brazil with destinations in Asia;

d coal shipments from the East Coast of the United States to Asia, in particular China;

e oil flowing from Ecuador to the East Coast of the United States;

f gas cargo originating from Trinidad and Tobago and destined for consumption in Chile;

g gas exports from the United States to Asia.

After the expansion of the Panama Canal, Panamax and parts of the Capesize fleet will be able to transit, whereas other Capesize ships and all ULOCs and VLOCs will not.

This is why we expect that the share of carriers in the 100,000–199,999 dwt range will increase and that this growth will come at the expense of ships in the 10,000–99,000 dwt range, with the fleet growth being captured by the larger ships and, in the long run, with the larger ships replacing the smaller ones.

Bulk carriers of 200,000 dwt and above are predominantly iron ore carriers. Neither ULOCs nor VLOCs can transit the Panama Canal (U.S. DOT, 2013) or the Suez Canal. Hence, for these ships, the expansion of the Panama Canal cannot be expected to have a positive impact.

Australia and Brazil are major iron ore exporters, followed by South Africa, India, Canada and Sweden. China is the major importer of iron ore, followed by Japan, the European Union and the Republic of Korea (UNCTAD, 2013). A potential negative effect of the expansion of the Panama Canal on very large carriers can thus not be expected to be large.

It is difficult to estimate whether the share of VLOCs will further rise owing to economies of scale. At the end of 2012, 18 Valemax (dry bulk ships above 400,000 dwt) were in operation, and after 2012, 10 additional Valemax were added to the fleet, with three more on order at the beginning of 2014. However, these ships are used for a very specific trade and some economies of scale have not fully materialized for political reasons. Our expectation is therefore that the share of 200,000 dwt ships will not increase owing to further economies of scale.

Table 41 – *Development of the distribution of dry bulk ships (including combined carriers) over size categories in terms of capacity*

Size categories bulk ships used in update study (dwt)	Distribution in 2012	Development until 2050	Distribution in 2050
0–9,999	1%	None	1%
10,000–34,999	9%	Trend of declining share will continue	6%
35,000–59,999	22%		20%
60,000–99,999	26%		23%
100,000–199,999	31%	As the Panama Canal is expanded, we expect this size category to increase at the expense of ships 10,000–99,999 dwt	40%
200,000–+	11%	Expansion of the Panama Canal could have a slight negative effect; no significant further economies of scale expected	10%

Liquefied gas carriers

LNG carriers

Given data availability, we apply the second methodology to project the number of LNG ships in the different size categories in 2050 (see Figure 41).

The first LNG cargo was shipped in 1959 (Danish Ship Finance, 2014); the market for LNG carriers is thus relatively young. The LNG fleet grew rapidly in the 1970s, stagnated in the 1980s, then started growing again in the 1990s (Stopford, 2009) and grew rapidly in recent years. At the end of 2012, total capacity of the fleet was more than one and a half times the size of the fleet at the end of 2006 (IGU, 2013).

In Table 42, the distribution of the LNG fleet in terms of numbers of ships over five size categories is given for 2012.

Table 42 – *Distribution of global LNG fleet over size categories in terms of numbers in 2012*

Capacity range (m^3)	Share
18,000–124,999	7%
125,000–149,999	62%
150,000–177,000	19%
178,000–210,000	0%
210,000–+	12%

Source: IGU (2013)

There is only a very small number of carriers of 18,000 m^3 and below. These 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 125,000–149,000 m^3, representing 62% of the global LNG fleet in 2012. The existing carriers with a capacity of 150,000–177,000 m^3 constituted 19% of the 2012 LNG fleet. Most of the carriers ordered fall into this category (IGU, 2013).

The category with the largest LNG ships consists of Q-Flex and Q-Max ships, a Q-Max ship having a capacity of 263,000–266,000 m^3. Thirteen Q-Max ships have been built so far. (Qatargas, 2014)

Depending on whether the LNG export projects submitted to the US Department of Energy are approved (currently four out of the 20 have been approved), the US could turn from a net importer to a net exporter of LNG (Deloitte, 2013)

The expansion of the Panama Canal could therefore play a crucial role in the LNG market, since at present only 10% of the LNG fleet can pass through the canal (Lloyd's List, 2012). After the expansion, about 80% of LNG ships will be able to transit. The only LNG carriers that have been identified as unable to transit the new locks due to their size are the 31 Q-Flex ships of 216,000 m^3 and the 14 Q-Max ships of 266,000 m^3 (BIMCO, 2013).

The impact on the size of the LNG carriers is not, however, straightforward: on the one hand, 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. In our projection, we therefore assume that the share of 50,000–199,999 m^3 ships will increase at the expense of very large carriers.

Table 43 – *Development of distribution of global LNG fleet over size categories in terms of numbers*

Size categories (m^3) differentiated in study	Distribution in 2012	Development until 2050	Distribution in 2050
0–49,000	7%	No change	7%
50,000–199,999	81%	Shift due to expansion of Panama Canal	90%
>200,000	12%		3%

While the size of LNG carriers can vary significantly between different ship types, on average a historical trend towards larger capacities can be observed (see Figure 47). The average size of LNG carriers rapidly increased in the 1970s from about 80,000 m^3 to about 110,000 m^3, then only slowly increased to 130,000 m^3 in 2006. After 2006, the average size increased rather rapidly again, partly due to the commissioning of larger Q-series ships. In 2012, the average capacity of an LNG carrier was approximately 148,000 m^3.

From the expected 2050 distribution of the LNG fleet as given in Table 43 and the assumption that the average ship size per size bin does not change compared to 2012, it can be concluded that in 2050 the average size of an LNG ship is expected to have a capacity of approximately 132,000 m^3. That means that the historical trend towards larger capacities would not continue.

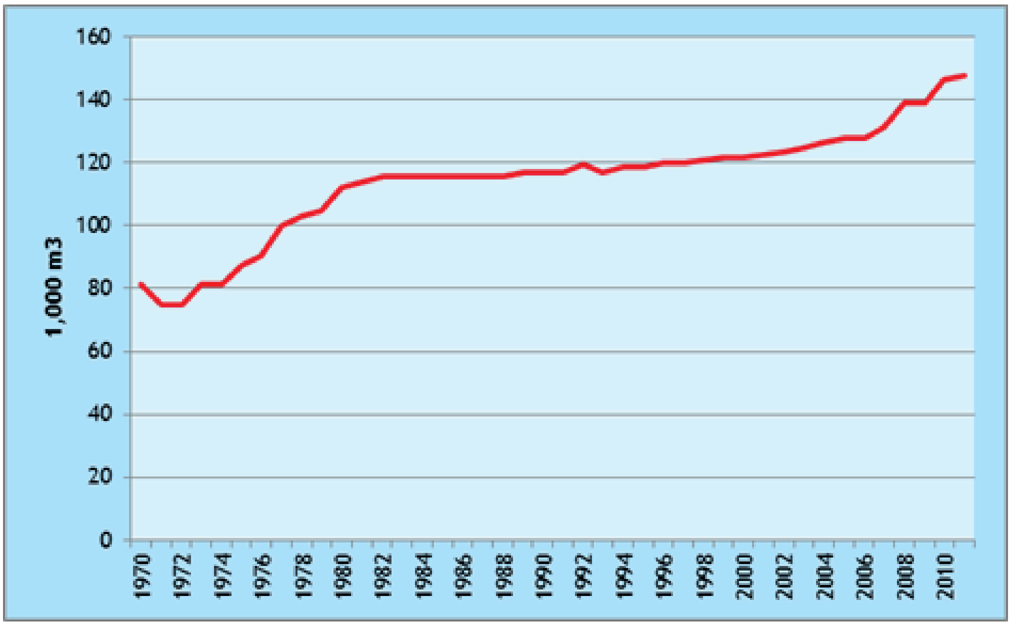


Figure 47: *Development of average capacity of LNG carriers over the period 1970–2011 and corresponding linear trend*

LPG carriers

Given the data availability, we apply the second methodology to project the number of LPG ships in the different size categories in 2050 (see Figure 41).

There are very different LPG carrier types in the market, depending on the cargo type carried, calling for different security standards, and depending on whether the respective gas is kept liquid by pressure or by cooling.

In Table 44, the distribution of the LPG fleet over nine size categories in terms of number of ships is given for end of 2011.

Table 44 – *Distribution of LPG fleet, end of 2011 (nine size categories)*

Capacity range (m^3)	**Share**
Up to 999	5%
1,000–1,999	23%
2,000–4,999	27%
5,000–9,999	18%
10,000–19,999	5%
20,000–39,999	10%
40,000–59,999	2%
60,000–99,999	12%
100,000–+	0%

Source: OPEC (2012)

About 70% of these ships had thus a capacity of less than 10,000 m^3. Regarding the other ships, about 15% fell respectively into each of the ranges 10,000–39,999 m^3 and 40,000–99,999 m^3. None of the ships had a capacity above 100,000 m^3.

Table 45 gives the distribution of LPG carriers over the three ship size classes differentiated in the emissions inventory and emissions projection.

Table 45 – *Distribution of 2012 LPG fleet in terms of numbers (three size categories)*

Capacity range (m^3)	**Share**
0–49,000	87%
50,000–199,999	13%
200,000–+	0%

About 87% of LPG carriers fell in the first size category (0–49,000 m^3), whereas 13% fell in the second size category (50,000–199,999 m^3). Since there were no ships with a capacity of 100,000 m^3 or above, no ships fell in the third category.

According to Platts (2013), the average size of very large gas carrier (VLGC) new builds has risen to around 84,000 m^3 from 82,000 m^3 in the 2000s. Assuming that this growth trend continues in the future, there will still be no LPG ships with a capacity of 200,000 m^3 in 2050.

Regarding the other two size categories, it is plausible to assume that the share of larger ships (second size category) will increase until 2050.

The second size category mainly comprises VLGCs. While VLGCs currently primarily navigate the long routes from countries in the Middle East region to Asia and from West Africa to the United States and Europe (Danish Ship Finance, 2014), VLGCs could play an important role in 2050 in trade between the United States and Asia.

Asian buyers, according to BIMCO (2013), are keen to purchase the volumes of LNG and LPG about to be processed for export at plants along the US Gulf Coast, and large gas carriers directed through the Panama Canal will enable them to realize the benefits of economies of scale and reduced voyage lengths.

Currently, some smaller VLGCs could use the Panama Canal, whereas all VLGCs will be able to transit the new locks (BIMCO, 2013).

Table 46 summarizes expected development to 2050.

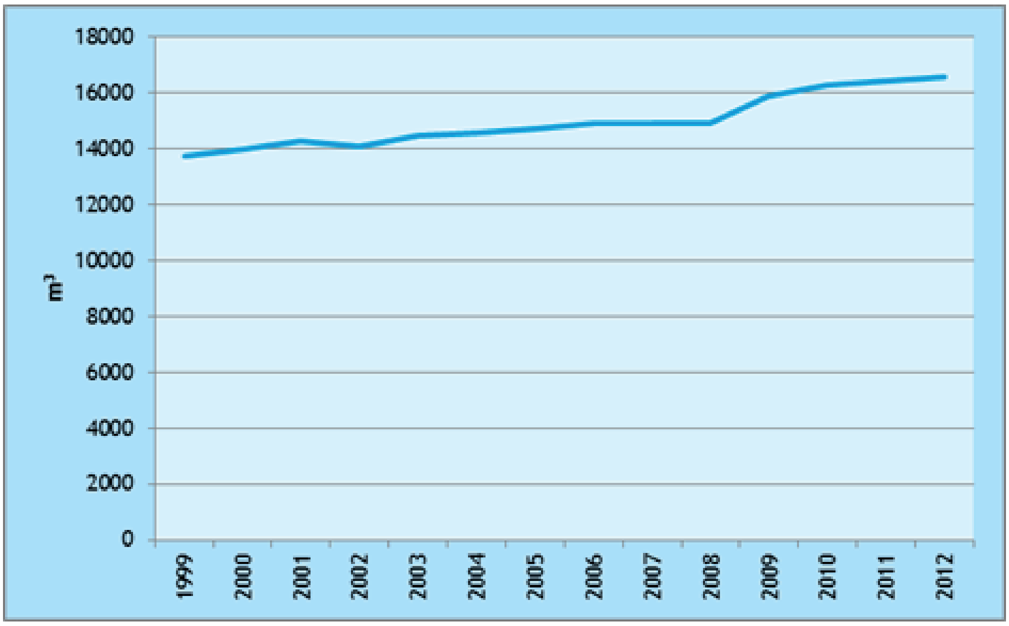
Table 46 – *Development of distribution of global LPG fleet in terms of numbers*

Capacity range (m^3)	Distribution in 2012	Development until 2050	Distribution in 2050
0–49,000	87%	Share will decline	75%
50,000–199,999	13%	Share of VLGCs will rise	25%
200,000–+	0%	No LPG carriers will become available	0%

The average capacity of an LPG carrier has gradually risen in the period 1999–2012: at the end of 1999 it amounted to about 13,700 m^3, and at the end of 2011 to about 16,100 m^3 (see Figure 48).

If this trend continued, an LPG carrier would on average have a capacity of 24,500 m^3 in 2050.

From the expected 2050 distribution of the LPG fleet as given in Table 46 and the assumption that the average ship size per size bin does not change compared to 2012, it can be concluded that in 2050 the average size of an LPG ship is expected to have a capacity of approximately 25,100 m^3, which is only slightly higher than expected from the historical trend.



Source: Based on OPEC (*Annual Statistical Bulletin* for the years 1999–2012)

Figure 48: *Development of the average size of LPG carriers in the period 1999–2012*

For LNG and LPG ships taken together, we expect the following development of the distribution of the gas carrier fleet in terms of numbers of ships.

Table 47 – *Development of distribution (in terms of numbers of ships) of the global gas carrier fleet*

Capacity range (m3)	Distribution in 2012	Distribution in 2050
0–49,000	68%	32%
50,000–199,999	29%	66%
200,000–+	3%	2%

If the average ship size per size bin does not change compared to 2012, the average size of a liquefied gas carrier will be approximately 85,000 m^3 or 50,000 dwt in 2050.

Regulatory and autonomous efficiency improvements

The projection of the future emissions of maritime shipping requires the projection of future developments in fuel efficiency of the fleet. In the period up to 2030, we distinguish between market-driven efficiency changes and changes required by regulation, i.e. EEDI and SEEMP. The market-driven efficiency changes are modelled using a MACC, assuming that a certain share of the cost-effective abatement options is implemented. The data for the MACC are taken from IMarEST (MEPC 62/INF.7). In addition, regulatory requirements may result in the implementation of abatement options irrespective of their cost-effectiveness. Between 2030 and 2050, we see little merit in using MACCs, as the uncertainty about the costs of technology and its abatement potential increases rapidly for untested technologies. In addition, regulatory improvements in efficiency for the post 2030 period have been discussed but not defined. We have therefore chosen to take a holistic approach towards ship efficiency after 2030.

EEDI and SEEMP

Ships built after 1 January 2013 must comply with EEDI regulation, and from the same date all ships must have a SEEMP. As a result, the efficiency of new and existing ships could change. As EEDI requirements become increasingly stringent over time, the efficiency of ships could also change.

This section reviews the impact of EEDI and SEEMP on the efficiency of ships, in order to incorporate it in the emissions projection model.

For the purpose of the emissions projection model, efficiency is defined as unit of energy per unit of distance for the relevant ship. A ship is characterized by the ship type and size. New ships are ships that enter the fleet from 2013.

According to resolution MEPC.203(62) and document MEPC 66/WP.10/Add.1, the attained EEDI of new ships built after 1 January 2013 must be at or below the required EEDI for that ship. The required EEDI is calculated as a percentage of a reference line which is specific to ship type and size. The reference line is the best fit of the estimated index values (a simplified EEDI which is calculated using default factors for specific fuel consumption and auxiliary engines, and does not take ice class or fuel-saving technologies into account). Over time, the distance to the reference line must increase, as shown in Table 48.

Table 48 – *Reduction factors (percentage) for EEDI relative to the EEDI reference line*

		Year of entry in the fleet			
		Phase 0	**Phase 1**	**Phase 2**	**Phase 3**
		1 Jan 2013–31 Dec 2014	**1 Jan 2015–31 Dec 2019**	**1 Jan 2020–31 Dec 2024**	**1 Jan 2025 and onwards**
Bulk carrier	20,000–+ dwt	0	10	20	30
	10,000–20,000 dwt	na	0–10	0–20	0–30
Gas carrier	10,000–+ dwt	0	10	20	30
	2,000–10,000 dwt	na	0–10	0–20	0–30
Tanker	20,000–+ dwt	0	10	20	30
	4,000–20,000 dwt	na	0–10	0–20	0–30
Container ship	15,000–+ dwt	0	10	20	30
	10,000–15,000 dwt	na	0–10	0–20	0–30
General cargo ship	15,000–+ dwt	0	10	20	30
	3,000–15,000 dwt	na	0–10	0–20	0–30
Refrigerated cargo carrier	5,000–+ dwt	0	10	20	30
	3,000–5,000 dwt	na	0–10	0–20	0–30
Combination carrier	20,000–+ dwt	0	10	20	30
	4,000–20,000 dwt	na	0–10	0–20	0–30
LNG carrier	10,000–+ dwt	na	10	20	30

		Year of entry in the fleet			
		Phase 0	**Phase 1**	**Phase 2**	**Phase 3**
		1 Jan 2013–31 Dec 2014	**1 Jan 2015–31 Dec 2019**	**1 Jan 2020–31 Dec 2024**	**1 Jan 2025 and onwards**
Ro-ro cargo ship (vehicle carrier)	10,000–+ dwt	na	5	15	30
Ro-ro cargo ship	2,000–+ dwt	na	5	20	30
	1,000–2,000 dwt	na	0–5	0–20	0–30
Ro-ro passenger ship	1,000–+ dwt	na	5	20	30
	250–1,000 dwt	na	0–5	0–20	0–30
Cruise passenger ship with non-conventional propulsion	85,000–+ GT	na	5	20	30
	25,000–85,000 dwt	na	0–5	0–20	0–30

Source: MEPC 62/24/Add.1, MEPC 66/WP.10/Add.1

EEDI baseline and specific fuel oil consumption

The reference line which is used to calculate the required EEDI is the best fit of the estimated index values of ships built between 1999 and 2009. The estimated index value is a simplified form of EEDI. It assumes an SFOC of 190 g/kWh for main engines and 215 g/kWh for auxiliaries.

A number of recent publications find that the average SFOC of engines currently entering the fleet is lower. CE Delft (2013), on the basis of an analysis of the Clarksons database, finds that modern ships have an average SFOC of approximately 175 g/kWh. Kristensen (2012) finds that modern marine diesel engines have SFOCs of 170 g/kWh. Buhaug et al. (2009) use an SFOC range from 170 g/kWh for two-stroke slow-speed engines to 210 g/kWh for four-stroke high-speed engines. For large engines (>5000 kW), which are typically used in ships that have to comply with EEDI, SFOC ranges from 165 g/kWh to 185 g/kWh.

In sum, there is evidence that the average SFOC of modern engines is about 175 g/kWh, rather than the 190 g/kWh assumed in the calculation of the reference line. Assuming that the SFOC of auxiliary engines is correct, and that auxiliary engines account for 5% of the total engine power (following resolution MEPC.212(63)), the efficiency improvement is 7.5% less than the required reduction factors.

Because very few ships have been built with an EEDI, there is no ex post information about the impact of EEDI on operational efficiency of ships. Ex ante evaluations of EEDI generally assume that design efficiency and operational efficiency are positively correlated and that operational efficiency improves proportionally to design efficiency. We follow this assumption and assume that design and operational efficiency are positively correlated and move proportionally.

EEDI stringency will result in more efficient designs. Given the assumptions on the specific fuel consumption (SFC) of the main engine in the calculation of the reference lines, we expect the efficiency improvements to be smaller than the value of the required reduction factors. Assuming that the SFOC of auxiliary engines is correct, and that auxiliary engines account for 5% of total engine power (following resolution MEPC.212(63)), the efficiency improvement is 7.5% less than the required reduction factors.

Table 49 – *Impact of the SFC on EEDI efficiency improvements*

Reduction relative to original baseline	Reduction relative to baseline, taking SFC into account
0%	–7.5%
10%	2.5%
20%	12.5%
30%	22.5%

Impact of EEDI on emissions of new builds

Bazari and Longva (2011) assume that the current normal distribution of attained EEDI will change to a skewed distribution with a peak just below the limit value. As a result, the improvement in average attained EEDI will be larger than the required improvement of EEDI (see figure below). As the figure shows, the difference between the average improvements and the face value of the required improvements diminishes with increasing stringency.

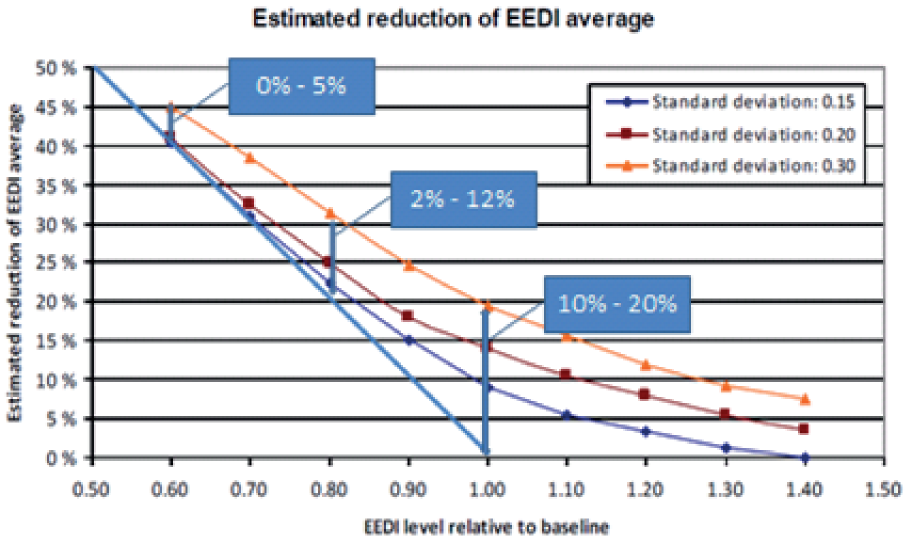


Figure 49: *Impact of the Poisson distribution on EEDI efficiency improvements*

Bazari and Longva (2011) conclude that waivers are unlikely to be used, as they bring risks and costs but no benefits.

Anink and Krikke (2011) calculate EEDI reduction factors assuming that all ships above the line improve their EEDI to the reference line and others will not act. Their results indicate that the improvement in efficiency is smaller than the value of the reduction, but it is not clear whether this is because many small ships are included in the sample, which are exempt from EEDI or have a lower reduction target, or because of their methodology.

Hence, there are two views on what the impact of EEDI regulation on new designs would be. One view is that it would improve the efficiency of all new ships, except for the most efficient ones. The other is that only the design of ships above the reference line would be affected. Both result in an average improvement in design efficiency that is larger than the reduction factor. The exact improvement depends on the share of current ships that are above the baseline and on the stringency: the larger the reduction relative to the baseline, the lower the difference between the average reduction and the required reduction.

In line with Bazari and Longva (2011), we assume that the average efficiency improvement of new ships increases from 3% in phase 0 to 22.5% in phase 3, according to the table below, as a result of the Poisson distribution of ship efficiency.

Table 50 – *Impact of the Poisson distribution on EEDI efficiency improvements*

Required reduction relative to baseline	**Average efficiency improvements of new builds relative to corrected baseline**	**Average efficiency improvements of new builds relative to baseline**
0%	10%	3%
10%	17%	11%
20%	24%	18%
30%	30%	22.5%

We follow Bazari and Longva (2011) in their analysis that it is unlikely that ship owners will apply for a waiver.

Impact of SEEMP on emissions

Bazari and Longva (2011) identify great uncertainty surrounding the effects of SEEMP. They speculate that 30% to 60% of the cost-effective operational measures will be implemented as a result of SEEMP.

Johnson et al. (2013) compare SEEMP with the ISO standard on energy management, ISO 500001, and with the International Management Code for the Safe Operation of Ships and for Pollution Prevention (International Safety Management (ISM) Code), and conclude that SEEMP lacks a number of factors that are considered to be crucial to the success of ISO 50001 and the ISM Code, such as the establishment of a baseline and setting goals, (top) management involvement and dealing with non-conformities. They conclude that "these gaps may be detrimental to the success of the SEEMP".

In sum, there is no established way of estimating the impact of SEEMP. It seems likely that only cost-effective efficiency improvements will be implemented. The current energy-efficiency gap could be reduced, but this might not necessarily be the case.

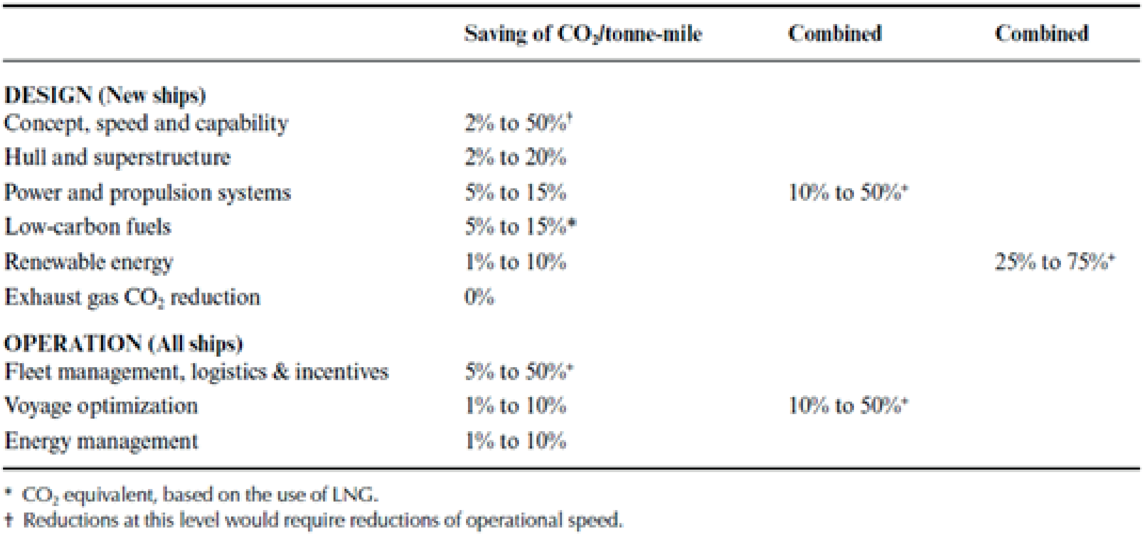
In our model, energy efficiency options are implemented as they become cost-effective in the MACC. We assume that 25% of the potential will not be realized owing to barriers to the implementation of cost-effective measures (CE Delft et al., 2012) and uncertainty about the benefits. We assume that the current level of unimplemented options will remain stable over time.

Long-term efficiency improvements

This section provides an overview of literature on efficiency improvements between 2030 and 2050.

Buhaug et al. (2009) estimate, on the basis of the results of a Delphi panel, that the efficiency of ships in 2050 could improve by 25% to 75% over 2007 levels (see table below). Of this, 5% to 15% is attributed to low-carbon fuels, which are modelled as changes in emissions factors and not as efficiency improvements in our model. A further unspecified but large share is attributed to speed, which is dealt with elsewhere in our model. All the non-speed and non-fuel options together result in a 50% efficiency improvement. Adding another 10% to take into account the non-speed elements of the category "concept, speed and capability", we estimate the resulting efficiency improvement over 2007 levels at maximally 60%.

Table 51 – *Assessment of potential reductions of CO_2 emissions from shipping by using known technology and practices (from Second IMO GHG Study 2009)*



	Saving of CO_2/tonne-mile	Combined	Combined
DESIGN (New ships)			
Concept, speed and capability	2% to 50%†		
Hull and superstructure	2% to 20%		
Power and propulsion systems	5% to 15%	10% to 50%†	
Low-carbon fuels	5% to 15%*		
Renewable energy	1% to 10%		25% to 75%†
Exhaust gas CO_2 reduction	0%		
OPERATION (All ships)			
Fleet management, logistics & incentives	5% to 50%†		
Voyage optimization	1% to 10%	10% to 50%†	
Energy management	1% to 10%		

* CO_2 equivalent, based on the use of LNG.
† Reductions at this level would require reductions of operational speed.

Documents MEPC 59/4/35 and MEPC 59/INF.27 (Japan) present case studies of efficiency improvements of ships. The case studies combine improvements from ship-size increases, speed reduction and the implementation of new technologies. Since our model addresses speed reduction and ship size separately (and we have written other discussion notes on these), we focus here on the impact of the implementation of new technologies. Japan estimates them to improve efficiency by 30% to 40% in 2040, while emphasizing that just a selection of technologies have been included.

Eide et al (2013) conclude that the cost-effective abatement potential in 2050 is in the order of 50%, assuming that LNG, biofuels and nuclear propulsion become viable options to replace fossil fuels. More precisely, they project the cost-effective efficiency improvement to be between 35% and 52%. Alternative fuels account for 0% to 38% of this improvement potential, with the higher shares being associated with the higher efficiency gains. Hence, exclusive of fuels, the cost-effective abatement potential appears to be 15% to 35%.

In sum, there is consensus that there is potential to improve the efficiency of ships further after 2030. The potential and especially the cost-effective potential are uncertain. It is likely that efficiency improvements will continue after 2030, although it is impossible to decide at this moment what share of the improvements will be market-driven and what share will be regulation-driven. Because of the high uncertainty of technological development over such a timescale, we will use two scenarios. One scenario coincides with the highest estimates in the literature, excluding speed and alternative fuels, which are accounted for elsewhere. The second scenario has more conservative estimates.

Conclusion

We assume that EEDI will drive efficiency improvements as shown in the table below for ships entering the fleet during phases 0 to 3.

Table 52 – *Impact of EEDI on operational efficiency of new ships*

		Year of entry in the fleet			
		Phase 0	**Phase 1**	**Phase 2**	**Phase 3**
		1 Jan 2013–31 Dec 2014	**1 Jan 2015–31 Dec 2019**	**1 Jan 2020–31 Dec 2024**	**1 Jan 2025 and onwards**
Bulk carrier	20,000–+ dwt	3	11	17	22.5
	10,000–20,000 dwt	na	0–11	0–17	0–22.5
Gas carrier	10,000–+ dwt	3	11	17	22.5
	2,000–10,000 dwt	na	0–11	0–17	0–22.5
Tanker	20,000–+ dwt	3	11	17	22.5
	4,000–20,000 dwt	na	0–11	0–17	0–22.5
Container ship	15,000–+ dwt	3	11	17	22.5
	10,000–15,000 dwt	na	0–11	0–17	0–22.5
General cargo ship	15,000–+ dwt	3	11	17	22.5
	3,000–15,000 dwt	na	0–11	0–17	0–22.5
Refrigerated cargo carrier	5,000–+ dwt	3	11	17	22.5
	3,000–5,000 dwt	na	0–11	0–17	0–22.5
Combination carrier	20,000–+ dwt	3	11	17	22.5
	4,000–20,000 dwt	na	0–11	0–17	0–22.5

We assume that SEEMP will result in operational improvements to the extent that they are cost-effective. We assume that the current level of unimplemented options will remain stable over time.

For efficiency improvements after 2030, we use two scenarios. The first scenario has a large increase after 2030, the second a smaller increase.

Table 53 – *Efficiency improvements in the period 2030–2050*

Scenario	Efficiency improvement in 2050 relative to 2012 levels
1	60%
2	40%

Fuel mix

Market and regulatory drivers

There are two factors that will mainly determine the future bunker fuel mix of international shipping:

1 the relative costs of using the alternative fuels; and

2 the relative costs of the sector's alternative options for compliance with environmental regulation.

The relative costs of using the alternative fuels depend on the relative price of the fuels, the availability of the fuels, retrofitting costs if necessary, possible differences in prices for ships, new-build or second-hand, as well as revenue changes associated with a possible change of cargo capacity.

If compliance with environmental regulation can be ensured by the use of certain fuels, ship owners will weigh the costs of using the fuels against of the costs of other compliance options.

The environmental regulation that can be expected to have the greatest impact on the future fuel mix are the NO_x and SO_x limits set by IMO (regulations 13 and 14 of MARPOL Annex VI respectively), which will become more stringent in the future and that will also hold in ECAs that may additionally be established in the future.

SO_x controls in regulation 14 apply to all fuel oil combustion equipment and devices on-board ships. The regulation limits the maximum sulphur content of the fuel oil used and has two stringency levels: one stringency level that holds in SO_x emission control areas (SECAs) and another, less stringent level for outside SECAs, also referred to as global requirements (see Table 54).

Table 54 – *IMO sulphur requirements*

Outside ECA (global requirement)	**Inside ECA**
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020*	0.10% m/m on and after 1 January 2015

Source: IMO (2014, a)).

* Depending on the outcome of a review, to be concluded in 2018, as to the availability of the required fuel oil, this date could be deferred to 1 January 2025.

Four SECAs have been established in 2014 to date (see Table 55).

Table 55 – *Emission control areas established in 2014*

	SO_x ECA	**NO_x ECA**
Baltic Sea area	X	
North Sea area	X	
North American area	X	X
United States Caribbean Sea area	X	X

Source: IMO (2014, b))

After 2012, the base year of this study, the sulphur requirements within and outside the SECAs will become more stringent. From the beginning of 2015, the maximum sulphur content of fuel oil must not exceed 0.1% m/m inside the SECAs, and either from 2020 or from 2025, depending on the availability of the required fuel oil, must not exceed 0.5% m/m outside the SECAs.

In principle, there are two ways of complying with these sulphur requirements. Using fuel oil with the required sulphur content is the primary method, and cleaning the exhaust gases to prevent sulphur oxide emissions is the secondary method.

Fuel types that fulfil global 2020/2025 (0.5%) as well as the 2015 SECA (0.1%) requirements are distillates, LNG, biofuels and other liquid or gaseous fuel options that can be used in dual-fuel engines, such as LPG, methanol, ethanol, and dimethyl ether.[1]

The global 0.5% requirement can be met by mixing low and high sulphur fuel (CONCAWE, 2012), whereas this is not possible for the 2015 SECA requirement of 0.1% (TransBaltic, 2012).

Also, low sulphur HFO (LSHFO) can be expected to fulfil only the global 0.5% and not the 0.1% sulphur requirement. LSHFO can either be produced from very low sulphur crude oils or, alternatively, high sulphur residues are treated to produce low sulphur marine bunkers. HFO containing less than 0.5% sulphur is obtained from crude oil with sulphur content less than approximately 0.15%. The level of sulphur content of crude oil needed to produce HFO with 0.1% sulphur content is even lower. Not only are such crude oils rare, they

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[1] See DNV GL (2014) for an overview on alternative fuels for shipping.

are also highly paraffinic, waxy crude oils that would be unsuitable for heavy fuel oil production for marine bunkers owing to their high pour points (TransBaltic, 2012). But even if only LSHFO with a 0.5% sulphur content was produced for use in maritime shipping, an investment of refineries in further desulphurization of high sulphur residues would be inevitable since the low sulphur vacuum gas oil (heavy oil leftover that can be further refined in a catalytic cracking unit) is currently used as feedstock for other purposes and since next to the maritime shipping sector there are hardly any other users of the high sulphur residues (Purvin & Gertz, 2009).

Since the SECA limit is lower than the global sulphur limit, ships which operate both outside and inside the SECA have the compliance option of switching fuel when entering the SECA if their fuel oil combustion equipment and devices allow this.

Next to using fuel with the required sulphur content, scrubbers for exhaust gas cleaning can be used as a secondary compliance method. When a scrubber is used, the ship does not have to use a fuel other than HFO, but the use of a scrubber will raise energy demand slightly.

Regulation 13 of MARPOL Annex VI sets NO_x emission limits for installed marine diesel engines of over 130 kW output power. The requirements limit the total weighted cycle emissions in terms of g/kWh and depend on the date of the construction of a ship and on the engine's rated speed. Currently, no specific stringency levels hold for NO_x emission control areas (NECAs), but ships constructed on or after 1 January 2016 will have to comply with NO_x Tier III standards when operating in the North American ECA or the United States Caribbean Sea ECA, which are already designated NECAs. In addition, Tier III requirements will apply to installed marine diesel engines when operated in other NECAs which might be designated in the future. However, Tier III will then apply to ships constructed on or after the date of adoption by MEPC of such an ECA, or a later date as may be specified in the amendment designating the NO_x Tier III ECA (IMO, 2014, c)).

Table 56 – *IMO NO_x limits*

Tier	Geographical scope	Ship construction date (on or after)	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
			$n < 130$	**$n = 130–1,999$**	**$n \geq 2,000$**
I	Global	1 January 2000	17.0	$45 * n^{-0.2}$	9.8
II	Global	1 January 2011	14.4	$44 * n^{-0.23}$	7.7
III	In North American and United States Caribbean Sea ECAs	1 January 2016	3.4	$9 * n^{-0.2}$	2.0

Source: IMO (2014, d))

Whereas the global Tier I and Tier II requirements can be met by adjustments in engine design and calibration, this is not the case for the Tier III requirements, which are 80% stricter than Tier I limits.

In its final report (MEPC 65/4/7), the Correspondence Group on Assessment of Technological Developments to Implement the Tier III NO_x Emission Standards under MARPOL Annex VI identified that the following technologies have the potential to achieve NO_x Tier III limits, either alone or in some combination with each other:

1 Selective catalytic reduction (SCR);

2 Exhaust gas recirculation (EGR);

3 The use of LNG, either dual-fuel (diesel pilot injection with gaseous LNG as main fuel) or alternative fuel arrangements; and

4 Other technologies: direct water injection, humid air motor, scrubbers, treated water scrubber, variable valve timing and lift, and dimethyl ether as an alternative fuel.

Fuel mix scenarios used in emissions projection model

The fuel mix is an exogenous variable in the CO_2 emissions projection model. It has two effects on the estimated emissions. On the one hand, there is the direct effect on the CO_2 emissions due to the different CO_2 emissions factors of the fuels, and on the other, there is an indirect effect via the cost-efficiency of the CO_2 abatement measures. If ships decide to comply with the air pollution regulation by switching from HFO to

MGO, the CO_2 abatement measure will become relatively more cost-effective since MGO is more expensive than HFO.

Table 57 gives the main compliance options of regulations 13 and 14 of MARPOL Annex VI, the main drivers for the future fuel mix.

Table 57 – *Main compliance options of regulations 13 and 14 of MARPOL Annex VI*

	Global 0.5% m/m sulphur limit	**SECA 0.1% m/m sulphur limit**	**NECA Tier III NO_x limit**
LSHFO	X		
Distillates	X	X (MGO)	
LNG	X	X	X
HFO + Scrubber	X	X	
Distillates + SCR/EGR		X	X

Note that in an area that is established as a SECA and a NECA (with Tier III requirements), only two main options seem to be viable currently – the use of LNG or the use of distillates together with SCR/EGR – because it is unclear at the moment whether the combination of HFO, scrubbers and SCR/EGR is technically feasible.

As explained above, ship owners will probably choose the compliance option with the lowest relative costs for the operational profile of their ships. The optimal compliance option will therefore most likely differ according to ship type, ship size and the specific trades. Together with the fact that the technical compliance options are still evolving and currently not produced at a large scale, making a cost estimate for 2050 very uncertain, and the fact that the development of the LNG infrastructure and the LNG bunker prices are highly uncertain, we decided not to derive fuel mix scenarios based on compliance cost estimations for 2050 but to set up plausible fuel mix scenarios. We therefore differentiate two scenarios: a high LNG case, in which we assume that extra ECAs will be established in the future, and a low LNG case, in which we assume that no extra ECAs will be established in the future.

The share of LNG in the fuel mix in the two scenarios is derived from literature.

In DNV (2012), four scenarios are considered which differ with respect to economic growth, fuel prices and environmental regulatory pressure and other characteristics like access to capital. In 2020, the highest share of LNG amounts to 9% in a scenario with relatively high economic growth, relatively high HFO and MGO prices but a very low LNG bunker price that is decoupled from the HFO price, with high pressure from environmental regulation (ECAs in all coastal areas and a high carbon price) and high access to capital. The scenario with the lowest share of LNG (2%) in 2020 is a scenario with relatively low economic growth, moderate fuel prices where the LNG price is not being decoupled from the HFO price, again with high pressure from environmental regulation (ECAs in all coastal areas and a carbon price that is lower than in the high LNG case) and low/limited access to capital.

In Lloyd's Register Marine and UCL Energy Institute (2014), the 2030 fuel mix for the main ship types (container ships, dry bulk carriers, general cargo ships and tankers) is estimated. In one scenario, a relatively low share of LNG is found for 2030 (4% in Competing Nations Scenario), whereas in the other two scenarios (Status Quo and Global Commons) a share of around 11% is expected respectively. However, none of the three scenarios considers an early (2020) switch to the global 0.5% sulphur requirement or the establishment of further ECAs, which is why we take the LNG share to be higher in the high LNG case.

The following table presents the fuel mix scenarios used for the emissions projection.

Table 58 – *Fuel mix scenarios used for emissions projection (% m/m)*

High LNG case/extra ECAs	**LNG share**	**Distillates and LSHFO***	**HFO**
2012	0%	15%	85%
2020	10%	30%	60%
2030	15%	35%	50%
2050	25%	35%	40%

Low LNG case/no extra ECAs	**LNG share**	**Distillates and LSHFO***	**HFO**
2012	0%	15%	85%
2020	2%	25%	73%
2030	4%	25%	71%
2050	8%	25%	67%

* Sulphur content of 1% in 2012 and 0.5% from 2020.

In both scenarios, we assume that the global 0.5% sulphur requirement will become effective in 2020. A later enforcement (2025) is accounted for in a sensitivity analysis.

Also, in both scenarios we assume that in 2020, 60% of the fuel consumption of the fleet (in terms of tons) consists of HFO. In the scenario, where extra ECAs are assumed to be established, this share decreases over time, whereas in the other scenario it does not. The share of the distillates then follows.

Emissions factors

Emissions factors

All emissions analysed here, except for HFC, PFC and SF_6, result from fuel combustion and are therefore calculated by multiplying fuel consumption with an emissions factor. The emissions factors depend on the type of fuel, and we distinguish between residual fuel oil (HFO), low sulphur fuel oil (LSFO), marine gas oil (MGO, a distillate fuel) and LNG. Emissions factors may also be affected by engine modifications (e.g. exhaust gas recirculation (EGR)), or exhaust gas treatment (e.g. selective catalytic reduction (SCR) or sulphur scrubbers). Some of these technologies to reduce emissions have a fuel penalty; others, such as SCR, allow for optimization of the fuel-efficiency of the engine and may result in a fuel-efficiency improvement. The fuel penalties are typically in the order of a percent, while the possible improvements may be larger. We do not make assumptions about the specific ways in which ships meet standards and we ignore fuel penalties or efficiency improvements, as these are small relative to the inherent uncertainties in the emissions projections.

Below, separate sections per species present the emissions factors in the base year and in future years.

CO_2

The emissions factors of CO_2 are expressed per tonne of fuel. For each fuel type, they remain constant over time. When calculating the emissions of LNG engines, we take into account that the brake-specific fuel oil consumption (SFOC) of LNG is 15% lower than the SFOC of HFO.

Table 59 – *CO_2 emissions factors (g/g fuel)*

Region	**Fuel type**	**Year**		
		2012	**2030**	**2050**
Global	HFO	3,114	3,114	3,114
	LSFO	3,114	3,114	3,114
	MGO	3,206	3,206	3,206
	LNG	2,750	2,750	2,750

CH_4

Methane emissions result from combustion of heavy fuel oils and distillates and from incomplete emissions of LNG. The emissions factors are constant over time.

Table 60 – *CH_4 emissions factors (g/g fuel)*

Region	**Fuel type**	**Year**		
		2012	**2030**	**2050**
Global	HFO	0.00006	0.00006	0.00006
	LSFO	0.00006	0.00006	0.00006
	MGO	0.00006	0.00006	0.00006
	LNG	0.05	0.05	0.05

N_2O

Nitrous oxide results from the combustion of fuels. Its emissions factors are constant over time.

Table 61 – *N_2O emissions factors (g/g fuel)*

Region	**Fuel type**	**Year**		
		2012	**2030**	**2050**
Global	HFO	0.00015	0.00015	0.00015
	LSFO	0.00015	0.00015	0.00015
	MGO	0.00016	0.00016	0.00016
	LNG	0.000108	0.000108	0.000108

HFC

Emissions from HFC result from leaks from cooling systems and air conditioners. They do not emerge from fuel combustion but are assumed to be driven by the number of ships. There are several HFCs with different GWPs. The most relevant are presented in the following table.

Table 62 – *HFCs used on board ships*

Species	**GWP**	**Notes**
R-22	1,810	R-22 (chlorodifluoromethane) has been the dominant refrigerant in air conditioners used on board ships. The production of R-22 has been phased out under the Montreal Protocol in many countries. We assume that it is used only in vessels built before 2000.
R-134a	1,300	R134a (1,1,1,2-Tetrafluoroethane) is used as a replacement for R-22 in vessels built from 2000 onwards
R-404a	3,700	R404a is a mixture of R125, R143a and R134a. It is used predominantly in fishing vessels but also in freezing and cooling equipment in other vessels.

Assuming that ships built before 2000 have a 25-year lifetime, R-22 will have become obsolete in shipping by 2025. We do not model that other HFCs will be phased out, that air conditioner leakage rates will change or that other coolants will replace HFCs. Under these assumptions, the following emissions per ship are calculated.

Table 63 – *HFC emissions per ship (tonnes per year)*

	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

PFC

The main application of PFCs on board ships that is of relevance is fire-fighting foams of the type AFFF (aqueous film-forming foam). In recent years, PFCs have been phased out by major manufacturers. Therefore, and because leakage from remaining stockpiles is regarded as negligible, we do not project PFC emissions from international shipping.

SF_6

Sulphur hexafluoride is not used on board ships to any significant degree. Supplies of SF_6 are distributed and transported in compressed gas cylinders. Significant emissions of SF_6 from shipping are not expected.

NO_x

Nitrogen oxide is formed when oxygen and nitrogen react under high pressure or at high temperatures, such as in engines. NO_x emissions from marine engines are regulated. Regulation 13 of MARPOL Annex VI sets NO_x emission limits for installed marine diesel engines of over 130 kW output power. The requirements limit the total weighted cycle emissions in terms of g/kWh and depend on the date of the construction of a ship and on the engine's rated speed. There are three stringency levels: Tier 1, Tier 2 and Tier 3. Tier 1 applies to ships built from 2000, Tier 2 to ships built from 2011, and Tier 3 to ships constructed on or after 1 January 2016, but only when they are operating in current NO_x emission control areas. For future emission control areas, Tier 3 will be required for ships built after the date of adoption by MEPC of such an ECA, or a later date if agreed by MEPC.

While Tier 1 and 2 can be met by adjustments in engine design and calibration, this is not the case for the Tier 3 requirements. The latter require either radically different engine designs (with exhaust gas recirculation), after-treatment of exhaust gases (selective catalytic reduction) or other fuels (LNG).

For our emissions projections, we assume that:

- All ships that entered the fleet from 2000 to 2010 meet Tier I.
- All ships that enter the fleet from 2011 onwards meet Tier II.
- All ships that enter the fleet from 2016 onwards comply with Tier III in ECAs. For modelling purposes, we assume that Tier III is met by using LNG. Compared to a scenario where some ships would use SCR or EGR to comply with Tier III and LNG would be used by other ships, our modelling overestimates the total NO_x emissions. In other words, our modelling is a conservative estimate of NO_x emission reductions. In case we do not project enough LNG to meet NECA requirements, we assume that Tier II ships will be Tier III compliant when sailing in NECAs, and that pre-2000 and Tier I ships will avoid NECAs.

- As stated above, we have two scenarios on ECAs and fuel use. The first scenario has a constant share of fuel used in ECAs, and we assume that half of the fuel consumption in current ECAs will be in NECAs from 2016 and the other half from 2025. The other scenario projects a doubling of the share of fuel used in ECAs. We assume that the NO_x Tier III requirements for the new ECAs come into force in 2030.

Table 64 – *NO_x emissions factors (g/g fuel)*

Scenario	**Fuel type**	**Year**		
		2012	**2030**	**2050**
Global average, low ECA, low LNG scenario	HFO	0.0903	0.0825	0.0760
	MGO	0.0961	0.0877	0.0808
	LNG	0.0140	0.0140	0.0140
Global average, high ECA, high LNG scenario	HFO	0.0903	0.0834	0.0690
	MGO	0.0961	0.0887	0.0734
	LNG	0.0140	0.0140	0.0140

Note that the lower emissions factor for NO_x in the low LNG scenario in 2030 is the result of the fact that this scenario requires more ships to use SCR or EGR to meet Tier III instead of switching to LNG.

NMVOC

The emissions of non-methane volatile organic compounds result from incomplete combustion of fuels. They are assumed to be constant over time.

Table 65 – *NMVOC emissions factors (g/g fuel)*

Region	**Fuel type**	**Year**		
		2012	**2030**	**2050**
Global	HFO	0.00308	0.00308	0.00308
	LSFO	0.00308	0.00308	0.00308
	MGO	0.00308	0.00308	0.00308
	LNG	0.003	0.003	0.003

CO

The emissions of carbon monoxide result from incomplete combustion of fuels. They are assumed to be constant over time.

Table 66 – *CO emissions factors (g/g fuel)*

Region	**Fuel type**	**Year**		
		2012	**2030**	**2050**
Global	HFO	0.00277	0.00277	0.00277
	LSFO	0.00277	0.00277	0.00277
	MGO	0.00277	0.00277	0.00277
	LNG	0.00783	0.00783	0.00783

PM

The emissions of particulate matter result from incomplete combustion of fuels and from the formation of sulphate particles, which is a result of sulphur emissions. They are assumed to be constant over time.

Table 67 – *PM emissions factors (g/g fuel)*

Region	**Fuel type**	**Year**		
		2012	**2030**	**2050**
Global	HFO	0.00728	0.00385	0.00385
	LSFO	0.00426	0.00385	0.00385
	MGO	0.00097	0.00097	0.00097
	LNG	0.00018	0.00018	0.00018

SO_2

The emissions of SO_2 result from the combustion of sulphur that is present in petroleum-derived fuels. Emissions factors will decrease as a result of MARPOL Annex VI regulations.

Table 68 – *SO_2 emissions factors (g/g fuel)*

Region	**Fuel type**	**Year**		
		2012	**2030**	**2050**
Global	HFO	0.025	0.005	0.005
	MGO	0.010	0.001	0.001
	LNG	0	0	0

Detailed results

This section presents the emissions (million tonnes) per scenario for 2012, 2020 and 2050.

Table 69 – *Scenarios 1 and 9 (RCP8.5, SSP5, high efficiency)*

Greenhouse gases		**2012**	**2020**	**2050**
CO_2	low LNG	810	910	1,900
	high LNG	810	890	1,800
CH_4	low LNG	0.02	0.26	2.10
	high LNG	0.02	1.20	6.50
N_2O	low LNG	0.04	0.04	0.09
	high LNG	0.04	0.04	0.09
HFC		37	40	79
PFC		0	0	0
SF_6		0	0	0
Other substances				
NO_x	constant ECA	24	26	49
	more ECAs	24	24	40
SO_2	constant ECA	5.90	3.90	2.30
	more ECAs	5.90	3.40	1.50
PM	constant ECA	1.70	1.30	1.80
	more ECAs	1.70	1.10	1.20
NMVOC	constant ECA	0.80	0.89	1.90
	more ECAs	0.80	0.88	1.80
CO	constant ECA	0.72	0.83	1.90
	more ECAs	0.72	091	2.30

Table 70 – *Scenarios 2 and 10 (RCP6.0, SSP1, high efficiency)*

Greenhouse gases		**2012**	**2020**	**2050**
CO_2	low LNG	810	890	1,400
	high LNG	810	870	1,400
CH_4	low LNG	0.02	0.25	1.60
	high LNG	0.02	1.20	4.80
N_2O	low LNG	0.04	0.04	0.07
	high LNG	0.04	0.04	0.06
HFC		37	39	61
PFC		0	0	0
SF_6		0	0	0
Other substances				
NO_x	constant ECA	24	25	37
	more ECAs	24	24	30
SO_2	constant ECA	5.90	3.80	1.70
	more ECAs	5.90	3.30	1.10
PM	constant ECA	1.70	1.30	1.30
	more ECAs	1.70	1.10	0.90
NMVOC	constant ECA	0.80	0.87	1.40
	more ECAs	0.80	0.86	1.30
CO	constant ECA	0.72	0.81	1.40
	more ECAs	0.72	0.89	1.70

Table 71 – *Scenarios 3 and 11 (RCP4.5, SSP3, high efficiency)*

Greenhouse gases		**2012**	**2020**	**2050**
CO_2	low LNG	810	870	850
	high LNG	810	850	810
CH_4	low LNG	0.02	0.25	0.94
	high LNG	0.02	1.20	2.90
N_2O	low LNG	0.04	0.04	0.04
	high LNG	0.04	0.04	0.04
HFC		37	39	40
PFC		0	0	0
SF_6		0	0	0
Other substances				
NO_x	constant ECA	24	25	22
	more ECAs	24	23	18
SO_2	constant ECA	5.90	3.70	1.00
	more ECAs	5.90	3.20	0.66
PM	constant ECA	1.70	1.30	0.80
	more ECAs	1.70	1.10	0.54
NMVOC	constant ECA	0.80	0.86	0.84
	more ECAs	0.80	0.84	0.81
CO	constant ECA	0.72	0.80	0.85
	more ECAs	0.72	0.88	1.00

Table 72 – *Scenarios 4 and 12 (RCP2.6, SSP4, high efficiency)*

Greenhouse gases		**2012**	**2020**	**2050**
CO_2	low LNG	810	870	1,100
	high LNG	810	850	1,000
CH_4	low LNG	0.02	0.25	1.20
	high LNG	0.02	1.20	3.60
N_2O	low LNG	0.04	0.04	0.05
	high LNG	0.04	0.04	0.05
HFC		37	39	49
PFC		0	0	0
SF_6		0	0	0
Other substances				
NO_x	constant ECA	24	25	27
	more ECAs	24	23	22
SO_2	constant ECA	5.90	3.70	1.30
	more ECAs	5.90	3.20	0.81
PM	constant ECA	1.70	1.30	0.99
	more ECAs	1.70	1.10	0.66
NMVOC	constant ECA	0.80	0.86	1.00
	more ECAs	0.80	0.84	1.00
CO	constant ECA	0.72	0.80	1.10
	more ECAs	0.72	0.88	1.30

Table 73 – *Scenarios 5 and 13 (RCP8.5, SSP5, low efficiency)*

Greenhouse gases		**2012**	**2020**	**2050**
CO_2	low LNG	810	910	2,800
	high LNG	810	890	2,700
CH_4	low LNG	0.02	0.26	3.10
	high LNG	0.02	1.20	9.50
N_2O	low LNG	0.04	0.04	0.14
	high LNG	0.04	0.04	0.13
HFC		37	40	110
PFC		0	0	0
SF_6		0	0	0
Other substances				
NO_x	constant ECA	24	26	72
	more ECAs	24	24	59
SO_2	constant ECA	5.90	3.90	3.30
	more ECAs	5.90	3.40	2.20
PM	constant ECA	1.70	1.30	2.60
	more ECAs	1.70	1.10	1.80
NMVOC	constant ECA	0.80	0.89	2.80
	more ECAs	0.80	0.88	2.70
CO	constant ECA	0.72	0.83	2.80
	more ECAs	0.72	0.91	3.40

Table 74 – *Scenarios 6 and 14 (RCP6.0, SSP1, low efficiency)*

Greenhouse gases		**2012**	**2020**	**2050**
CO_2	low LNG	810	890	2,100
	high LNG	810	870	2,000
CH_4	low LNG	0.02	0.25	2.30
	high LNG	0.02	1.20	7.10
N_2O	low LNG	0.04	0.04	0.10
	high LNG	0.04	0.04	0.09
HFC		37	39	85
PFC		0	0	0
SF_6		0	0	0
Other substances				
NO_x	constant ECA	24	25	54
	more ECAs	24	24	43
SO_2	constant ECA	5.90	3.80	2.50
	more ECAs	5.90	3.30	1.60
PM	constant ECA	1.70	1.30	1.90
	more ECAs	1.70	1.10	1.30
NMVOC	constant ECA	0.80	0.87	2.10
	more ECAs	0.80	0.86	2.00
CO	constant ECA	0.72	0.81	2.10
	more ECAs	0.72	0.89	2.50

Table 75 – *Scenarios 7 and 15 (RCP4.5, SSP3, low efficiency)*

Greenhouse gases		**2012**	**2020**	**2050**
CO_2	low LNG	810	870	1,200
	high LNG	810	850	1,200
CH_4	low LNG	0.02	0.25	1.40
	high LNG	0.02	1.20	4.20
N_2O	low LNG	0.04	0.04	0.06
	high LNG	0.04	0.04	0.06
HFC		37	39	54
PFC		0	0	0
SF_6		0	0	0
Other substances				
NO_x	constant ECA	24	25	32
	more ECAs	24	23	26
SO_2	constant ECA	5.90	3.70	1.50
	more ECAs	5.90	3.20	0.95
PM	constant ECA	1.70	1.30	1.20
	more ECAs	1.70	1.10	0.77
NMVOC	constant ECA	0.80	0.86	1.20
	more ECAs	0.80	0.84	1.20
CO	constant ECA	0.72	0.80	1.20
	more ECAs	0.72	0.88	1.50

Table 76 – *Scenarios 8 and 16 (RCP2.6, SSP4, low efficiency)*

Greenhouse gases		**2012**	**2020**	**2050**
CO_2	low LNG	810	870	1,500
	high LNG	810	850	1,500
CH_4	low LNG	0.02	0.25	1.70
	high LNG	0.02	1.20	5.20
N_2O	low LNG	0.04	0.04	0.07
	high LNG	0.04	0.04	0.07
HFC		37	39	66
PFC		0	0	0
SF_6		0	0	0
Other substances				
NO_x	constant ECA	24	25	39
	more ECAs	24	23	32
SO_2	constant ECA	5.90	3.70	1.80
	more ECAs	5.90	3.20	1.20
PM	constant ECA	1.70	1.30	1.40
	more ECAs	1.70	1.10	0.96
NMVOC	constant ECA	0.80	0.86	1.50
	more ECAs	0.80	0.84	1.40
CO	constant ECA	0.72	0.80	1.50
	more ECAs	0.72	0.88	1.80